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4D Printing: Technology Overview and Smart Materials Utilized

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Abstract: 4D printing is a cutting-edge technology that allows for the creation of dynamic, self-assembling structures by utilizing cutting edge, newly introduced smart materials. It builds upon traditional 3D printing by adding the dimension of time, allowing printed objects to change shape or behavior over time. This is achieved through the use of smart materials, such as shape memory alloys or polymers, which respond to external stimuli such as heat or moisture. These materials are engineered to have specific properties that can be triggered by specific conditions such as temperature, humidity, light, or other physical forces. 4D printing enables the creation of structures that can adapt to their environment and perform specific functions, such as objects that change shape in response to temperature changes, or structures that can self-assemble in response to a specific trigger. Overall, 4D printing is an exciting and rapidly advancing technology that has the potential to revolutionize the way we design and create structures. The ability to create structures that can change shape or behavior over time opens up new possibilities for a wide range of applications. As the technology continues to evolve, we can expect to see more innovative uses of 4D printing in a wide range of scientific fields such as architecture, aerospace, and biomedical engineering demanding the creation of highly complex and dynamic structures that can adapt to changing environments.

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

Introduction

4D printing and smart materials are two cutting edge technologies that are being used to create the next generation of products (Tsaramirsis *et al*., 2022; Dalenogare *et al*., 2018). 4D printing is an extension of 3D printing (Kantaros *et al*., 2022; 2021; Kantaros and Piromalis, 2021a; Gibson, 2017) that involves the integration of smart materials into the printing process, allowing for the creation of objects that can change shape or properties over time in response to external stimuli such as temperature, light, or pressure. Smart materials, on the other hand, are materials that can change their properties in response to external stimuli such as temperature, light, or pressure. Together, these technologies can be used to create a new generation of products that are more functional, versatile, and adaptable than anything we've seen before.

One of the main problems that 4D printing aims to solve is the design and fabrication of objects that can adapt to changing environmental conditions or perform specific functions in response to external stimuli. For example, 4D printed objects could be used in various fields, such as biomedical engineering, aerospace, architecture, and robotics. Overall, the goal of 4D printing is to create objects that are more versatile, adaptive, and efficient than their 3D printed counterparts and that can potentially address a range of complex problems in various industries.

4D Printing

4D printing is a relatively new technology that combines the principles of 3D printing with the fourth dimension of time. 4D printing refers to the ability to print 3D objects that can change shape or function over time, without the need for manual intervention. This is achieved by incorporating smart materials, such as shape memory alloys and polymers, into the 3D printing process (Chu *et al*., 2020; Mahmood *et al*., 2022; González-Henríquez *et al*., 2022).

One of the major advantages of 4D printing is that it enables the creation of highly complex and dynamic structures that can adapt to changing environments. For example, 4D printed structures can be designed to change shape in response to temperature, humidity, or other environmental factors. This can have a wide range of

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applications in fields such as architecture, aerospace, and biomedical engineering (Ge *et al*., 2014).

Another advantage of 4D printing is that it allows for the creation of self-assembling and self-healing structures. For example, 4D-printed structures can be designed to automatically assemble themselves into a desired shape, without the need for manual intervention. Additionally, 4D printed structures can be designed to repair themselves in the event of damage, which can be beneficial in fields such as transportation and construction (Tibbits, 2014).

Despite its potential, 4D printing is still a relatively new technology and there are many challenges that need to be addressed before it can be widely adopted. One of the major challenges is the need to develop new materials and techniques that can be used in the 4D printing process. Additionally, there are also many open questions surrounding the ethical and legal implications of 4D printing, such as issues related to intellectual property and liability.

Smart Materials

Smart materials are materials that can change their properties in response to external stimuli such as temperature, light, or electromagnetic fields. These materials have been used in a variety of applications, including aerospace, automotive, and biomedical engineering. However, they are especially relevant in the field of 4D printing, where they are used to create 3D printed objects that can change shape or function over time (Sharma *et al*., 2022; Zhang *et al*., 2022a).

Shape Memory Alloys (SMAs) are one of the most commonly used smart materials in 4D printing. Shape Memory Alloys (SMAs) are a type of smart material that can change shape when heated or cooled and can return to their original shape when the temperature changes again. These alloys are made up of a combination of metals, such as nickel titanium or copper zinc aluminum, that exhibit the unique property of shape memory. The ability of these alloys to return to their original shape, known as the "memory effect," is due to a phase transformation, which occurs at a specific temperature range (Shukla and Garg, 2022).

SMAs have a wide range of applications in various fields such as aerospace, automotive, biomedical, and, especially relevant, 4D printing. In 4D printing, they can be used to create structures that can change shape in response to temperature changes. For example, a 4D printed structure made from SMAs could be designed to open or close in response to changes in temperature, which can improve energy efficiency in buildings. Additionally, SMAs can also be used in medical applications such as implantable stents, orthodontic wires, and even artificial muscles. Other applications include actuators, sensors, and dampers in the aerospace and automotive industries. These properties make them ideal for creating 4D printed objects that can change shape in response to temperature. For example, a 4D printed structure made from shape memory alloys could be designed to close or open in response to changes in temperature, which can improve energy efficiency in buildings (Zhang *et al*., 2022b; Srivastava *et al*., 2022; Chiu *et al*., 2022; Hariri *et al*., 2022; Li *et al*., 2022; Ruth *et al*., 2022).

Another class of smart materials used in 4D printing is Shape Memory Polymers (SMPs). Shape Memory Polymers (SMPs) are a type of smart materials that exhibit the ability to change shape in response to external stimuli, such as temperature, light, pH, or pressure. These polymers can be designed to return to their original shape after deformation, which is known as the shape memory effect. SMPs are typically composed of a thermoresponsive polymer and a crosslinking agent, which allows the polymer to retain its shape after heating and cooling (Khalid *et al*., 2022a; Dayyoub *et al*., 2022).

SMPs have a wide range of potential applications in various fields such as biomedical engineering, aerospace, and, especially relevant, 4D printing. In 4D printing, SMPs can be used to create structures that can self-assemble or self-fold. This property makes them suitable for creating complex structures such as medical implants, drug delivery devices, and even robots. Additionally, these polymers can also be used in areas such as packaging, textiles, and construction. They can be used to create self-healing materials, flexible hinges, and even smart textiles. SMPs have the potential to revolutionize the way we design and build structures and the possibilities are endless (Pisani *et al*., 2022; Zhang *et al*., 2022c; Zeng *et al*., 2022; Ramezani and Monroe, 2022; Razzaq *et al*., 2022).

Piezoelectric materials are also used in 4D printing. Piezoelectric materials are a type of smart materials that have the ability to generate an electrical current when subjected to mechanical stress and also can change shape when an electrical current is applied to them. These materials are made of crystals or ceramics that have a specific crystal structure, such as quartz or barium titanate. The piezoelectric effect is due to the alignment of the crystal structure, which generates an electrical charge when the material is deformed (Behera, 2022; Sekhar *et al*., 2022).

Piezoelectric materials have a wide range of applications in various fields, such as energy generation, sensors and actuators, and, especially relevant, 4D printing. In 4D printing, piezoelectric materials can be used to create structures that can change shape in response to external forces, such as wind or water flow. They can be used to generate energy through the piezoelectric effect and can also be used as sensors and actuators. For example, piezoelectric materials can be used to create flexible and efficient energy harvesting devices, such as shoe insoles that generate energy when a person walks. Additionally, they can also be used to create structures that can move or change shape in response to external forces (Meng *et al*., 2022; Habib *et al*., 2022; Sheeraz *et al*., 2022).

In this context, the importance of smart materials is vital for the proper functionality of 4D printing technology. The following section discusses the unique characteristics and properties of such materials.

Smart Materials Utilized in 4D Printing

A classification of smart materials utilized in the field of 4D printing is depicted in Fig. 1.

Shape Memory Alloys (SMAs) are a type of smart material that can change shape when heated or cooled and can return to their original shape when the temperature changes again. These alloys are made up of a combination of metals, such as Nickel Titanium (NiTi) or Copper Zinc Aluminium (CuZnAl), that exhibit the unique property of shape memory. The ability of these alloys to return to their original shape, known as the "memory effect," is due to a phase transformation, which occurs at a specific temperature range.

NiTi alloys are the most widely used shape memory alloys due to their excellent shape memory properties, biocompatibility, and corrosion resistance. They can be used in medical devices such as stents, orthodontic wires, and even artificial muscles. Additionally, NiTi alloys can be used in aerospace, automotive, and civil engineering for actuators, sensors, and dampers (Samal *et al*., 2022; Teixeira *et al*., 2022).

CuZnAl alloys, on the other hand, are a new class of shape memory alloys that have a low transformation temperature and high thermal stability, making them suitable for use in high temperature applications, such as aerospace and automotive. They also have good corrosion resistance, making them suitable for use in harsh environments. CuZnAl alloys have been used in the aerospace industry for actuators, sensors, and dampers. They have also been used in the automotive industry for engine valves, suspension systems, and exhaust systems (Huang *et al*., 2022; Nithyanandh *et al*., 2023).

Shape Memory Polymers (SMPs) are a type of smart material that exhibits the ability to change shape in response to external stimuli, such as temperature, light, pH, or pressure. These polymers can be designed to return to their original shape after deformation, which is known as the shape memory effect. SMPs are typically composed of a thermoresponsive polymer and a crosslinking agent, which allows the polymer to retain its shape after heating and cooling.

One of the most important and widely used SMPs is Polyurethane (PU) based SMPs. These polymers have a good thermal response, mechanical properties, and processability, making them suitable for various applications such as biomedical engineering and 4D printing. PU-based SMPs have been used to create self-assembling and self-healing structures, drug delivery systems, and even robots. Additionally, PU-based SMPs have been used in the field of textiles, creating smart fabrics that can change shape and properties in response to temperature or light (Sikdar *et al*., 2022; Du *et al*., 2022).

Fig. 1: Smart materials used in the 4D printing field

Another important SMP is the Poly Ethylene Oxide (PEO) based SMPs. These polymers have a good thermal response and a high glass transition temperature, making them suitable for high temperature applications. PEO based SMPs have been used to create self-healing materials, flexible hinges, and even smart textiles. Additionally, these polymers have been used in the field of biomedical engineering for creating implantable medical devices that can change shape or function over time. In conclusion, SMPs are a versatile and promising class of smart materials that have the ability to change shape in response to various stimuli and return to their original shape. Polyurethane based and polyethylene oxide based SMPs are among the most important and widely used SMPs (Arif *et al*., 2022; Wang *et al*., 2022a).

Piezoelectric materials discussed earlier in the manuscript, are also a type of smart materials. One of the most important and widely used piezoelectric materials is lead Zirconate Titanate (PZT). PZT is a ceramic material that can generate a large amount of electrical charge in response to mechanical stress. PZT has a good piezoelectric coefficient and can be used in a wide range of applications, such as actuators, sensors, and energy harvesters. PZT has been used in medical devices such as ultrasonic imaging, in the aerospace and automotive industry for actuators, and even in the field of robotics for creating flexible and efficient energy harvesting devices (Koh *et al*., 2022).

Another important piezoelectric material is Lithium Niobate ($LiNbO_3$). $LiNbO_3$ is a crystalline material that can be used to create optical devices, such as modulators and waveguides, and has been used in telecommunications and optical signal processing. $LiNbO_3$ has a good piezoelectric coefficient and can be used in a wide range of applications, such as actuators,

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sensors, and energy harvesters. Additionally, $LiNbO_3$ can be used to create structures that can move or change shape in response to external forces, such as wind or water flow. Piezoelectric materials are a versatile and promising class of smart materials that have the ability to generate an electrical current when subjected to mechanical stress and also can change shape when an electrical current is applied to them. Lead Zirconate Titanate (PZT) and Lithium Niobate ($LiNbO_3$) are among the most important and widely used Piezoelectric materials (Palatnikov *et al*., 2023).

Magneto Rheological (MR) fluids are a type of smart material that can change viscosity in response to a magnetic field. These fluids are typically composed of small, micron sized particles suspended in a liquid carrier. The particles are typically made of iron or other magnetic materials and when exposed to a magnetic field, they align and create anisotropy in the fluid, which leads to a change in viscosity (Ramkumar *et al*., 2022).

One of the most important and widely used MR fluids is ferrofluid. Ferrofluid is a liquid that contains iron particles suspended in a carrier liquid such as water, oil, or kerosene. Ferrofluid can be used to create structures that can change shape in response to a magnetic field, making it useful in various fields such as robotics, aerospace, and biomedical engineering. Ferrofluid can be used to create actuators and dampers and also to create structures that can move or change shape in response to external forces, such as wind or water flow (Oehlsen *et al*., 2022).

Another important MR fluid is the carbonyl iron powder (CIP) based MR fluid. CIP-based MR fluid is a type of MR fluid that uses carbonyl iron powder as the magnetic particle. CIP-based MR fluid has high responsiveness, high stability, and high durability. CIP based MR fluids have been used in various fields such as aerospace and automotive for actuators and also in the field of robotics for creating flexible and efficient energy harvesting devices. MR fluids are a versatile and promising class of smart materials that can change viscosity in response to a magnetic field. Ferrofluid and Carbonyl Iron Powder (CIP) based MR fluids are among the most important and widely used MR fluids (Ha *et al*., 2022).

Thermochromic materials are a type of smart materials that change color or opacity in response to temperature changes. These materials are typically made of inorganic or organic compounds that exhibit a reversible change in color or opacity when the temperature changes. The color change is typically caused by a change in the crystal structure of the material or the movement of ions within the material (Hakami *et al*., 2022; Crosby and Netravali, 2022).

One of the most important and widely used thermochromic materials is Leuco dye. Leuco dyes are a class of colorless, organic compounds that can be used to create thermochromic inks and coatings. These dyes change color when they are heated and return to their original color when they are cooled. Leuco dyes have been used in various fields such as textiles, packaging, and security printing. They can be used to create smart fabrics that change color in response to temperature and also in packaging to indicate the temperature of the product inside (Sokolov *et al*., 2022; Sanjabi *et al*., 2023).

Another important thermochromic material is Vanadium (V) oxide. Vanadium (V) oxide is an inorganic compound that exhibits a reversible change in its crystal structure when the temperature changes, resulting in a change in its color. Vanadium (V) oxide has a broad range of applications in various fields such as energy harvesting, thermal imaging, and temperature sensing. Vanadium (V) oxide has been used in the field of building science, creating smart windows that change color in response to temperature changes, and also in the field of thermal imaging, creating devices that can detect the temperature of an object. Thermochromic materials are a versatile and promising class of smart materials that change color or opacity in response to temperature changes. Leuco dyes and Vanadium (V) oxide are among the most important and widely used thermochromic materials. They have been used in various fields such as textiles, packaging, security printing, energy harvesting, thermal imaging, and temperature sensing applications (Tolstopyatova *et al*., 2022; Faizan *et al*., 2022).

Photoresponsive polymers are a type of smart material that can change shape or properties in response to light. These polymers are typically composed of a polymer matrix and a light sensitive component, such as a chromophore or a photosensitizer, that is able to respond to specific wavelengths of light. The change in shape or properties can be caused by various mechanisms such as changes in the polymer's conformation, changes in the polymer's crosslinking or network structure, or changes in the polymer's refractive index (Lalan *et al*., 2022; Hu *et al*., 2022).

One of the most important and widely used photoresponsive polymers is Spiropyran (SP) based polymers. Spiropyran is a light sensitive component that can change its conformation when exposed to light, leading to a change in the polymer's properties. SP-based polymers have been used to create self-assembling and self-healing structures, drug delivery systems, and even robots. Additionally, SP-based polymers have been used in the field of textiles, creating smart fabrics that can change shape and properties in response to light (Rad *et al*., 2022).

Another important photoresponsive polymer is the Azobenzene (AB) based polymer. Azobenzene is a light sensitive component that can change its conformation when exposed to light, leading to a change in the polymer's properties. AB-based polymers have been used to create self-assembling and self-healing materials, flexible hinges, and even smart textiles. Additionally, these polymers have been used in the field of biomedical engineering for creating implantable medical devices that can change shape or function over time. Photoresponsive

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polymers are a versatile and promising class of smart materials that can change shape or properties in response to light. Spiropyran based and Azobenzene based polymers are among the most important and widely used photoresponsive polymers. They have been used in various fields such as biomedical engineering, textiles, and 4D printing, and have the potential to revolutionize the way we design and build structures (Drake *et al*., 2022).

Electroactive Polymers (EAPs) are a type of smart materials that can change shape or properties in response to an applied electric field. These polymers are typically composed of a polymer matrix and a component that can respond to an electric field, such as a conducting polymer or an ionic polymer. The change in shape or properties can be caused by various mechanisms such as changes in the polymer's conformation, changes in the polymer's crosslinking or network structure, or changes in the polymer's refractive index (Maksimkin *et al*., 2022; Engel *et al*., 2022).

One of the most important and widely used EAPs is Polypyrrole (PPy) based polymers. PPy is a conducting polymer that can change its conformation when an electric field is applied, leading to a change in the polymer's properties. PPy-based polymers have been used to create actuators, sensors, and energy harvesters. PPy-based polymers have been used in various fields such as robotics, aerospace, and biomedical engineering (Huo *et al*., 2022).

Another important EAP is the Poly Vinylidene Fluoride (PVDF) based polymers. PVDF is an ionic polymer that can change its conformation when an electric field is applied, leading to a change in the polymer's properties. PVDF-based polymers have been used to create actuators, sensors, and energy harvesters. PVDF based polymers have been used in various fields such as robotics, aerospace, and biomedical engineering. They have also been used in the field of building science, creating smart windows that can change their transparency in response to an applied electric field (Saxena and Shukla, 2022). Electroactive polymers are a versatile and promising class of smart materials that can change shape or properties in response to an applied electric field. Polypyrrole based and Poly (vinylidene fluoride) based polymers are among the most important and widely used EAPs.

Self-healing polymers are a type of smart material that can repair themselves when they are damaged. These polymers typically contain a healing agent, such as a liquid or a solid, that can flow or migrate to the damaged area and repair the polymer matrix. The healing agent can be triggered by various mechanisms such as temperature, pH, light, or mechanical stress (Bei *et al*., 2022).

One of the most important and widely used self-healing polymers is thermally activated self-healing polymers. These polymers contain a healing agent that is activated when the polymer is heated above a certain temperature. When the polymer is damaged, the healing agent flows to the damaged area and repairs the polymer matrix. Thermally activated self-healing polymers have been used to create self-healing coatings, adhesives, and even electronic devices (Zhang *et al*., 2022d).

Another important self-healing polymer is the pH sensitive self-healing polymer. These polymers contain a healing agent that is activated when the pH of the polymer changes. When the polymer is damaged, the healing agent flows to the damaged area and repairs the polymer matrix. pH-sensitive self-healing polymers have been used to create self-healing coatings, adhesives, and even electronic devices. They have also been used in the field of biomedical engineering, creating implantable medical devices that can repair themselves when they are damaged. Self-healing polymers are a versatile and promising class of smart materials that can repair themselves when they are damaged. Thermally activated self-healing polymers and pH-sensitive self-healing polymers are among the most important and widely used self-healing polymers. They have been used in various fields such as coatings, adhesives, electronic devices, and biomedical engineering (Zhao *et al*., 2022a).

Thermoplastic Elastomers (TPEs) are a type of smart materials that combine the properties of both thermoplastics and elastomers. These materials exhibit the flexibility of elastomers and the processability of thermoplastics. TPEs are typically composed of a thermoplastic polymer and a rubber polymer, which are blended together to create a material that has both elastic and plastic behavior. TPEs can be processed using various methods such as injection molding, extrusion, and blow molding (Steube *et al*., 2022).

One of the most important and widely used TPEs is Styrenic Block Copolymers (SBCs). These TPEs are composed of a styrene polymer and a rubber polymer, typically polybutadiene, which are blended together to create a material that has both elastic and plastic behavior. SBCs have good mechanical properties, good processability, and good resistance to chemicals, making them suitable for a wide range of applications such as seals, gaskets, and automotive parts (Maji and Naskar, 2022).

Another important TPE is Thermoplastic Polyurethanes (TPUs). TPUs are composed of a polyurethane polymer that can be processed using various methods such as injection molding, extrusion and blow molding. They have good mechanical properties, good resistance to chemicals, and good abrasion resistance. TPUs have been widely used in various applications such as automotive parts, medical devices, and industrial hoses. Thermoplastic elastomers are a versatile and promising class of smart materials that combine the properties of both thermoplastics and elastomers. Styrenic block copolymers and thermoplastic polyurethanes are among the most important and widely used TPEs. They have been used in various fields such as automotive, medical devices, and industrial hoses (Shehata *et al*., 2022).

Hydrogels are a type of smart material that is composed of a network of polymer chains that can absorb and retain large amounts of water. These materials can be made from a variety of natural or synthetic polymers, such as Polyethylene Glycol (PEG), Polyvinyl Alcohol (PVA), or alginate. Hydrogels have a wide range of mechanical properties, from soft and flexible to stiff and brittle, depending on their composition and structure (Manzoor *et al*., 2022).

One of the most important and widely used hydrogels is PEG-based hydrogels. PEG-based hydrogels are composed of polyethylene glycol (PEG) and have good mechanical properties, biocompatibility, and biodegradability. PEG-based hydrogels have been used in various biomedical applications such as tissue engineering, drug delivery, and wound healing. They can mimic the extracellular matrix and provide a suitable environment for cell growth and proliferation (Ghauri *et al*., 2022).

Another important hydrogel is alginate-based hydrogels. Alginate-based hydrogels are composed of a naturally derived polymer extracted from brown seaweed. They have good biocompatibility and biodegradability. Alginate-based hydrogels have been used in various biomedical applications such as tissue engineering, drug delivery, and wound healing. They can mimic the extracellular matrix and provide a suitable environment for cell growth and proliferation. Additionally, Alginate-based hydrogels have been used in the food industry as thickening agents and gelling agents. Hydrogels are a versatile and promising class of smart materials that can absorb and retain large amounts of water. PEG-based hydrogels and Alginate-based hydrogels are among the most important and widely used hydrogels. They have been used in various fields such as biomedical engineering, tissue engineering, drug delivery, wound healing, and the food industry (Murab *et al*., 2022; Antunes *et al*., 2022; Abdelbasset *et al*., 2022).

Applications

One of the most exciting applications of 4D printing and smart materials is in the field of architecture. 4D printing can be used to create complex and unique architectural designs that would be difficult or impossible to produce using traditional manufacturing methods. Smart materials can be used to make these structures more adaptable, by allowing them to change shape or stiffness in response to changes in temperature or pressure. This could lead to the development of buildings that are more energy efficient and resilient to natural disasters. For example, smart materials can be used to create windows that automatically adjust their tinting to control the amount of light entering a room or to create walls that expand or contract to regulate temperature.

4D printing and smart materials are revolutionizing the field of architecture, enabling architects and builders to create structures that are not only visually striking but also dynamic and responsive to the environment. 4D printing technology allows architects to embed smart materials into the design of a building, giving it the ability to change shape, properties, or functionality over time in response to external stimuli such as temperature, humidity, light, or even mechanical stress (Sakin and Kiroglu, 2017; Tay *et al*., 2017; Watkin, 2023). Figure 2 depicts a case where such an item exhibits 87% of volume reduction as a result of the application of external stimuli.

One of the most promising smart materials used in 4D printing in architecture is Shape Memory Alloys (SMAs) discussed earlier in the manuscript. It can be programmed to change shape in response to a specific temperature. This can be used in architecture to create self-adjusting structures that can change shape in response to temperature changes, such as window shutters that open and close to control the amount of light and heat entering the building or even self-adjusting bridges that can expand and contract in response to temperature changes.

Another important smart material used in 4D printing is Shape Memory Polymers (SMPs). SMPs can be programmed to change shape in response to various stimuli such as temperature, light, or pH. These materials can be used in architecture to create self-healing structures, such as façades that can repair cracks or damages, or even self-assembling structures that can change shape in response to external conditions.

Piezoelectric materials are also used in 4D printing in architecture. These materials can generate an electrical charge when they are deformed, which can be used to create self-powered structures such as self-powered lighting systems or even self-powered sensors that can monitor the structural integrity of a building.

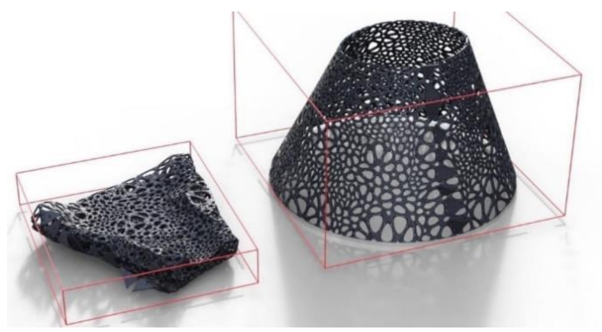

Fig. 2: 87% of volume reduction as a result of the application of external stimuli (3D Learning Hub, 2023)

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In conclusion, 4D printing and smart materials are transforming the field of architecture by enabling architects to create structures that are not only visually striking but also dynamic and responsive to the environment. With the ability to embed smart materials into the design of a building, architects can create structures that are not only more energy efficient and sustainable but also more adaptable to the environment. 4D printing technology can also improve the safety and longevity of buildings by creating self-healing and self-monitoring structures, which can prevent or repair damage and detect structural issues before they become critical. Furthermore, 4D printing allows architects to create new forms and shapes that were not possible before, making architecture more expressive, dynamic, and engaging. Overall, 4D printing and smart materials have the potential to revolutionize the way we design and build structures, making them more resilient, efficient, and adaptive to the environment.

Another potential application of 4D printing and smart materials is in the field of transportation. 4D printing and smart materials are revolutionizing the field of transportation, enabling engineers and manufacturers to create vehicles and transportation systems that are not only more efficient but also more adaptable to the environment. 4D printing technology allows engineers to embed smart materials into the design of transportation systems, giving them the ability to change shape, properties, or functionality over time in response to external stimuli such as temperature, stress, or even energy (Khalid *et al*., 2022b; Ntouanoglou *et al*., 2018; Haleem *et al*., 2021; Li *et al*., 2017). Figure 3 depicts a relevant automotive part fabricated in an aforementioned way.

One of the most promising smart materials used in 4D printing in transportation is Shape Memory Alloys (SMAs). SMAs can be programmed to change shape in response to a specific temperature, which can be used in transportation systems to create self-adjusting structures that can change shape in response to temperature changes, such as wing flaps that can adjust their shape to optimize aerodynamics, or even self-adjusting suspension systems that can adapt to different road conditions.

Fig. 3: Additive manufactured automotive part (Carlota, 2022)

Another important smart material used in 4D printing is Shape Memory Polymers (SMPs). These materials can be used in transportation systems to create self-healing structures, such as tires that can repair punctures or damages, or even self-assembling structures that can change shape in response to external conditions.

Piezoelectric materials are also used in 4D printing in transportation. These materials can generate an electrical charge when they are deformed, which can be used to create self-powered systems such as self-powered lighting systems or even self-powered sensors that can monitor the structural integrity of a vehicle.

Thus, 4D printing and smart materials are transforming the field of transportation by enabling engineers to create vehicles and transportation systems that are not only more efficient but also more adaptable to the environment. With the ability to embed smart materials into the design of transportation systems, engineers can create structures that are more resilient, energy efficient, and adaptive to the environment. 4D printing technology can also improve the safety and longevity of transportation systems by creating self-healing and self-monitoring structures, which can prevent or repair damage and detect structural issues before they become critical. Overall, 4D printing and smart materials have the potential to revolutionize the way we design and build transportation systems, making them more efficient, adaptable, and sustainable.

The medical field is also a potential application of 4D printing and smart materials (Wang *et al*., 2022b; Osouli-Bostanabad *et al*., 2022; Mallakpour *et al*., 2022; Kantaros and Piromalis, 2021b; 2022; Kantaros *et al*., 2021; Kantaros, 2022a-b). 4D printing and smart materials are revolutionizing the field of medicine, enabling medical researchers and practitioners to create medical devices and implants that are not only more effective but also more adaptable to the patient's body. 4D printing technology allows researchers and practitioners to embed smart materials into the design of medical devices and implants, giving them the ability to change shape, properties, or functionality over time in response to the patient's body. Figure 4 depicts a computer image of 4D printed airway splints, which grow over time to help babies breathe.

Fig. 4: A computer image of 4D printed airway splints, which grow over time to help babies breathe (Medical Technology, 2023)

One of the most promising smart materials used in 4D printing in medicine is hydrogels. Hydrogels are a class of materials that can absorb and retain large amounts of water, which can be used in medical devices and implants to create structures that mimic the extracellular matrix and provide a suitable environment for cell growth and proliferation. Hydrogels can also be designed to release drugs or other therapeutic agents in a controlled manner, which can improve the effectiveness of treatments (Malekmohammadi *et al*., 2021; Champeau *et al*., 2020).

A smart material category earlier discussed in the manuscript and used in 4D printing is Shape Memory Polymers (SMPs). SMPs can be programmed to change shape in response to various stimuli such as temperature, pH, or mechanical stress. These materials can be used in medical devices and implants to create self-healing structures, such as stents that can repair themselves when they are damaged, or even self-assembling structures that can change shape in response to the patient's body (Zhao *et al*., 2022b).

Piezoelectric materials are also used in 4D printing in medicine. These materials can generate an electrical charge when they are deformed, which can be used to create self-powered systems such as self-powered sensors that can monitor the health of a patient or even self-powered prosthetic devices that can respond to the patient's movement (Grinberg *et al*., 2019).

In this context, 4D printing and smart materials are transforming the field of medicine by enabling researchers and practitioners to create medical devices and implants that are not only more effective but also more adaptable to the patient's body. With the ability to embed smart materials into the design of medical devices and implants, researchers and practitioners can create structures that are more resilient, efficient, and adaptive to the patient's body. 4D printing technology can also improve the safety and longevity of medical devices and implants by creating self-healing and self-monitoring structures, which can prevent or repair damage and detect health issues before they become critical. Overall, 4D printing and smart materials have the potential to revolutionize the way we design and build medical devices and implants, making them more effective, adaptable, and sustainable.

Results and Discussion

4D printing is a cutting-edge technology that allows for the creation of dynamic, self-assembling structures. It builds upon traditional 3D printing by adding the dimension of time, allowing printed objects to change shape or behavior over time. This is achieved through the use of smart materials, such as shape memory alloys or polymers, which respond to external stimuli such as heat or moisture.

One of the main advantages of 4D printing is its ability to create structures that can adapt to their environment and perform specific functions. This opens up new possibilities for a wide range of applications in fields such as architecture, medicine, and robotics. For example, in architecture, 4D printing can be used to create buildings that can adapt to changing weather conditions, such as by opening and closing windows or shading systems in response to sunlight. In medicine, 4D printed structures can be used to create medical devices that can change shape or behavior in response to changes in the body. In robotics, 4D printing can be used to create robots that can change shape or function in response to specific conditions.

However, 4D printing also has some downsides (Kantaros and Karalekas, 2013; 2014; Kantaros *et al*., 2013; Petrescu and Petrescu, 2019; Petrescu *et al*., 2017; Aversa *et al*., 2016a-b). One of the main challenges is that the technology is still in its early stages of development and there are many technical hurdles that need to be overcome. Additionally, 4D printed structures can be quite complex and difficult to design, which can limit the number of people who are able to use the technology. Furthermore, the cost of 4D printing can be quite high, which can limit its accessibility to many individuals and organizations.

Another downside is that the smart materials used in 4D printing are still relatively new and their long-term performance and durability are not yet fully understood. The smart materials also might have some environmental issues and hazards and their disposal may require special consideration.

Overall, 4D printing is an exciting and rapidly advancing technology that has the potential to revolutionize the way we design and create structures. While it offers many advantages, there are also some downsides that need to be considered. As the technology continues to evolve, it will be important to address these challenges in order to fully realize the potential of 4D printing.

Conclusion

In conclusion, 4D printing and smart materials are emerging technologies that have the potential to revolutionize the way we design and create products. 4D printing allows for the creation of products that can change shape or function over time, which can increase efficiency and effectiveness. Additionally, 4D printing can reduce waste and costs by creating products that can be used for multiple purposes. Smart materials also have many advantages, such as the ability to change properties in response to external stimuli, which opens up many new possibilities in manufacturing.

However, it is important to note that 4D printing and smart materials are still relatively new technologies and there are limitations and potential risks to consider. 4D printed products may be more expensive to produce than traditional products and it may be difficult to predict how they will behave over time. Smart materials are also relatively new and more research is needed to fully understand how they behave over time. Additionally, smart materials are often more expensive than traditional materials.

Despite these limitations, 4D printing and smart materials have the potential to greatly benefit many industries in the future. It is important to continue researching and developing these technologies to fully realize their potential while also addressing their limitations.

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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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