Introduction to 4D printing technology and its applications in the field of mechanical engineering

(Part 1)

https://b2n.ir/4dprinting

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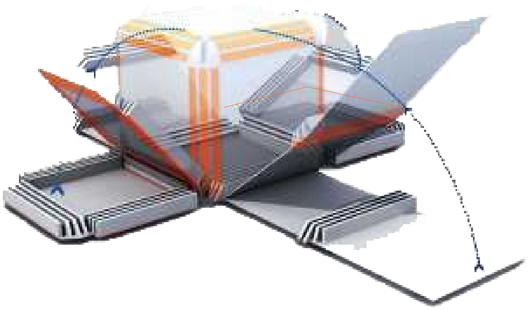


Abstract

Research into 4D printing has attracted unprecedented interest since 2013 when the idea was first introduced. It is based on 3D printing technology, but requires additional stimulus and stimulus- responsive materials. Based on certain interaction mechanisms between the stimulus and smart materials, as well as appropriate design of multi-material structures from mathematical modeling, 4D printed structures evolve as a function of time and exhibit intelligent behavior. Stimuli such as heat, humidity, pH, and light trigger the actuation of printed objects without motors or wires. Smart materials that respond to external stimuli are good candidates for 4D printing. Unlike 3D printing, 4D printing is time dependent, printer-independent, predictable, and targets shape, property and functionality evolution. This allows for self-assembly, multi-functionality, and self-repair.

This research presents a comprehensive review of the 4D printing process and summarizes the practical concepts in different fields especially engineering and related tools that have a prominent role in this field.

https://www.aparat.com/v/ln4DF/4d_printing

1. Introduction

3D printing was invented in the 1980s and has been applied in various fields, ranging from biomedical science to space science. 4D printing, a recently developed field originating from 3D printing, shows promising capabilities and broad potential applications.

4D printing was initiated and termed by a research group at MIT (Tibbits [1]). It relies on the fast growth of smart materials, 3D printers, and mathematical modeling and design (Choi et al. [2]). 4D printing shows advantages over 3D printing in several aspects (Jacobsen [3]).

In this review, a general guideline is provided by deconstructing the 4D printing process into several main sections.

These sections include definition, scope, motivation, shapeshifting behaviors, material structures, materials, shape- shifting mechanisms and stimuli, mathematics, and applications.

1.1. Definition

4D printing was initially defined as 4D printing = 3D printing + time (Fig. 1), where the shape, property, or functionality of a 3D printed structure can change as a function of time (Tibbits [1]), (Tibbits [4]), (Tibbits et al. [5]), (Ge et al. [6]), (Pei [7]), and (Khoo et al. [8]). As the number of studies conducted on this technology increases, a more comprehensive definition of 4D printing is presented here. 4D printing is a targeted evolution of the 3D printed structure, in terms of shape, property, and functionality. It is capable of achieving self-assembly, multi-functionality and nd self-repair.

It is time-dependent, printer-independent, and predictable. As mentioned above, 4D printing can fabricate dynamic structures with adjustable shapes, properties, or functionality (Tibbits et al. [5], Pei [7] and Gladman et al. [10]).

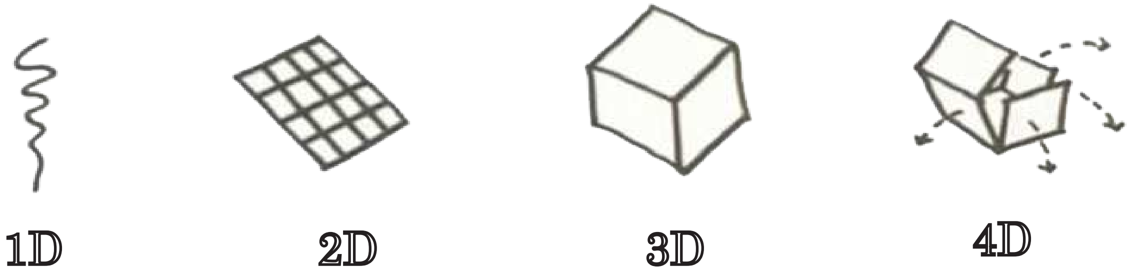
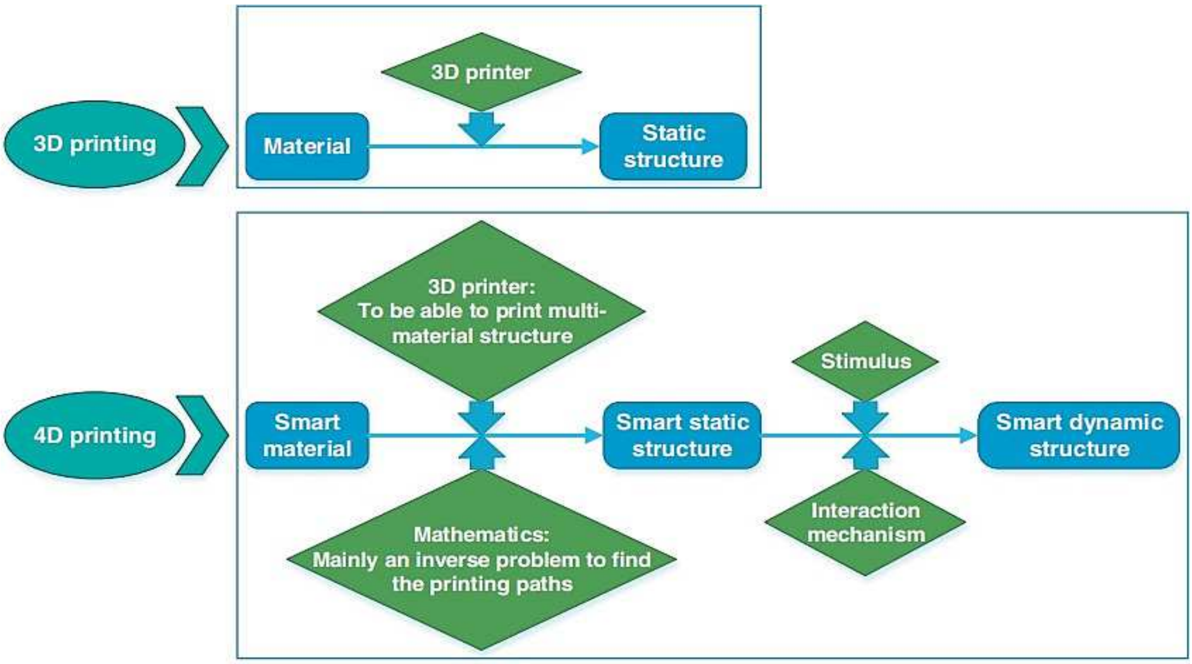


fig. 1. A simple illustration of the concept of 4D printing

This capability mainly relies on an appropriate combination of smart materials in the threedimensional space (Gladman et al., 2016) [10].

Mathematical modeling is required for the design of the distribution of multiple materials in the structure. There are at least two stable states in a 4D printed structure, and the structure can shift from one state to another under the corresponding stimulus (Zhou et al. [11]). The main differences between 3D printing and 4D printing are illustrated in Fig. 2.

As illustrated in Fig. 3, the fundamental building blocks of 4D printing are 3D printing facility, stimulus, stimulus-responsive material, interaction mechanism, and mathematical modeling.



.**fig. 2.** the differences between 3D printing and 4D printing

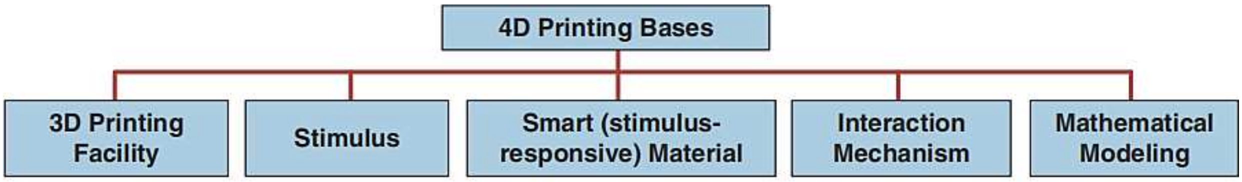


fig. 3. 4D printing bases

These elements enable targeted and predictable evolution of 4D printed structures over time and are discussed in further detail below:

• 3D printing facility:

Usually, a 4D printed structure is created by combining several materials in the appropriate distribution into a single, one-time printed structure (Raviv et al. [12]). The differences in material properties, such as swelling ratio and thermal expansion coefficient, will lead to the desired shape-shifting behavior.

Therefore, 3D printing is necessary for the fabrication of multi-material structures with simple geometry.

• Stimulus:

Stimulus is required to trigger the alterations of shape/ property/functionality of a 4D printed structure. The stimuli that researchers have used in 4D printing thus far include water [4,5,10,12,13], heat [6,14–18], a combination of heat and light [19], and a combination of water and heat [10,20]. The selection of the stimulus depends on the requirements of the specific application, which also determines the types of smart materials employed in the 4D printed structure.

• Smart or stimulus-responsive material:

stimulus-responsive material is one of the most critical components of 4D printing. Stimulus-responsive materials can be classified into several sub- categories, as shown in Fig. 4.

The capability of this group of materials is defined by the following characteristics: selfsensing, decision making, responsiveness, shape memory, selfadaptability, multi-functionality [8], and self- repair. Several review studies on stimulus-responsive materials have been provided by Roy et al. [21], Stuart et al. [22], Sun et al. [23], and Menget al. [24].

• Interaction mechanism:

In some cases, the desired shape of a 4D printed structure is not directly achieved by simply exposing the smart materials to the stimulus. The stimulus needs to be applied in a certain sequence under an appropriate amount of time, which is referred to as the interaction mechanism in this review paper. For example, one of the main interaction mechanisms is constrained-thermo-mechanics. In this mechanism, the stimulus is heat and the smart material has the shape memory effect. It contains a 4-step cycle. First, the structure is deformed by an external load at a high temperature; second, the temperature is lowered while the external load is maintained; third, the structure is unloaded at the low temperature and the desired shape is achieved; fourth, the original shape can be recovered by reheating the structure.

• Mathematical Modeling:

Math is necessary for 4D printing in order to design the material distribution and structure needed to achieve the desired change in shape, property, or functionality. Theoretical and numerical models need to be developed to establish the connections between four core elements: material structure, desired final shape, material properties, and stimulus properties. These will be discussed in additional detail in the following sections.

A 4D printed structure can be regarded as a child born from the marriage between a 3D printer and smart materials. It can walk by being exposed to the external stimulus through an interaction mechanism, and it learns how to walk properly with the assistance of mathematics.

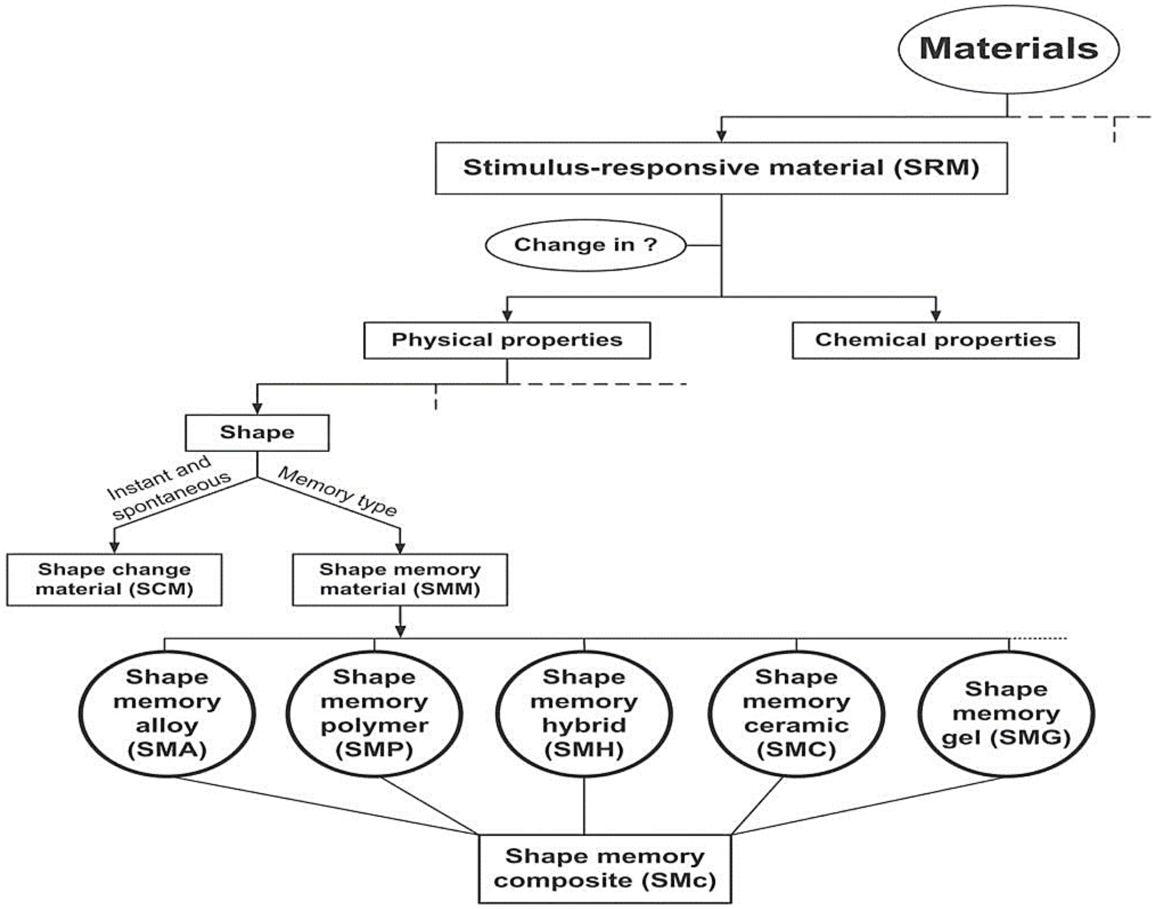


fig. 4. stimulus-responsive materials

1.2. Motivations

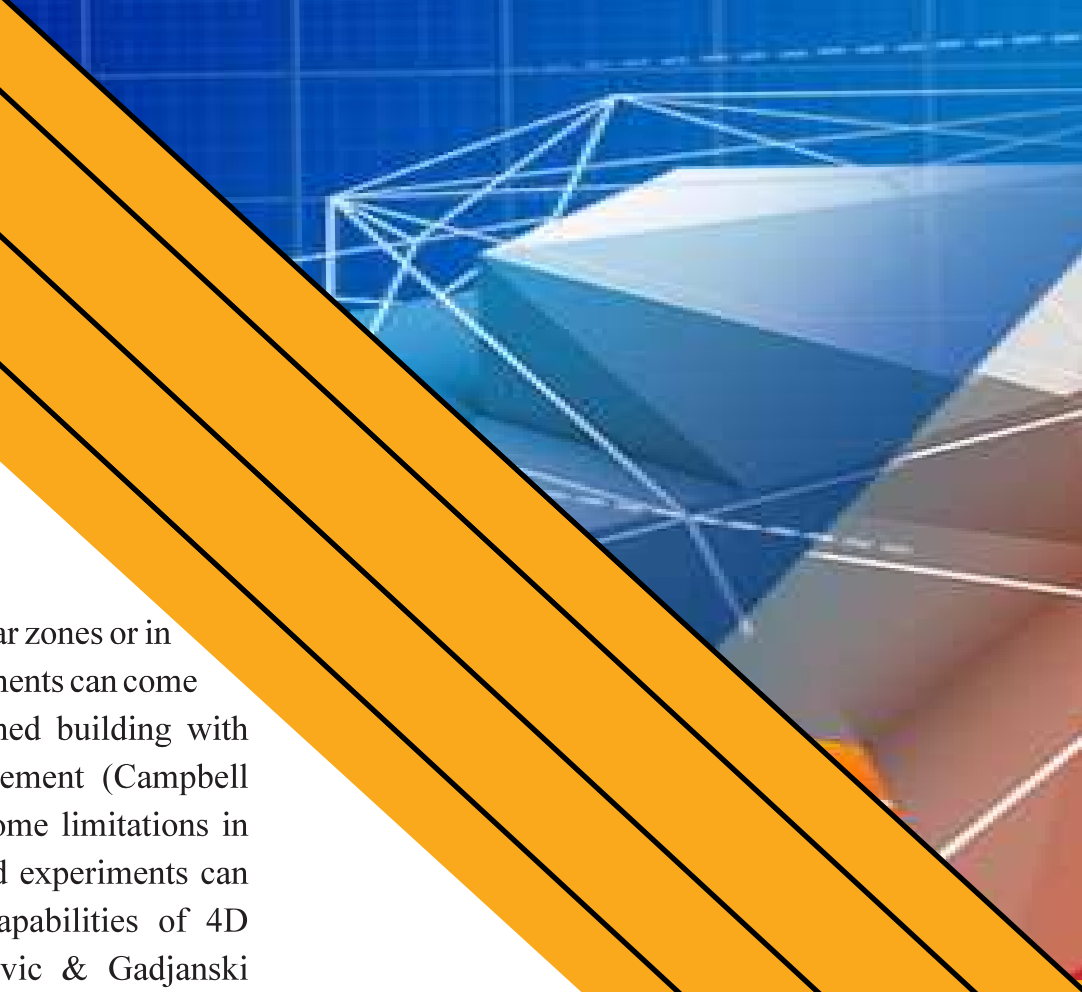
4D printing opens new fields for application in which a structure can be activated for self- assembly, reconfiguration, and replication through environmental free energies (Tibbits [4]). This brings several advantages, such as significant volume reduction for storage, and transformations that can be achieved with flat-pack 4D printed structures. The latter may include transformations to 3D structures required during actual applications [4]. Another example is that instead of directly creating a complicated structure using the 3D printing process, simple components from smart materials can be 3D printed first and then self assembled to reach that final complex shape (Zhou et al. [11]). In general, the potential applications of 4D printed structures can be classified into the three categories: self-assembly, multi-functionality, and self repair.

Self-assembly

Self-assembly extends from the nanoscale to the planetary scale [25,26]. Currently, researchers are interested in macroscale applications (Campbell et al. [26]). One example is the transfer of equipment parts to the inside of a human body through a small hole. The parts can then self- assemble at the desired location for medical purposes (Zhou et al. [11]). Another future application of selfassembly will be on a large scale and in a harsh environment.

Individual parts can be printed with small 3D printers and then self-assembled into larger structures, such as space antennae and satellites (Tibbits et al. [5]). This capability paves the way for the creation of transportation systems to the International Space Station (Choi et al. [2]).

Further applications include self-assembling



buildings, especially in war zones or in outer space where the elements can come together to yield a finished building with minimum human involvement (Campbell et al. [26]). Moreover, some limitations in architectural research and experiments can be removed with the capabilities of 4D printing (Čolić-Damjanovic & Gadjanski [27]).

Multi-functionality or self-adaptability

Adaptive infrastructures are another application of 4D printing (Campbell et al. [26]). 4D printing can integrate sensing and actuation directly into a material so that external electromechanical systems are not necessary (Tibbits et al. [5]). This would decrease the number of parts in a structure, assembly time, material and energy costs, as well as the number of failure- prone devices, which is usually utilized in current electromechanical systems (Tibbits et al. [5]). Multi-functional and self-adaptive 4D printed tissues (Khademhosseini & Langer [28]; Jung et al. [29]) and 4D-printed personalized medical devices, such as tracheal stents (Zarek et al. [30]), are other fascinating applications of 4D printing.

Self-repair

The idea of self-assembly can be utilized for self-disassembly. The error-correct and self- repairing capability of 4D manufactured products show tremendous advantages with regard to reusability and recycling (Tibbits [4]). Self-healing pipes (Campbell et al. [26]) and self-healing hydrogels (Taylor et al. [31]) are some of the potential applications.

2. Shape-shifting behaviors

The shape-shifting behaviors considered in 4D printing include folding, bending, twisting, linear or nonlinear expansion/contraction, surface curling, and the generation of surface topographical features. These features include wrinkles, creases, and buckles.

The shapes can be shifted from 1D to 1D, 1D to 2D, 2D to 2D, 1D to 3D, 2D to 3D, and 3D to 3D. It should be noted that a structure that shows 1D-to-1D shape-shifting over time is also considered to be a 4D printed structure. This is because this structure is initially 3D printed and then evolves over time. Before reviewing the shape-shifting types and dimensions in 4D printing, some relevant definitions are presented first.

2.1. Shape-changing vs. shape-memory materials

Zhou et al. [32] explained that shape-shifting materials could be divided into two sub-classes: shape-changing materials and shapememory materials. A shape-changing material changes its shape immediately after a stimulus is applied, and returns to its permanent shape immediately after the stimulus is removed.

This type of transformation is limited to simple affine alterations such as linear volume expansion and shrinkage (Zhou et al. [32]). On the other hand, the shape- memory effect (SME) involves a two-step cycle. Step 1 is the programming step in which a structure is deformed from its primary shape then held in a metastable temporary shape, and Step 2 is the recovery step in which the original shape can be recovered with an appropriate stimulus (Sun et al. [11], Zhou et al. [32], and Zhou et al. [33]).

Therefore, shape-memory materials can maintain a temporary shape until an appropriate stimulus is applied, and shape-changing materials cannot. The shape memory effect (SME) can be further classified into two subsets: (1) One-way shape memory materials, and (2) Two-way shape memory materials (Zhou et al. [32]).

one issue with classical one-way SME is irreversibility (Hager et al.[34]). After the original shape is recovered, a new programming step is needed to re-create the temporary shape

This issue can be avoided with two-way SME, which can alter shape in a reversible manner (Hager et al. [34]). This concept is illustrated in Fig. 5.

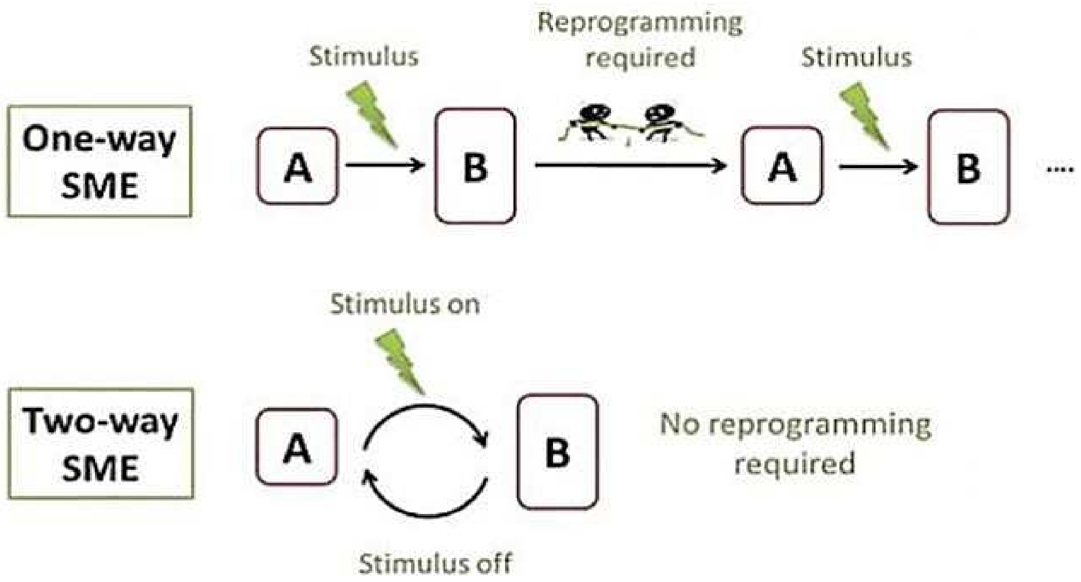


fig. 5. illustration of thedifferent one way and two way shape memory materials (Hager et al {34})

2.2. Dual, triple, and multi shape memory effects

Shape memory materials belong to the category of stimulus responsive materials shown in Fig. 5. Hager et al. [34] described that in shape memory materials, the permanent shape is “memorized” by the material and alterations between a permanent and a temporary shape occur. A dual-SME material includes one permanent shape and one temporary shape, while a triple-SME material has one permanent shape and two temporary shapes. Similarly, a multi (n)-SME material has one permanent shape and (n-1) temporary shapes [34].

2.3. Surface topography

Surface topography is the representation of local deviations of a surface from a flat plane. Typical features include wrinkling, creasing, and buckling, as shown in Fig. 8. These features usually occur under compressive loading conditions (Wang & Zhao [43]) and have been quantitatively studied by (Wang and Zhao [43]).
They allow for an approach based on the Maxwell stability criterion to predict the initiation and growth of various types of these features.