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From 3D to 4D printing: approaches and typical applications †

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Abstract

With the additional dimension, 4D printing is emerging as a novel technique to enable configuration switching in 3D printed items. In this paper, four major approaches, namely self-assembly of elements, deformation mismatch, bi-stability, and the Shape memory effect (SME), are identified as the generic approaches to achieve 4D printing. The main features of these approaches are briefly discussed. Utilizing these approaches either individually or in a combined manner, the potential of 4D printing to reshape product design is demonstrated by a few example applications.

Keywords: 3D printing; 4D printing; Bi-stability; Deformation mismatch; Product design; Self-assembly; Shape memory effect

1. Introduction

While 3D printing is becoming popular in more and more communities [1-6], the term of 4D printing has just been recoined. This new dimension provides great potential to further widen the application areas of 3D printing. Although non-uniform material property itself may be defined as the additional dimension to 3D printing [7], in this paper, this additional dimension only refers to the ability of a 3D printed item to switch its geometric configuration (including surface morphology) from one to another in a fully controllable manner [8-11]. A particular stimulus, such as heat (thermo-responsive), solvent (chemo-responsive) and light (photo-responsive), etc., may be applied to activate the switching process in an either reversible or non-reversible fashion. Note that as well-known, traditional origami is a typical example of configuration/shape switching, but via manual folding/unfolding a piece of paper.

Fundamentally, 4D printing is highly relevant to a couple of well-developed techniques, namely deployable mechanism/structure, bi-stable structure, compliant mechanism, (active) assembly/disassembly, stimulus-induced deformation mismatch, and shape memory/change effect based technology, etc. [8, 10, 12-26].

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The purpose of this paper is twofold. One is to briefly summarize major approaches which are applicable to realize 4D printing and the other is to present some typical applications to demonstrate the great potential of 4D printing to reshape product design.

2. Major approaches for 4D printing

At present, 3D printing provides a cost effective technique to fabricate customized items in a small quantity. The new dimension of shape switching in 4D printing requires at least two stable configurations/shapes in a 3D printed item before and after the right stimulus is applied. Although the actual environmental condition(s) may change due to the presence of the right stimulus, e.g., with or without immersing into a solvent, these configurations must be structurally stable, which means that the Degree-of-freedom (DOF) must be at least zero in any stable configuration.

A few approaches based on some well-established mechanisms may be applied to achieve shape switching in a controllable manner.

2.1 Self-assembly of elements

Self-assembly or self-integration of elements/components is really a fascinating alternative approach to fabricate sophisticated structures [11]. A potential application of this concept is to deliver the components of a machine or device to deep inside of a human body through a tiny hole and then assemble them at the required position for surgical operation [27]. If biodegradable materials are used for all components, the machine or device is able to fully disappear after a certain period of time. This approach may eliminate many problems in current practice of minimally invasive surgery, in particular, the difficulties in delivery and removal of a whole set of surgical device via one small hole [28-30].

These individual components may be 3D printed and automatically assembled when certain conditions are applied [10]. As compared with other mechanisms, this is relatively new and the geometrical dimensions of the elements must be carefully designed. The extra function of automatic disassembly in a later stage may be realized, if this mechanism is integrated with other mechanisms, such as, the shape memory effect discussed in Sec. 2.4.

2.2 Deformation mismatch

Deformation mismatch is a commonly observed phenomenon. It may be induced by the difference in some physical properties (such as, coefficient of thermal expansion and swelling ratio). With current 3D printing technology, we are now able to print multiple materials [31]. A gradient stimulus field may also result in significant deformation mismatch.

Upon heating, a piece of bi-layered beam tends to bend toward one direction if each layer has a different coefficient of thermal expansion [32]. If what applied is a temperature field, given some particular configurations (e.g., joule heating of NiTi-Si micro beam reported in Ref. [33]), the beam may quickly bend toward one direction and then to the opposite direction. On the other hand, a gradient temperature field is also able to induce non-uniform distortion within a piece of uniform material.

For bi-layered thin film structures, ultra-thin films made of graphene atop a polymeric thin film may result in the best folding/unfolding effect upon temperature variation due to extremely small thickness and remarkable difference in the coefficient of thermal expansion between graphene and polymeric materials.

In the case of gel based bi-layered structures (with either only one layer of gel or two layers of gels), different swelling ratio in these two layers is able to induce folding/unfolding of the structure. Apart from using two different materials, one gel with a gradient cross-linking level is an alternative to achieve non-uniform swelling/shrinkage ratio within the gel to practically achieve switching of configuration [22, 26].

In some real practice, the stimulus may not be applied uniformly throughout the whole piece of a material due to various reasons (such as, gradient temperature or solvent absorption etc.), which may result in buckling or other instability phenomena [34, 35]. Note that in the case of solvent absorption, there are three types of solvent transport formats, namely highly uniform (such as, hydrogel in water [16]), gradient transition (such as, PU in water [35]) and sharp transition (such as, PMMA in ethanol [34]).

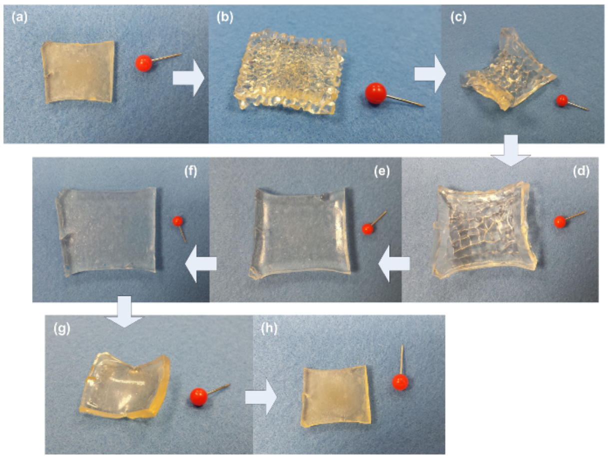


Fig. 1. Evolution of morphology of a piece of tough hydrogel upon wetting in room temperature water (a-f); drying in dry cabinet (g); finally heating with a piece of steel flat plate atop to flatten it (h). (a), (g) and (h) are fully dried.

Figs. 1(a)-(f) reveals the evolution of the morphology of a piece of flat tough hydrogel in the process of wetting in room temperature water (about 22°C). Refer to Refs. [36, 37] for the properties of this tough hydrogel. As we can see, due to the transport nature of water penetration, wrinkling, which belongs to local buckling, happens first (Figs. 1(a) and (b)), followed by global buckling (Figs. 1(c) and (d)). In general, eventually water content becomes more or less uniform within the whole piece of hydrogel and thus buckling phenomenon slowly disappears (Figs. 1(e) and (f)). Upon drying inside a dry cabinet (relative humidity: 30%; about 22°C), the piece of fully wetted flat hydrogel becomes uneven again due to a highly gradient distribution of water content within the gel in the quick drying process (Fig. 1(g)). Only after heating to above the glass transition temperature (Tg) of the hydrogel and preferably with a piece of small flat steel plate atop, the hydrogel fully returns its original shape and size (Fig. 1(h)).

2.3 Bi-stability

Under certain conditions, a structure with zero DOF may have two (or even more) stable positions, and the structure is able to switch from one stable position to the other if properly loaded to induce slight deformation [17, 19]. Technically speaking, this type of structure is called bi-stable structure. Of course, elastic steel arch is a typical example of bi-stable structure. Fig. 2 reveals the concept of a morphing wing based on a bi-stable structure, which is made of acrylic [poly (methyl methacrylate), PMMA] and assembled using plastic pins.

Compliant mechanism is featured by the unique character of hingeless structures [24, 25], which is just right for 3D printing to avoid the assembly process.

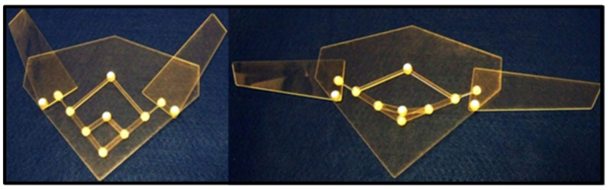


Fig. 2. Concept of a bi-stable structure based morphing wing.

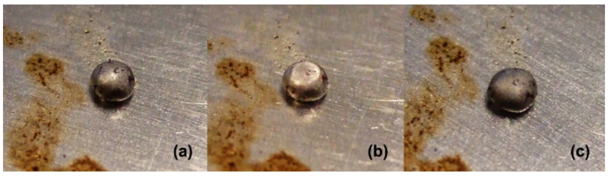


Fig. 3. The heating-responsive SME of solder based on surface tension: (a) A droplet of solder; (b) after compression to flatten its top at room temperature; (c) after heating to the melting temperature.

A combination of compliant mechanism and the concept of bi-stable structure provides a simple way to achieve 4D printing, and in the meantime, fully eliminate the problem of friction at the pin-joints for better precision in both positions.

2.4 Shape memory effect

After being quasi-plastically deformed, only at the presence of the right stimulus, a Shape memory material (SMM) is able to recover its original shape [38, 39]. This phenomenon is termed the Shape memory effect (SME) [40], which is different from another stimulus-induced behavior, namely the Shape change effect (SCE)[41], in which the magnitude of shape change (with or without hysteresis) is proportional to the applied stimulus [42, 43]. According to, for instance, Ref. [44], most, if not all, polymers have the heating-/chemo-responsive SME. Furthermore, depending on the exact working conditions, a material might have the SME and/or the SCE. For example, at a relatively lower water content, shape recovery of a piece of hydrogel may be induced upon heating or wetting in an high humidity environment; while at a relatively higher water content, the hydrogel responses to mechanical loading in a rubber-like manner, i.e., with the mechano-responsive SCE [16]. Upon wetting or drying, hydrogel swells or shrinks. This is typical water-responsive SCE.

Although many special mechanisms may be applied to achieve the SME (e.g., surface tension in Fig. 3 for solder), some working mechanisms are generic and thus applicable in many applications [28, 45, 46].

Normally, a full SME cycle of a SMM includes two processes, namely programming and recovery [40, 42, 47, 48]. In the programming process, the material is deformed into the required temporary shape; while in the recovery process, the right stimulus is applied for shape recovery.

Given a piece of Polyurethane (PU) wire, quasi-plastic stretching results in a residual strain. Upon heating to above its glass transition temperature (Tg), it is able to fully recover its original length. If we dip the pre-stretched PU wire into Dimethylformamide (DMF) to dissolve its surface, after drying (to form a thin layer of PU without pre-strain) and then heating for shape recovery, wrinkles may be produced on its surface. As the Young's moduli of the pre-strain-free layer and the underneath pre-strained core are about the same, if the processing parameters are carefully selected (the amount of residual strain and the thickness of the pre-strain-free thin layer), the wavelength of the resulted wrinkles can be easily tuned to achieve structural coloring [49, 50]. This approach (and similar ones) should be generic and applicable for self-coloring of polymeric materials without involving coating or nano imprinting [51-53].

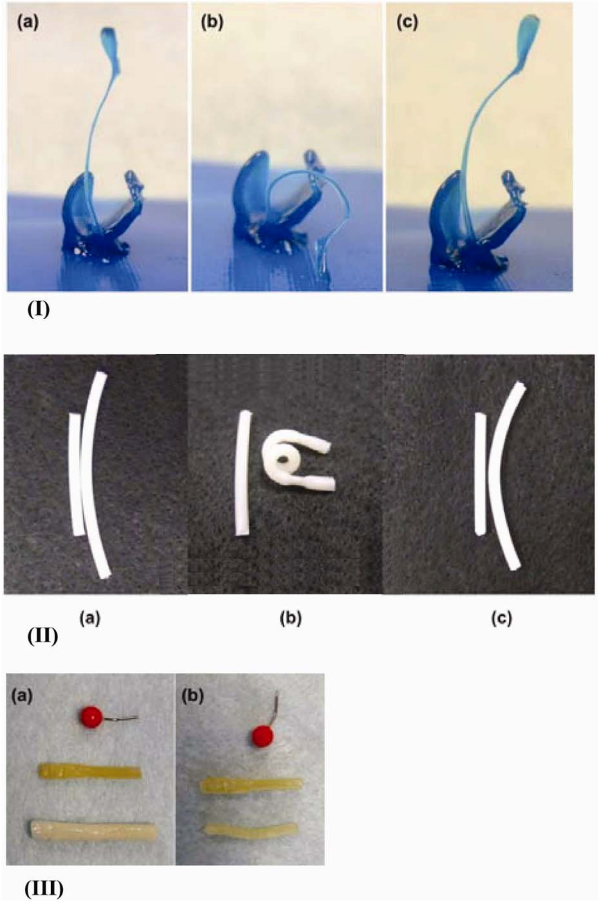
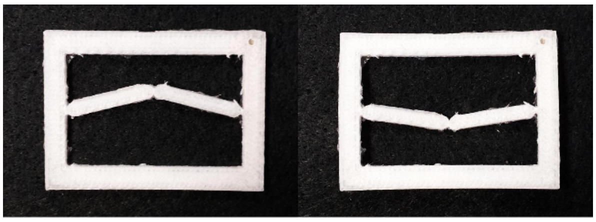


Fig. 4. Heating-responsive SME in three typical filaments used in 3D printing: (I) PLA. (a) Sculpture made by melting 1.75 mm diameter PLA filament; (b) after programming; (c) after heating in hot water. (Reproduced from Ref. [12]) (II) ABS. (a) Two short pieces of 1.75 mm diameter ABS filament; (b) the right piece is deformed into the temporary shape; (c) after heating for shape recovery. (III) PVA (1.75 mm diameter filament). The left ends of both pieces are impressed using a pair of pliers. After that, the bottom piece is immersed into room temperature water for water-activated shape recovery (a); or is heated for heating-induced shape recovery (b). The pin at the top is presented only for reference.

Many polymeric materials currently used in 3D printing have been proved to have the excellent SME. Refer to Fig. 3



(a) (b)

Fig. 5. 3D printed (nylon) bi-stable structure using compliant mechanism: (a) and (b) are two stable positions.

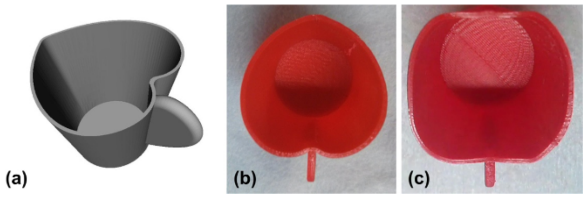


Fig. 6. Heart shaped cup: (a) Model for 3D printing; (b) 3D printed cup (PLA); (c) after deformation.

for the SME in three typical thermoplastic filaments for 3D printing, namely, Polylactide (PLA), Acrylonitrile butadiene styrene (ABS), and Polyvinyl alcohol (PVA). Ultraviolet (UV) cured thermoset polymers, such as VeroWhitePlus RG835 used for Projet type of 3D printers, also have good capability for shape recovery.

It should be pointed out that some polymers may crystallize upon over-heating. For example, the heating-responsive SME of PLA is fully repeatable only if heating temperature is always below about 90°C. Over-heating (for instance, using boiling water) induces crystallization in PLA, so that PLA becomes hard for quasi-plastic deformation (i.e., recoverable deformation after heating induced SME) at high temperatures. This feature is not always a disadvantage, and may be utilized to ensure better stability of the targeted configuration after shape recovery.

3. Potential applications

It should be pointed out that 4D printing is still in its early development stage. Herein, some example applications are presented to demonstrate its potential to reshape product design in many ways.

Note that except for printing VeroWhitePlus RG835 (Figs. 8 and 11), a Makerbot Replicator 2 desktop 3D printer was used to fabricate the 3D items reported in Figs. 5-7, 9 and 10. Filaments used for Makerbot Replicator 2 are 1.75 mm in diameter.

Fig. 5 presents a very simple bi-stable structure. It is printed using Nylon, which has good elasticity and ductility. As it is designed based on the compliant mechanism, it is hingeless and able to switch between two stable positions in a fully repeatable manner.

In Fig. 6, a heart shaped cup is designed using Solidworks

Fig. 7. Demonstration of heating-responsive SME in a 3D printed PLA spring.

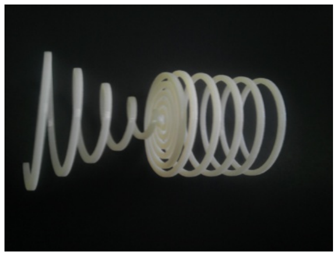


Fig. 8. 3D printed plug (VeroWhitePlus RG835) for temporary endovascular embolization (Reproduced from Ref. [12]).

and then printed using PLA filament. After deformation, the heart shape becomes hard to recognize. Upon pouring hot water into it, heart shape returns. If boiling temperature water is used for shape recovery, the cup becomes hard to deform at high temperatures due to crystallization, so that the heart shape becomes virtually permanent.

In Fig. 7, a PLA spiral spring is 3D printed. After heating in hot water (less than 90°C), it is taken out and then flattened. Upon placing inside hot water again, it fully recovers its original shape. This programming-recovery process can be repeated many times without any apparent deterioration. As an extension of this concept, another spring (plug) which is in a more sophisticated configuration is designed and 3D printed using VeroWhitePlus RG835 as the material to verify the concept of endovascular embolization (Fig. 8). At high temperatures, this spring can be straightened and then stored into a catheter. Upon delivered to the required position, it can be pushed out and recover its original shape upon heating to body temperature.

PLA is biodegradable and has been approved by The Food and Drug Administration (FDA), USA for implanted medical devices. PLA surgical staples have been used as an alternative to biodegradable sutures in minimally invasive surgery for wound closure. With the heating-responsive SME of PLA,

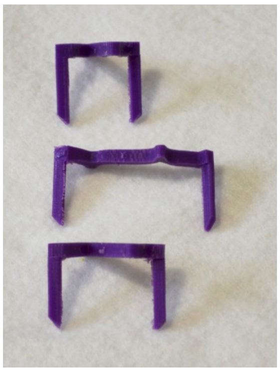


Fig. 9. Biodegradable PLA staple with self-tightening function. Top: as printed shape; middle: after programming (stretching); bottom: after heating for shape recovery (Reproduced from Ref. [12]).

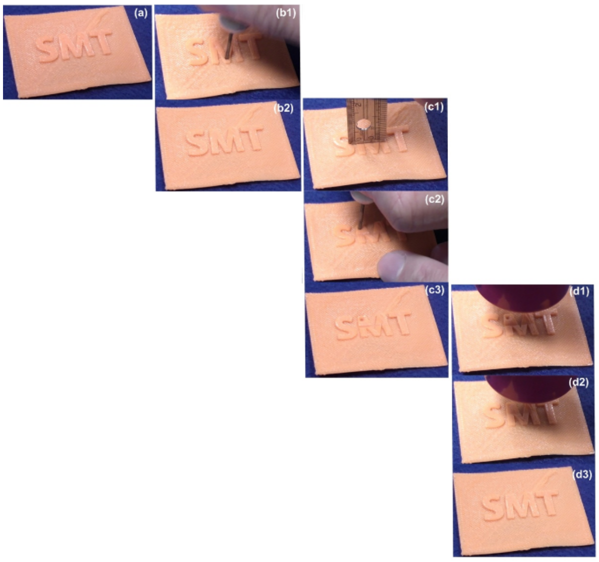


Fig. 10. The SCE and SME in 3D printed PLA card.

now the PLA staple can have the self-tightening function upon heating to slightly above body temperature (about 45°C, which is within the glass transition temperature range of PLA) [28]. Fig. 9 reveals a prototype of 3D printed PLA surgical staple, which can be stretched and then heated for self-tightening. Since the actuation stress of PLA during shape recovery is not high (a few MPa at the most), over-tightening can be effectively avoided.

The main advantage of 3D printing is personalized design and individual fabrication, while the major disadvantage of 3D printing is high cost and time consuming due to personalized design and individual fabrication.

The concept of fabricating 2D layered/patterned structures and then converting into 3D structures upon applying the right stimulus (mostly by means of applying or removal of the right solvent) has been well developed [22, 54]. With the current 3D printing technology, sophisticated 2D layered structures can be designed and fabricated to eventually form 3D structures via stimulus-induced self-origami [8].

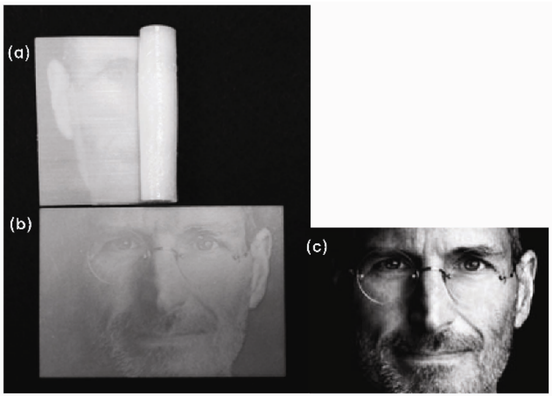


Fig. 11. Comparison of 3D printed cards ((a) partially rolled from backside; (b) as printed, front side); original photo (c) of Steve Jobs, which is used to generate the stl file for 3D printing.

Fig. 10(a) is a piece of 3D printed PLA card with protrusion "SMT" atop. Upon heating to high temperatures, the card becomes soft. A dot impression made by a stylus disappears instantly, which reveals the SCE of PLA at high temperatures (Fig. 10(b)). In the subsequent cooling (in air) process, the new impressions (line and dot) made by a ruler and stylus, respectively, largely remain (Fig. 10(c)). Heating using a hair dryer fully removes both impressions, which indicates the excellent heating-responsive SME (Fig. 10(d)).

Instead of precise scanning to obtain the true 3D configuration, we can quickly generate a quasi-3D model for 3D printing from a 2D image file, such as a photo. Based on a photo of Steve Jobs [Fig. 11(c)], thin cards of him as shown in Fig. 11(a) and (b) are 3D printed using VeroWhitePlus RG835. Although the total thickness of these cards is only slightly thicker than ordinary plastic name card, which is almost the limit of current commercial 3D printers, good printing result is observed. Since the cards are so thin, time and material used in printing are minimized. Furthermore, upon heating in hot water, the card can be rolled easily to prevent direct reading. Only heating again in hot water or using a hair dryer can unfold it to reveal the printed image or message.

Active assembly is a technique for automatic assembly without step by step manual operation. On the other hand, the concept of active disassembly has been proposed as an eco-friendly technique to automatically separate the components of obsolete electrical devices for effective recycling [55-57]. A recent development is to utilize the SME for both active assembly and disassembly using various kinds of conventional engineering plastics [12, 14].

As shown in Fig. 12, this hexagonal piece is made of small hydrogel balls by compressing them at high temperatures (above the Tg of dry hydrogel). Upon heating again, the hydrogel balls recover their original shape, so that the hexagonal piece splits into small balls. Wetting in water is another way to trigger active disassembly. These hydrogel balls can be reused again and again. Other types of polymers, such as,

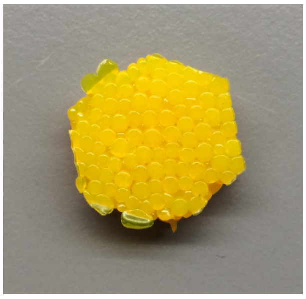


Fig. 12. A hexagonal piece made of compressing dry hydrogel balls at high temperatures.

Ethylene vinyl acetate (EVA) [58], may be used to avoid the problem of accident wetting triggered disassembly in hydrogels. However, the mechanical strength of the assembled pieces in this way is not high. Integrated with the self-assembly approach discussed in Sec. 2.1, these small components may be pre-deformed into the specified shape(s) to improve the strength of the assembled piece, while the feature of active disassembly remains.

4. Conclusions

4D printing is a fascinating way to enable configuration switching in 3D printed items. In this paper, four major approaches, namely self-assembly of elements, deformation mismatch, bi-stability, and the shape memory effect, are identified as the generic techniques to achieve 4D printing. The main features of these approaches are discussed. Utilizing one or more of these approaches, the potential of 4D printing to reshape product design is demonstrated by a few sample applications.

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