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

(Part 2)

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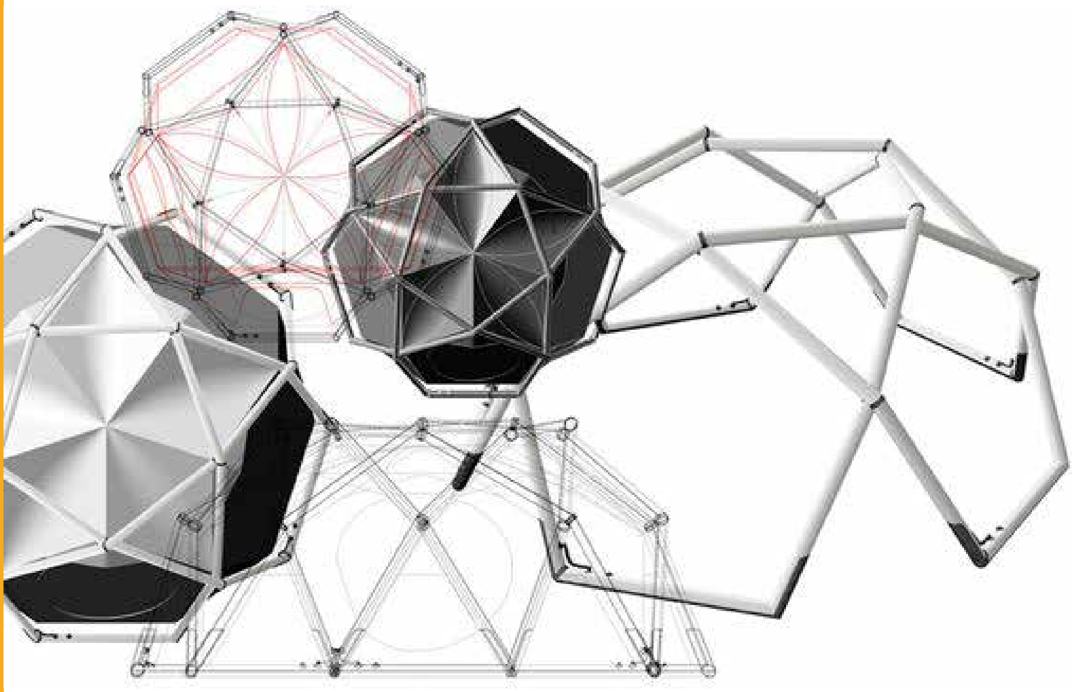


Abstract

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

Materials

The development of smart material should pursued in parallel with the development of printers. Currently, many 4D printing applications are limited because of unsatisfactory material properties. For example, 4D printing can fabricate artificial muscles;

however, the mechanical properties of current materials are insufficient to yield the desired performance and functions of actual biological muscles (Loh [61]). Therefore, the development of advanced smart materials with desirable properties that are also compatible with printers is crucial to advance the application of 4D printing. Programmable materials, such as carbon fiber, wood, and textiles, have undeniable influence in many applications, including aerospace, automotive, clothing, construction, healthcare and utility (Loh [61]).

Discussions

From analyzing existing studies, there are two requirements for materials in the 4D printing process: printability and intelligence (Fig. 6).

If the materials cannot be printed, the 4D structure cannot be manufactured. Many studies utilized a rheology modifier to provide a suitable material viscosity for extrusion-based printing processes. Similarly, the photo-initiator and the crosslinking and sacrificial agents are several other aspects that need to be considered for proper material printability. If the structure contains only non-active materials, it cannot achieve any targeted changes over time as a response to the stimulus. Schweiger et al. [72] studied multilayered anterior teeth and defined "multi-material- 3D-printing" as a 4D printing process. This is not the 4D printing process discussed in this paper because the structure does not contain any smart material.

Some applications require dual-responsive materials. For example, the shape-shifting behavior of a material can be triggered by both water and heat. Triple and other multi-responsive materials have not been considered in the 4D printing process so far and can be studied in the future.

Another issue is the degree to which the smart materials can respond to stimulus. Some smart materials can sense stimulus but only provide minimal actuation or respond after a very long time. The responsivity of smart materials needs to be further studied as well.

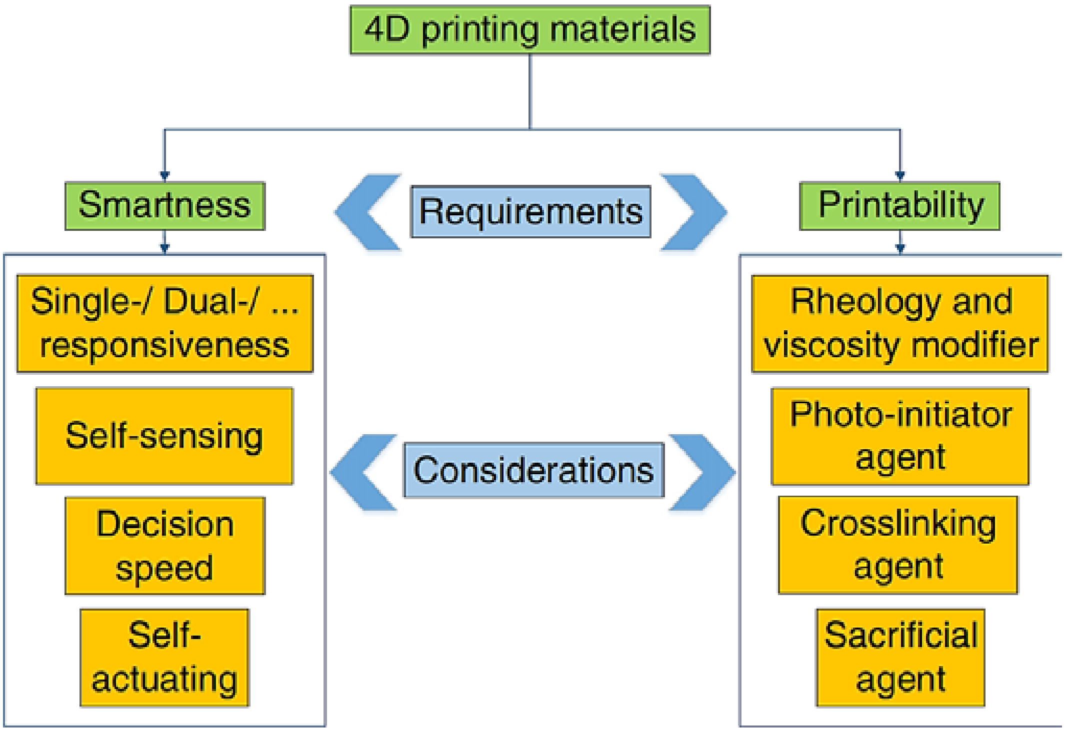


Fig. 6 4D printing materials

Applications

5.1 Self-assembly and self-folding structures

In April 2014, Skylar Tibbits of the Massachusetts Institute of Technology showed a combination of 3D printed plastic with an "intelligent material" that self-assembles in water. Tibbits refers to this as "4D printing" (Walton, 2013). The core of 4D printing is the Connex multi-material technology.

With Connex multi-material technology, a single print, with multi-material features, can transform from any 1D strand into 3D shape, a 2D surface into 3D shape or morph from one 3D shape into another. The Connex multi-material technology allows the researchers to program different material properties into each of the various particles of the designed geometry and harness the different water-absorbing properties of the materials to activate the self-assembly process. With water as its activation energy, this technique promises new possibilities for embedding programmability and simple decision-making into nonelectronic-based materials. An example of 4D printed objects that were preprogrammed to respond to a stimulus – water – and change into other shapes is shown in Figure 7. The top figure shows a 1D object morphed into a 2D object – when inserted into water, the snake-like object forms the letters “MIT”. The two figures show how one can also create self-folding cubes from both flat and wireframe structures. Other applications in Figure 8 show a single strand that self-transforms from the letters “MIT” into the letters “SAL”, a flat surface that self-folds into a truncated octahedron and a flat disc that self-folds into a curved-crease origami structure. Skylar along with Stratasys Ltd. and Autodesk, Inc. using Stratasys’ Connex multi-material printer and a new polymer developed to expand 150 per cent when submerged in water conducted these experiments. A new application was embedded into the Autodesk software, Project Cyborg, to simulate the dynamics of 4D printed objects and their material optimization. This technology has attracted substantial press attention around its potential for manufacturing (Tibbits, 2014).

Another 4D printing technology involves embedding wiring or conducting parts into special compliant components during the 3D printing job. After the object is printed, the parts can be activated by an external signal to trigger full assembly actuation (Figures 9 and 10).

This approach has potential implications for areas such as robotics, furniture and building construction.

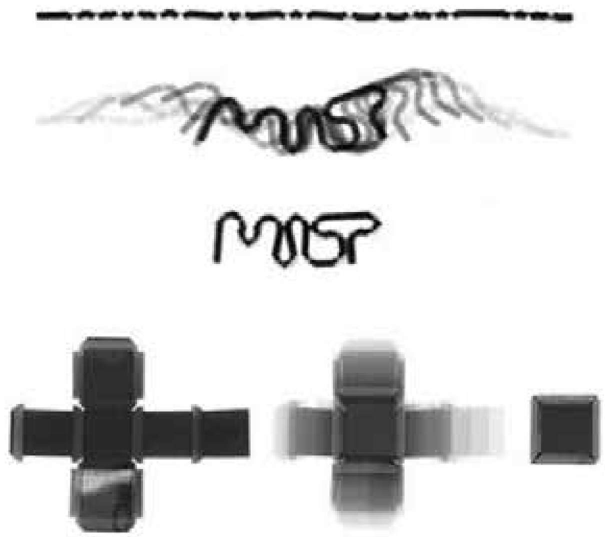


Fig. 7 A single strand that self-folds into the letters “MIT” and a flat surface that self-folds into a closed cube

Fig. 8 A single strand that self-transforms from the letters “MIT” into the letters “SAL”(self-assembly lab), a flat surface that self-folds into a truncated octahedron, and a flat disc that self-folds into a curved-crease origami saddle structure

Other 4D printing approaches include composite materials that can morph into several different complicated shapes based on a different physical mechanism and heat activation (Ge et al., 2013). Also, demonstrations have been made of materials that self-fold because of light exposure (Ying et al., 2012).

Developed an ALM technology for SMG, which is currently used in the manufacture of smart medical bandage, zoom lens and bionic robot, etc.

Raised an ALM technology for SMP, and used this to fabricate intelligent structures that have self-assembly and self-folding functions (Tolley et al., 2013; Felton et al., 2015). First, the SMP is accumulated to a rigid substrate board. After solidification, the SMP and the rigid substrate board are tightly combined to a plane structure. Then, under external stimulus such as light, temperature, current, etc., the SMP generates a volume expansion or contraction, which makes the plane structure become a 3D structure (Figure 11).

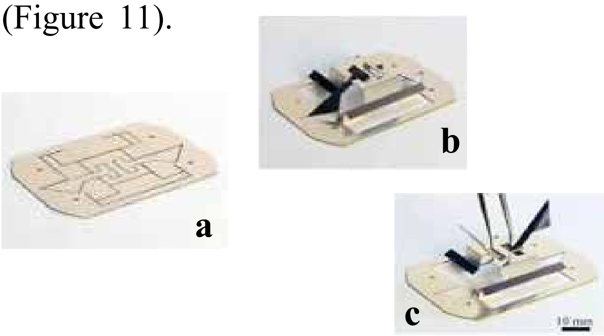


Fig. 11 (a) A flat composite programmed to fold into a bumblebee-like structure; (b) the bumblebee after folding; and (c) the bumblebee with its wings raised

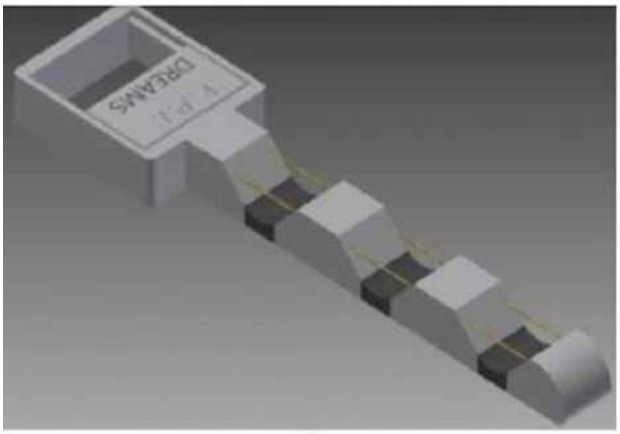


Fig. 9 Robotic finger designed and created via in situ embedding with an AM process

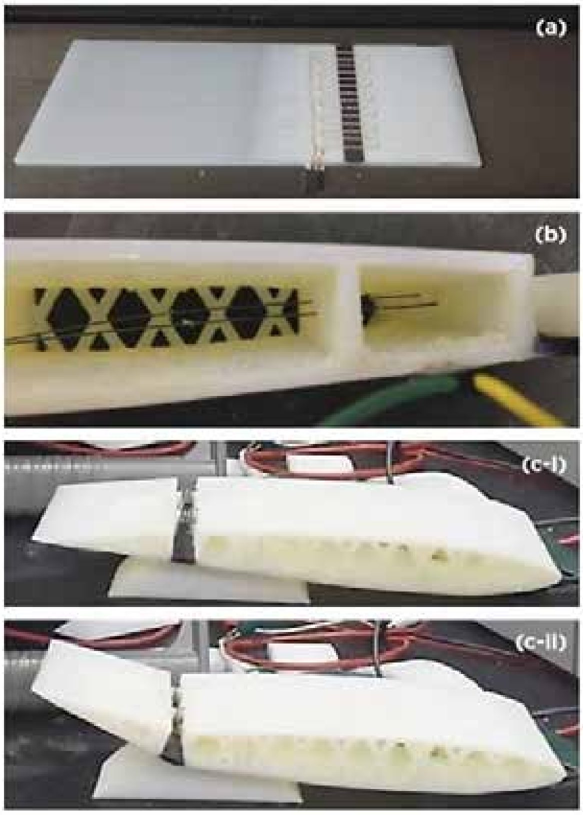


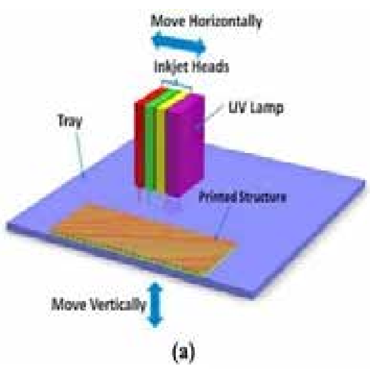
Fig. 10 Integrated sensing and actuating wing flap manufactured via a materials jetting process

5.2 Active composites structures

Ge et al. (2013) proposed to implement a 4D printing technology by using multi-material ALM technology. In their method, the SMP fiber is combined with an organic polymer matrix by printing them simultaneously. With the result that the structure they make can be changed with time. Figure 12 shows the printing process of the SMP fiber and organic polymer matrix. Figure 12(a) is the schematic showing the printing process of printed active composite materials. The inkjet heads move horizontally above the tray depositing multi-material droplets of polymer ink at prescribed positions, wiping them into a smooth film, and then UV photo polymerizing the film. After one film layer is completed, the tray moves down to print the next layer. Figure 12(b) is the schematic of a printed active composites (PAC) lamina. Fibers are oriented at an angle from the x-direction (the loading direction).

If they combine the intelligent structure in Figure 12 with another organic polymer layer to form a double-layered structure, by changing the temperature, the transformation of bending deformation and initial shape can be realized. And the bending deformation amplitude of the intelligent structure can be changed by changing the direction of the SMP fiber.

So, the deformation of the structure is controlled. Figure 13 shows the anisotropic shape memory behavior of the active lamina to create PAC laminates.



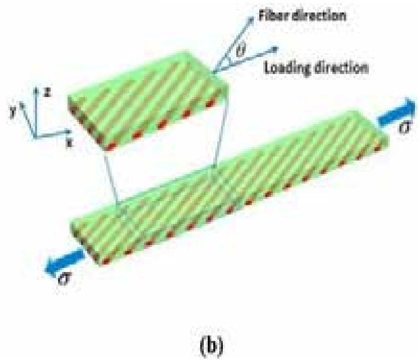
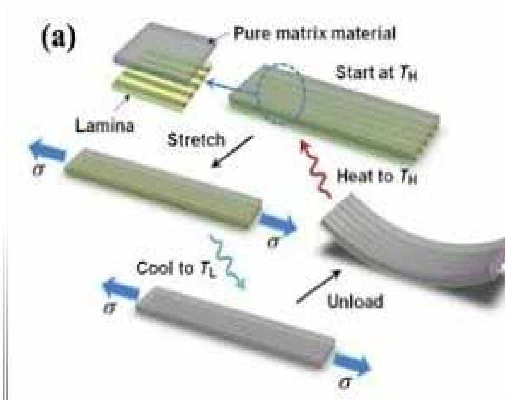


Fig. 12 Schematic illustrating the PAC printing process



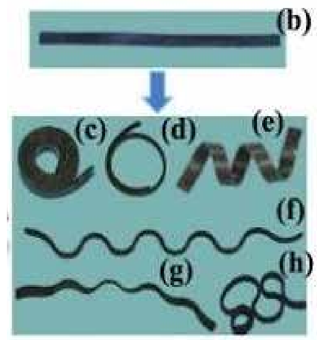


Fig. 13 Complex low-temperature shapes of active composite laminates obtained by design of the laminate architecture

Recently, Malone and Hod (2006) selected an IPMC from the literature and their own preliminary experiments as most promising for freeform fabrication. They performed material formulation and manual device fabrication experiments to arrive at materials that are amenable to robotic deposition, and developed an ALM process that allows the production of complete IPMC actuators and their fabrication substrate integrated within other freeform-fabricated devices. Malone and Hod (2006) freeform-fabricated simple IPMCs, explored some materials/performance interactions and preliminarily characterized these devices in comparison to devices produced by traditional methods.

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UAM refers to combining metal foils with the ultrasonic wave at room temperature, so that 3D solid structures can be realized layer by layer.

Use the UAM technology to combine the SMA and other intelligent materials into the metal matrix, and the shape of obtained intelligent structure can be changed according to different demands (Figure 14). Also, this technology can realize the health monitoring and life prediction of intelligent structure. At present, the intelligent structure can be used in the design and manufacture of intelligent vehicles and intelligent aerocrafts

5.3 Environmental adaptive mechanism and structural health monitoring

A lot of intelligent material also has driving function and sensing function, such as SMA. It not only can be used as an actuator to produce deformation under different temperatures but also can measure the strain, temperature and crack inside the structure in real time, detecting the fatigue and damage.

Proposed the ultrasonic additive manufacturing (UAM) technology to combine different metal materials and intelligent materials into intelligent structures. This kind of intelligent structure has the function of shape changing under different circumstances and the function of structure monitoring (http://spie.org/

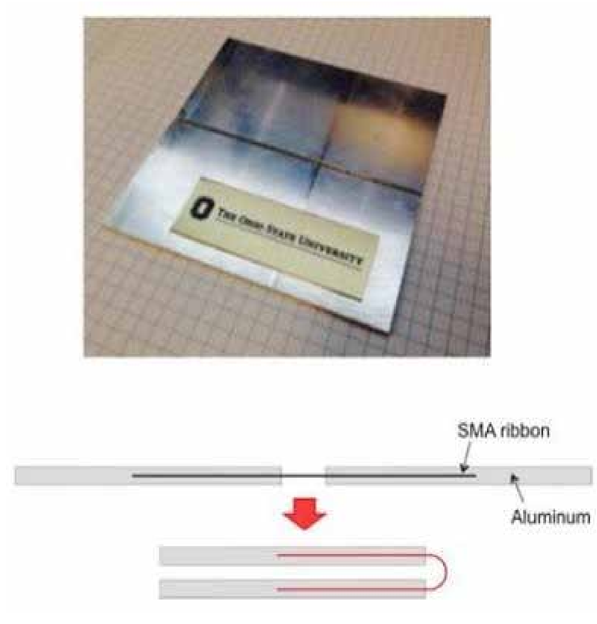

Fig. 14 Aluminum hinge actuated by shape memory (nickel titanium) wires

5.4 Self-deployable systems

Tolley et al. (2013) fabricated self-deployable systems (SDSs) by ALM technology with SMP (Samuel et al., 2013). They use the ALM technology to combine the SMP material and hard matrix material into an intelligent structure, which can realize self-assembly and self-folding under external environmental stimulus. SDS can be applied to detectors, logistics, etc. (Samuel et al., 2013). One of the most famous applications in detectors is the Inchworm Robot. By controlling the repeated bending and folding of the Inchworm Robot, its progressive motion can be realized (Figure 15). Figure 15(a) is the two-dimensional inchworm robot, before it has folded into its functional shape. Figure 15(b) is the folded inchworm, after the servo and battery have been added. This robot weighs 29 g, and moves at a rate of 2 mm/s.

To show self-deployability, a schematic is shown in Figure 16. Locomotion is achieved by angling the "feet" at the bottom of the front and back walls [Figures 16(a) and (b)] to create an asymmetric friction. The front wall fold angle relative to the robot body is 45°, and the back wall fold angle is 135°. Sidewalls [Figure 16(c)] are included at right angles to the robot body to improve structural rigidity.

A single dynamic hinge in the middle is controlled by a slider– crank mechanism actuated by a linear servo. The servo is driven by a 0.3 Hz triangle wave from a microcontroller (ATtiny13, Atmel), and powered by a 7.4 V lithium polymer battery (EFLB1202S20, E-flite). The servo is mounted on a platform that folds up 45° from the body [Figure 16(d)].

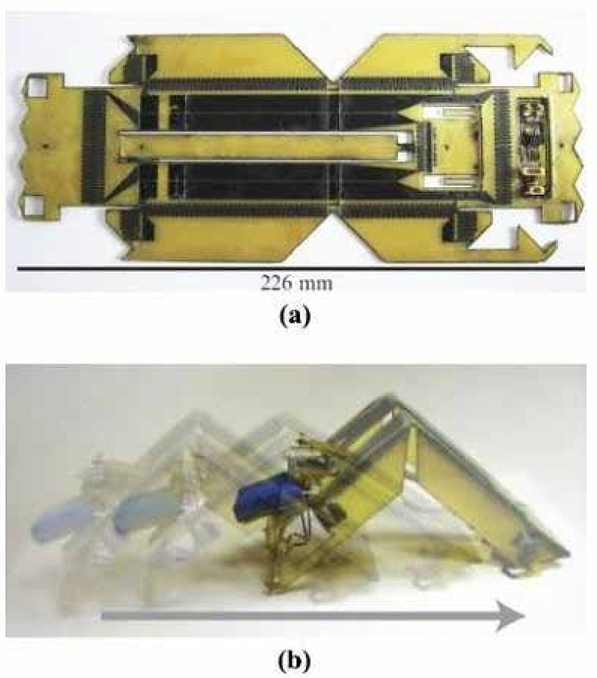

Fig.15 the inchworm robot

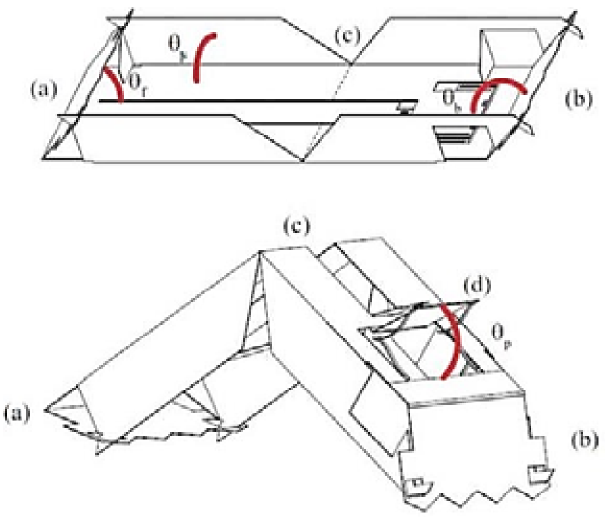

Fig. 16 the inchworm robot after the folding of its front-, backand sidewalls

5.5 4D printing in robotics

4D-PRINTED TWO-WAY ACTUATORS

Materials were chosen for their physical properties, cost and ease of use. A 125-mm-thick sheet of polyetheretherketone (APTIV 1,000, Victrex) is used as a passive substrate because of its high flexural strength (163 MPa) and resistance to fatigue along folds. Pre-stretched polystyrene (KSF50-CIJ, Grafix) was chosen for the contractile layer because of its high compressive strain (50 per cent) when heated above its relatively low transition temperature (160°C) (Ying et al., 2012). The circuits are made on a composite consisting of an 18-mm copper layer and a 12-mm sheet of polyimide.

After completion of the folding process and manual addition of a servo and battery, the inchworm robot weighed 29 g and measured 145 mm in its extended position.The robot was capable of moving on paper at a rate of 2 mm/s for a 0.3 Hz contraction frequency, or 0.8 body lengths per minute, and consumed 0.9 W during locomotion.

Because of the complexity of asymmetric surface friction, this speed was irregular. The stroke length of the foot displacement measured 10 mm; therefore, only 20 per cent of the motion was converted into locomotion, and the rest was lost to slippage. The contraction frequency was chosen because higher frequencies resulted in even more slippage.

shape memory materials (SMMs) are key materials for engineering the next generation of smart robotic 4D-printed actuators. There are two types of SMMs in terms of their morphological transformations: one-way and two-way. One-way SMMs are those that can be programmed into a specific shape.

Upon an external stimulus, such as temperature, they undergo a shape transformation that remains once the stimulus is removed. Conversely, two-way SMMs can reversibly morph between two different shapes by a switching stimulus, essentially a complex bimorph mechanism. To date, most 4D-printed SMMs are one-way (Fig. 17A) (6). One of the first 4Dprinted components with two-way actuation was reported by Qi et al. (7). Their approach created a composite structure of two different polymer components, a responsive hydrogel and a one-way shape-memory polymer.

In this combination, switching between two different configurations is caused by swelling or shrinking of the hydrogel, while the shapememory polymer acts as a component for regulating the time in which the morphological transformation occurs. Two-way morphing was shown with several 2D and 3D constructs, such as strips, rings, periodic structures, and origami architectures. Other researchers have recently 4D-printed liquid crystal elastomers (LCEs) capable of performing rapid and reversible robotic functions (Fig. 17, B and C) (8, 9). LCEs undergo large and reversible shape transformations in response to external stimuli such as temperature or light.

4d-printed soft robotic components for future medical devices

With the increasing adoption of robotics in health care, 4D-printed robotic actuators, especially those made of soft components, will play a crucial role in the development of future medical robotic technologies. Considerable research has focused on the development of soft materials for medical robotic applications because these materials exhibit characteristics—such as biocompatibility, biodegradability, and adaptability—that are essential for medical interventional tools. Although we have seen a tremendous development of 3D-printed soft robotic components, approaches that will enable the miniaturization of 3D soft, smart materials have not yet been developed.

4D-printed small-scale soft structures will enable us to create minimally invasive surgical tools, smart microscaffolds and microstents, and miniaturized adaptive drug delivery reservoirs. However, 3D printing techniques are not yet able to produce miniaturized smart materials with 3D submicrometer details; in some extreme cases, only features with minimum sizes of ~200µm can be attained. A promising technique is two-photon polymerization (2PP),

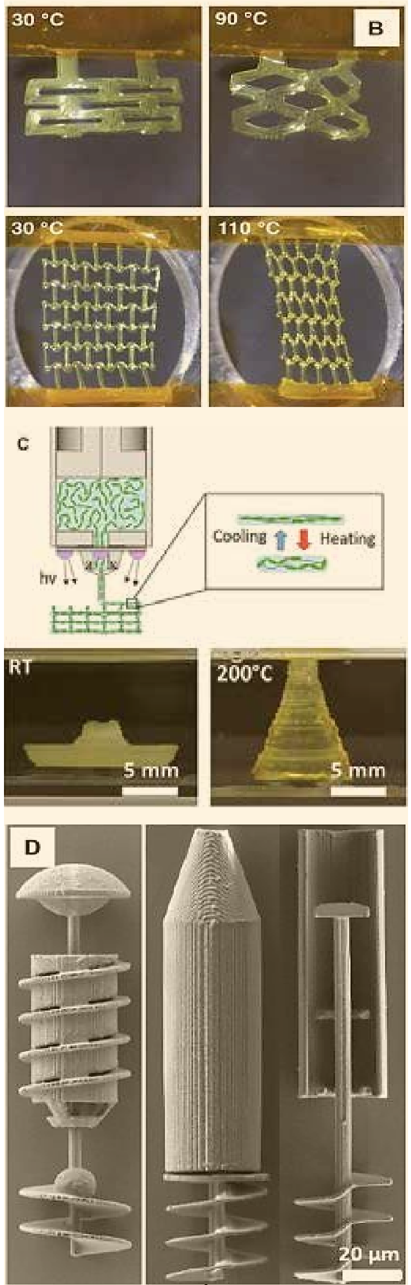

Fig. 17 Four different examples. 4D printing of a one-way SMM (A) (6), 4D printing of a two-way SMM based on LCEs [(B) (8) and (C) (9)], and 3D printing of a wirelessly controlled Archimedes screw pump obtained by 2PP (D) (10). RT, room

also known as 3D laser lithography, which enables the fabrication of high-resolution 3D microarchitectures with heights from a few hundred nanometers up to several millimeters and layer thicknesses below 1 µm. Using this fabrication approach, highly complex smallscale robotic devices have been reported. For example, Huang et al. (10) used 2PP for the fabrication of magnetic microtransporters with a wirelessly controlled Archimedes screw pumping mechanism (Fig. 17D). However, 4D printing of soft microstructures using 2PP has not been widely reported.

Perspectives

Whether a robotic system consists of a set of arms with end effectors or an assembly of micro- and nanoscale components, the incorporation of 4D-printed materials in these devices will enable new capabilities not currently available.

Although substantial research has been devoted to producing 3D-printed microscale robotic tools, the tools are typically made of nonresponsive, stiff materials. The use of 4D printing in the field of small-scale robots remains unexplored because of challenges in miniaturizing smart materials with available 3D printing techniques.

Producing arbitrary shapes made of two-way responsive materials is also crucial for the successful development of tomorrow's robotic actuators. The integration of other materials, such as magnetic or lightresponsive micro- and nanostructures, to form 4D-printed composite components will also bring new opportunities in smart robotic actuators. We encourage the robotics community to explore radically new material and fabrication approaches to make 4D printing as ubiquitous as 3D printing.

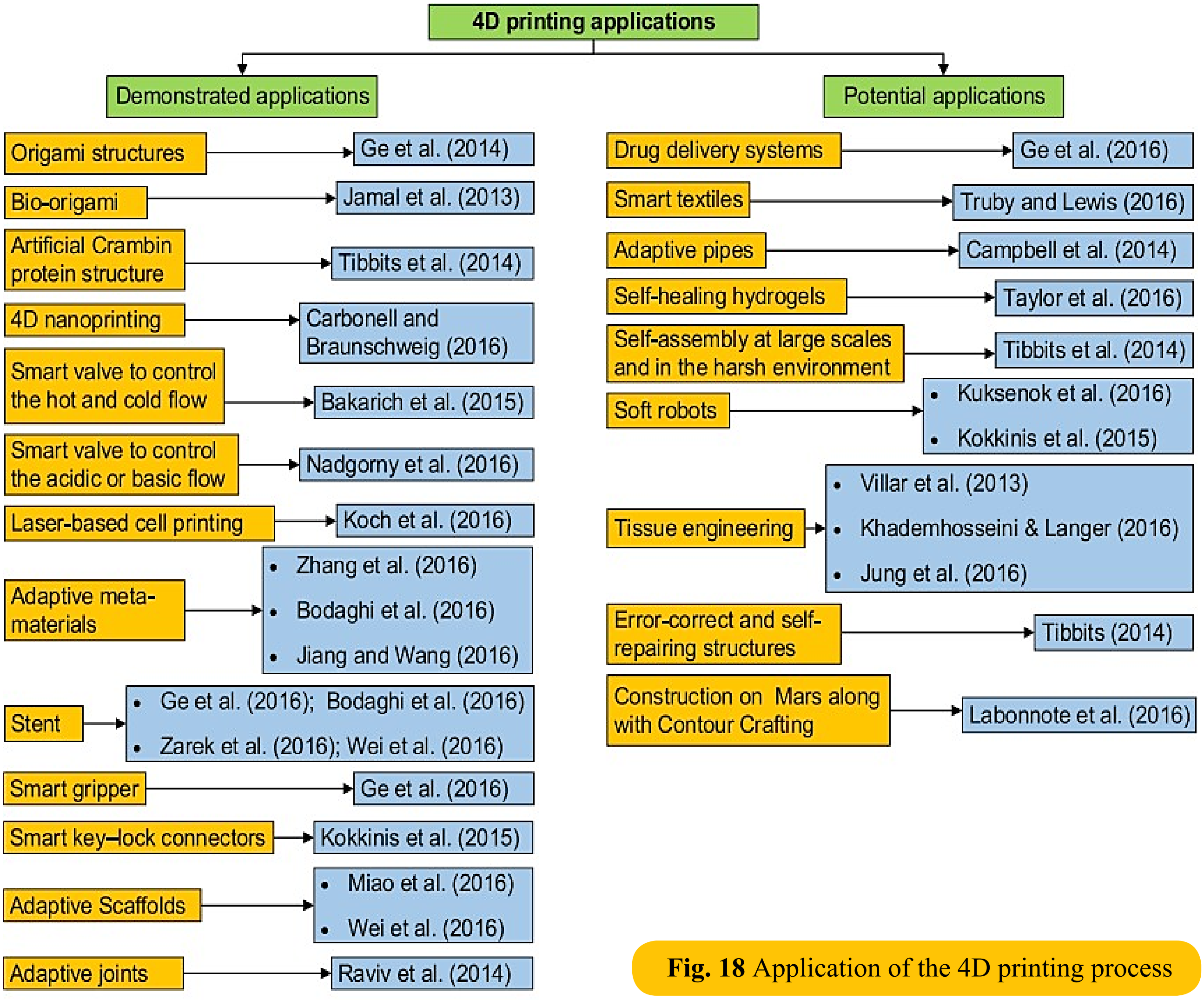

Fig. 18 Application of the 4D printing process

Conclusion

4D printing is the art of combining science with engineering technology. The scientific aspect of 4D printing is related to fundamental research into developing new smart materials, stimuli, and mathematical modeling. From the engineering aspect, the 4D printing process enables innovative and fascinating applications that can hardly be achieved with conventional manufacturing processes. The term, "4D printing," was coined in 2013 and since then has received a growing level of attention from various disciplines. The foundation of the 4D printing process includes the 3D printing process, stimulus, smart or stimulus-responsive materials, interaction mechanisms, and mathematical modeling. These properties enable changes in shape/property/functionality after Printing, as a function of time. In addition, 4D printing has three main capabilities: self-assembly, multi-functionality, and self-repair. More studies need to be performed in the area of self-repair compared with the other two. Mathematical modeling is necessary in the 4D printing process primarily for three reasons: the prediction of the shape shifting as a function of time; the prevention of collisions between components of the structure during self-assembly operations, and finally, reduction of the number of trial-and-error experiments. The mathematical models used in the 4D printing process can be developed based on a desired shape, material structure, material properties, and stimulus properties.4D printing can be utilized in various scales in interesting applications. To improve and maximize the potential applications of the 4D printing process, a large amount of multidisciplinary research needs to be conducted in the future.

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