4D printing and robotics

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Abstract

Shape-memory materials and two- or three-dimensional printing techniques combine to form a new paradigm that will advance robotics.

If one takes a step back and considers how roboticists prototyped nearly all robotic mechanisms a decade ago and how we were primarily limited to mills, drills, lathes, and ordering parts over the internet, the dramatic impact of three-dimensional (3D) printing on the field of robotics becomes obvious. This "new" manufacturing process (that took over three decades to come to fruition) has become so ubiquitous that we often worry that young mechanical engineers are no longer adept at many of the manufacturing skills we consider to be fundamental. As 3D printing continues to penetrate into society, even into supermarkets, the next phase of this technology has become apparent. By bringing new classes of materials into 3D printing such as shape-memory materials (SMMs), this technology can be integrated with self-organizing concepts such as origami robots to create a new paradigm. This is often referred to as "4D printing," a term credited to Skylar Tibbits in his 2013 TED talk (www.youtube.com/watch?v=0gMCZFHv9v8) in which he referred to 3D-printed structures with an embedded capability of spatiotemporal transformation. We are now beginning to see reports on a variety of these types of structures that undergo shape transformations after being printed. The field is rapidly emerging, and many new classes of devices are being proposed.

As with many areas of robotics, 4D printing begins with a focus on materials (*1*). While a process that prints a 3D structure that then transforms itself into a new shape can be clearly categorized as 4D printing, we do not necessarily need to start with 3D structures. If we print 2D structures that then undergo an out-of-plane conformation change, we have also created a 4D-printed structure, as recently reported for 2D hydrogel shape-morphing structures (*2*, *3*) and for 2D self-folding elastomers (*4*). We can also categorize printed origami robots as a subset of 4D-printed robotics (*5*). More broadly, 4D-printed robots are stimuli-responsive 3D structures, regardless of whether their pretransformation state was 2D- or 3D-printed. There are two main approaches for 4D-printing robots. We can 2D-print a combination of smart and conventional materials to achieve anisotropic stresses. Alternatively, we can 3D-print shape-memory materials. Current research is focused primarily on 4D printing smart robotic components with actuation.

4D-PRINTED TWO-WAY ACTUATORS

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. 1A) (6). One of the first 4D-printed 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 shape-memory 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. 1, B and C) (8, 9). LCEs undergo large and reversible shape transformations in response to external stimuli such as temperature or light.

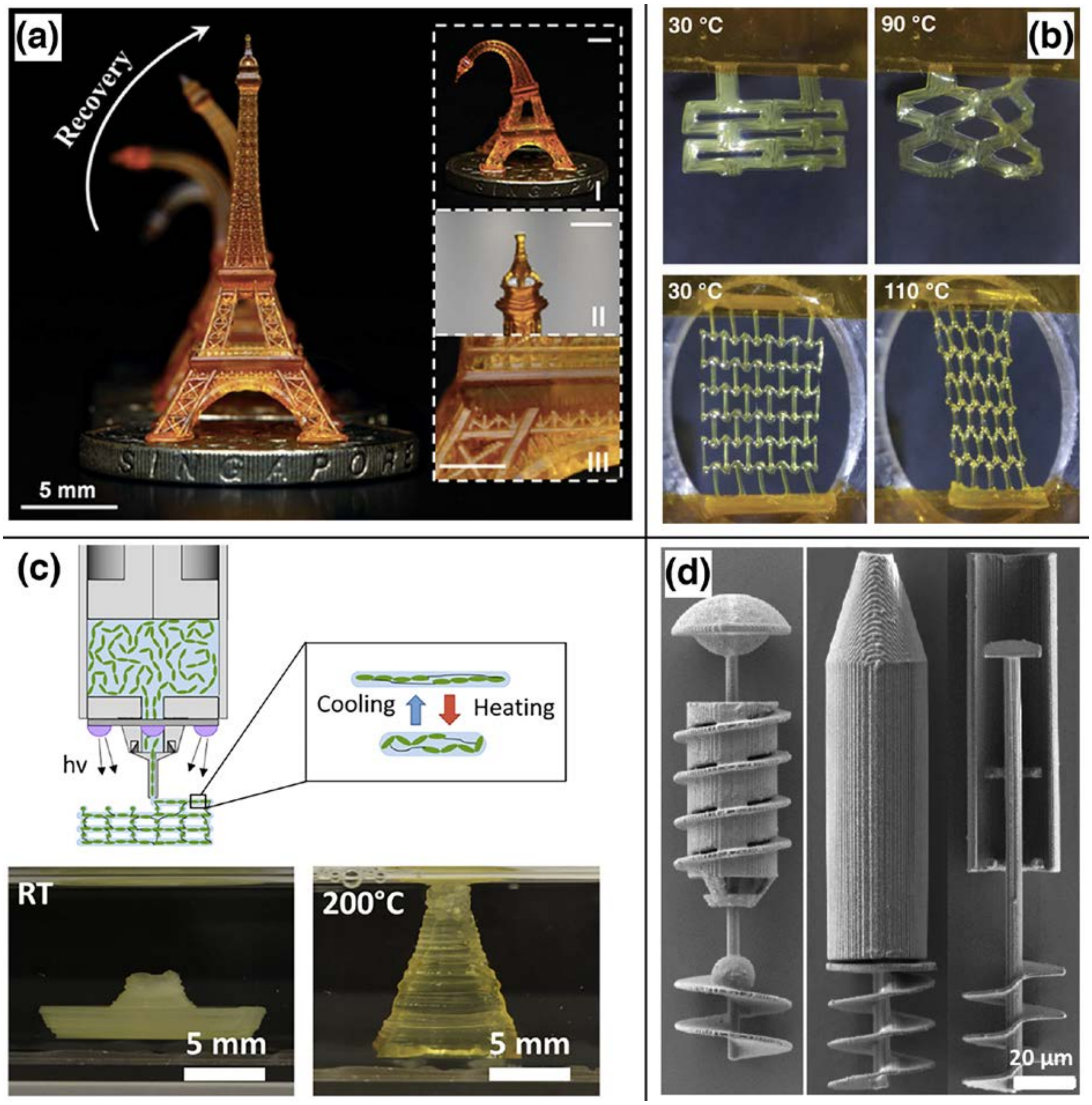

Fig. 1 Four different examples.

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 temperature. [Credit for (C): Reprinted with permission from (*9*). Copyright 2017 American Chemical Society.]

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 ~200 μm can be attained. A promising technique is two-photon polymerization (2PP), 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 small-scale 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. 1D). 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 light-responsive 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.

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