Chapter 4
Applications of 4D Printing Technology

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ABSTRACT

4D printing technology is destined to revolutionize the industrial world. These are some of its possible achievements and applications: 1) Medicine and surgery: in 2015, a medical team from Michigan University saved the lives of three babies with respiratory problems by inserting a 4D printed implant. This polycaprolactone device, designed to fit each patient, was designed to adapt its size to the child's growth and to dissolve itself when no longer necessary. 2) Clothing and footwear: 4D printing technology allows the manufacturing of clothing that adapts to the body's shape and movement. 3) Aeronautics and automotive: the NASA has developed an intelligent metallic fabric with 4D printing technology. Various applications of 4D printing are discussed in this chapter.

1. INTRODUCTION

3D printing is a well-known additive manufacturing technology that allows researchers, manufacturers, and private users to fabricate custom 3D objects using computer software such as computer aided design (CAD) (Shin et al., 2017). Due to the highly customizable nature of 3D printing it has found use in a number of fields such as fabrication of fashion jewellery (Yap & Yeong, 2014), polymer printed textiles (Pei et al., 2015), supercapacitors, mechanical metamaterials and sensors, bio-hybrid robotics (Stanton et al., 2015) and tissue scaffolds. Several additive manufacturing technologies have been developed for processing pure polymers and polymer nanocomposites (Farahani et al., 2016) such as stereolithographic (SL), digital light projection (DLP), direct inkjet and extrusion-based printing as well as liquid deposition modelling (LDM). They enable less expensive free form fabrication of complex, customized and multi-scale 3D geometries for application in a vast range of fields, from tissue engineering scaffolds (Mu et al., 2017) to strain and skin like sensors.

The introduction of smart materials which are responsive to external stimuli has found use in shape recovery, sensors and actuators (Liu et al., 2016). 3D printing technology has been used to make static

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structures from digital data in 3D coordinates, 4D printing adds the concept of change in the printed configuration over time, dependent on environmental stimuli. Shape morphing systems can be found in many areas including smart textiles (Meng et al., 2012), autonomous robotics, biomedical devices, drug delivery and tissue engineering. The natural analogues of such systems are exemplified by nastic plant motions, where a variety of organs such as tendrils, bracts, leaves and flowers respond to environmental stimuli such as humidity, light or touch by carrying internal turgor, which leads to dynamic conformations governed by tissue composition and microstructural anisotropy of cell walls. 4D printing is inspired by these botanical systems. 4D printing has the economic, environmental, geopolitical, and strategic implications of additive manufacturing while providing new and unprecedented capabilities in transforming digital information of the virtual world into physical objects of the material world. The fourth dimension in 4D printing refers to the ability for material objects to change form and function after they are produced, thereby intelligent materials become a key issue in this technology. This paper reviews the development and capabilities of the 4D printing technology and investigates its applications and suggests its future impact.

2. FUNDAMENTALS OF 4D PRINTING

3D printing technology has been used to make static structures from digital data in 3D coordinates, 4 D printing adds the concept of change in the printed configuration over time, dependent on environmental stimuli. The key difference between 3D and 4D printing are the smart design and smart materials as 4D printed structures may transform in shape or function. This implies that the 4D printed structures should be fully programmed in detail by accounting for any anticipated time-dependent deformation of the object (Choi et al., 2015). 4D printing was firstly introduced by a research group of Massachusetts Institute of Technology (MIT) and defined as the fabrication of 3D printed structures with adaptable and programmable shapes, properties or functionality as a function of time (Tibbits, 2014).

Intelligent materials are able to sense stimulus from the external environment and create a useful response. Thus, intelligent materials can be seen as those which provide a means of achieving an active intelligent response in a product that would otherwise be lacking and have the potential to yield a multitude of enhanced capabilities and functionalities (Wang, 2017).

Three key aspects must be fulfilled for 4D printing to take place. The first is the use of stimuli responsive composite materials that are blended or incorporate multi-materials with varying properties being sandwiched layer upon layer. The second is the stimuli that will act on the object causing it to animate. Examples of these stimuli include heating, cooling, gravity, ultraviolet (UV) light, magnetic energy, wind, water or even humidity. The last aspect is time for the simulation to occur, and the final result is the change of state of the object (Pei, 2014).

2.1 Smart Materials

Smart materials are essential to the development of 4D printing research. Smart materials don't necessarily have to possess the ability to change shape. Materials that have the ability to change colour, hardness or transparency are also important in camouflage technology, signalling, detecting foreign substances and biomedical applications (Lendlein, 2010). The time dependent change in shape, property or functionality can be triggered by different type of stimuli. Gladman et al used water to activate 4D printed