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4D Printing – Dawn of an Emerging Technology Cycle

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4D Printing – Dawn of an Emerging Technology Cycle

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Abstract

Purpose:	This article reviews state-of-the-art developments in 4D printing, discusses what it is, investigates new applications that have been discovered and suggests its future impact
Approach:	The article clarifies the definition of 4D printing and describes notable examples covering material science, equipment and applications
Findings:	This paper highlights an emerging technology cycle where 4D printing research has gained traction within additive manufacturing. The use of stimuli-responsive materials can be programmed and printed to enable pre-determined reactions when subject to external stimuli

Keywords:	3D Printing, 4D Printing, Additive Manufacturing, Functionally Graded Rapid Prototyping, Variable Property Rapid Prototyping
Paper type:	General review

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Introduction

There have been incredible advancements in Additive Manufacturing over the past decade. 3D printing has reached a critical mass where these machines are now a common sight in product design companies and institutions. As conventional 3D printing technology matures, creeping up in the background is 4D printing. This is where “time” as the fourth dimension is combined with conventional 3D printing technologies. It is not about how long it takes for a part to be printed; but rather the fact that the 3D printed object still continues to “shape shift” and evolves over a period of time (Pei, 2014). Some may ask what is the value in all of this? The main difference is that conventional 3D printing produces parts that are generally static and inanimate whereas 4D printing involves carefully designed geometries with precisely controlled deposition of different materials or active fibres that can reshape when subject to external stimuli. Think about the bi-metallic strip that we are all familiar with in school textbooks. The strip consists of two different metals that expand at different rates when heated. One side will bend one way when hot and the other side will curve in the opposite direction when cold. Now imagine having a bi-metallic strip being 3D printed where it will react to the environment, which in this case ambient heat is the stimuli. We can apply this to a practical product such as a 3D printed window blind that will bend and close to shade the home; or if one desires, opens when the sun is up. Therefore for 4D printing to occur three aspects must be fulfilled. 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 stimulus that will act on the material. Examples of stimuli include heating, cooling, gravity, ultra-violet light, magnetic energy, wind, water or even humidity. The energy sources can come naturally from the environment or through human intervention such as applied tensional or compression forces like shaking or squeezing. The last aspect to be fulfilled is the amount of time for the simulation to occur and the final result is the change of state of the object. For example, the 3D printed part may have pre-determined areas that will bend when subject to magnetic energy, portions that expand when moisture is absorbed, or even areas that breakdown and bio-degrade when exposed to UV light. The BioMolecular Self-Assembly concept by Tibbits and Olson (2012) is an example where a flask containing separate parts are shaken and then self-assembled when the independent pieces find each other (Figure 1).

Figure 1: BioMolecular Self-Assembly (Tibbits, Olson and Autodesk, 2012)

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The concept of “self-assembly” has been used inter-changeably with 4D printing. However for this paper, the author defines 4D printing as the process of building a physical object using appropriate additive manufacturing technology, laying down successive layers of stimuli-responsive composite or multi-materials with varying properties. After being built, the object reacts to stimuli from the natural environment or through human intervention, resulting in a physical or chemical change of state through time. This means that the end result of 4D printing is not limited to self-assemblies but also other states of change.

Novel Applications in 4D Printing

Over the last few months, we have seen a plethora of projects exploring potential applications of 4D printing with proof-of-principle prototypes being demonstrated. Very recently, MIT researchers revealed a “bakable robot” made up of printed components that fold into a prescribed three-dimensional structure when subjected to heat (Hardesty, 2014). This requires exact control of angles at which the heated sheet would fold. The material structure is composed of a polyvinyl chloride (PVC) sheet sandwiched between two films of rigid polyester. When hot, the PVC layer contracts and the edges fold, leading to the pre-determined geometry being formed. The earlier paper by Byoungkwon and Rus (2012) described the use of algorithms to program and control the sheet which could self-fold into a desired shape. Other working prototypes that were demonstrated include a self-folding coil and a strain sensor that could vary the current passing through it when compressed. Researchers at Harvard University also developed a proof-of-concept 3D printed lamp that incorporates polymers that contain "shape memory" characteristics. The rest of the sheet consists of layers of copper, paper and foam. When subjected to heat, the flat surface folds into a lamp. They claim that nearly all of the parts were printed using a 3D printer, such as the shape-memory polymers, the structure, the mechanical switch, the wiring and the capacitive touch sensors. Only the wires and the LED were manually added to the product (Figure 2).

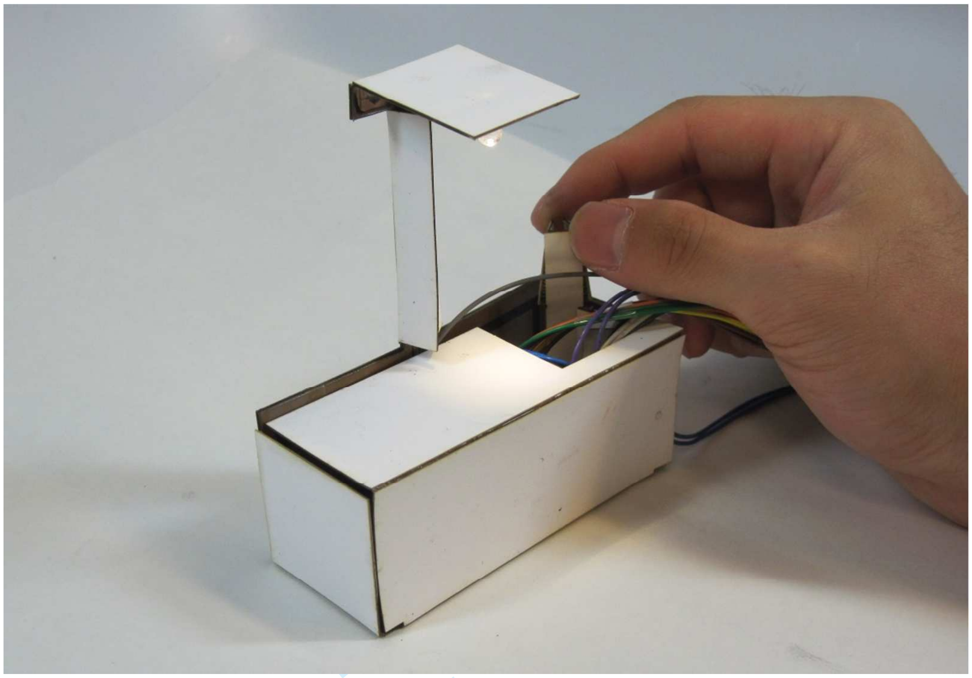

Figure 2: The self-assembly lamp (Byoungkwon A. and Rus, D., 2012).

Ge et al. (2013) also proposed printing glassy shape memory polymer fibres with an elastomeric matrix which can be thermo-mechanically programmed to take on three-dimensional configurations such as bending, coiling, twisting, folding and non-uniform contouring. They take a step further by designing a similar self-folding box fabricated by using those Printed Active Composites that serve as hinges connecting the inactive plates of a stiff plastic that can assemble itself. The United States Army Research Office has recognised the importance of this field and awarded The University of Pittsburgh (2013) a joint-grant to develop adaptive, biomimetic composites that can reprogram their shape, properties, or functionality based upon external stimuli. The consortium of researchers claim that this responsive functionality means that 3D printed parts do not need to be built for a specific purpose but can be continually reconfigured to suit the surrounding environment.

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The Foreseeable Future

Multi-material printing at this time is still limited and one of the most widespread commercial systems in the market is PolyJet printing from Stratasys that was patented in early 2000. In principle, the technology is similar to how inkjet printers work. The Objet Connex 3D Printer which uses this technology jets layers of UV-curable liquid photopolymer onto a printing bed which allows composite materials with predetermined mechanical properties known as “digital materials” to be produced. A variety of elastomer characteristics including shore hardness, elongation at break, tear resistance and tensile strength can be reproduced. Earlier this year, the Objet500 Connex3 was launched, now enabling as many as 46 colours to be printed in a prototype that was not commercially possible just a few years ago. At the time of writing, the company has now increased the number of grey and subtle colour options, combined with varying levels of translucency (Stratasys, 2014).

Creating “4D-ready” materials with varying optical and mechanical characteristics must also account for constraints such as materials expanding or contracting differently when cured. The paper by Vidimče et al. (2013), brings up the stark reality that the demand for a continuous mixture of multiple materials at increasing resolutions with larger print volumes is a huge computing effort and often results in a calculation bottleneck and output delays. They highlighted that existing software is only capable of processing polygon meshes within a single material per object and this is difficult for continuous gradation between multiple materials which is required for advanced multi-material applications. Such Functionally Graded Materials (FGM) or Variable Property Rapid Prototyping (VPRP) comprise compositions that vary over the volume of a given object. In a paper, Oxman (2011) described the process of building parts with varying densities using concrete, changing the elasticity in rubber, or varying the translucency in glass. The objective was to improve the structural and environmental performance, increasing material efficiency and also optimising the material distribution. In another project, Oxman et al. (2011) developed a rapid fabrication apparatus that could dynamically vary the cellular structure of materials. For instance, they used cement and concrete foam and the density was controlled by mixing aluminium powder and lime (Figure 3). The porosity decreased as the ratio of aluminium to cement increased which in turn creates a more efficient use of material by optimizing the stiffness in relation to the overall weight.

Figure 3: Radial density gradient in a concrete sample produced by varying ratio of foaming agent (aluminium powder) (Oxman et. al., 2011)

This is parallel to the natural world where the structure of wood varies in terms of fibre density and direction in growth to improve the material performance; or in the cell structure of tendons in arthropods that require flexural strength. The rapid fabrication apparatus by Oxman (2011) is supported with Variable Property Modelling software that translates model parameters to material properties such as electrical conductivity; and stiffness or softness to simulate the electrical and structural performance. The software control is written in Processing which is an open source programming language that facilitates data visualization; and the blend of material is controlled by the mix ratio and not the total output (the volume). Prior to Oxman's work, other researchers proposed other ways of specifying volumetric representations such as Jackson (2000) who suggested methods involving tetrahedrons and voxels; or using dithering methods that considered the anisotropic properties of fluids when using 3D inkjet printing (Liu et al., 2004; Zhou et al., 2004). Vidimče et al.'s work (2013) is unique as their OpenFab approach offers a scalable architecture that is able to efficiently specify the geometry and material of printable objects. This is achieved using Fablets which are written in OpenFL similar to C-programming that can describe parameters such as surface and volume functionality as well as the type of texture and material. More importantly, the software generates and sends data to the printer in packets rather than a large file. Their work is promising as they successfully fabricated samples showing variation of material properties with a commercial multi-material 3D printer (Figure 4).

Figure 4: Varying colour and squishiness over the model using OpenFab (Vidimče et al., 2013)

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4D Fused Deposition Modelling

Another area for growth potential in 4D printing is Fused Deposition Modelling (FDM) which was identified by Espalin et al. (2013) who acknowledged that very little work on FDM has been explored for multi-material fabrication even though production-grade thermoplastics are already commercially available. Although most filament-based units have a single nozzle, machines with multiple-extruders are becoming more popular. The availability of having several extruders is advantageous as it allows different materials and colours to be printed within a single build. However, there is a limit to the number of extruders that can be incorporated within the enclosure. Therefore, the next logical step is to have a single extruder with an incorporated filament changer that can selectively switch filaments without being interrupted by a change process. This “filament changer” was filed as a patent by MakerBot Industries, Llc. on 21 September 2012 (US 20140034214 A1). Taking a step further, the company also described an integrated transition unit so that when switching filaments, residual material or colour is either removed or compensated in advance to ensure that a high quality print can be achieved. Most importantly, the patent application also described a processor that would control the delivery rate of the build material, paving the way for a true multi-colour / multi-material fabrication capability for Fused Deposition Modelling systems (Boyer, et al., 2014). Hergel and Lefebvre (2014) also suggested that the impact of unwanted oozing plastic could be reduced by having a more optimal extruder azimuth angle and ensuring that the build proximity between the nozzle and the part is sufficiently close to wipe off any residual material. Taking a step further, they developed a tool-path planner to conceal other oozing defects during multi-material prints, which is important to avoid contamination. Reiner et al. (2014) also proposed a dual-colour mixer to produce a continuous stream of two-tone imagery. They suggested that through small geometric offsets, the required tone can be varied without the need to switch print heads within a single layer. The work by Espalin et al. (2013) is particularly important as they successfully demonstrated the working process of combining two legacy FDM machines that were modified to operate as a single unit where a total of three extrusion tips could be utilised. The first machine would produce a uniform thickness of 0.254mm, and the second modified machine could print thin layers of 0.127mm and narrow roads of 0.254mm for the exterior regions; while the interior regions could be printed with thicker layers of 0.508mm and wide roads of 1.27mm. As a stoke of ingenuity, they installed a moveable build platform that could transport the work piece between the two FDM machines and this setup enabled a variable layer thickness and road width to be achieved which reduced the overall build time by up to 35%. Their work is important as it could potentially allow different materials to be kept separated from each printer, thus reducing the contamination of materials.

In terms of materials being suitable for FDM, Graphene has been touted as the next wonder substance and scientists have discovered that this new form of carbon has excellent properties such as good strength and good electrical conductivity. It is no wonder that this is one of the more exciting materials that may soon become available for 3D printing. One concept is the use of polymers infused with Graphene that could improve the mechanical strength of the thermoplastic as well as its electrical and thermal conductivity. The concept was patented in January 2014 by Graphene 3D Laboratories Inc. (2014), which is a spin-off company between Lomiko Metals Inc. and Graphene Laboratories Inc. that exploits high-performance materials specifically for 3D Printing. If commercialised, this exciting filament could pave the way for making functional electronic devices. Other independent manufacturers have also jumped on the bandwagon and have offered a plethora of novel materials where some can be recognised as “4D-ready”. Examples include PolyFlex from Polymakr which is a soft and flexible filament that bends when subject to stress, the flexible filament from MakerBot that can be kneaded and reshaped when heated in hot water, or the exciting PolyMorph material that claims to be able to change its shape when indirectly heated (Polymakr, 2014). Other materials include carbon fibre reinforced Polylactic Acid (PLA) from proto-pasta which is one of the stiffest materials available in a filament form, or the Poro-Lay line of filaments (Lay-Felt, Lay-Tekkks, Lay-Fomm, Gel-Lay) developed by Köln-based engineer, Kai Parthy who claims that these experimental filaments with fibrous and porous structures are conductive when the pores are filled with electrolyte. Thermocromatic filaments have been available for a while in the market where the colour of the material changes at different temperatures. However, the new MakerBot light-responsive Photochromatic PLA Filament takes a step further where it is sensitive to ultra-violet rays and changes colour when in direct sunlight. Gazing into the near future, the range and availability of materials will no doubt increase where we will see improvements in terms of strength, durability, quality of surface finish and added-functionality. Other materials such as aluminium may not be made available due to health concerns (Hoskins, 2013) and there will also be greater awareness in terms of sustainability concerns and economic recovery for material use.

As print volumes and build speeds increase, and as associated costs fall, multi-material printing will gain greater traction and all of these developments in 4D printing are very exciting. However if user expectations are not met, it could lead to confusion among early adopters and may potentially damage the reputation of the additive manufacturing industry. It will be a few more years before sufficient practical knowledge, the availability of specialised software and hardware, and chemo-mechanically responsive materials enter the market for widespread use, heralding the era of 4D printing.

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BioMolecular Self-Assembly (Tibbits, Olson and Autodesk, 2012)
423x230mm (72 x 72 DPI)

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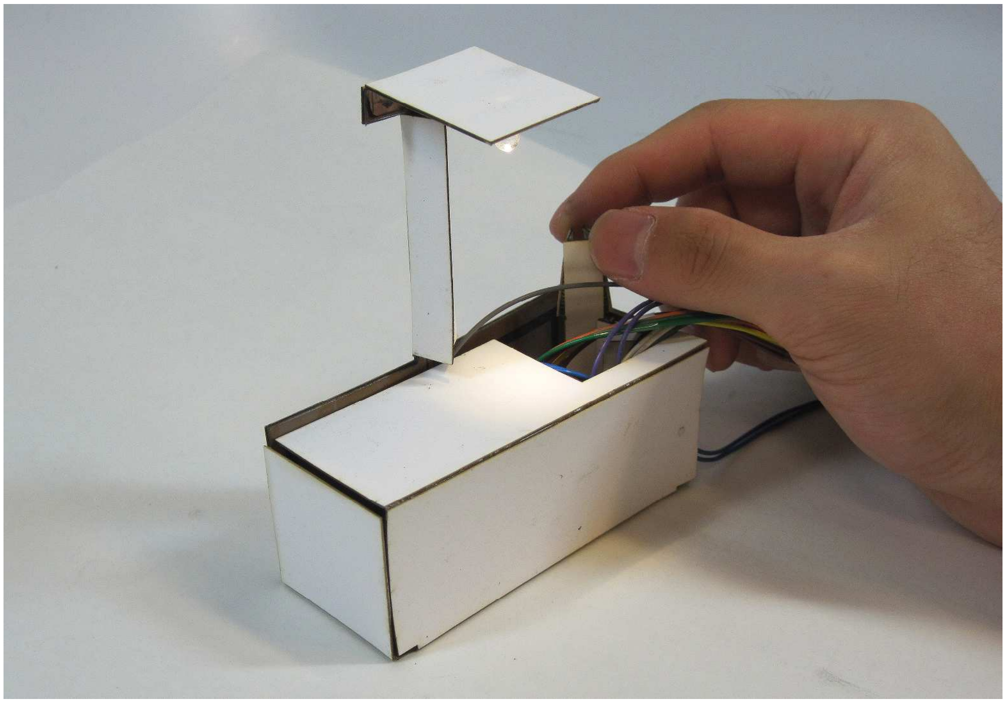

The self-assembly lamp (Byoungkwon A. and Rus, D., 2012).
423x294mm (180 x 180 DPI)

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Radial density gradient in a concrete sample produced by varying ratio of foaming agent (aluminium powder) (Oxman et. al., 2011)
1058x439mm (72 x 72 DPI)

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Varying colour and squishiness over the model using OpenFab (Vidimče et al., 2013)
317x122mm (240 x 240 DPI)

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