International Journal of 3D Printing Technologies and Dijital Industry
Uluslararası 3B Yazıcı Teknolojileri ve Dijital Endüstri Dergisi

A SHORT REVIEW ON 4D PRINTING

Fraz A. KHAN[1], H. Kursat CELIK[2,*], Okan ORAL[3], Allan E.W. RENNIE[4]

[1]Dept. of Farm Machinery and Power, University of Agriculture Faisalabad, Faisalabad, Pakistan
[2]Dept. of Agricultural Machinery and Technology Engineering, Akdeniz University, Antalya, Turkey
[3]Dept. of Mechatronic Engineering, Akdeniz University, Antalya, Turkey
[4]Lancaster Product Development Unit, Lancaster University, Lancaster, United Kingdom

ABSTRACT

Additive Manufacturing can be described as a process to make 3D objects by adding layer upon layer of material, the material traditionally being plastics, metals or ceramics, however ‘smart’ materials are now in use. Nowadays, the term “3D Printing” has become a much-used synonym for additive manufacturing. The use of computing, 3D solid modelling applications, layering materials and machine equipment is common to majority of additive manufacturing technologies. Advancing from this 3D printing technology, is an emerging trend for what is being termed “4D printing”. 4D printing places dependency on smart materials, the functionality of additive manufacturing machines and in ingenious design processes. Although many developments have been made, limitations are still very much in existence, particularly with regards to function and application. The objective of this short review is to discuss the developments, challenges and outlook for 4D printing technology. The review revealed that 4D printing technology has application potential, but further research work will be vital for the future success of this technology.

Keywords: Additive Manufacturing, 3D Printing, 4D Printing, Smart Materials

4B YAZDIRMA (4D PRINTING) ÜZERİNDE BİR KISA İNCELEME

ÖZET

Katmanlı imalat; üç boyutlu objelerin uygun malzemeler kullanılarak katman-katman inşa edilmesi süreci olarak tanımlanabilmektedir. Genellikle kullanılan malzemeler plastik, metal veya seramikler olmakla birlikte son günlerde akıllı malzemelerinde bu teknolojide yer aldığı görülmektedir. Günümüzde yaygınlaşan bu teknolojide “üç boyutlu yazdırma (3D Printing)” kavramı genel terminoloji olan “katmanlı imalat” yerine de kullanılabilmektedir. Nümerik hesaplama yöntemleri, üç boyutlu katı modelleme uygulamaları, katman imalatta kullanılan malzemeler, bu işlemlerde yer alan makine elemanları/sistemleri katmanlı imalat teknolojilerinin başlıca gereklilikleri arasında yer almaktadır ve gün geçtikçe bu alanlarda yeni teknolojik gelişmeler görülmektedir. Bu bağlamda üç boyutlu yazdırma kavramının ötesinde ileri düzey teknoloji eğilimi ile yeni bir kavram olan “dört boyutlu yazdırma (4D Printing)” teknolojileri günümüzde artık uygulamaya konan yeni nesil bir katmanlı imalat yöntemi olarak karşımıza çıkmaktadır. 4D katmanlı imalat; akıllı malzemelere, katmanlı imalat makinelerinin işlevselliğine ve imalat yöntemine özgü tasarım süreçlerine bağımlı olarak ilerlemektedir. Bu konuda başarılı çalışmalar ortaya konsada hali hazırda imalat/ürün işlevselliği ve uygulamaları konularında önemli sınırlamalar bulunmaktadır. Bu çalışmanın amacı 4D katmanlı imalat konusundaki teknolojik gelişmeleri ve uygulamada karşılaşılan sınırlamaları göz önüne alan genel bir bakış ortaya koymaktır. Çalışma sonucunda bu konuda faydalı literatür bilgileri toparlanmış ve 4D katmanlı imalat uygulamalarının ileri düzey imalat teknolojileri içerisinde yer alması için umut verici bir potansiyele sahip olduğu ancak bu konuda daha çok araştırmanın yürütülmesi gerekliliği vurgulanmıştır.

Anahtar Kelimeler: Katmanlı İmalat, 3B Yazdırma, 4B Yazdırma, Akıllı Malzemeler

1. INTRODUCTION

In the late 1980s, the great achievements were made in the field of what has later become known as additive manufacturing with many of the first additive manufacturing processes being introduced commercially [1-3]. Additive Manufacturing is a process used to build up 3D components or objects by adding layer-upon-layer of material, the material being plastics, metals or ceramics. The use of computers, 3D solid modelling software (Computer Aided Design (CAD)), layering of materials and operation of machine equipment are all common to additive manufacturing technologies. Additive manufacturing has vast application in many fields from the development of prototype [4, 5] through to the fabrication of living biological structures [6-9]. Additive manufacturing has many benefits but one problem is that the majority of fabricated components are static and inanimate with the exclusion of moving assemblies [10]. Additive manufacturing (or 3D printing technology) has been the driving force behind the manufacture of many materials for particular applications, however, one group of materials being developed recently are smart materials, being used to give rise to the new trend of “4D printing”. Due to recent developments in multi-materials fabricating, for example using Poly-Jet process (Stratasys Ltd) and printing of functionally graded metal parts by using selective laser melting (SLM Solution), significant development is forecast for the success of 4D printing. According to statistical analysis in 2018 the market of additive manufacturing grew 28.6 percent to US$ 12.8 billion [11]. This promising market opportunity highlights the change in attention to focus on the research necessities for 4D printing technology and related applications in related scientific and industrial areas. This is the main motivation of this short review.

2. DEFINITION OF 4D PRINTING

Although smarts materials are used in many research areas, it is difficult to describe an exact catch-all introduction for smart materials [12]. Leo [13] defines them as “smart materials are those material which convert thermal energy into mechanical work”. According to Varadan *et al.* [14] smart materials are those materials which can change material properties or shape in response to the external environment. The use of smart materials in 3D printing technology has given rise to the introduction of 4D Printing, attracting much interest since 2013 when the idea was first presented [4, 15]. At its core, 4D printing is dependent upon the smart material, additive manufacturing technologies and design [16]. 4D printing has many benefits over 3D printing in several features [17]. The earliest definition of 4D printing was that it was equal to “3D printing” plus “time” [2, 3, 4, 18-21]. A more detailed 4D printing definition is presented following a number of studies which is “process of fabrication of objects with smart materials which are better than 3D printing materials in term of shape, properties, and functionalities”. The basis for 4D printing and the core disparity between 3D printing and 4D printing can be demonstrated in the schematic in Figure 1. In recent developments of additive manufacturing technology, there are two main matters which directly affect the future of 4D printing. 1) What does 4D printing offer? 2) The recent advancement in additive manufacturing and continuing development in smart materials indicates that there are now more prospects for the future potential of the technology to be exploited. Anna Balazs made a research on 4D printing, describes the use of 4D printing materials that can transform themselves due to external stimuli [22].

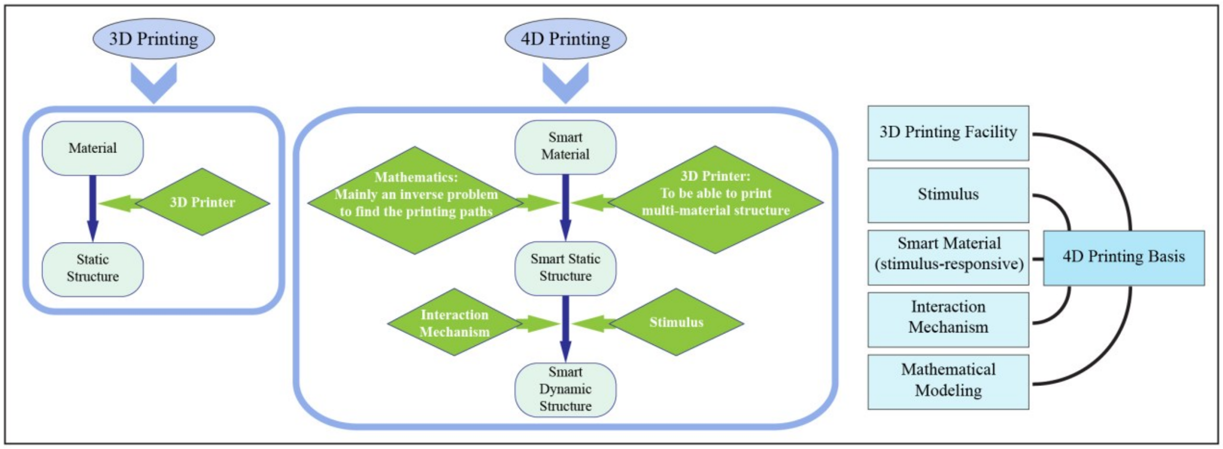

Figure 1. The core disparity between 3D and 4D printing [15].

3. DEVELOPMENTS IN 4D PRINTING

Recently, many developments have been made by the researchers active in the 4D printing area. Some of these developments include the shape-shifting behaviour of parts, material structures and response to various stimuli, all considered in 4D printing applications and simulated through mathematical modelling of the 4D printing process. 4D printed material related developments are discussed in this section. There are two categories for recently developed 4D printing materials: single and multiple materials / composites.

3.1. 4D Printing of Single Material

In achieving the required response, how 'smart' a material is will play an important role for printed structures or product sub-parts that may consist of a single or a mixture of smart and conventional materials. Self-adaptability, self-sensing, shape memory and multiple functionalities are the qualities that are sought of smart materials [23, 24, 68]. Recently developed 4D printed materials include shape memory alloys (SMAs) [25-27], shape memory polymers (SMPs) [42, 43] and enhanced smart nanocomposites [28].
Piezoelectric materials are another important type of smart material. It produces an electrical voltage when practicing an external load and vice versa [28-30]. The applications for piezoelectric materials include energy gathering [28, 31-33], actuators [28, 30-32, 34], and transducers [30, 31, 34]. Making a complex 3D structure with a piezoelectric polymer material is very difficult to achieve; there is a need to improve the manufacturability of piezoelectric polymer material so that this material will have potential in the various application fields which require nano scale piezoelectric polymer materials such as bio diagnostic implement and imaging systems [28].

The core of the shape memory effect (SME) is direct transformation of thermal energy into mechanical work which can be done by SMA material [35]. Transformation occurs in the SMA in two different phases; low and high temperature phases. When the SMA changes its shape, or deforms during the low temperature phase and reverses it shape during the high temperature phase, the shape memory effect can be seen [35-37]. When the SMA material transforms its shape, during the mechanical action super-elasticity can be observed [35]. This property is also known as the mechanical memory of the material. Nickel-titanium (NiTi) is a good example of a SMA having both of these properties [26, 27]. In the NiTi SMA material, a variation in Ni/Ti ratio can change the transformation temperature [26, 38-40]. NiTi SMA material, a many application in engineering fields based on its functional properties [26, 27, 40] such as biomedical implants [39, 40], micro-electromechanical systems and electrical devices [41].

SMPs are also single smart materials. These smart materials have unique designed properties which are stimuli-responsive, so can transform their shape by the application of external impulses such as temperature, moisture, magnetic field, and light etc. [42, 43]. These smart materials have some drawbacks when compared with SMAs [43], including low strength, low working temperature and low young's modulus. Advantages of SMP smart materials includes low cost, low density, and easily controllable working temperature.

3.2. 4D Printing of Multiple Materials

The existence of the 3D additive manufacturing technology is an important factor for designing components with multiple materials. For fabrication in multi-material, the Polyjet 3D printing application is one of the most advantageous technologies used. Some examples of 4D printed multi-material printing are discussed in this section.

Actuators are an important type of 4D printed multi-material component, used for the development of soft robots. Traditionally, hard materials (metals, ceramics, and some hard plastics) are used to develop the robots [44, 45]. The drawback of these robots manufactured with such materials is that they are therefore not suitable for all applications, as it is not possible to get large structural deformation [44, 46]. Due to these types of problems, the concept of soft robotics has been introduced in this field. In this field, some attempts are made to build the qualities of natural organisms in robots by using soft smart materials [44, 47]. Electroactive polymers (EAPs) are an example of soft-smart materials [44, 45]. These materials can transform electrical energy into mechanical work [44, 48].
Self-progress materials are another example of 4D printed multi-material. Self-progress materials are those which, when exposed to water, transforms into their pre-designed shape [47]. Self-progress materials are made up of hydrophilic polymers which absorb water and achieve a larger volume (usually twice the original volume). Three different types of self-progress structures have been developed [47], indicating that these structures have a great potential for application in many fields such as in energy, biosensor and military applications.

Active origami is also an example of 4D printed multi-material. These materials provide great insight about how to compact large objects into small volumes. Traditionally, origami was used for cartons, airbags for automobiles and photovoltaic solar cells with shape converting ability [49]. According to definition, origami objects have the self-ability to fold and unfold. Use of multi-material technology to create printed active parts and check their ability is one of the useful achievements in 4D printing of active origami [19]. Here it should be highlighted another research area that is shape recovery of active origami or controlled sequential folding. Production of SMPs with controlled sequential shape recovery features is recent research done by Yu *et al.* [43].

Recently, the 4D bio-printing concept or laser assisted bio-printing has been introduced [50]. There is an increase in demand of transplantable organs and this cause a shortage [6, 8, 51]. To generate one or more biological functions, the use of material transfer/transport processes for designing and assembling biologically connected materials (cells, molecules, tissues, and biodegradable biomaterials) with given arranger is known as bio-printing [8]. The main advantages of bio-printing includes great precision in locating the unlike cells and appropriateness to produce high cell density tissue [8, 52]. The additive manufacturing of smart hydrogels is another category of 4D bio-printing [53]. This material has an ability to retort to external stimuli such as electrical signals, light, temperature, pH, and magnetic field.

4. THE CHALLENGES AND OUTLOOK FOR 4D PRINTING

4D printing has a very bright future because this is a new area of research and has the potential to solve number of industrial issues. Although this technology has many benefits, the challenges associated with successful implementation and application are also acknowledged. These challenges could be technology related, materials related or design related.

In the technology related limitations, the inadequate availability and suitability of manufacturing technology is a major challenge in the 4D printing field. For 4D printing, only two 3D printing technologies named as Poly-jet technology for produce multi-material parts and selective laser melting (SLM) technology for producing metallic components are being used. Due to this challenge, only few types of smart materials are available in 4D printing field.

Oxidation and changes in the phase transformation behaviour, microstructural defects, rapid solidification and directional cooling can be counted as some of the problems due to the smart materials properties [54]. More research will be required in the field of smart material to handle these types of issue as these would challenge the successful improvement of 4D printing.

The design of smart components is one of the most significant issues that face the field of 4D printing. Actuators are good examples of a smart part. For an actuator to work properly, the membranes must be in a pre-strain state. Unfortunately, no current additive manufacturing technology is available to fabricate pre-strained membranes directly. Therefore, more research will be needed to develop this type of technology for the future implementation of 4D printing for such applications.

5. APPLICATIONS of 4D PRINTING

4D printing has vast applications in many fields, most especially in biomedical applications. Momeni *et al.* underlines that in many practices, 4D printing can has significant advantageous in directly producing complicated 3D parts [15].Here the most important point is that producing lower-dimensional less complex object would provide easy, fast produced components with lower manufacturing costs. Furthermore, the storage and transportation of lower-dimension components would be promising. However, current technology come across with some limitations in 4D printing applications because of unsatisfied single material properties or material combinations. Here, studies on 4D printed artificial muscles can be a good example. In these type of studies desired performance and functions of the muscles are considered as insufficient as some of properties belong to the materials used in printing operations should be improved [55, 69]. Therefore it would not be wrong to say that advances of the 4D printing technology is directly related to advances of the smart materials and material adaptation to the 4D printing devices. Some of the leading applications of 4D printing are summarized in Table 1.

Table 1. 4D printing applications.

Year	Researcher	4D Printed Structure	Applications
2016	Ge et al. (56)	Smart Gripper	Applied in drug delivery system
2016	Ge et al., Bodaghi et al., Zarek et al., and Wei et al. (56-59)	Slent	Expand human vessels
2016	Bodaghi et al., Zhang et al., Jiang and Wang (57, 60, 61)	Adaptive Meta-materials	Used as switch b/w two different dynamic states For soft robots Used as reversible shape-shifting connectors
2016	Nadgorny et al. (62)	Smart Valve	Control the acidic and basic flow
2016	Wu et al. (63)	Smart Structure	Smart hoot, smart trestle and smart insect-like
2015	Bakarich et al. (64)	Smart Valve	Control the hot and cold flow
2015	Kokkinis et al. (65)	Smart key-lock connectors	Used as a physical connection b/w biological components in the body such as tendons and muscle
2014	Tibbits et al. (21)	Artificial Crambin Protein Structure	Solution for biomedical problems
2014	Ge et al. (66)	Origami Structures	Storage and Transportations
2014	Raviv et al. (47)	Smart Joints	Used in other structures in practice like prosthetic finger
2013	Villar et al. (67)	Droplets network	Used as tissue engineering substrates

6. CONCLUSION

A short review on 4D printing technology has been presented in this paper. The developments in 4D printing were grouped as: 4D printing of unique smart materials (shape memory alloys, smart nanocomposites, and shape memory polymers); 4D printing of multiple material (actuators, self-progress structures, and active origami); and 4D bio-printing. The divergence between 4D of single/unique smart material and 4D printing of multiple materials was also discussed which is based on the limiting factor of changes. The restricting factor of 4D printing of single/unique materials is the smartness of single/unique smart material components and restricting factor for 4D printing of multi-material is the range of changes in multi-material parts. The challenges and outlook for 4D printing was also discussed. In short, it would not be wrong to say that more research is vital for the future of 4D printing. This short review contributes to further research into the usage of 4D printing as a developmental step of additive manufacturing for application in related industrial areas.

ACKNOWLEDGEMENTS

The abstract of this study was published and presented in The Third International Congress on 3D Printing (Additive Manufacturing) Technologies and Digital Industry (3D-PTC2018) (19-21 April, 2018, Antalya, Turkey). Additionally, the authors wish to acknowledge that this study is partly supported financially by The Scientific Research Projects Coordination Unit of Akdeniz University (Turkey) and Lancaster Product Development Unit (LPDU) in Lancaster University (United Kingdom).

REFERENCES

[1] Donnell JO, Ahmadkhanlou F, Yoon HS, Washington G. All-printed smart structures: a viable option? Active and Passive Smart Structures and Integrated Systems. 2014; 9057.
[2] Pei E. 4D printing - revolution or fad? Assembly Automation. 2014; 34:123–127.
[3] Pei E. 4D printing: dawn of an emerging technology cycle. Assembly Automation. 2014; 34: 310–314.
[4] Tibbits S. The emergence of "4D printing", TED Conference. 2013.
[5] Chua CK and Leong KF. 3D printing and additive manufacturing: principles and applications. 4th ed. Singapore: World Scientific Publishers. 2014.
[6] Seliktar D, Dikovsky D, Napadensky E. Bioprinting and tissue engineering: recent advances and future perspectives. Israel Journal of Chemistry. 2013; 53:795–804.
[7] Huang SH, Liu P, Mokasdar A, Hou L. Additive manufacturing and its societal impact: a literature review. International Journal of Advanced Manufacturing Technology. 2013; 67:1191–1203.
[8] Chua CK and Yeong WY. Bioprinting: principles and applications. Singapore: World Scientific Publishing Co. Pte. Ltd. 2015.
[9] Murphy SV and Atala A. 2014. 3D bioprinting of tissues and organs. Nature Biotechnology. 2014; 32:773–785.
[10] Maidin S, Campbell RI, Pei E. Development of a design feature database to support design for additive manufacturing. Assembly Automation. 2012; 32(3):235-244.
[11] https://www.statista.com/statistics/284863/additive-manufacturing-projected-global-market-size/.
[12] Bogue R. Smart materials: a review of capabilities and applications. Assembly Automation. 2014; 34:3–7.
[13] Leo DJ. Engineering analysis of smart material systems. Hoboken, NJ, Canada: John Wiley & Sons, Inc. 2007.
[14] Varadan VV, Chin LC, Varadan VK. Modelling integrated sensor/actuator functions in realistic environments. In First European Conference on Smart Structures and Materials, Forte Crest Hotel, Glasgow. 1992.
[15] Momeni F, Hassani SMM, Xun Liu N, Jun Ni J. A review of 4D printing. Materials and Design. 2017; 122: 42-79.
[16] Choi J, Kwon OC, Jo W, Lee HJ, Moon MW. 4D printing technology: a review. 3D Printing and Additive Manufacturing. 2015; 2:159–167.
[17] Jacobsen M. Clearing the way for pivotal 21st-century innovation. Giftedness and Talent in the 21st Century, Springer. 2016; 10:163–179.
[18] Khoo ZX, Teoh JEM, Liu Y, Chua CK, Yang S, An J, Leong KF, Yeong WY. 3D printing of smart materials: a review on recent progresses in 4D printing. Virtual and Physical Prototyping. 2015; 10:103–122.
[19] Ge Qi, Qi HJ, Dunn ML. Active materials by four dimensions printing. Applied Physics Letters. 2013; 103:131901-1–5.
[20] Tibbits S. 4D printing: multi-material shape change. Archit. Des. 2014; 84:116–121.
[21] Tibbits S, McKnelly C, Olguin, C, Dikovsky D, Hirsch S. 4D printing and universal transformation. ACADIA 14: Design Agency [Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 9781926724478] Los Angeles 23-25 October 2014; pp. 539-548.
[22] University of Pittsburgh. [Pitt-led research team receives grant to develop four-dimensional printing to create adaptive materials]. Swanson School of Engineering, University of Pittsburgh, Pittsburgh, PA, available at: www.engineering.pitt.edu/News.aspx?id¼2147508574. Accessed 1 February 2014.
[23] Varadan VK, Vinoy KJ, Gopalakrishnan S. Smart material systems and MEMS: design and development methodologies. Chichester: John Wiley & Sons Ltd, Great Britain. 2006.
[24] Kamila S. Introduction, classification and applications of smart materials: an overview. American Journal of Applied Sciences. 2013; 10:876–880.
[25] Meier, H, Haberland C, Frenzel J, Zarnetta R. Selective Laser Melting of NiTi shape memory components. 4th, International conference on advanced research and rapid prototyping; Innovative developments in design and manufacturing advanced research in virtual and rapid prototyping. 2009; Leiria, Portugal.

[26] Meier H, Haberland C, Frenzel J. Structural and functional properties of NiTi shape memory alloys produced by Selective Laser Melting. London: Innovative Developments in Virtual and Physical Prototyping. 2012; 291–296.
[27] Dadbakhsh S, Speirs M, Kruth JP, Schrooten J, Luyten J, Humbeeck JV. 2014. Effect of SLM parameters on transformation temperatures of shape memory nickel titanium parts. Advanced Engineering Materials. 2014; 16(9):1140–1146.
[28] Kim K, Zhu W, Qu X, *et al.* 3D optical printing of piezoelectric nanoparticle-polymer composite materials. ACS Nano. 2014; 8(10): 9799–9806.
[29] Lin D, Nian Q, Deng B, Jin S, Hu Y, Wang W, Cheng GJ. Three-dimensional printing of complex structures: man-made or toward nature? ACS Nano. 2014; 8(10):9710–9715.
[30] Uchino K. The development of piezoelectric materials and the new perspective. In: K. Uchino, ed. Advanced piezoelectric materials - science and technology. Padstow, Cornwall: Woodhead Publishing. 2010; 1–43.
[31] Lang SB, and Muensit S. Review of some lesser-known applications of piezoelectric and pyroelectric polymers. Applied Physics A -Materials Science and Processing. 2006; 85:125–134.
[32] Vijaya MS. Piezoelectric materials and devices-applications in engineering and medical sciences. Boca Raton, FL: CRC Press. 2013.
[33] Wong, CH, Dahari Z, Manaf AA, Miskam MA. Harvesting raindrop energy with piezo electrics: a review. Journal of Electronic Materials. 2015; 44(1): 13–21.
[34] Rajabi AH, Jaffe M, and Arinzeh, TL. Piezoelectric materials for tissue regeneration: a review. Acta Biomater. 2015; 24:12–23.
[35] Fremond M, and Miyazaki S. Shape memory alloys. Wien: Springer - Verlag GmbH. 1996.
[36] Trasher MA, *et al.* Thermal cycling of shape memory alloy wires using semiconductor heat pump modules. Presented at the First European Conference on Smart Structures and Materials, Forte Crest Hotel, Glasgow. 1992.
[37] Leo DJ. Engineering analysis of smart material systems. Hoboken, NJ, Canada: John Wiley & Sons, Inc. 2007.
[38] Frenzel J, George EP, Dlouhy A, Somsen C, Wagner MFX, Eggeler G. Influence of Ni on martensitic phase transformations in NiTi shape memory alloys. Acta Materialia. 2010; 58:3444–3458.
[39] Bormann T, Schumacher R, Muller B, Mertmann M, de Wild M. Tailoring selective laser melting process parameters for NiTi implants. Journal of Materials Engineering and Performance. 2012; 21:2519–2524.
[40] Elahinia MH, Hashemi M, Majid T, Bhaduri SB. Manufacturing and processing of NiTi implants: a review. Progress in Materials Science. 2012; 57:911–946.
[41] Sharma N, Raj T, and Jangra KK. Applications of nickel-titanium alloy. Journal of Engineering and Technology. 2015; 5:1–7.
[42] Lendlein A, and Kelch S. Shape-memory polymers. Angewandte Chemie International Edition. 2002; 41: 2034-2057.
[43] Yu K, Ritchie A, Mao Y, Dunn ML, Qi HJ. Controlled sequential shape changing components by 3D printing of shape memory polymer multi-materials. Procedia IUTAM. 2015; 12:193–203.
[44] Rossiter J, Walters P, and Stoimenov B. Printing 3D dielectric elastomers actuators for soft robotics. Proc. Of SPIE. 2009; 7287.
[45] Bauer S, Gogonea SB, Graz I, Kaltenbrunner M, Keplinger C, Schwodiauer R. 25th anniversary article: a soft future: from robots and sensor skin to energy harvesters. Advanced Materials. 2014; 26(1):149–162.
[46] Ahn SH, Lee KT, Kim HJ, Wu R, Kim JS, Song SH. Smart soft composite: an integrated 3D soft morphing structure using bend-twist coupling of anisotropic materials. International Journal of Precision Engineering and Manufacturing. 2012; 13(4):631–634.
[47] Raviv D, Zhao W, Mchnelly C, *et al.* Active printed materials for complex self-evolving deformations. Scientific Report, 4. 2014.
[48] Bar-Cohen Y. Electroactive polymers as actuators. In: K. Uchino, ed. Advanced piezoelectric materials - science and technology. Padstow, Cornwall: Woodhead Publishing. 2010; pp, 287–317.
[49] Ge Qi, Dunn CK, Qi HJ, Dunn ML. Active origami by 4D printing. Smart Materials and Structures. 2014 23(9) 1–15.
[50] Poietis. Bioprinting 4D by laser. 2014, 2015. (www.poietis.com)
[51] Ozbolat IT, and Yu Y. Bioprinting toward organ fabrication: challenges and future trends. IEEE Transactions on Biomedical Engineering. 2013; 60:691–699.
[52] An J, Teoh JEM, Suntornnond R, Chua CK. Design and 3D printing of scaffolds and tissues. Engineering. 2015; 1(2): 261–268.
[53] Wang S, Lee JM, and Yeong WY. Smart hydrogels for 3D bioprinting. International Journal of Bioprinting. 2015; 1:3–14.

[54] Frazier, WE. Metal additive manufacturing: a review. Journal of Materials Engineering and Performance. 2014; 23:1917–1928.
[55] Loh XJ. Four-dimensional (4D) printing in consumer applications, Polymers for, Personal Care Products and Cosmetics. 2016; 20:108–116.
[56] Ge Q, Sakhaei AH, Lee H, Dunn CK, Fang NX, Dunn ML. Multi-material 4D printing with tailorable shape memory polymers. Sci. Rep. 2016; 6.
[57] Bodaghi M, Damanpack A, Liao W. Self-expanding/shrinking structures by 4D printing. Smart Mater. Struct. 2016; 25:105034.
[58] Zarek M, Mansour N, Shapira S, Cohn D. 4D printing of shape memory-based personalized endoluminal medical devices. Macromol. Rapid Commun. 2016; DOI.
[59] Wei H, Zhang Q, Yao Y, Liu L, Liu Y, Leng J. Direct-write fabrication of 4D active shape-changing structures based on a shape memory polymer and its nanocomposite. ACS Appl. Mater. Interfaces. 2016; DOI.
[60] Zhang Q, Zhang K, Hu G. Smart three-dimensional lightweight structure triggered from a thin composite sheet via 3D printing technique. Sci. Rep. 2016; 6.
[61] Jiang Y, Wang Q. Highly-stretchable 3D-architected mechanical metamaterials. Sci. Rep. 2016; 6.
[62] Nadgorny M, Xiao Z, Chen C, Connal LA. Three-dimensional printing of pH responsive and functional polymers on an affordable desktop printer, ACS Appl. Mater. Interfaces. 2016; 8:28946–28954.
[63] Wu J, Yuan C, Ding Z, Isakov M, Mao Y, Wang T, Dunn ML, Qi HJ. Multi-shape active composites by 3D printing of digital shape memory polymers, Sci. Rep. 2016; 6.
[64] Bakarich SE, Gorkin R, Spinks GM. 4D printing with mechanically robust, thermally actuating hydrogels. Macromol. Rapid Commun. 2015; 36:1211–1217.
[65] Kokkinis D, Schaffner M, Studart AR. Multi-material magnetically assisted 3D printing of composite materials. Nat. Commun. 2015; 6.
[66] Ge Q, Dunn CK, Qi HJ, Dunn ML. Active origami by 4D printing. Smart Mater. Struct. 2014; 23:094007.
[67] Villar G, Graham AD, Bayley H. A tissue-like printed material. Science. 2013; 340:48–52.
[68] Blaney, A., Alexander, J.M., Dunn, N.S., Richards, D.C., Rennie, A.E.W., Anwar, J., Adaptive materials: Utilising additive manufactured scaffolds to control self-organising material aggregation. In: Proceedings of the 14th Rapid Design, Prototyping and Manufacturing Conference. Lancaster University, Loughborough, pp. 49-57. ISBN: 9781526203038
[69] Mirabedini A., Aziz S., Spinks GM., and Foroughi J. Wet-Spun Biofiber for Torsional Artificial Muscles. Soft Robotics. December 2017, 4(4): 421-430. https://doi.org/10.1089/soro.2016.0057.