4D Printing

K. Raghavendra, M. Manjaiah and N. Balashanmugam

Abstract With evolution and change in environment, Nature's structures and its material system exists with products having multiple designs and dimensions. Inspired by Nature's ability to develop structures with complexity, various research works are carried out to develop newer technology to build complex products with more design dimensions. In the process of bio mimicking nature's fabrication process 3D printing has captured the imagination of everyone from industry to research experts. However, there are various challenges need to be addressed in the process of 3D printing related to material system and product functional dynamicity. Hence, to overcome the limitations of 3D printing in flexible product development, 4D printing was generated with one or more additional design dimensions. 4D printing invented by MIT research group relies on fast growth of smart materials, 3D printers, mathematical modelling and design, and shows advantages over 3D printing. This article presents a comprehensive overview of 4D printing concept, applications and future scope for research.

Keywords 4D printing · Material · Design · Product development

1 Introduction

Ever since the industrial revolution, manufacturing sectors of all domains exhibited factories with complex mechanisms for production. 3D printing in the past thirty odd years has changed production scenario without tooling, assembly lines or supply

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chains making it a classic riotous technology. Hence, seeing the current capabilities of advanced manufacturing, it can be ensured that conventional goods, engineering components and customized medical products will be developed with aid of 3D printing factories [6, 10].

Manufacturing sectors of all engineering disciplines are under the process of technological transformation promising the establishment of customizable and sustainable manufacturing environment for the betterment of the industries.

New forms of engineering such as Additive Manufacturing are giving raise to the new industries such as 3D printing, 4D printing or direct digital manufacturing. These set of industries can be used in all industrial sectors comprising of aerospace, civil, electronics, and medical industries. Especially in medical sector, these technologies can be used in development of customized surgical tools, human implants, replacement of tissues and organs and many more [12].

Decades back with the advent of 3DP, objects developed were only tested outside human body for medications and treatments. However, with introduction of 4DP researchers are developing samples of human organs for drug and functionality testing. This can support researchers to develop human organs with desirable capabilities as compared to human body natural limits.

The right implementation of 3D and 4D printing technologies can positively transform the world in the manufacturing industries domain rapidly leading to Third Industrial Revolution through elimination of limitations encountered in the period of first and second stage industrial revolution.

1.1 3D Printing

3D printing is an additive manufacturing process, where in, the products are developed by depositing layers using different 3D techniques for designed Computer Aided Design (CAD) model or 3D scanners used to scan a model and convert it into digital data. In here, the development of objects is controlled by optimizing position and adhesion of specimen in 3D space. 3D printing is a process which turns the digital data into physical product by depositing layer by layer. 4D printing is based on the 3D printing technology, it uses a special material and refined design that is planned to prompt 3D print to change its shape.

2 Advancement in 3D Printing

Additive manufacturing also known as 3D printing has been associated with Rapid prototyping from past 30 years [5]. Research in 3D printing technology has attracted unprecedented interest since 1980s [8]. Since then, 3D printing has become a multibillion dollar business rapidly growing in industries for development of prototypes. However, the assignment of properties of materials and distribution of the same along

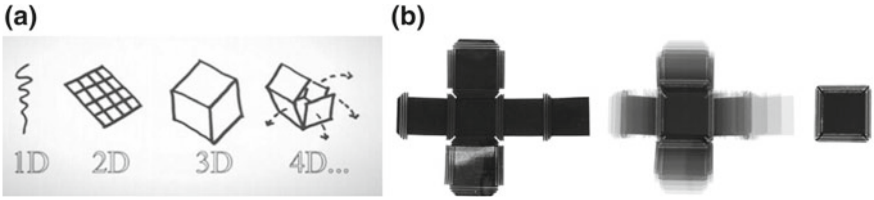

Fig. 1 **a** Simple illustration of the concept of 4D printing (P1) **b** REF T4 flat surface that self-folds into a closed cube developed using 4DP [12]

multiple dimension and direction cannot be modulated in 3D printing techniques though they develop accurate models and complex designs.

In order to overcome these limitations of 3D printing, a new technology was developed by Skylar Tibbits of **Massachusetts Institute of Technology (MIT)** in 2013 [14]. The research carried out at MIT focused on development of system smarter in solving the problems associated with reduction in wastage of energy, materials, money, time and increase in positive properties of the product. In order to achieve these, Tibbits proposed a combined concept of logic matter, materials with mathematical data programming known as **4D printing**.

Integration of mathematical models with 3DP process functionally defines the functionality of 4DP components. Figure 1a illustrates the geometrical phenomenon of 4DP. During functional products development process, the minute dimension or the micro sized part of the product is initially printed, later the structure's major dimensions are printed for enhancing the performance of the functionality of the product. Hence optimizing the process of the 4DP will lead to fast and low cost development of the component.

2.1 4D Printing: Reinventing Manufacturing

4D printing is the time targeted evolution of 3D printing. It is defined as 3D printed object where the shape, property and functional change occurs with respect to time. More comprehensively defined as per number of studies conducted on this study, it is a targeted evaluation of 3D printed object capable of performing self-assembly and multi functionality. In here, the targets are focused on development of objects having ability to memorize the structure shape, property and function before and after application of loads.

4D printing can be applied in diverse industries/fields including aerospace, automotive, electronics, medical and education. The technology can revolutionize interdisciplinary fields of industries by benefitting the process of product development at lower processing costs. In 4D printing, the time, effort and cost to create complex designs are comparatively lower in comparison to conventional manufacturing pro-

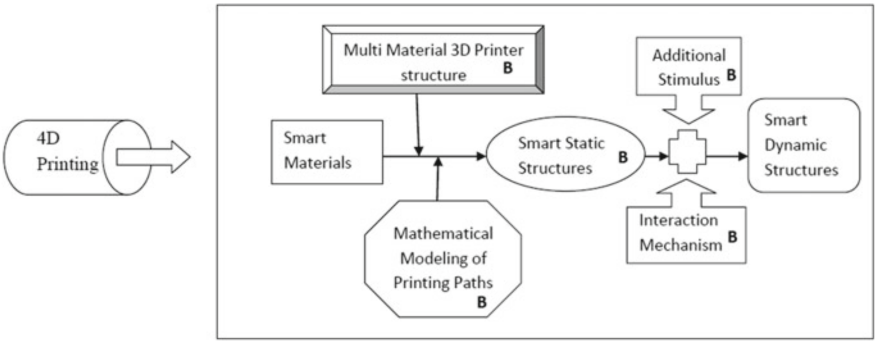

Fig. 2 4D printing with working bases

cesses. Hence 4D printing will possibly be the technology to redefine the currently existing manufacturing processes.

2.1.1 Working Principle-4D Printing

4D printing is a system having the ability of fabricating dynamic structures with adjustable shapes properties or functionality [14]. This capability can be obtained by having appropriate combination of smart materials in 3D space [13]. In order to design such complex structures mathematical modeling is desired. Hence, as shown in Fig. 2, the fundamental building blocks for effective working of a 4DP system are, 3D printing facility, stimulus, responsive material, interaction mechanism, and mathematical modeling. The optimal combination of these elements has contributed to effective evolution of 4D printed structures over time.

2.1.2 Elements for Effective Working of 4DP

I. 3D printing facility: use of 3D printing apparatus is necessary for fabrication of multi material structures with simple and complex geometry having differences in material properties such as swelling ratio, coefficient of thermal expansion etc. this will enhance the property of the structure in shape-shifting behavior.

II. Stimulus: on a need basis system, in order to trigger the change and regain of shape/property/functionality of a 4D printed structure stimulus are stipulated for a 4D printed structure. The stimulus include water, heat and light, and a combination of water and heat [12]. Stimulus are generally selected based on the specific application and the smart materials involved in the same.

III. Smart or stimulus responsive materials: is the most important component of 4D printed structure. For effective working of the 4DP structure the material should fulfill properties such as, self-sensing, decision making, responsiveness, shape memory, self-adaptability, and multi functionality and self-repair [8]. Hence processing the same with the combination of 3DP facility and stimulus is of prior importance.

IV. Interaction mechanism: in some cases application of stimulus in a predetermined sequence defines the effectiveness of a 4D printed structure with respect to the 4th dimension time.

V. Mathematical modeling: mathematical modeling defines the design of material distribution and structure during printing by providing desired shape, property and functionality. Development of theoretical and numerical models will lead establishment of connections between 4 core elements namely; material structure, shape, material properties and stimulus properties.

4D printing is an invention made with effective combination of 3D printing and smart materials. The effectiveness can be achieved by exposing to the external stimulus through an interaction mechanism and through assistance of Mathematics.

3 Biomimetic

Biomimetic is the modern technological approach followed for replication of Nature's way of behavior in synthetic product by fabrication processes through technology surveys knowing the limitations in functionality of the materials and the processes being used.

The behavior and organization of material with time is as shown in Fig. 3. It defines the response of a system to the environmental conditions and constraints based on the material structure. Hence, seeing the materials compositions of the material system, for replication of the same in the artificial system the process involved in the development of the system should be deliberate and preconceived in design of materials, dimensions, and shape to achieve necessary functions and necessary constraints. This is considered very crucial as anisotropy in natural materials is omnipresent with most materials exhibiting anisotropic behavior in accordance to their function and behavior.

However, in technology associated with biomimetic and additive manufacturing, limitations always arise in prototyping with current methods of fabrication and materials. Hence, a new approach such as the 4D printing with use of one or more additional dimensions of materials grade, adaptation and response over time, along with control over volumetric anisotropy is being developed by research team to address such mismatch in biomimeting.

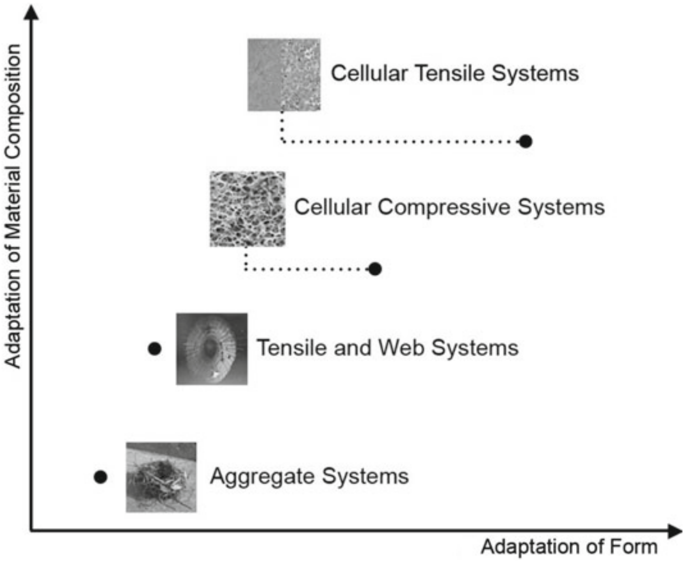

Fig. 3 Composition and form in Nature's material systems [15]

4 4D Printing Materials

Material homogeneity is omnipresent in nature and the functional material gradient determines the efficiency of a product through spatially varying compositions and properties [2]. However, industrially produced components comprise of homogeneously defined forms and materials of parts. Hence, development of such components though have manufacturing components and design tools, they may compromise with certain improvements in strength, weight, functionality and measurement. In order to overcome these limitations of material property after processing, a strategic control of material property density and directionality in the generation of complex smart structures known as digital anisotropy was introduced by researchers at **MIT** [14] to achieve controlled gradients of stiffness and elasticity. Table 1 presents some of the significant advantages of 4D printing over 3D printing.

4D printing materials are intelligent materials which do active functions from the external atmosphere and make a useful response, but this would include physical sensing materials such as piezoelectric or magnetostrictive compounds are categorize as "intelligent". The material provides an active response in a product that would otherwise be lacking and have the potential to yield a multitude of enhanced capabilities and functionalities [9]. The intelligent materials capabilities are reported in Table 2.

Table 1 4D printing over 3D printing [3]

Sl. no	Advantages over traditional manufacturing	3D Printing (3DP)	4D Printing (4DP)
1	Improvement in freedom for design	Generic conventional fabrication processes limits the product development with increase in design complexity due to machine ability constraints. Also, machining capability is reduced with the kind of material being used. However, in 3DP materials can be selected based on the design requirement and not on the machine capability	Freedom for design and development is much better in 4DP than 3DP and conventional processes. 4DP will allow development of parts with anisotropy property
2	Reduction of cost even with increase in complexity of design	Cost is high in conventional processes due to limitation in machining complex shapes and complicated materials. In 3DP additive manufacturing process since parts are printed layer by layer no additional cost is contributed	Since the process of 4DP is completely streamlined no additional cost of any matter exists in development of simple or complex structures
3	Demand based production customization	Products can be printed on a 3DP for any customized design of product requirement with no additional cost	Since 4DP is the advanced version of 3DP any complex customized product can be generated without any cost loss
4	Product customization with mass production	3DP can develop products with customizable design without changing machine and increasing the cost	4DP can further enhance the capability of personalization of products which can be universally accepted
5	Simplification of manufacturing process	Since the process of 3DP involves direct conversion of standardized digital file into physical product, human intervention with respect to operator skill is minimized	In 4DP structures can be activated through external stimulus to obtain complex functional structures and systems

(continued)

Table 1 (continued)

Sl. no	Advantages over traditional manufacturing	3D Printing (3DP)	4D Printing (4DP)
6	Single system comprising of both prototyping and production	Multiple usage of fabrication techniques is minimized in 3DP as prototypes/test parts can be made with same procedure in 3DP using a single system	In 4DP, since materials are embedded and created with dynamic functionality, higher expectation of product performance can be framed in 4DP fabrication process than any other fabrication techniques
7	Elimination of supply chains and assembly lines for complex products	3DP is a one shot fabrication process as many assembly lines and multiple fabrication units are eliminated	Since products of multiple functionality can be developed with 4DP supply chains and assembly lines are eliminated
8	Elimination of actual product transportation across the world	Since the technology is similar to most of the process able materials, products can be redeveloped with same functionality using 3DP with similar design data	Since voxels of 4DP can develop multifunctional objects game changing design to production can be gifted to the manufacturing world
9	Optimization of product properties	Since 3DP has the ability to process composites of required materials, desired properties can achieved	Use of multi materials through programmable matter (PM) in 4DP can lead to development of products with optimized customizable properties
10	Instantaneous production on a global scale	Rate of production can be increased in the global scale using 3DP as digital data of the product can be transferred to any part of the world in fraction of minutes	In 4DP, collection of voxels can enable matter formation on demand and digital data can be transferred anywhere in the world
11	Magnification of innovation ability	Very minimum limitations to product development with 3DP due to less limitations in engineering constraints	With 4DP, any material and any functionality can be developed for a product. Hence, there shall exist almost no technological limitation with 4DP

(continued)

Table 1 (continued)

Sl. no	Advantages over traditional manufacturing	3D Printing (3DP)	4D Printing (4DP)
12	Endless implementation of engineering ideas in design and development	Ease and clarity of 3DP technology can create direct relationship between the designer and the product with no space to confusion in fabrication process	4DP can create products a step ahead of 3DP due to the capability of development of multifunctional objects and material programming leading to development of dynamic and intelligent physical models

Table 2 The intelligent material capabilities

Function	Description
Shape memory	Shape changes by external stimuli
Self-assembly	Allows automated assembly
Self-actuating	Automated actuation in response
Self-sensing	Allows automated detection and sometimes quantification of external stimuli

4.1 Shape Memory Polymers (SMPs)

Shape memory polymers are the evolving active class of polymers that can be used in a wide range of application in biomedical devices and microsystems [7]. SMP have an ability to alter the shape in a predefined way to form a temporary transformation to permanent transformation when it exposed to appropriate stimuli-triggered dynamic processes. This characteristics of SMP helps in application of 4D printed materials as a shape changes with respect to time dependent. These materials have high elastic deformability, low cost, light weight and extremely biocompatible and biodegradable. These materials functions are largely depend on the glass transitions temperature (T_g). Thermoresponsive SMPs the temporary shape is presented by heating the polymer to a glass transition temperature (T_g) and then reforming into temporary shape by the physical force. Among all the SMPs thermoresponsive are the most widely applied derivatives, which demonstrates a broad tuneable range of mechanical, thermal and optical properties [1]. Also among many other applications, these polymers are used to generate medical support devices such as stents and catheters. Since such complex applications demand multiple functionality shape memory effect, polymers such as acrylates, polyurethanes and other multiple polymer blends are used. Also, in order to achieve multiple functionality within the developed device, SMP's are pre and post processed to achieve shape memory mechanisms. To achieve this, indirect heating methods using infrared light of electronic triggers is generally performed to enhance the shape recovery mechanism property. However, direct heating of SMP's is generally considered in processing SMP's.

Fig. 4 Microstereolithogrphy 3D printed thermoset polymer [11]

4.2 Thermoset Shape Memory Polymers

Thermoset SMP's are the blend of thermoset resins or polymers of similar monomers of designed composition leading to shape memory system. The monomer combinations involve polyethylene glycol or polybutadiene to form shape memory cyanate system. With aid of synthesizing/polymerizing materials such as soya oil epoxidized acrylate these polymers can be made use in fabrication of scaffolds with different printing techniques. Figure 4 represents 3D printed article developed using table top stereolithography system. Similarly UVLED digital light processing printer can also be used for such developments. Hence, with controlled UV light and LASER light projecting systems, networks can be developed via printing through high resolution projection systems.

4.3 Shape Memory Thermoplastic Polymers

Thermo plastic polymer is a polymer generally used as printing ink in 3D printers. Polyurethane elastomer was used as TPSM material by [16]. Study showed commercially available pallets of DiAPLEXMM4520 from SMP technologies having a crystallanity of 350wt% was found to be feasible for processing in 3DP. Also, shape memory filaments processable with 3DP were found in bulk. However, in order to process such materials the process parameters such as nozzle temperature, scanning speed and part cooling in 3DP initially needs to be essentially optimized in a controlled environment for establishing high quality structures. Based on optimization of process parameters of 3DP, 3D structures were fabricated with good shape memory properties.

4.4 Self-healing Hydrogel Materials

Polymeric materials are being synthesized with self-healing properties for application in 3D bio mimicking of tissue such as external skin. Hydrogel monomers/polymers are considered to be the effective raw materials due to its outstanding properties of 3D network structure and water retention capabilities fulfilling the conditions of extracellular matrix. Thus, soft hydrogels are preferred as ideal materials for preparation of scaffolds in tissue engineering applications. Applications of hydrogels vary from wound dressings, personal hygiene products and contact lenses. Currently, hydrogels are also extensively researched for biologically active compounds for use in drugs, antibodies and development of implants. Hydrogels motivate 4DP as they can be used as self-healing materials in normalizing wound tissues having the dynamic process behaviour of 4DP.

5 Applications

4D printing technology has the ability to upgrade current manufacturing business environment. Study on materials with self-changing properties will increase the application areas of 4D printed articles.

Currently researchers are exploring 4D printed structures in various fields of applications due to material's anisotropic and shape memory property. Beyond the simple regular applications, complex shelf life structures are investigated. Figure 5 shows development of prosthetic fingers for humans. Also, multicellular matrices can be made to grow into functional organs along with replacement tissues. Figure 6 shows the droplets network of tissue engineering substrate used as a support for the

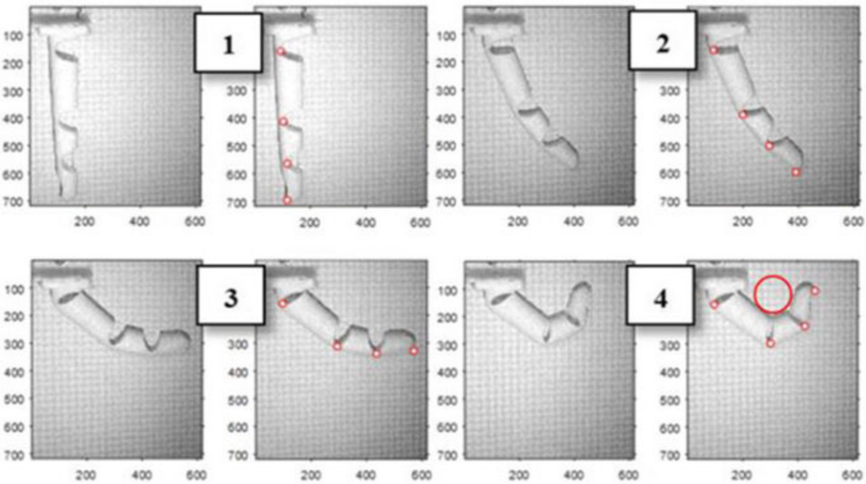

Fig. 5 Self-bending prosthetic finger [12]

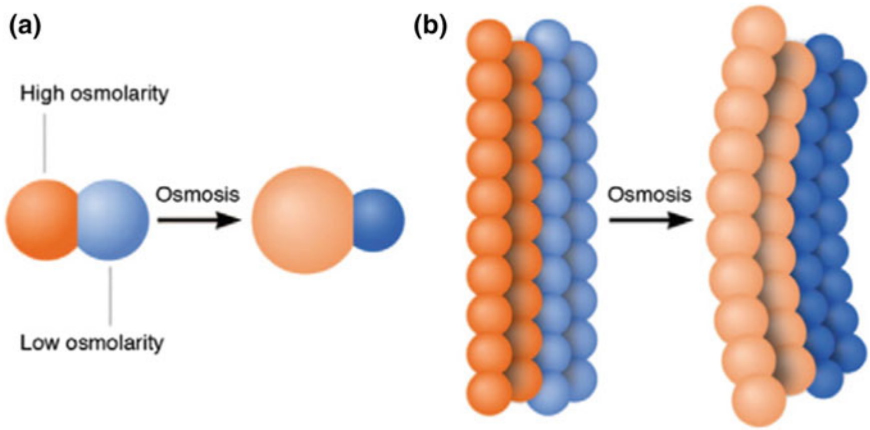

Fig. 6 **a** Osmosis effect between two droplets, **b** macroscopic deformation arising from osmosis effect [4, 12]

failing tissues functionality. Using 4DP technology dynamic reversible functional behavior with in a product can be achieved. Hence, if the shape shifting cycles of 4D printed structures can be equalized in comparison to the natural element capability, this technology can be used with multiple disciplines for various applications.

6 SWOT Analysis

SWOT is a process that shall lead to strategic planning for future of industries implementing 4DP in product development cycle. The factors of SWOT are as defined in the following:

1. Strength:
   - Raw materials and the manufacturing process programming used have high rate of efficacy due to Programmable Materials (PM).
   - Mathematical modeling has the ability to control structure functionality.
   - Materials can be programmed based on the need with multiple compositions.
   - Structure with varying functionality can processed using cuing currently available 3D printers.

2. Weakness:

    - Requires extensive domain knowledge of 3DP and Mathematical modeling as the 3DP and the material used for the 4DP system is completely mathematical program controlled.
    - Hard to define accuracy through variation in optimization of process parameters for controlling functionality of size and shape.
    - Requires experts to be processing 4DP in a controlled environment.

3. Opportunities:

    - Can be highly useful in development of artificial skin and organs especially in warzone and space.
    - Helpful in development of biocompatible medical implants of complex size and shape.
    - 4DP can be exclusive made useful in development of smart structures.

4. Threats:

    - Since new categories of raw materials are defined for process based on the functionality requirement, health effects on users and manufacturers are of major concern.
    - Ethical and technical issues relating to the application of 4D Printed products is also a major issue.

7 Conclusions

- All technologies in the modern manufacturing world are generally inspired from the nature.
- Natural systems comprising natural materials continuously adopt and evolve over a period of time leading to changes in working pattern. In order to replicate such elements processing of structures is highly dependent on materials and processing technology. One such process involved in replication of natural systems is 4DP.
- The current technology of 4DP revolutionized by Skylar Tibbits of MIT-USA is an updated version of 3DP started by Hull 30 years ago. In 4DP various technological enhancements as compared to 3DP were implemented relating to material processing and printing technology.
- 4DP is one of the technologies developed to replicate natural elements showcasing anisotropic properties. 4DP still is in superficial stage of exploration in the modern manufacturing domain. However, in order to fulfill this requirement Programmable Matter (PM) has been significantly researched in design, control and modulation of property and behavior across spatial scales for higher efficiency and effectiveness during additive manufacturing. Programmable matter and 4DP has the ability to revolutionize medical implant and other manufacturing sectors. However, the

technology needs to grow exponentially in real engineering and science research to compete with the current state of the art technology.

- With complete optimization of 4DP technology implants of medical industries will reach higher stature. Hence 4DP can be the future of manufacturing sector especially in the medical industries if proper care is taken to enhance the technological aspects of the same and there by produce cheaper products to the market.
- Hence, it can be concluded that 4DP shows a very high potential to become a new platform for bio inspired additive manufacturing technology that can perform as efficient and effective as natural systems and contribute to the welfare of human beings through evolution of stable medical implants.

8 Future Scope

In the coming years the several challenges needs to be addressed in the technological areas of 4DP, which are as following:

1. Design: suitable CAD software to support development of Programmable Materials (PM) based technological/scientific products.
2. Materials: optimization of material properties during production to create PM wit multifunctional properties.
3. Adhesion of particulates: extensive study on behavior of materials when embedded to achieve required property.
4. Energy: energy optimization to activate the PM according to the design requirement.
5. Electronics: control of electronic systems for effectiveness and efficiency.
6. Programming: digital and physical communications of voxels through programs as the defined product will be anisotropic in nature.
7. Adaptability to different environments: design and programming the product for different environmental conditions.
8. Assembly: micro and macro scale assembly during manufacturing and accidents.
9. Standardization: development of standards to incorporate 4DP in mass production.
10. Certification: certification of 4D printed products and raw materials.
11. Cost: initial cost of the 4DP system and raw materials.
12. Testing and characterization techniques for proving the effectiveness of product developed by 4DP system.
13. Technology for recycling 4DP systems and its products developed and reuse of raw materials.

References

1. Belmonte A et al (2015) Effect of the network structure and programming temperature on the shape-memory response of thiol-epoxy "click" systems. Polymers 7(10):2146–2164. https://doi.org/10.3390/polym7101505
2. Callister WD, Rethwisch DG (2009) Materials science and engineering: an introduction, 8th edn. Wiley, Hoboken
3. Campbell TA, Tibbits S, Garrett B (2014) The next wave: 4D printing programming the material world. Atlantic Council
4. Chang J et al (2018) Advanced material strategies for next-generation additive manufacturing. Materials 11(1). https://doi.org/10.3390/ma11010166
5. Gao B et al (2016) 4D bioprinting for biomedical applications. Trends Biotechnol 34(9):746–756. https://doi.org/10.1016/j.tibtech.2016.03.004 (Elsevier Ltd)
6. Ge Q et al (2014) Active origami by 4D printing. Smart Mater Struct 23(9). https://doi.org/10.1088/0964-1726/23/9/094007
7. Hassan RU, Jo S, Seok J (2018) Thermorheological characteristics and comparison of shape memory polymers fabricated by novel 3D printing technique. Funct Mater Lett 11(02):1850031. https://doi.org/10.1142/S1793604718500315
8. Khoo ZX et al (2015) 3D printing of smart materials: a review on recent progresses in 4D printing. Virtual Phys Prototyping 10(3):103–122. https://doi.org/10.1080/17452759.2015.1097054 (Taylor & Francis)
9. Li X, Shang J, Wang Z (2017) Intelligent materials: a review of applications in 4D printing. Assembly Autom 37(2):170–185. https://doi.org/10.1108/AA-11-2015-093
10. Ma J et al (2017) Spatial control of functional response in 4D-printed active metallic structures. Sci Rep 7:1–8. https://doi.org/10.1038/srep46707
11. Miao S et al (2017) 4D printing of polymeric materials for tissue and organ regeneration. Mater Today 20(10):577–591. https://doi.org/10.1016/j.mattod.2017.06.005 (Elsevier Ltd)
12. Momeni F et al (2017) A review of 4D printing. Mater Des 122:42–79. https://doi.org/10.1016/j.matdes.2017.02.068 (Elsevier Ltd)
13. Sydney Gladman A et al (2016) Biomimetic 4D printing. Nat Mater 15(4):413–418. https://doi.org/10.1038/nmat4544
14. Tibbits S (2014) 4D printing: multi-material shape change. Architectural Des 84(1):116–121. https://doi.org/10.1002/ad.1710
15. Tsai EY (2013) 4D printing : towards biomimetic additive manufacturing. Massachusetts Institute of Technology. Available at: http://dspace.mit.edu/handle/1721.1/91821
16. Yang Y et al (2016) 3D printing of shape memory polymer for functional part fabrication. Int J Adv Manuf Technol 84(9):2079–2095. https://doi.org/10.1007/s00170-015-7843-2