Modern concepts and application of soft robotics in 4D printing

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Abstract: Recent developments in (AM) additive developed normally Three-dimensional (3D) printing is a term used to describe printing that is three-dimensional in nature, have enabled researchers to use traditional production methods to create previously unthinkable, complex shapes. Usage of smart materials by the way of adopting the external stimuli in printing is part of a 3D-printing research division called 4D-printing. 4D-printing allows for the development of dynamically controllable shapes on-demand by the addition of sometime as another dimension. The potential of 4D-printing has been significantly expanded by recent advances intelligent synthetic materials, new printers, processes of deformation and mathematical modelling. This paper deals with improvement in the area of 4D-printing, with a importance on its practical applications. With explications of their morphing mechanisms, Smart materials are discussed and produced using 4D-printing. Moreover, case study on soft robotics is discussed. We end with 4D Printing problems and future opportunities.

Keywords: 4D Printing, shape memory, additive manufacturing, future opportunities.

1. Introduction

Additive processing and manufacturing generally referred to as 3D printing, continues to develop nearly over 4 decades of manufacturing and enable researchers to generate intricate models and shapes that were formerly not viable using usual manufacturing methods. Researchers can construct complex, bio-inspired, Multi-material designs, remotely controlled robots, optimization algorithms and machine learning designs, medicine delivery systems, and even bio-tissue micro-environments using 3D printing [1-3]. Material extrusion method, powder bed fusion method, Photo polymerization process, material jetting method, sheet lamination method, direct energy deposition and binder jetting, are common technologies for 3D printing. Stereolithographic and fused deposition modeling are among the most used of all of these processes FDM is a material extrusion technique that involves feeding of the filament into the high-temperature nozzles, and then depositing the melted material on a layer-by-layer sheet. Stereo lithography is adapted and step by step method of photo polymerization, scanning the liquid Ultra Violet -curable matter with a laser. This skill can attain enhanced print resolution and superior speed than Fused Deposition Modelling, but it is outlying high cost compare to other
materials [4-6]. Although the speedy development in Additive Manufacturing technology, 3D printing is not commercially used for large-scale production yet, due to its significant slow processing time delay and unnecessary competition between eminence and size. However, for its high customizability and the ability to print complex geometries, 3D-printing is broadly recognized by researchers. Furthermore, new developments in software for CAD and original materials further broaden the 3D printing stage. 4D printing technology is directly linked to 3D printing, where new 4D printing possibilities will be created. The various 4D-printing research topics are divided into three categories: machinery development, deformation processes, and mathematical modelling. Equipment production involves the synthesis of novel resources characterize by various types of response and advance printing skills, all of these are major part of 4D printing. In theory, 4D-printing technology are an expert type of 3D-printing. Fused deposition modelling, Direct inkjet treatment, laser-assisted bioprinting and selective laser fusion, stereo lithography is the 4D printing methods currently available. On the basis of different types of smart materials, the printer should be carefully selected as shown in the figure 1 [7-9].

![Figure 1. Schematic diagram of Structural design](image)

The focus of the work on deformation mechanisms is to understand sequential flip, geometry design, hinge design and pattern design. intellectual capacity of these mechanisms is important for practical structures in 4D printing as mentioned in the schematic diagram shown in the figure 2. The field of mathematical modelling includes backward prediction, which provides a target shape and function for the printing profile, and onward calculation that model the deformation process given the initial profile [10-12].

![Figure 2. Schematic diagram of Mathematical Modelling](image)
2. Smart Materials

Recent innovations in the field of so called multi material 3D printing have made material positioning more springy and accurate. Capabilities necessary for comprehensive 4D printing technologies. In this particular section, identification of 4D printing suitable materials based on their conservational and time-based stimuli. Moisture, temperature, electricity, current, light and captivating fields are among the stimuli addressed.

2.1 Thermo-responsive

Either of two mechanisms primarily causes the deformation of thermo-stimuli constituents: the (SME) Shape memory effect or the (SCE) Shape shift effect. SME-based materials are called (SMM) Materials with shape memory, which could be additional divided into(SMA) Shape memory alloys, (SMP)Shape memory polymers, (SMH) Shape memory hybrids, (SMC) Shape memory ceramics, and (SMG) Shape memory gels. The researchers prefer Shape memory polymers most for their ease of printing. In general, Shape memory polymers have glass conversion temperature high than working temperatures. They are planned over their glass transfer temperatures under complex heat and mechanical treatments, and then chilled to be set in a temporary form free of exterior setting. After its temperature rises above its transition temperatures, the specimens are returned to its original or permanent state. Various Shape memory polymers materials are updated to be printable by researchers to exploit their unique properties. Ying et al. produces a Shape memory polymers ball using Stereo lithography, where, under Ultra Violet light, the liquefied resins are further polymerized to repair the eternal shape as shown in the figure 3. The ball will stretch into a flat plane and with high durability withdraw backwards. Printed some floral Shape memory polymers that could bloom when heated. Smart grippers that do not need assembly or electromechanical components are also developed using this technology. Recent findings from various researchers predominantly revealed the possible steps in pre-programming of an SMP arrangement by using the heating mechanism well in FDM printers [13-15].

![Figure 3. Types of shape Memory](image)

2.2 Moisture-responsive

The great appreciation of their widespread stimulation and their extensive choice of applications are of great interest to Materials that are sensitive to moisture or water. Hydro gels are exceptional humidity reactive materials as their hydro helps them to extend their original volume by up to 200 per cent. In addition, as a group of conducive polymer materials, hydro gels demonstrate higher possibility of printability. The benefit of by means of hydro gels is that they are biocompatible and are easy to print with through ink script. Although it will give deliberate low overturn reaction means researchers have
to wait for many hours to dry and shrinking hydro gels. To program hydrogel behavior, the swelling must be filled with anisotropy. Gladman et al. mixed cellulose fibrils with hydro gel ink, which can be balanced by the shear force induced by contact with the ink print. This arrangement makes the longitudinal strain 400% increase that of the transverse swelling strain. The 4D-printed structure can be configured in this way. Mao et al. printed a structure in which rigid materials constrain hydrogels in single direction, causing the bulge to be directed anisotropically. Zhang et al. report rapid responses after developing tinny hydrophobic possible films made of cellulose stearoyl esters (CSEs) which could react more quickly and accurately. Hydro gels are usually submerged in a different environment that allows to absorb water until the dispersion point of their moisture, which restricts the intermediate controllability of hydro gels. The swelling of hydro gels can therefore be managed via the aqueous environment temperature. Breger et al. manufactured pNIPAM-AAc soft-hydro gels micro gripper joints, which are gradient annoyed, connected. The reversible actuation can be accomplished by changing the saturation point by cooling or heating the water in which the gripper is submerged [16-18].

2.3 Photo-responsive

Further, current possibly could be used as a secondary stimulus for 4D printers when it is close to light. Miriyev et al. showed a printed soft and non-natural muscle, which made of a silicone elastomer and their corresponding ethanol mixture. Resistive heating produces heat when a current is applied, allowing the ethanol to evaporate. The ethanol quantity is considerably increased because of the phase transition from liquid to gas, which expands the matrix as a whole. The current is also used to monitor water absorption and desorption of (PPY) poly pyrrole films. Okuzaki et al used polypyrrole films on an origami micro robot's feet with different geometries to reduce resistance when it moved forward. A voltage pushes the top on ward when positioned in a humid environment due to moisture absorption, and the tail follows up when the absence of voltage induces desorption [19-21].

2.4 Magneto-responsive

Magnet-responsive materials are 4D-printed commercial structures that adversely respond to constructive magnetic fields. In a hydrogel printed micro gripper, Breger et al incorporated magnetic nano particles and achieve isolated be in command of by adding attractive fields. In pre-processing, embedding is carried out where ferric oxide powders are conversely mixed with a material solution. In the polymer and metal printing market, this technology has potential as well. The print size restriction, which must be small enough to be exaggerated by the attractive field, is one drawback of this method.

3. Case study: soft robotics

Modern robots, largely because inflexible materials prepare them, contain drawbacks in conducting natural and submissive operation such as a human handgrip or the complex movement of a tentacle. Thus, the area of spongy robotics has arisen in which some spongy materials, mainly different varieties of elastomers, are used as a connection between robots and their surroundings. Compared to traditional robots, these spongy materials allow for mild contact with delicate substance and provide greater resistance to damaging forces as shown in the figure 4.
3.1 Shape-changing possible actuators

Miriyev et al constructed a widely accepted composite material which could be used as a McKibben spineless actuator (SA) shape. The SA consists of a matrix of spongy silicon elastomer packed with ethanol, with the spongy voids. Thanks to the simplicity of composite planning and handling. It can be printed in 3D using traditional techniques. It works by applying heat which passes through resistive heating method, which causes the confined ethanol to evaporate, which briefly causes the elastomer matrix to further expand. The subsequent material, which has a low compactness of 0.83 g/cm³, can resist stresses of up to 900 percent and 1.3 MPa. The material could lift its own weight by a maximum of 1700 times, Miriyev et al thought. The Soft actuator is inexpensive, eco-friendly and easy to assemble. The structure is made up of a dielectric elastomeric placed between two flexible electrodes. Dielectrics have been thoroughly researched for different uses, predominantly as actuators.

3.2 Hydraulic and pneumatic actuators

Supporting overhanging structures, particularly internal or difficult-to-access geometries, is a major challenge in 3D printing. Support systems are usually designed at the same time as the finished product. The support framework is either: (1) written in a way that further weakens their corresponding interface property between the backing material and the finish product to help and to completely remove the support structure, or (2) dissolves the backing material into a solution and consecutively acquires the final product structure. Nevertheless, both strategies cannot help removing internal support systems without repetitive alterations in nature. This has impeded 3D-printing with usable internal geometries of complex structures. For the creation of intricate structures by using non-curing liquid as the backing material, MacCurdy et al demonstrated an inkjet-based 3D-printing technique. Pneumatic actuators constructed from lightweight and inflatable materials are Artificial Pneumatic Muscles (PAMs). PAMs are small in weight and can exert relatively large forces. Combining these features with flexibility in 3D printing will profusely allow for multifarious pneumatically actuated mechanisms. By using fused deposition modeling (FDM) technology, Yap et al. 3D has successfully printed soft and pneumatic actuators and tested the efficiency of the actuators. The printed actuators can additionally produce great forces, and recurring fatigue tests demonstrated that the actuators are precisely and extremely durable. Moreover, the direction of the actuation (i.e. bending) is dependable and precise [22].

4. Challenges and futuristic opportunities

Though a fresh technology, 4D-printing has the skill to crack a lot of real-case studies. But there are still many challenges to be addressed in this region. The boundaries of existing 3D printers for handling basic 3D printing are a major challenge. Problems such as the avoidance of support systems, particularly for fragile internal structures, the simultaneous printing of different groups of materials

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**Figure 4.** Schematic diagram of Smart Material

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**Legend:**
- Smart Material
- Heat Responsive
- Moisture Responsive
- Photo Electro Magnet
(e.g. polymers and metals), the absence of low-cost and durable print materials, and sluggish printing times. There is a urgent necessity to adapt printing technologies significantly or to create new printing technologies. In order to overcome some of these 3D printing issues, profound 5-axis 3D printing is actually of boundless attentiveness. Another significant challenges encountered in this field is the limitation placed on the physical properties of 4D-printed assemblies by the anticipated shape or further so called property transformations. For instance, the consecutive compactness of the locker structures requires certain polymer ratios. Advances have been made with a wide variety of mechanical properties in smart printable materials, this area of work is very much essential to advanced 4D-prints. Other issue includes slow as well as inconsistent action, lack of governing and intermediate deformation states, and restricted material supply. More efficient stimulus application strategies, in order to find out the improved heat application processes in thermo-responsive SMPs, or their constructive methodologies for significantly controlling hydrogels' moisture absorption, may be explored in future studies. Such improvements may also allow for higher actuation accuracy. In addition, property changes arise as a consequence of macroscale systemic changes that may be disagreeable. Knowing the effects of the structural pattern scale and the dynamics of transformation will further allow of greater flexibility and their much needed applicability; this shows the potential of extensive use and upcoming opportunities in the area of 4D printing [23-24].

5. Conclusions

4D-printing has successively progressed over the past few years and confidently promises its impact in other areas. In this particular research, we discuss their different use cases, highlighting comprehensive strategy work on 4D-printing and its possible applications. In particular, we indeed discuss possible case studies in three variety of areas, soft robotics, self-construction structures and therapeutic devices where possibility of innovative 4D-printed devices performed functions, that would be great difficult or extremely costly to manufacture using outdated methods of production.4D-printed devices are possible candidate for applications in uncommon environments, owing to their enormous customizability and lack of mechanical parts. In the medical industry in which patient-specific designs are key, 4D-printed systems have enormous potential. Surgical operations involving 4D-printing have already been carried out and have shown successfully to what degree the impact of 4D-printing has increased. 4Dprinting can further improve surgical therapies, soft robotics, targeted drug delivery, and so-called further unthought-of fields of engineering with developments in printable mathematical models, smart materials and printing technologies.

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