Review on Advancements in 4d Printing with Smart Materials

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Abstract: 4D printing or Adaptive Manufacturing is the successor of 3D printing or Additive Manufacturing. In 4D printing smart materials or programmable materials are used to make 3D product. These products upon the presence of a suitable stimuli will be able to reshape themselves in a pre-coded shape. Researchers are developing new materials that can respond to various environmental triggers, such as humidity, temperature, and light. 4D printing can enable the creation of complex structures that are difficult or impossible to achieve using traditional manufacturing methods. In this paper we are going to see the types, properties and the fields of application of smart materials which are equally important as that of 4D printing technology along with the analysis of future trends and challenges in applying this revolutionary technology.

Index Terms: 4D Printing, 4D printing, Manufacturing, Smart materials, Shape changing.

I. INTRODUCTION

Printing technologies have advanced rapidly in recent years, with significant improvements in accuracy, speed, material properties, and manufacturing costs [1]. 4D printing is a novel advancement to 3D printing technology, which comes after stereo lithography a type of Rapid Prototyping. Here the fourth dimension is Time and that over time static objects will transform and adapt. The products will be able to reshape themselves in a pre-coded shape. 4D printing is focused on developing materials and newer printing techniques that could reduce the time taken for assembly of parts, in turn improving the overall efficiency of the manufacturing process [1].

Although not commercially available, self-assembly is just a beginning of a whole innovative world of manufacturing with minimum energy. As environmental, economic, human and other constraints continue to fluctuate, we will eventually need dynamic systems that can respond with ease and agility. 4D Printing is the first of its kind to offer this exciting capability. This is truly a radical shift in our understanding of structures, which have up to this point, remained static and rigid (think aerospace, automotive, building industries etc) and will soon be dynamic, adaptable and tunable for on-demand performance. 4D printing has the potential to revolutionize the field of medicine [2] by allowing for the creation of smart implants, prosthetics, and tissue engineering scaffolds that can adapt to the patient's needs over time. For instance, researchers are working on developing 4D printed implants that can change shape and adjust to the growth of the surrounding tissue. 4D-printed devices are well-suited for applications in unusual environments due to their unique combination of customizability and lack of mechanical elements [3]. Moreover, 4D printing can offer a personalized approach to medical treatment by allowing the fabrication of patient-specific implants, prosthetics, and anatomical models that match the individual anatomy and pathology. This can enhance the accuracy, safety, and efficacy of surgical procedures and reduce the risks of complications or rejections [4].

Liquid crystal elastomers (LCEs) and shape memory polymers (SMPs) are two types of smart materials that are commonly used in the development of multifunctional composites. LCEs are known for their ability to generate rapid and reversible shape changes in response to external stimuli, such as temperature or light. However, they are relatively soft and require a constant temperature to retain their deformed shape. On the other hand, SMPs have favorable mechanical properties and can be programmed to change shape in response to a specific stimulus, such as heat, light, or electricity. However, only a few types of SMPs can achieve reversible actuations, which limits their applicability in multifunctional composites [5].

Multi-material structures can be classified into three types based on their distribution: uniform distribution, gradient distribution, and special patterns. Smart materials, also known as responsive or intelligent materials, are materials that can sense and respond to external stimuli by changing their properties, such as shape, stiffness, color, or conductivity. The most common types of stimuli that can activate smart materials include temperature, moisture, light, magnetic fields, and electric fields. Smart materials have a wide range of potential applications in fields such as medicine, engineering, and robotics, where their ability to respond to external stimuli can be used to create more efficient and effective devices and systems [6].

Overall, 4D printing holds great promise for the future of science, technology, and medicine, as it combines the power of additive manufacturing with the flexibility of dynamic materials and the precision of imaging techniques. However, there are still many challenges to overcome, such as the scalability, reproducibility, and regulatory aspects of 4D printing, as well as the ethical and social implications of its use.

II. 4D PRINTING TECHNOLOGY.

The essentials of 4D printing technology are shown below in Figure.1.

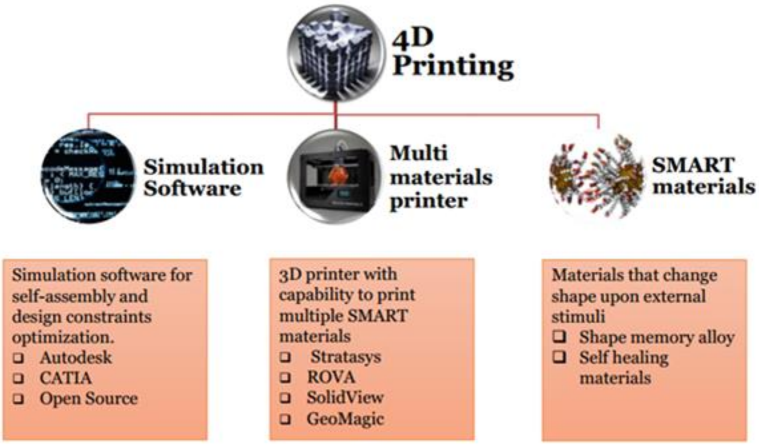

Fig. 1 Elements of 4D Printing Technology

II.1 Stages of 4D printing

The procedure of 4-D printing involves three distinct stages. They are

1. Design.
2. ii. Fabrication.
3. iii. Simulation.

1. Design.

A computational approach usually used for designing self-evolving structures that vary over time due to environmental interaction. The first step is to align the initial and final status of the models. From this alignment we are able to derive the angles and lengths required to fabricate self-evolving structures. Curves have a trivial (natural) parameterization, hence mapping between curves can be reduced to length normalization. For surfaces a more sophisticated alignment is required. Calibration between the materials and desired angles/lengths were performed empirically on physically printed models. The two stretching primitives are relatively simple to calibrate. A linear stretching primitive expands by 0.432 mm (from 0.813 mm to 1.245 mm) per disk when submerged in water, hence, the number of required disks is trivially evaluated. The ring stretching primitive simply follows basic geometry rules, where half of its circumference becomes the deformed length. By repeating the experiments multiple times, create a lookup table containing the angular and temporal information for this example.

2. Fabrication

The physics of 4D printing often requires multiple materials to be embedded into a single 3D structure. For example, the materials needed for fabrication of primitives (especially the joint component) may be different from the material used in the main structure. Here use the Stratasys Connex 500 multi-material 3D printer with a spatial resolution of 300DPI, which is approximately 85 micrometer in the XY axes, and about 30 micrometer in the Z axis (depth) The printing time of our method varies from one hour to eight hours depending on shape and complexity.

The Connex printer deposits a UV curable polymer using inkjet heads and cures layer by layer using UV light to create the complete 3D structure. This printer is able to print materials with different properties (such as color, hardness, and transparency) simultaneously. It enables us to arrange the stretching and folding primitives in different orientations, which allows stretching and folding to happen at the desired position in the 3D vector space. Moreover, it can be used to generate Digital Materials (DMs) that represent distinct combinations of both components in different proportions and spatial arrangements. A DM inherits its properties from the parent materials and its structure can be digitally adjusted to have any set of properties in the available range. Since the mixing occurs on the tray, the spatial arrangement of the components plays a significant role in the generated DM characteristics and it provides additional flexibility in the DM engineering process. The generated parts are printed with a rigid plastic base and a material that expands upon exposure to water. The expanding material is a very hydrophilic UV curable polymer with low cross-link density that when exposed to water it absorbs and creates a hydrogel with up to 200% of the original volume.

3. Simulation

Here the simulation is done using a spring-mass model with nonlinear constraints, to fully encompass the stretching and folding behaviours observed in the design and fabrication and to avoid shearing or twisting forces. Here the simulation is not done for the movement in the molecular level but learned the kinematics movement of the entire model.

III. SMART MATERIALS

Smart materials are also known as ‘Programmable Materials’. Smart materials are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields.

III.1 Types

Self-Healing Materials

Self-healing material in a historical perspective:- The state of stone bridges and aqueducts from the Roman age is still quite good, despite the fact that they have been there for centuries. The secret is in the ‘mortar’ – based on volcanic ash and lime. The ancient Romans used in their constructions to glue the bricks together. Lime dissolves in rain water, and can seep to cracks. When the water vaporizes, the lime deposits inside the crack. One modern example is a Self-healing smart phone made by LG, the G-Flex, which is curved and has a self-healing polymer coating on the back: Light scratches disappear before your eyes.

Smart Metal Alloys (Shape Memory Alloys)

Shape memory alloys (SMA's) are unique class of metals that can recover apparent permanent strain when they are heated above certain temperature. Ni-Ti is a typical example for the same.

Dielectric elastomers

Dielectric elastomers (DEs) are smart material systems that produce large strains. They belong to the group of electroactive polymers (EAP).

IV. APPLICATIONS

1. SMA has a potential application in Morphing Air Craft.. It can overcome the limitations of current flight technology by adapting the geometry of lifting surfaces to pilot input and different flight conditions characterizing a typical mission profile . Improvement to long-term performance, reliability and response of metal actuators is required for this to become a reality.
2. Dielectric material has a potential application that it can be used to make artificial muscles. Dielectric elastomers require an external circuit with a high bias voltage source to polarize them. To be feasible in real life application, need to drastically reduce this voltage requirement.
3. Nano Scale Objects in Biomedical Engineering. E.g Cardiac tube/Stent.4D printed stent to be maneuvered to a spot and then change form. For example, 4D printed stent that is introduced into an artery and when ultrasound energy is applied it balloons up to its needed configuration.
4. Electro active Polymers can be used to make artificial limbs. An applied voltage changes the polymer's composition or molecular structure so that it expands, contracts or bends . The motion is smoother and more lifelike than movement generated by mechanical devices.
5. Transformative shoe for multiple activities. If you start running, it adapts to being running shoes If you play basketball, it adapts to support your ankles If you go on grass, it grows cleats. If it is raining, it becomes waterproof.
6. 4D printed tyre compound which provide adaptive grip on road condition.
7. Current pipe system is very rigid. To cater for higher flow capacity, we have to replace the whole pipe line. For that the adaptive 4D manufacturing capability can produce capacity adaptable pipes
8. Insulation wall that can adapt to outside temperature. Self-adaptive wall that maintain heat during winter and less insulation property during summer.
9. Current robot systems are very rigid due to inherent mechanical property of motors and gears etc. By precise geometry arranging of multiple transformative materials, we can achieve desired motion, action upon applied energy End result is more human like robot which can perform more delicate job.

V. ADVANTAGES OVER TRADITIONAL MANUFACTURING.

- Increased product design freedom
- No cost for complexity
- On-demand production in batches of one
- From mass production to mass customization
- Simplification of manufacturing process
- From making prototypes to manufacturing finished products
- Eliminating supply chains and assembly lines for many products
- Designs, not products, move around the world
- Instant production on a global scale
- A major boost to innovation
- Stimulation of new interest in design and engineering

VI. TECHNICAL CHALLENGES

Some technical challenges that need to be addressed in the coming years include.

1. Design—How do we program future CAD software to encompass programmable materials with multi-scale, multi-element and dynamic components?
2. Materials—How do we create materials with multifunctional properties and embedded logic capabilities?
3. Adhesions between voxels—How can we ensure that adhesion among voxels is comparable to normally fabricated systems, while simultaneously allowing reconfigurability or recyclability after use?
4. Energy—How can we generate, store, and use passive and abundant energy sources to activate individual voxels and PM?
5. Electronics—How do we efficiently and effectively embed controllable electronics (or electronic-like capabilities) at the submillimeter scale?
6. Programming—How do we program and communicate with individual voxels (3d pixel) both physically and digitally? How do we program variable state-changes (3+ physical states)?
7. Adaptability to different environments—How do we program and design environmentally responsive voxels?
8. Assembly—What external forces would be needed to cause macro-scale self-assembly of voxels?
9. Standardization—Can standards (e.g., as produced by ISO) be created to ensure seamless interaction among PM voxels and systems?
10. Certifications—Can PM systems be certified technically through normal channels, or will wholly new certifications be required (e.g.,aircraft parts that require rigorous FAA certifications)?
11. Physical and cyber security—How can we embed programmable capabilities into objects while still ensuring they are secure?
12. Affordable manufacturing techniques—Can routine manufacturing of PM systems be made economically viable for small- and large-scale manufacturers?Characterization—How will we characterize dynamic systems of voxels? Will new metrology equipment be required?

13. Recycling—How can we ensure the voxels can be disassembled and reconfigured for reuse or error-correcting for self-repair? Of course, there are also fundamental limitations to PM based on the laws of physics.

VII. CONCLUSIONS

So we have seen the possibilities and challenges of self-evolving complex structures. Traditional mechanical means of stretching, folding and bending will soon be replaced by expanding printed materials. Also it showed that a solid surface can be programmed to sense the environment and actively self-deform. The new primitives are rich enough to construct multi-purpose structures that can change their geometry. We are facing an era where design of soft deformable structures will alter industry and consequently our lives. Adaptive manufacturing became accessible to all, and we can say that, self-deforming structures will be one of its most important descendant.

Programmable matter and 4D printing certainly have the potential to appear “magical,” but they are grounded in real engineering and science research that is only now emerging due to recent technological advances. Several near term applications of PM are on the horizon. Nevertheless, we note that more substantial applications will require significant infusion of resources (greater funding, training of researchers, federal centers devoted to PM research, development of new fabrication and measurement equipment, etc.). As with 3D printing, the United States has the opportunity to lead in 4D printing research and applications, but this will require increased and sustained funding and policy support for programmable matter research and development.

Through programmable matter and 4D printing, there exists the potential to create a new class of disruptive technologies comparable to—and far beyond—3D printing. It does not seem fanciful to imagine a world in which a new form of matter formation could enable form and function modification at the flip of a switch—a world in which one could make intelligent LegoTM-like bricks that can assemble, become multifunctional and morphable into almost any 3D object, and disassemble at will. Such a future—with both its promises and challenges—awaits us

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