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ADVANCEMENTS IN THE RESEARCH OF 4D PRINTING-A REVIEW

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Abstract: 4D printing is the method of 3D printing where the fourth dimension is the time and the shape or structure of the printed body which can change with respect to time. Many researches have conducted experiments to find if this new idea of 4D printing would work and have become successful in their research among them Skylar Tibbits is the first person to start the research in association with Stratasys and Autodesk. Hence the objective of this research work was to review about the different experiments conducted by different researches and prove that 4D printing technology is possible. In the present work, a survey of 4D printing was carried out and the different experimental procedures were discussed. Also the specifications of the technology used to demonstrate the experiment and their advantages are discussed. Few researchers have used the concepts of shape memory polymers to demonstrate their experiment and few have used the upcoming technology of the water absorbing materials and hydrogels to demonstrate their experiments. More or less the different materials used to demonstrate give the same result but what differ with respect to each other is with respect to their properties such as cost, availability, chemical properties, physical properties and etc. Final conclusion of the present work was that this technology is sure to change the world when put into work but because of the complexity it would take time for this to become a reality. 3D printing has already captured our mind and adding fourth dimension to the equation would do wonders which anyone on earth has ever witnessed till date.

Keywords: Shape memory polymer, Hydrogel, Programmable matter, printed active composites, Bio-compatible materials

1. PROLOUGE

Technology has always been amazing us with its beautiful inventions in the nature by making the life of human simpler to a greater extent. 3D printing technology is one such ingenious technological invention that gives a great contribution to manufacturing industry mainly, and to many other fields such as medical, construction, etc. 3D printers are now available at a price below \$1000 US making it affordable to many. This technology has found great uses from printing simple toys to constructing buildings and organ transplants and many more. But this is not the end of invention in the field of



manufacturing, a new era is about to begin. Researchers have come up questioning much more can be done with 3D printing [1]. The answer is the structures that can transform themselves with respect to the program written prior to the manufacture, this idea named as 4D printing which making people amaze with its numerous applications in manufacturing industries, medical field, Construction field and many more.

4D printing is the next evolution of 3D printing where there is an addition of the dimension i.e., time to the conventional 3D printing process. Though the knowledge about this technology has not yet reached to common people in the world still there is a lot of research going on in different labs at universities and research centres, each one getting different results which demonstrate that this technology could be brought into reality very soon.

A definition of 4D printing could be: "The use of a 3D printer is to print objects which could change/alter their shape after the manufacturing. This change could be taken place due to many factors such as air, heat, and other chemical reactions caused due to materials used in the manufacturing of these objects".

Some advancements in this field of research are the creation of hydrogel from scientists at University of Wollongong in Australia and the incorporation of shape memory polymer fibre in the composite which also leads to some research study in the field of composites also. And using the materials which could respond to water i.e., water absorbing materials which could respond or change shape when placed in water. In many such demonstrative ways by using different types of materials researches have been successful in proving the possibilities of 4D printing.

So far people have an idea of what 3D printing is? 4D printing is the next level of this technology. 4D printing is based on the idea of 3D printing itself. 3D printing is also called the additive manufacturing which prints the object layer by layer, once a design of the object is given and the material is fed to the printer. The same way 4D printing is also known as programmable technology which uses 3D printers to print and material which is fed to the printer is pre-programmed to change its shape and respond correspondingly to the nature such as change in temperature or pressure change and many such parameters. As we are also aware of bio-printing a fabulous technology which has evolved from the 3D printing and helping save lives of many people by printing organs in human body. The same when printed using 4D printing has amazing results. Usually the organs in a body respond without any outside intervention and that is what we are expected to achieve. The printing of the human organs and tissues and this could be possible by the new idea of 4D printing as told by few researches. Apart from these the new 4D technology has numerous applications in various fields such as architecture, clothing, food, health, military, transport which has drawn an attention of researches to contribute something to the world through this technology.

2. MAIN ARTICLE

The field of research was started by Skylar Tibbits the present head of MIT's self-assembly laboratory in association with **Stratasys** and **Autodesk**. The basic concept of 4D printing is that the structure transforms in a pre-programmed way and transforms over time. This concept of structural deformation is age old, the demonstrations of structural deformation are the "**memory**" and smart material properties, the widely used among these is the shape memory alloy (a change in temperature triggers a shape change). The important part of Skylar Tibbits work on 4D printing is the **object connex multi-**

material 3D printing technology which allows researchers to program different material properties into each of various particles of different water absorbing properties of materials to activate the self-assembly process[3]. What makes the idea define a new revolution is the numerous applications it has got. A few are discussed below:

- Home appliances and products that can adapt to heat or moisture to improve comfort or add new features to better working.
- Shoes which can transform themselves according to the use required.
- Buildings that could assemble and disassemble themselves.
- Printing bio components that can be implanted to human body.
- In aeroplane wings which transform themselves according to the flow of air for better lift.
- Smart valves, connections and sensors for infrastructure lines that can fundamentally respond to control-flow.

Many such applications are advantages of this technology which have made it a trending concept to study about.

So, the challenge ahead is how this concept can be brought into a reality. Different research groups from different universities have ingenious approaches towards the concept. Apart from the success of these approaches there are many limitations and challenges of this technology:

- Since deformations can be applied and performed more often, the material will degrade over a period of time so improvements are very much required in long term durability.
- PM (programmable matter) could be threatening to the national security as material world could be change in an unpredictable way, morphing of wings to crash air planes, programming to disassemble a building when it is manually operated and many such threatening disadvantages.
- Environmental, human and other such constraints keep fluctuating, so we will need dynamic systems that can respond with ease and agility.
- Some technical challenges such as programming the CAD software, creating materials with multifunctioning properties, adaptability to different environmental conditions and etc. [4]

The various experiments conducted by different group of researchers prove that this technology can be a reality.

3. DIFFERENT APPROACHES OF 4D PRINTING

3.1 Testing by Skylar Tibbits:

Skylar Tibbits the man behind the evolution of this technology proved with his research that this technology is not just a dream but is soon going to be a reality. Skylar Tibbits constructed a 2D grid structure that deforms automatically by shrinking across a 3D surface.

Experimental approach: Print 3D demonstrations using materials with different properties.

Materials in which one part of the material remained rigid and the other expanded up to 100% of its previous volume. Materials which expand were strategically placed on the main structure to produce joints that stretched and folded

For example: straw which bends when activated by water [3] Figure 1 explains the 3D printed shape that resembled the initials “MIT” was shown to evolve into the formation that looks like the initials “SAL” (Self-assembly laboratory). Figure 2 shows a flat surface self-folding into a tetrahedron.

Both the figures illustrate the self-assembly process of the objects printed on a 3D printer which were incorporated with igneous combination of materials which could deform according to the need. Basically, what Tibbits does in his work is he gives the printer a geometric code base on the object design such as angles and dimensions. He also gives codes with respect to how the object should change shape when exposed to outside forces such as water, movement or temperature change.[5]

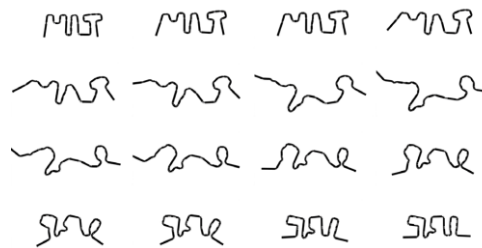


Figure 1: 4DP examples that show the single-strand evolving of initials “MIT” into “SAL”
(curtesy:www.SJET.us)

3.2Stratasys connex technology

Skylar Tibbits feels making this concept on a human scale is difficult but says at least some companies are interested in it. Stratasys is one such company which is helping in Skylar in his field of research. This is a technology where a single print with a different material features can transform any 1D strand into 3D shape, 2D into 3D or morph into another.

Object connex multi-material 3D printing technology is as shown in the figure 2.

An important part of Skylar Tibbits work allows researchers to program different material properties into various particles of designed geometry and obtain different water-absorbing properties of materials to activate the self-assembly process. Here the activation technology is water. This activation technology has new possibilities for including programmability into non-electronic materials. For example a robot like behaviour without depending on complex electro-mechanical devices.[6]



Figure 2: Stratasys object connex multi-material 3D printer (curtesy: www.3ders.org)

Advantages of obtaining water absorbent materials:

- There would be no change in the chemical structure
- Can be programmed to change the physical structure as required

- Few water absorbing polymers can absorb up to 300 times their own weight
- Low density
- Highly effective

Limitations:

- Their water absorbing capacity may reduce if there are any ions in the water.
- The process of making water absorbent materials might be costly.

3.3 Jerry Qi (Associate professor of Mechanical Engineering at Georgia Inst. of technology, USA)

Jerry Qi is one among the researchers who are working to make this technology a dream come true.

With his idea of using composite materials to test if this could work he has set no limits for his research.

3.3.1 Development of 4D printing:

They incorporated “shape memory” polymer fibres into composite materials. And developed unique “printed active composites” whose design is to include precise location of certain shape-memory fibres that will behave in its own way when exposed to an external stimulus [7]. Shape-memory is not a new concept it is an example of self-assembly wherein the object remembers the shape and deforms by responding to the conditions. Shape memory is not only the one there are many such examples also for the self-assembly.

3.3.2 How Qi’s 4D printing technology works:

The research team designed specific fibre architecture at laminate level for several composites. Composites were created with interesting thermo mechanical behaviours based on the fibre architecture, size, orientation, spatial variation of and many such parameters. The printed active composites (PAC’s) are soft materials consisting of glass polymer fibres that reinforce an elastomeric matrix. These fibres are influenced by shape-memory effect, used to create the active part of composites.

The PAC’s (printed active composites) were then thermo mechanically programmed to take 3D configurations (shapes). The change in shape is controlled through the design of in-homogeneities at micrometre level. The complete 3D design of fibres and matrix was printed from a CAD file using an object connex 260, 3D printer. Then a process which results in a layer that contains matrix and fibre was made by depositing the polymer ink droplets at about 70°C and then wiped into a soft and smooth film and later UV photo polymerized. The entire composite design was then analysed by printing multiple film layers to create individual lamina, multiple lamina and then the 3D laminate. [7]

Advantages of Shape Memory Polymers:

- Have good recovery strain
- Density is low
- Cheaper in cost

Drawbacks of Shape Memory Polymers:

- Relatively low modulus
- Low strength

3.4 Creation of Hydrogels:

The way scientists at “Wyss Institute for Biologically inspired engineering at Harvard” approached towards the concept is impressive. An orchid by which 4D printing was inspired is shown in figure 5. They created structures similar to as discussed in the Skylar tibbits process. Both Skylar tibbits and this process seem to share few common advantages and drawbacks.

Wyss Institute developed hydrogel structures which change their shape when placed in water. They are able to respond to the nature in the same way plants do. Using flowers, leaves and tendrils they took cellulose fibres from wood, to work with some sort of matter that give plants their unique properties. They then manipulate the cellulose to form hydrogel structures. They are basically multi-layered, complex internal structures with controllable physical properties. Hydrogel is good at absorbing water. Once the material was designed they used a mathematical model to print the material in a specific manner so that it would transform in a defined way and would transform its shape in any way desired.[8]

Advantages of hydrogels:

- They have a degree of flexibility similar to natural tissues.
- Hydrogels that are sensible to environment have the ability to sense pH and temperature changes.
- They possess good transport properties.
- Hydrogels are biocompatible.
- Hydrogels are easy for modifications.

Disadvantages of Hydrogels:

- Hydrogels are expensive.
- Hydrogels are non-adherent; they may need to be secured by a secondary dressing
- Hydrogels have low mechanical strength
- They are difficult in handling
- Loading is a difficult

Types of hydrogels:

- Natural polymers
Ex: Dextran, Chitosan, Collagen
- Synthetic polymers:
Ex: Poly (vinyl alcohol)

Although 3D printing is now taking its position in the creation a new revolution in the manufacturing industry by getting people know about the technology yet its complete application is not found in India. For example, china is constructing buildings using 3D printers, and in many other countries people have started to use this technology in many fields possible. 3D Bio printing is a concept which is taking shape now. It is process of creating tissues and organs by depositing materials known as bioinks layer-by-layer in addition they begun to incorporate the printing of scaffolds. These scaffolds can be used to regenerate joints and ligaments. Construction 3d printing is the technology that uses 3D printers to fabricate buildings or construction components. This process of construction is used because it meets the demands of architectures and engineers with high value, high performance building components.

Once the present 3D printing technology is put into complete use, the concept of 4D printing can be implemented based on then scenario of how the nature has changed after 3D printing. The 4D printing first finds its base in 3D printing itself. Some special property materials which would be required for the 4D printing could be printed by using 3D printers. What makes 4D printing special over the 3D printing is that the buildings which are built using 3D printers could be pre-programmed to assemble or disassemble themselves. And the application in biomaterial field where you could print bio components that could be later implanted in human bodies and as a result find change in shape and function without external intervention.

4. Overcoming the cons of 3D printing in 4D Technology:

- **Limited use of materials:**

3D printers presently are limited to the use of only few materials such as resin and plastic. For the help of 4D printing a new software can be developed accordingly and add some specifications to the printer so that the printer can use a wide range of materials for printing as the materials used in 4D printing are entirely different with different properties.

- **Limited size:**

Right now only small size items can be built using 3D printers. So, measures can be taken while manufacturing the 4D printers in the future to overcome this drawback and make it helpful to print all kinds of necessary objects.

5. Few cons similar in 3D printing and 4D Printing:

- **Creation of dangerous items:**

Apart from printing useful items this technology can be used to print objects which are a harm to the society and to the national security with great precision and since 4D printing is the advanced level of 3D you could expect more threats and dangers in many ways.

- **Decrease employment in manufacturing sector:**

Definitely as the job of manufacturing engineer becomes simple because everything in these processes are computer based and automated would be a great problem of unemployment in large populated countries such as India and others.

6. Few pros similar in 3D printing and 4D printing:

- **Varied options of manufacturing:**

We will have various options of manufacturing the product. The customization based on our requirement is easy. And we will have a design freedom and the design can be made based on your requirement and suitable materials can be used to manufacture

- **Reduced need of storage of products:**

Unlike the conventional technology these 3D printing and 4D printing of products can be built only which are going to be sold, there will be no need of storage of the materials.

- **Advanced healthcare:**

As everyone is aware of the advancements in printing of organs and tissues for human body using 3D printing there is more that can be achieved in this process by using the 4D printing technology.

Table1. Process Parameters

	Shape memory polymer Parameters	Range
Jerri Qi's experiment	Density(g/cm ³):	0.9-1.2
	Extent of deformation:	Up to 800%
	Required stress for deformation(MPa):	1-3
	Stress generated upon recovery:	1-3
	Transition temperature(⁰ c):	-10.100
	Recovery speed:	1s-min.
	Processing conditions:	<2000c low pressure
	Costs:	<\$10/lb
	Shape recovery ratio:	Recovery ratio upon bending is above 90%
	Water absorbing polymers Parameters	
Skylar Tibbits demonstration	Absorption of water:	Purely a physical change, no change in chemical structure. Presence of valence cations in the solution gives the polymer ability to bond with water molecules.
	chemical structure:	Classified as hydrogel when cross-linked. Absorb aqueous solution through hydrogen bonding with water molecule.
	Example of physical change:	When sodium chloride is added to hydrated polymer water diffuses

	out
Amount of water absorbed:	Superabsorbent polymer may absorb 300 times its own weight(from 30-60 times its own volume)

7. Cost Analysis of 4D Printing:

The need to reduce the costs of manufacturing and processing, would accelerate the global market of 4D printing over the coming years. This technology possess a new business model to cater to the current business requirements by offering reduced need for capital, inventories, time-to-market, which increases the market efficiency. A 4D printed product would lead to lesser manufacturing, transportation and handling costs which would lead to saving of resources and efforts, sustaining the environment. The global 4D printing market size is expected to be USD 65.4 million by 2019.

Among the different materials used for 4D printing, the programmable carbon fibres is expected to witness a healthy growth by 2025 owing to its high stiffness, low weight, and tensile strength which can be used for various industrial applications. Programmable wood and programmable textile are both expected to grow nearly 20%. Programmable textile find application in furniture, shipping etc. Military and defence is expected to be largest growing sector by 2025, since they have several benefits from this technology. Aerospace would follow military and defence holding a market share of over 25%. From a regional perspective North America is expected to witness a high growth accounting for a major share in the overall market.

8. Conclusion:

As 3D printing continues to grow in its applications and evolve high quality materials at large scales, it is sure that this new concept of 4D printing would provide many ingenious ways in creating highly functional and complex surfaces. Several notes have already been made on the impact of 4D printing on the environment. Its potential of work and applications have made it better than the conventional objects or processes and is taking an edge over them and is making the topic a debateable one. Though there might be problems in adopting the technology, once the idea comes in to reality it would set a new era and would make the life simpler and easier. Now that we all have seen 3D printing just imagine what wonders can be witnessed by adding time to the equation. Some of the ingenious minds in collaboration with companies interested in unveiling the technology have done exceptional works in this field of 4D research. This technology in present is in R&D stage. So get ready to witness a whole new technology which would change the entire functioning of the world making the life on earth a better one and simpler one.

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