4D Printing

ENGR 220

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Abstract

4D printing is an innovation on 3D printing that introduces the dimension of time to 3D printing's additive manufacturing methods and allows for the creation of dynamic objects that can morph over time and respond to their environment. The field has grown rapidly and has the potential to change many engineering disciplines from biomedical, to civil, and mechanical engineering. This paper will give a broad overview of the field and discuss its potential to affect the various engineering disciplines. A brief overview of the technology will show how the technology is connected to additive manufacturing and 3D printing. The definition of 4D printing will be explored along with some of different categories of 4D printed structures, and different stimuli that a 4D printed object can be made to respond to. The properties shared between the various 4D structures will be described. The commonly used process for 4D printing will be explained. Some of the proven and proposed future application for this relatively new technology will be explored. Finally, some of the current research in this area will be highlighted to show where the technology has currently progressed to.

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Introduction

Additive manufacturing was an innovation in the 1800s that brought with it many advantages. Reductions in cost because of less reliance on molds and the reduction of waste as material was added to existing structures rather than being removed. This technology was innovated on further over 100 years later with the advent of 3D printing. This new technology commercialized the process and made it more affordable and more efficient. While traditional additive manufacturing is still used for more industrial purposes, 3D printed brought additive manufacturing to the home as the printers became smaller and more affordable. 3d printing also allowed for more complex geometries to be attained than what was possible with traditional additive manufacturing due to the printer's ability to be precisely programmed. But the technology was still limited because the 3D printers made mostly static objects. In 2013 this limit was removed with the introduction of 4D printing. Now printed objects were dynamic and could morph and change after a set amount of time. Using calculations before printing, the precise structure needed to produce the desired changes could be designed and the existing printers could be told how to print in addition to what to print. This new field grew rapidly because of its potential for changing large portions of multiple engineering disciplines.

Motivation

Since I was first exposed to additive manufacturing and the idea of 3D printing, it has fascinated me. Seeing a 3D printer in action reminded me of the replicators from Star Trek and the idea that we might see technology like that in the future makes me excited. Originally the idea was to do this project on 3D printing itself and explore its applications to various fields such as medicine and especially engineering. However, once I learned that 4D printing was an even newer technology on the rise, I immediately changed my mind. I am writing my report on 4D printing because the idea of 3D printing with the added element of time is intriguing and the technology is wholly new to me. I wanted to research something that I know almost nothing about rather than discussing something I have experience with.

1. History

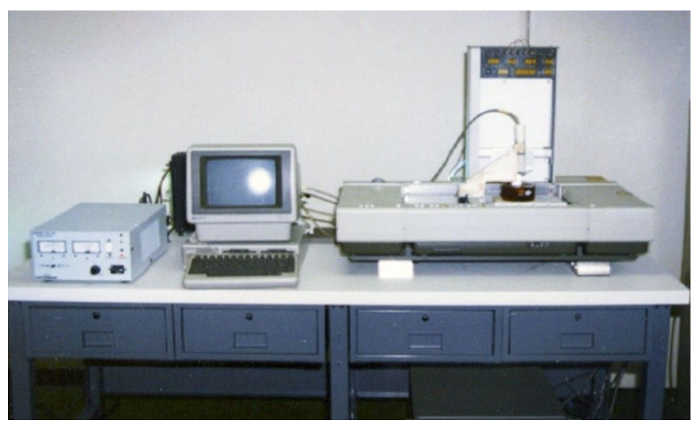
While a recent technology itself, 4D printing has its roots in 3D printing and additive manufacturing. To allow a better understanding of 4D printing a strong foundation will be created by briefly discussing the history of Additive Manufacturing, 3D printing, and 4D Printing itself.

1.1 Brief History of Additive Manufacturing and 3D Printing

Image 2: A modern 3D printer

The earliest ideas of additive manufacturing can be found in the work that Francois Willeme performed in the mid to late 1800s. In 1859, he used 24 cameras placed at different angles to produce rudimentary 3D models, and in 1892 he patented a machine that could layer a few different materials to create topographical maps. It was not until the early 1980s that the first 3D printer that resembles those we have today was created. Dr. Hideo Kodama from the Nagoya Municipal Industrial Research Institute was the first to create a machine able to make 3D prototypes by layering photopolymers. However, this machine was never commercialized. A few years later, Charles Hull created a smaller and slightly more efficient 3D printing machine (Image 1) that was commercialized. It used a similar process of layering photopolymers that were then cured using UV light. Hall also developed the STL file format which is still used for most 3D printing today. The field grew rapidly with new 3D printing methods being invented

Image 1: Charles Hull's fir



in the years following Hull's successful machine. Some of those different processes include a method in which a laser is used to melt powder into a solid object, fused deposition modeling in which a material is heated and extruded through a nozzle to create an object layer by layer, and bioprinting in which layers of cells are precisely printed to allow the creation of functioning tissue. As the technology has developed, the printers have gotten smaller, more efficient, faster, and cheaper (image 2) all while producing higher quality and more complex objects [7]. The next step in the evolution of this technology was the idea to print objects that evolve over time, and that idea is the basis of 4D printing.

1.2 History of 4D Printing

The idea of 4D printing was first introduced by Skylar Tibbits in 2013 during a Technology, Entertainment, Design (TED) talk [1]. Mr. Tibbits' research focusses on creating materials that can self-assemble or be programmed for other functions. He is the founder and co-director of the Self-Assembly Lab at MIT, which has made great progress in the subfield of 4D printing which focusses on self-assembly [4]. Since his TED talk, he has gone on to publish multiple papers on 4D printing [1]. Since its introduction in 2013, the field of 4D printing has grown rapidly especially over the last 5 years. For example, in 2017, 86 unique publications on 4D printing were released. In 2019 the number had more than doubled with 189 publications having been released about 4D printing [2]. The field of 4D printing is still growing and much like its predecessor, 3D printing, this rapid development is expected to continue as more and more groups begin to study this exciting branch of additive manufacturing [3].

2. Definition

4D printing is an emerging form of Additive Manufacturing (AM) that, while related to 3D printing, has one key difference. This difference is the added fourth dimension which represents predictable and planned evolution or morphing over time. This evolution and morphing come from the combination of active and passive materials to create multi-material structures. The are some single material 4D printed object but they are less common and have received less research. The passive materials include more conventional construction materials like polymers or fabrics. The active materials are the part of the 4D printed structure that respond to external stimuli to perform the shape change or other response. The active materials can be more conventional materials that have desired properties but more often they are smart materials that be programmed with certain responses [1]. To fine tune the response to stimuli, the printers are programmed to print the active and passive materials in precise locations in the structures being constructed. The responses to different stimuli are varied and include actuation, folding, bending, expansion, topographical change, and color change. There are many different types of stimuli as well. They include temperature, light, water, electricity, magnetism, and pH changes [2]. These will be expanded upon when talking about the applications of this technology.

2.1 Types of Morphing Behavior

Nearly all morphing behavior seen in 4D printed materials is the result of "relative expansion" between the active and passive material. This is because various types of anisotropy between the two types of materials can be encoded. Anisotropy is the phenomenon in which a material's mechanical properties are affected by the direction in which the force is applied because of the way the molecules in the structure are arranged [1]. For an example think of wood. Because of woods grain structure, it is stronger in one direction than another. The Shape morphing behaviors of most 4D printed materials have four types of physical mechanisms, mass diffusion, thermal expansion, molecular transformation, and organic growth. Mass diffusion is the result of mass change due to absorption or adsorption of the "guest material" or stimulus.

This extra mass is then redistributed throughout the material to cause expansion or extension of certain pieces. Thermal expansion is simply a change in size of the material due to changes in temperature. Molecular transformation takes place with mass and temperature being held constant. This type of transformations can be the result of electric or magnetic field, light mechanical force, or responses to UV radiation. In the case of an electric or magnetic field, dipoles in the material are aligned along the field causing a shape change. Light mechanical stress can align polymer chains or grains in a material to cause a shape change. These changes through molecular transformation take time to develop. Organic growth involves a living active material and its growth over time, or in response to stimuli, can cause shape, mass, and size changes. This type of morphing is most often observed in bioengineering where they are studying 4D printing of cells, proteins, soft tissues, and organs [1].

3. Properties of 4D Printed Materials

Objects created with 4D printing can be composed of many different materials so the mechanical and chemical properties of 4D printed objects can vary greatly. However, there are some properties that are unique to 4D printed smart structures and are necessary to their function. Perhaps the most important property to the function is the "shape memory effect" (SME). The SME is a result of the materials programming during creation, and it is the materials ability of the materials structure to remember two or more shapes that it can switch between in response to stimuli. There are three different classifications of the SME. The "one-way shape-memory effect" is when the material can remember its original shape only and must be reprogrammed to change to any other chapes. The "two-way shape memory effect" is seen in a material that has two configurations that it can switch between at two separate ends of a stimulation spectrum such as high and low temperatures or a negative or positive electric field. The "multiple-shape memory effect" is simply when a material can remember and switch between more than two distinct shapes. Repeated cycles of switching between shapes can cause degradation, however. 4D printed materials can only go through so many shapes before they begin to crack or form delamination's. To stave off this degradation parts need to be made with a high degree of "repeatability" or their ability to perform many cycles of configuration changes without noticeable damage.

Also, within 4D printed materials there are a few different classes of materials that have their own unique properties in addition to those properties outlined earlier. "Smart Materials" are materials that are able to convert energy from one form to another such as turning thermal energy into mechanical work for actuation. "Functionally Graded Materials" are substances that have a varied composition and structure that is varied gradually over its volume. An example of this is printed concrete that has a density that varies over its volume. "Programmable Materials" are self-explanatory, they are materials that can programmed to change their properties for specific applications or situations. For most programmable materials, this programming can be done any time after they are printed and multiple times to change their properties over the use of the object. The most popular program for doing this at present is GrabCAD. There are many other types of materials within 4D printing such as "Metamaterials" and "Tunable Materials" but, these and other type of 4D printed materials are just ideas or theoretical at this time and they have not been extensively studied [2]. As the field grows, many more classes of 4D printed materials will be discovered and yet unknown common properties between all classes will be noticed.

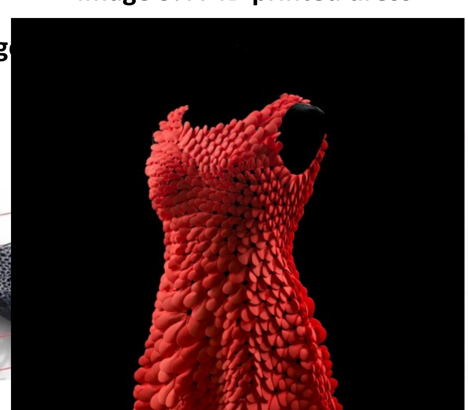
4. Process

The essential part of 4D printing is a printed materials ability to evolve over time. However, for objects made though 4D printing, these evolutions must be predictable, reproducible, and controlled. To this end, mathematics is introduced into the process before printing commences. Calculations done before printing allow those who want to 4D Print objects to program the printers and tell them how to print an object, not just what to print. What materials to use on what layer, in which section of the object, and what direction to print those layers are all factors that affect the response to stimuli that a printed object will have [2]. These calculations done before hand vary based on material, desired reaction, type of stimulus, and application. Because of this variation, there is no general formula but there is a common thread between them. Most if not all equations currently used are derived from the equations in a typical Mechanics of Materials course. Equations for stress, strain, curvature, deflection, torsion, angle of twist, and thermal expansion are used to derive equations necessary for creating objects that morph correctly. The formulas derived must be tailored to the specific situation but most, if not all, come from these basic Mechanics of Materials principals [1]. These calculations beforehand allow the avoidance of trial and error when performing 4D printing which would waste materials and time [2]. Once the structure is derived to fit the situation at hand, commercial 3D printers are used to make the object and are programmed to print the materials in the exact orientations needed [6].

5. Applications

4D printing is a varied field with many possible, exciting applications. However, many of the applications to be discussed are still theoretical or

Image 5: A 4D printed dress



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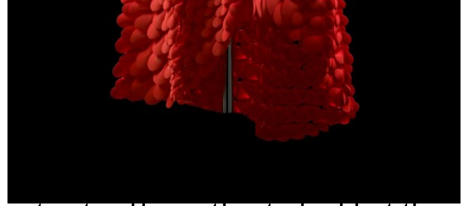
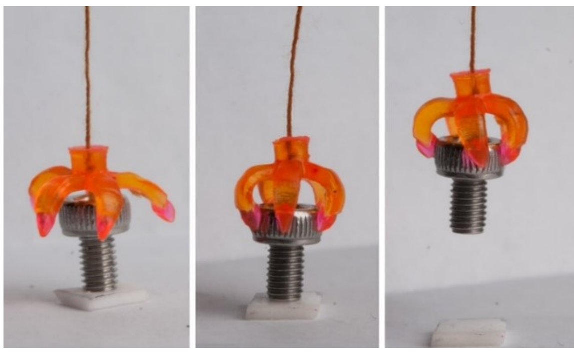


extrapolations about the development of the field. Many are not yet sufficiently studied but they are still worth mentioning to show why this field has grown as quick as it has. The first proposed application is self-assembly. Parts could be printed separately by separate 3D printers, or the object can be printed in a compressed or folded form (Image 3). Then, spurred by a stimulus, these parts would assemble into a structure bigger than the printer itself [1]. One theorized object is the printing of self-folding furniture. The furniture would be printed and shipped in a compressed, folded-up state that would unfold into a piece of usable furniture. This saves

Image 4: Example of autonomous actuation



d, and it saves on shipping space as well [6].

ly would be the self-assembly of buildings on other

collection of possible application exists in the

functional organs. Proper functioning of organs is

structure. Researcher’s hopes are that the process of 4D printing can be used to effectively imitate these internal structures and successfully print internal organs for use in transplants. However, the question with this is whether the human body would accept these printed organs [1]. Another application in the medical field is the possibility or personalized medicine. This is medicine that can by fully customized too each patients’ specific needs [3]. Another application being proposed in the medical field is that of self-folding proteins [6]. Another possible application is actuation without the help of outside forces or electrical motors. This function allows 4D printed objects used for this application to move, bend, twist, lift, or fold autonomously (Image 4). This is based on the idea of mass diffusion, as the 4D printed object would be able to move its own matter or matter from an absorbed stimulus to new locations within itself in order to perform mechanical work [2]. 4D printing has also been proposed to be used for self-repair of objects. The main use for this type of application would be for piping. Piping that could repair crack and kinks itself has been proposed for everything from home plumbing to major natural gas pipelines. This application has also been proposed for infrastructure with the idea of self-repairing bridges or roads. However, the application to major infrastructure would be costly and most likely only used for very specific small sections of bridges or roads more prone to damage instead of the whole structure. Another application in the piping would by pipes that adjust their diameter in response to water demand or pressure requirements. A surprising application of 4D printing is in the realm of fashion. The proposed applications are clothes that change based on the activity or weather. On the activity side proposed ideas are shoes that could adjust their cushioning when running to provide better comfort during that activity or clothes that change their structure to be more flexible when becoming more active. In response to weather there are a few possibilities. In the response to high temperatures, 4D printed clothes could shorten sleeves or pant legs, or become thinner to allow wearers to cool down. As the weather cools down, the clothes could re-lengthen, become thicker, and even create insulation for the wearer. In response to inclement weather, such as rain, the clothes structure could reconfigure into something that is water-resistant or even waterproof that would help keep the wearer dry. Also, in the realm of fashion is printing clothes that incorporate a self-folding aspect in order to be printed as one piece by printers that are many times smaller than the dress. One example of this was printed by a Massachusetts design studio called “Nervous System.” Their dress (Image 5) is a system of hinged petal that is printed in a compressed, folded-up stat that unfolds by itself after printing [6]. The possibilities are seemingly endless when thinking about the possible application of this relatively new technology, however it is still limited by what current 3D printers can be programmed to do and what can be predicted by current mathematical models derived by researchers. As these improve in tandem there is no doubt that some of these proposed applications will be fully realized.

6. Current Research

Just as the proposed applications of 4D printing are varied, so is the scope of the current research. The leader of this research is the Self-Assembly Printing Lab at MIT. Led by Skylar Tibbits, the man that first introduced 4D printing in 2013, they have studied the potential for 4D printing of furniture and small objects that can unfold into their final shape after printing, The MIT lab has also done work on the self-adjusting clothing mentioned in the applications section. Another notable group doing research in 4D printing is the University of Wollongong in Australia. The team at this institution has been able to successfully 4D print a water valve that closes itself once a certain high temperature threshold is reached. This is possible because of a hydrogel ink used in printing that reacts rapidly to high temperatures. This accomplishment demonstrates the potential for 4D printing's use in plumbing applications [6]. Other current research focusses on finding applications of 4D printing in response to one stimulus. For responses to solvent stimuli, one current study is attempting to create 4D printed biomimetic structures. Biomimetic structures are synthetic structures that mimic biochemical processes. In this study they were able to effectively control the swelling of a composition of cellulose fibrils when immersed in water by precisely controlling the printing direction of each fiber. For responses to magnetic stimuli, one study was able to perform 4D printing with an ink that was doped with aluminum platelets and control how its shape changed in response to magnetic fields. For responses to thermal stimuli, A team of researchers 4D printed an object composed of materials with different reaction temperatures. The effect of this was a multi-stage shape change with each stage occurring at precise times by controlling the rate of change of temperature. Two separate studies explored responses to light stimulus. The first study created a microrobot that only moved when exposed to UV light. The movement mechanism was a sort of leg that unfolded when exposed to UV light and folded back to its original shape when exposed to visible white light. The other study exploring responses to light stimulus created a container with light sensitive hinges that only opened when exposed to sunlight and reclosed when taken out of the sun [3]. The final study to be highlighted involved Slippery Rock University's Dr. Jheng-Wun Su. The study was focused on the biomedical applications of 4D printing technology, specifically on creating minimally invasive devices for insertion into the body. The idea with these devices is that they can be printed compressed and folded as much as possible as to require the smallest incision to be inserted into the body. The current "shape memory polymers" (SMPs) proposed for this purpose have transition temperatures that make implantation difficult. The study at hand demonstrates printing of a new SMP that has a transition temperature range of 20 to 37 degrees Celsius which is body temperature. This makes to the new SMP better for insertion into the human body [5].

Summary

4D printing is a relatively new technology that is a natural progression from the additive manufacturing innovation of 3D Printing. The technology was introduced in 2013 by Skylar Tibbits, an assistant professor at MIT, in a TED talk. In the eight years since its introduction, the field has grown rapidly because of the technology's versatility and potential. The fourth dimension that this field adds to 3D printing is time. Products printed through the methods used in 4D printing can morph and change their properties over time. This is made possible by controlling how an object is printed in terms of the materials used, where to print those materials, and in what orientations to print them. To determine these controlling factors, equations must first be derived from Mechanics of Materials equations such as stress, strain, curvature, deflection, torsion, etc. to fit the unique situation. These equations are then used to predict how a proposed structure will respond to stimuli and fine tune the structure to the desired responses before printing. This process can create a large variety of objects with special morphing properties to fit a myriad of applications. Just a few of these applications are self-assembling printed furniture or buildings, personalized medicine, self-repairing structures, and clothing that responds to the environment. While most of these applications are simply theories at the current time, many have been effectively demonstrated through of work of places like the Self-Assembly Printing Lab at MIT. The current research on 4D printing has yielded exciting results and this is surely a field to keep an eye on.

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