Technological comparison of 3D and 4D printing

Dilip Gurung

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Abstract:

This thesis majorly presents technological advancement of various 3D printing technologies and introduction of 4D printing technology. The pages includes introduction section with the literature review containing detailed explanation of majority of 3D printing technologies as well as the field that has been highly influenced by this mechanism. With the main objective of finding and analyzing technological difference between 3D printing and 4D printing, both technologies are further broken down and analyzed using SWOT analysis method. A number of available 3D printers and 4D printers are selected randomly with their specifications. Based upon investigative data from the reliable internet sources, these printers are rated from the reviews regarding print quality, ease of use, reliability, failure rate, customer service and price.
Furthermore, this thesis investigates challenges and obstacles while adopting these printing technologies. Existing 4D printing process, ongoing development and future application areas and major factors that separates 4D printing technology from 3D printing are discussed. The result section includes rating of these two technologies based upon SWAT review and market analysis of both printing industry.

Keywords:	3D printing,4D printing, Stereolithography, FDM, SLS, EBM, Smart Materials, Self-assembly, SWAT analysis
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List of abbreviations and acronyms

3D – Three Dimensional

4D – Four Dimensional

SLA – Strereolithography Apparatus

MSL – Micro stereolithography

SLS – Selective Laser Sintering

EBM – Electron Beam Melting

FDM – Fused Deposition Modeling

DMLS – Direct Metal Laser Sintering

BPM – Ballistic Particle Manufacturing

LOM – Laminated Object Manufacturing

SGC – Solid Ground Curing

CAD – Computer Aided Design

DMD – Digital Micro Mirror Device

DLP – Digital Light Processing

LCD – Liquid Crystal Display

ABS – Acrylonitrile-Butadiene-Styrene

PLA – Poly Lactic Acid

FDA – Food and Drug Administration

CNC – Computer Numerical Control

PVDF – Polyvinylidene fluoride

NOL – Naval Ordnance Laboratory

UV – Ultraviolet

PCL – Polycaprolactone

USD – United States Dollar

CAGR – Compound Annual Growth Rate

FOREWORD

I wish to express my sincere gratitude to Mirja Andersson, Degree Programme Director, Principle Lecturer in Energy and Materials for the outstanding supervision throughout this thesis. The inspiration and guidance has been vital for me to complete this thesis. In addition, I also would like to thank Mr. Stuart Buddle for the technical support.

Lastly, A huge appreciation and thanks to all my friends and family for their continuous encouragement and support over the years.

1. INTRODUCTION

1.1 Background

As printing is no more just about ink and paper, printing technology has surpassed its traditional paper and ink process to three dimensional (3D) process and furthermore, four dimensional printing technology (4D). We all are very much familiar with two dimensional printing i.e. printing pages from normal printer at home or office. This thesis is more focused on 3d printing and 4d printing technology.

With the history dated back to late 1980's, 3D printing technology has brought revolutionary changes in field of manufacturing systems (Industry 3. , 2016). Like any other technological revolution, 3D printing technology is the ultimate product of vision, action and dedication of engineers who are brave enough to transform their vison make it happen. But as the advanced and rapid development in printing technology has taken itself to next level, 3D printing has allowed the printing of smart materials designed to change shape and function, so called 4D printing technology. With a great potential to transform everything from our daily lives, it has become disruptive technology for future advanced manufacturing systems.

1.2 History

The earlier version of 3D printing technology dates back to late 1980's. During those time it was known as Rapid Prototyping rather than 3D printing. Charles (Chuck) hull invented first Stereolithography apparatus (SLA) machine in 1983 (Industry 3. , 2014) and currently he is cofounder of one of the largest company working in 3D printing sector, 3D Systems Corporation (systems, 2016). Though the patent of rapid prototyping was obtained by him, In May 1980, Dr Hideo Kodama of Nagoya Municipal Industrial Research Institute of Japan filed the very first patent application for Rapid Prototyping which was unsuccessful. (Plastics, 2016)

Stereolithography is a technique of creating three-dimensional objects with a computer controlled moving laser beam layer by layer from liquid polymer that hardens with the exposed laser beam. (Materialise, 2016)

Stereolithography technique was ground breaking development towards prototyping because of fast and more cost effective way. 3D Systems later introduced SLA-1 in 1987 which was first commercial Rapid prototyping system. In 1987, Carl Deckard from University of Texas introduced Selective Laser Sintering (SLS) technology and issued a patent in 1989, later acquired by 3D systems corporation. (Industry 3. , 2016)

In 1989, Scot Crump, who is co-founder of Stratasys Inc. introduced a new technique called Fused Deposition Modelling (FDM) which is widely used nowadays for 3D printing. (Stratasys, Stratasys, 2016) Same year, EOS was founded in Germany. EOS pioneered in the field of Direct Metal Laser Sintering (DMLS) and provider of highly productive Additive Manufacturing Systems for plastic materials. (eos, 2016)

Within 1990's to 2000, many 3D printing technologies were developed such as Ballistic Particle Manufacturing (BPM), Laminated Object Manufacturing (LOM), Solid Ground Curing (SGC) and Three Dimensional Printing (3DP). Most of technology were focused on research development of industrial manufacturing process.

1.3 Objective

With the increasing potential and opportunities that come along with printing technology, more people are realizing the importance of 3D printing technology. Nowadays 3D printers are making its way to the offices, educational institutions, factories, medical institutions and even at homes. As the 3D printing technology is moving rapidly and taking over its traditional approach, there is a new dynamic approach emerging which is called 4D printing technology. Technology brings challenges and need to be addressed promptly. Current products and 3D printing hype, is it successful enough to take over traditional system? Will 4D printing technology be able to surpass current 3D technology hype and how much effective will it be in real world scenario? Design issues, smart multi-functional materials, material programming and cost are the basic challenges.

This thesis work focuses on researching and comparing different types of 3D printing technology and 4D printing technology. The main objective is to find key aspects that separates and bridges these two disruptive printing mechanism. Furthermore, to find a perfect printing technology to be used at school and possibility of 4D printing method.

2 LITERATURE REVIEW

2.1 3D Printing Technology

Most people are familiar with inkjet or laser printer those days that prints documents and photographs. Texts and images are printed by controlling and placing ink or toner on the surface of paper. In similar way, 3D printers prints objects by controlling the position and adhesion of specimen in 3D space. It is an additive manufacturing process, where materials are added precisely unlike subtractive process where materials are removed to get final object.

For 3D printing of an object, digital model of specimen is required in the computer. 3D model can be designed using computer aided design (CAD), Solid works or other different modelling software. Also, 3D scanner can be used to scan a model and convert it into digital data. Furthermore, slicing software is needed in order to slice up the model into many cross sectional layers and finally to be sent to 3D printer where model is printed layer by layer forming a complete 3D printed object.

2.2 Types of 3D Printing Technology

2.2.1 Stereolithography

Stereolithography is one the oldest 3d printing method. Patented by Charles Hull, co-founder of 3D Systems, Inc in 1986, this printing technology converts liquid plastics into solid 3D objects. Stereolithography apparatus (SLA) machine or printer is needed in order to work with Stereolithography technique. As most of the 3d printing techniques require digital file that contains information about dimensional representation of an object. Those digital data are then converted to the format that is recognized by printer. Standard Tessellation Language (STL) format is most commonly used for stereolithography. Those STL file contains information for each layer since, printing process is done layer by layer.

How SLA works?

Stereolithography technique is light based technology that creates layer of given model with liquid polymer. The SLA machine exposes liquid polymer and laser starts to form individual layer of the item.

The laser is controlled and monitored by two galvanometers. After each layer is built, plastic hardens and printer drops down in the tank with a fraction of millimeter depending upon chosen layer height and then next layer is solidified as per laser instruction until whole object is built.

Key components of printer:

The Laser

The laser generates energy to turns liquid polymer from liquid to solid state.

The Galvanometers

This controlled hardware controls and projects laser beam repeatedly across the built surface. Galvanometers reflects laser path with oscillating, finely tuned mirror and positions the laser accurately.

The Resin Tank

The resin tank is an optically transparent apparatus located in the bottom part. As the laser contacts thin layer of resin it chemically hardens bonding nearby layer and creating watertight structure.

Form 1+ is a SLA printer for home use developed by Formlabs. (Formlabs, 2017)

Figure 1. Form 1+ printer for Stereo lithography 3D printing (Formlabs, 2017)

The time required to print an object using this printer varies on size and types of SLA 3D printers. Although being considered as oldest 3D printing technology modern companies still use this technology to create prototype of the product. 3D systems Inc. and Forma labs are one of them. Despite of time efficient to produce an object and cost effective relatively with other means of prototyping, stereo lithography isn't most common process to print final product.

2.2.2 Fused Deposition Modeling

Fused deposition modeling (FDM) technology was developed and invented by Stratasys ltd. founder Scott Crump, in 1980s. (Stratasys, Stratasys, 2016) Since then Stratasys has continued leading the 3D printing stry developing and extending its systems towards field of manufacturing, designing, engineering and educational sectors. Fused deposition modeling techniques are used to print functional prototypes as well as final end use products. Because of its high performance and engineering grade thermoplastic, this printing process is widely used by engineers, manufacturers and other professionals.

How Fused Deposition Modeling works?

The modeling process includes building of object layer from the bottom by heating and extruding thermoplastic filament which is similar to previously defined stereo lithography technique. The process is simple as below:

1. Pre-processing: Pre-processing includes preparation of digital file of an object or CAD file and slicing of the file type required by the printer. The path to extrude thermoplastic material is calculated.

2. Production: The heater inside 3D printer melts the thermoplastic filament to semi liquid state and places along the extrusion path as per the object dimension. The resolution and precision if this printing process varies with the type of 3D printer and thermoplastic materials used. Scaffolding process occurs during production phase, the 3D printer adds material where support is needed and vice versa.

3. Post-processing: The final product is achieved in this state by removing away from the printer. Support structure are removed either by breaking or by dissolving in water for water soluble support structures.

Application areas of Fused Deposition Modeling

Concept Models

FDM provides better combination of concept modeling and visualization applications. Concept models helps to provide detailed information regarding accuracy, material properties, color and other features. Those concept models can be used to sales and marketing in order to give first look of product and excite interest of customers.

Function Models

With this modeling technique, it is possible to print fully functional part. Thermoplastic materials like ABS and polycarbonate provides strong and tough structure model with accuracy.

Rapid Prototyping

Rapid prototyping offers huge advantage in speed and cost compared to alternative manufacturing techniques such as injection molding or die casting. FDM process is helpful in rapid manufacturing process such as developing custom parts, replacement parts and other production parts.

Apart from those, prototypes can be used to create pattern for creating molds with the help of FDM or FDM process can be used as pattern generator.

Characteristics of Fused Deposition Modeling:

- Design freedom.
- This technology is easy and simple to use.
- Easily creates good sized strong, non-brittle geometrically complex structure.
- Thermoplastics used in this production process are mechanically strong and clean to environment.
- Apart from above advantages, the main disadvantage is time consuming slow process and post processing. The model needs to be sanding and filling for good surface finish.

Fused Deposition Modeling 3D printers:

1. Mojo (affordable desktop printer)
2. Fortus 900mc (production series printer)

Figure 2. 3D Printer Mojo from Stratasys (Stratasys, Stratasys, 2016)

2.2.3 Digital Light Processing

Digital Light Processing (DLP) is another 3D printing process similar to Stereolithography technology. Based on Digital Micro Mirror Device (DMD) developed by Texas Instruments, Digital Light Processing (DLP) is a new way to project and display information with superior image quality, high brightness projection. Digital Micro Mirror Device (DMD) is a fast, reflective digital light switch that controls light source precisely using binary pulse width modulation technique. This process is widely applicable in movie projectors, cell phones and 3D printings. (Industry 3. P., 3D Printing Process, 2016)

Previous electronic projection display technology have various limitation regarding its image quality, brightness and color reproduction. To overcome such limitation Digital Light Processing technology has major key advantages and they are as listed below:

- Noise free, precise image quality with digital gray scale and color reproduction.
- Based upon reflective DMD without polarized light, DLP is more efficient than transmissive liquid crystal display (LCD) technology.
- Easily program higher resolution patterns because of close spacing of micro mirrors that projects video images as seamless picture.
- Micro mirror array exposes whole layer in one shot and builds faster than point by point technologies.

How DLP technology works?

DLP technology is based on an optical semiconductor Digital Micro mirror Device (DMD), which uses mircromirrors made of aluminum to reflect light to make picture. DMD often referred as DLP chip because in the same way as central processing unit (CPU) is heart of computer, DMD is the key ingredient of Digital Light Processing.

The whole process includes conventional source of light such as lamp, liquid crystal display panel which is applied to whole surface of building structure and liquid plastic resin placed in transparent resin container. The liquid plastic resin hardens quickly when exposed to large amount of light. After each layer is created, it moves up and next layer starts until whole design is complete.

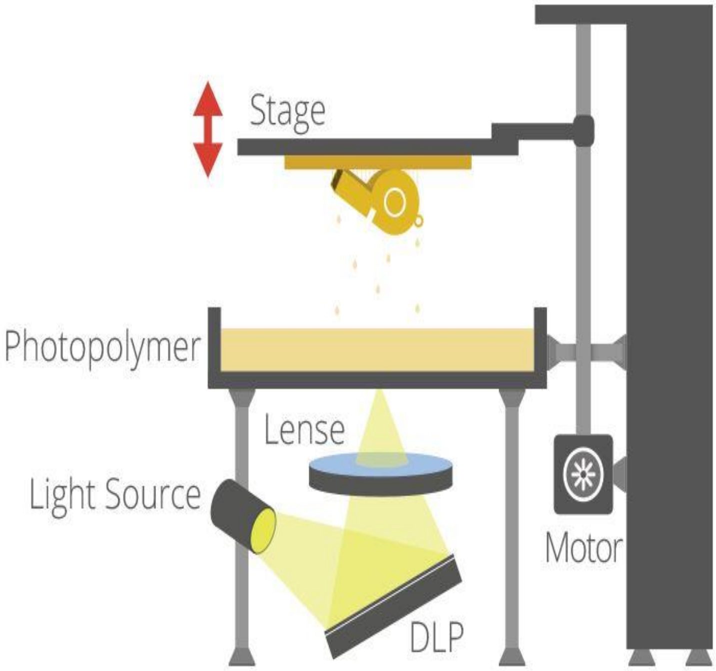


Figure 3. Digital Light processing (Industry 3. P., 3D Printing Process, 2016)

DMD enables uniquely fast and accurately projected patterned light that exposes layer and hardens the resin. An entire layer is projected with single pattern and built within short period of time without having any layer complexity. Smooth and accurate finished parts are achieved by controlling resolution of image plane and adjusting layer of thickness. Those all combined advantages proves DLP technology more reliable and ideal solution for 3D printing technology. (Goldy Katal, 2013)

Application areas:

- Rapid prototyping
- Jewelry casting
- Custom medical implants production
- Hearing aids and Dental restorations
- Mold design
- Automotive manufacturing
- Aerospace manufacturing

Figure 4. Micro plus High-Res 3D printer from envisionTec (envisionTEC, 2016)

2.2.4 Selective Laser Sintering (SLS)

Selective Laser Sintering technique is also laser based 3D printing process similar to Stereolithography. Initially, this technology was developed by Carl Deckard and Joe Beaman from Texas University in 1980. Later in 2001, 3D Sytems Inc. developer of Stereolithography printing technology acquired Selective Laser Sintering process from the original developer. Stereolithography and Digital light processing mechanism use liquid resin in the vat however this process uses powdered material instead of liquid resin. (Industry 3. P., History of 3D Printing, 2016)

How Selective Laser sintering works?

SLS process is similar to Stereolithography process but uses powdered materials instead of liquid resin. The materials like nylon, ceramics, glass, aluminum, silver or steel can be used for printing. Due to variety of materials that can be used, this 3D printing process is widely used for customized products.

This process starts with laser beam containing dimension information exposed over a powder of material. The exposure of laser beam interacts with the powder surface and turns into solid surface. As each layer is completed, it lowers down and the roller smooths powdered surface in order to create next layer which then fuses with previous layer. This process continues until whole structure is built. After the completion, whole powder bed is removed from the machine and excess powder is removed. (Systems, 2016)

Metal sintering requires much higher powered laser beam and higher temperature during process comparing to plastic materials. Cooling time is considered according to the material used.

SLS doesn't need any support structure as the compact powdered bed works as support base for the printed layer.

Diagrammatical representation of Selective Laser Sintering

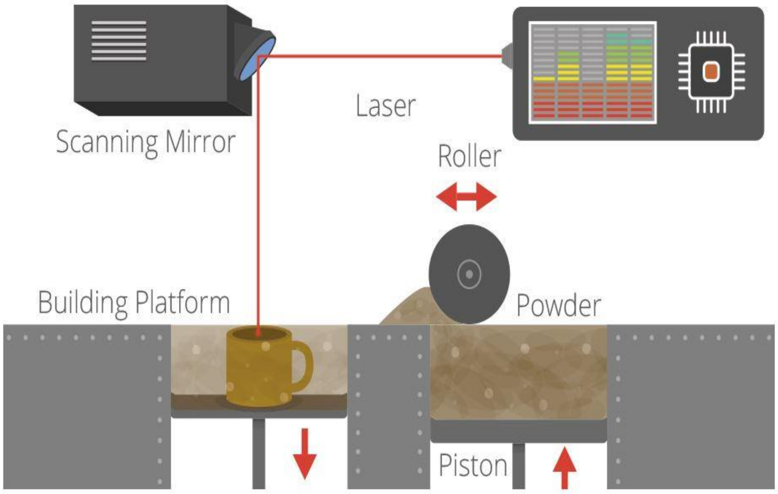


Figure 5. Selective Laser Sinstering process (Industry 3. P., 3D Printing Process, 2016)

Figure 6. ProMaker P1000 (Group P. , 2015)

2.2.5 Selective Laser Melting (SLM)

Selective Laser Melting process is almost identical to Selective Laser Sintering (SLS). The main mechanism that separates this from SLS is highly powered laser beam fully melts the metal powder into solid 3D object. Similar to the SLS process, high laser beam is exposed towards the powdered bed, powerful laser beam melts the metal powder fully forming layer of solid object. The process starts over and over creating next layer until full 3D structure is printed. Materials that can be used for this process are metals including high quality stainless steel, aluminum, cobalt, titanium and nickel based alloys. Size of powder grain sizes between 10 to 60 micrometers. (Sculpteo, Selective laser melting, 2016)

SLM manufacturing method is useful to manufacture complex geometries structures with thin walls, hollows and undercuts. Also, SLM process deals with difficulties of tooling surfaces which is physically inaccessible and restriction design.

Selective Laser Melting Machine SLM 500

Figure 7. SLM 500 (Solutions S. , 2016)

2.2.6 Electron Beam Melting (EBM)

Electron Beam Melting is another additive manufacturing technologies especially for metal parts. Similar to Selective Laser Melting, this 3D printing technology creates dense metal parts and components layer by layer of metal powder, melted by electron beam. The high power electron beam generate energy to melt metal powder fully. Whereas, Selective Laser Melting process uses high power laser beam for melting purpose. (EBM, EBM Electron Beam melting- in the forefront of Additive Manufacturing, 2016)

Electron Beam Melting uses metal powder as a material which then melts and forms 3D part layer by layer with the help of computer controlled high power electron beam. This process is carried out inside vacuum under very high temperature up to 1000 degree centigrade.

Comparing to SLM process, Electron Beam Melting is slow process and costly. Limited availability of materials and its high cost makes EBM process not so popular. Although EBM process is demanding for developing orthopedic implants and aerospace applications. Titanium Ti6AI4V, Titanium Ti6AI4V ELI, Titanium Grade 2, Inconel 718, Arcam ASTM F75 Cobalt-chrome are some standard materials used in this process. (EBM, EBM Electron Beam melting- in the forefront of Additive Manufacturing, 2016) The diagrammatical representation of Electron Beam Melting process is shown in figure 8.

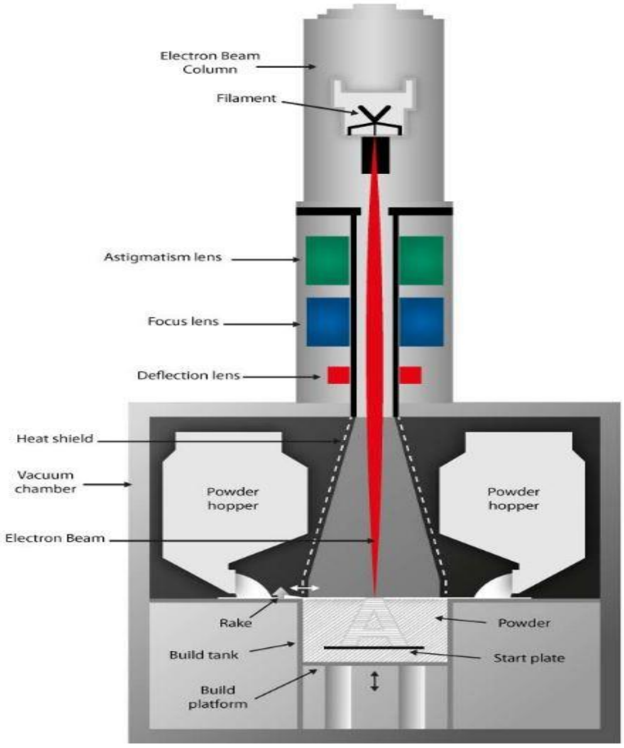


Figure 8. Electron Beam Melting process. (EBM, EBM Hardware, 2016)

Arcam Q10 plus is the new generation EBM machine designed specifically for cost efficient high volume production of orthopedic implants. Developed by Arcam AB group, their other 3D printer Arcam Q20plus is capable of producing aerospace components such as turbine blades and structural airframe components.

Figure 9. Arcam Q10plus - for orthopedic implant manufacturing (EBM, EBM Hardware, 2016)

2.2.7 Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing is the most affordable and fastest way to print 3D shapes. In simple form, sheets of different types of materials are bonded together and cut in the right structure according to the 3D model. Developed by California-based Company Helisys Inc. LOM process is mainly used for prototyping rather than production purpose.

LOM Process:

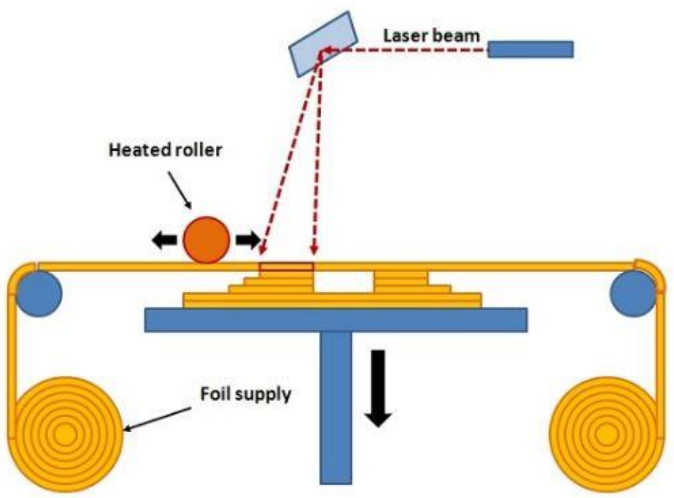


Figure 10. Laminated Object Manufacturing process (magazine, 2014)

In this process, the layered material coated with and adhesive layer is rolled on the building platform. The feeding roller heats and melts the adhesive layer which then glued to the previous layer. Computer controlled laser or knife traces and cuts to desired dimensions of the part. After each layer is completed, the platform moves downwards and new sheet of material is pulled towards building section and adhered to it with heated roller. The process continues until 3D part is fully printed. (magazine, 2014)

Post process includes machining and drilling in order to give perfect smooth appearance. Those section where excess material has been removed or cut can be sealed with paint or sanded. Paint helps to protect from moisture and water specifically for paper materials.

LOM Materials

As almost any material can be glued, this process is versatile. Plastics are also used in this technology but the most common material used is paper. Papers are cheap and easily available also cutting process is comparatively easier than plastics and metals.

Cubic Technologies, the successor to Helisys Inc. is the main manufacturer of Laminated Object Manufacturing printers. (Technologies C. , 2007) Apart from Cubic Technologies, Irish company Mcor technologies Ltd. is offering particular type of LOM technology called Selective Deposition Lamination (SDL). SDL is a paper based technology with coloring feature in the print, hence producing multicolor 3D printed objects. (Technologies M. , 2013)

SD300 is a desktop 3D printer with LOM technology that costs around $15000 from Cubic Technologies.

Figure 11. SD 300 3D printer (Technologies C. , 2007)

2.3 3D Printing Materials

To complete the 3D printing process, printing materials are mandatory requirement. Materials in additive printing technology or 3D printing has direct impact over the final outcome. Each and every 3D printing technology process material through external energy sources such as heat, light, laser, electricity and other directed energies. The quality of final 3D printed object is the materials' mechanical and chemical composition along with better combination with the energy applied. The compatibility of the material with the energy source and technology further enhances and explores next stage towards development of 3D printing industry. Advancing technologies allows and encourages more positive material adaption towards development in 3D manufacturing. As the build process continues with new improvement, the selection of material widens as well.

The 3D printing materials are available in various material types along with their different states. In order to achieve fine result, material types and properties are precisely developed to adapt the process. Materials are used as powder, resin, pellets, granules required as per the printing process. With the rapid development of 3D manufacturing technology, more advanced materials are developed and new applications are emerging. The most popular and used 3D printing materials are described below. (Shapeways, 2016)

Plastics

As plastics products are everywhere and used almost every time, current generation need no explanation. Nylon also called Polyamide is the most commonly used plastic material. Because of its durability, flexibility and strong character, nylon is used commonly in powder form. Nylon is perfect all-rounder and allows for fully functional end products.

ABS is another strong plastic material used for 3D printing. ABS provides high strength with high temperature resistance. It has shock absorption feature with high impact resistance.

Polypropylene is tough, flexible and durable. Fine detailed model with smooth surface enables building precision prototypes.

Biodegradable plastic, Polylactic acid (PLA) is mostly used in filament form. (Solutions P. , 2016)

Metals

Steel is one of the strongest metal used in powder form. Other common metal elements are aluminum, bronze and cobalt chromium. Metals are mostly used in Selective Laser Sintering (SLS), Selective Laser Melting (SLM) process and Electron Beam Melting (EBM) process. (Industry 3. , 2016)

Ceramics

Ceramics are not so commonly used and new group to materials. They are unique material with the possibilities of creating smooth surface texture and geometry. (Industry 3. , 2016)

Paper

Laminated Object Manufacturing technology uses paper as one of the material to print 3D body. As paper are inexpensive, safe, eco-friendly and recyclable, they are mostly applied in prototyping rather than production. (Industry 3. , 2016)

Food

Food 3D printing is the latest trend in additive manufacturing field. Chocolate is the most commonly used material for designing and printing eye watering models. Mmuse-Delta Model Desktop Food 3D Printer prints pancakes, chocolates and candies of desired model. (Store, 2016)

Other materials

We know strength is the main property of a material. In some cases strength is not all what we expect, flexibility of a material helps decreasing stress and absorb shock. NinjaFlex is an advanced material developed by NinjaTek Company. NinjaFlex is extruded urethane filament offering from 500% to 1000% of elongation. (Tek, 2016)

Another product from Stratasys named Ultem is a polytherimide having tensile strength of about 16.5 kilo pound per square inch (ksi) and glass transition temperature of 422 degree Fahrenheit. (Stratasys, Stratasys, 2016) Graphene filament helps to develop conductive materials such as electric circuits.

2.4 3D printing Application

The technology of 3D printing has broaden its limit from aerospace design to health care, industry to space and daily hold to advanced high tech products. The diagram below represents some of the major fields involving 3D printing technology.

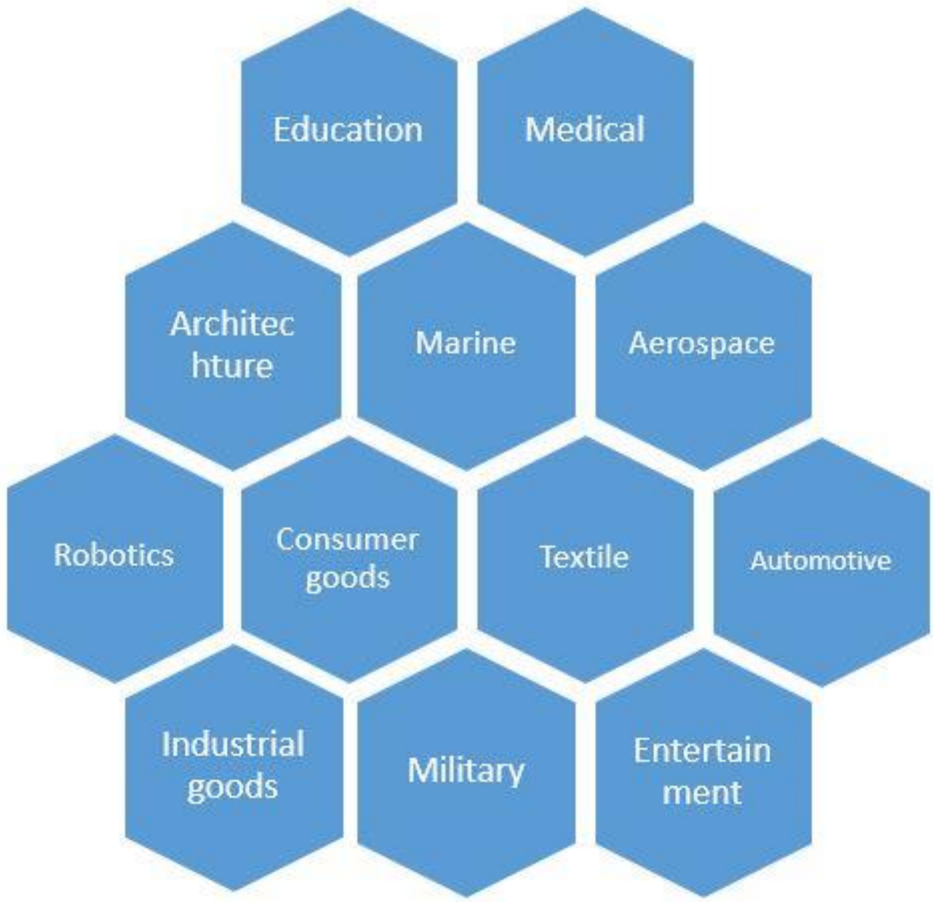


Figure 12. Application Areas of 3D Printing

2.4.1 Education

Learning is always easier and effective with right tools. Nowadays most of the educational institutes have 3D printing machine in their lab. Different company offers affordable desktop 3D printers and are easily available in the market. The curriculum incorporated with 3D printer inside the classroom helps students prepare for success in the field of engineering. It allows student to understand how easily one can transform 3D file to complete 3D model. Allowing yourself to physically manipulate and test complex ideas and visually transform them into complete functioning body provides new dimension to the educational experience, also brings the professional experience inside classroom.

Students can boost their career opportunities by targeting potential employers' product building inside classroom. Our school Arcada University of Applied Sciences also has 3D printing lab with multiple 3D printing machine.

In 2013, University of Alabama-Huntsville students designed 3D printed fire sensor that mounts to unmanned helicopter designed to detect forest fires and even gunshots in remote forest areas. (Technologies J. , 2011)

2.4.2 Medical Field

A Scot girl named Hayley Fraser rom Inverness was born without fully-formed fingers on her left hand. She is thought to be the first child in UK to have prosthetic hand made from 3D printing technology. In 2014, her parents David and Zania Fraser designed pink hand for their daughter with help of US-base E-nable, which is network of volunteers who design and develop prosthetic limbs for children. 3D printing continues to transform manufacturing world and doctors are more hopeful that it could help 30 million people worldwide who are in need of artificial limbs and braces.

Figure 13. Hayley Fraser without and with 3D printed hand (News, 2014)

The medical materials created using 3D printer provides excellent visualization and smart dimensional stability. The ability to develop fully working medical parts overnight that are ready for clinical trials helps doctors and researchers to predetermine best possible outcome. Some of the medical devices can be very small in size with complex geometry which is indeed difficult to produce. In this scenario, 3D printing allows manufactures to easily design and create best fitting durable parts with exceptionally fine details and outstanding surface finish.

US Food and Drug Administration (FDA) is responsible for protecting public health by ensuring and regulating drugs, biological products, medical supplies, food supply, cosmetics and many others. Table 1 shows some of the 3D printed products and their approval year by FDA. There are about FDA approved 85 medical products. (society, 2016)

Table 1. 3D printed products approved by Food and Drug Administration (Administration, 2016)

FDA Approval year	Product	Manufacturer
2013	3D printed polymeric cranial device implant	Oxford Performance Materials Inc.
2013	Cranial bone void filler	Tissue Regeneration Systems
2013	Triathlon titanium tibial baseplate, for knee arthroplasty	Stryker Corporation
2014	3D printed denture base	DENTCA
2014	Polymeric implant for facial indications	Oxford Performance Materials Inc.
2015	Spritam (leveriracetam), prescription pill for epilepsy	Aprecia Pharmaceuticals

2.4.3 Aeronautics and Aerospace

With the evolution and rapid development in aerospace sector, the aeronautics and Aerospace industries are focusing more on design optimization. Optimization process is challenging specially in aerospace sector because of geometric design and complexity. Also parallel helpful as well since it saves time, material and cost. 3D printing process allows manufacturers to design and build complex shapes which is challenging and time consuming when using traditional manufacturing process. (Sculpteo, Mastering Aeronautics and Aerospace prototyping, 2016)

Czech Aircraft Company, Evektor which is focused on designing lightweight aircraft along with parts for automotive and consumer equipment, uses Dimension 3D printer as part of its internal design function and Fortus 900mc, both from Stratasys. A case study shows that Evektor saved up to 80% of prototyping and production cost using Fortus 900mc 3D printer. (Technologies J. , Aerospace, 2016)

3D printing for aerospace and aeronautics accelerates the development cycle significantly. Traditional CNC production process is expensive and replacing with 3D printing dramatically reduces production cost and time. Production grade thermoplastics are the ideal solution for aerospace industry with its lightweight and intense flame retardant capability.

2.4.4 Architecture

By developing complex, durable models of buildings and other structures, 3D printing technology helps clients to better visualize the design. The concept of customer details can be visually transformed and represented in order to win customers' attention. With the help of this technology expense and time in producing building model reduce significantly.

In 2015 June, A Chinese company named Winsun, successfully built five-storey building and 1,100 square meter villa using 3D printer. (Cnet, 2015) In 2016, Vice President and

Prime Minister of United Arab Emirates and Ruler of Dubai His Highness Sheikh Mohammad bin Rashid Al Maktoum inaugurated world's first 3D printed office located on Emirates tower premises. (Dubai, 2016)

Those examples of 3D printed office buildings showcases modern model of construction and utilization of future technology in people lives.

2.4.5 Automotive

With the help of rapid prototyping, prototyping of any product can be shortened from months to days. This helps to shorten the production development time and improves final product by increasing number of iterations. Automotive engineers can work more iteratively, test more thoroughly in order to get accurate output and confidence during production process. 3D production printer reduces cost by replacing expensive time consuming CNC-milled parts. Ergonomically designed assembly parts performs better technically and provides eye catching interiors. To keep their system at forefront of engine design, Sports car maker Koenigsegg and Motorcycle maker Ducati rely on this technology to develop accurate and durable prototypes quickly. (Stratasys, Compressing the design cycle of Ducati, 2013) Design plays the important role in the field of automotive industry. There is no limitation in complex geometries hence this technology allows designer to unleash their creativity and carve their concept. With lighter and stronger parts, designs are improving. The customization using 3D printing is unlimited, any virtual products can be easily turned into reality. Wherever the printer is located or available, any number of parts can be printed easily. This means there is no need to produce large number of parts at once and store them. Parts can be created directly whenever required. Spare parts can simply be stored as digital 3D file and can be printed on demand.

Automaker Honda revealed tiny single seater electric car during CEATEC 2016, a Japanese consumer electronics show. As the tiny car is just a prototype, the whole body is almost entirely made up of 3D printed panels. (Pattni, 2016)

Figure 14. 3D printed Honda electric car (Pattni, 2016)

2.4.6 Consumer goods and electronics

We are often forced to choose the products that has been offered by the retailers. Sometimes it can be frustrating to find and use similar product every time.

3D printing technology offers fully customization of products as requirement by the customers which is win-win situation for both. Creativity and innovation speeds up with the right tool and 3D printing offers flexibility and speed while developing new hardware and consumer products.

Professional 3D printers allows to create high quality products such as casing for electronic devices, bottle openers and other spare parts for household items with the choice of color and dimensions. (Technologies J. , Consumer Goods, 2016)

2.4.7 Military and Defense

A UK bases company, Design reality developed prototype of gas mask respirators for UK Ministry of Defense and US Fire Services. The company uses Object260 Connex1 multi-material 3D printer from Stratasys, which takes up only a tiny space inside office. Replacing much larger space area and complex CNC milling process, this printing technology reduces 5-6 days of prototyping process to few hours. (Stratasys, 3D Printing, 2013)

As explained above about application areas of 3D printing technology, military sector has also benefitted more and expanding its area. Similar to other industries, 3D printing allows military and defense industry the freedom to design and create end use part, low volume tooling, complex geometry yet precise prototypes. Military and defense products needs to be fully reliable and effective in order to insure the safety standard. More prototyping and functional testing is required to evaluate whether a part will function precisely as intended.

Texas based company, Solid Concepts manufactured fully assembled 3D printed functional Model 1911 automatic pistol using Laser Sintering Technology (LST). (Szondy, 2013)

In 2013 December, British fighter jets flew for the first time using parts made from 3D printing. Components including protecting covers for cockpit radio and guards for power take-off shafts, were manufactured by company using 3D printer. (Kharpal, 2014)

2.4.8 3D printing in Space

The first version of 3D Printer was launched into orbit on September 21, 2014. Zero-G printer, which is designed to operate in zero gravity condition. The printer was built under a joint partnership between NASA MSFC and Made In Space. (MadeInSpace, 2015)

Daily life aboard the International Space Station is challenging. Because of gravitational condition limits of technology are pushed beyond expectation. Astronauts on the Space Station often maintain and repair equipment themselves and there is always chances of not having proper tools. As transporting tools and parts from earth is not easier and quicker option. 3D printer comes handy during those situation. It is believed that approximately 30 percent of the parts on the Space station by 3D printer.

Made in Space partnered with Low’s Innovation Lab to launch first commercial printer to space. The printer was installed this year, 2016 with an idea of providing tools to space and technology towards earth. (Lowe'sInovationLabs, 2016)

Figure 15. First 3D printed wrench in space (Lowe'sInovationLabs, 2016)

Why 3D printing In Space?

- Creating parts and tools that are broken or lost.
- Minimizing cost of launching tools in space.
- Recycling of parts.
- Enables product manufacturing in space.

2.5 4D Printing Technology

It has been more than 30 years since the first patent was issued for Stereolithography Apparatus (SLA), invented by Charles (Chuck) Hall in 1980´s. Initially known as Rapid Prototyping technology, with further advancement now called additive manufacturing or 3D printing technology. (Industry 3. , 2014) Nowadays, 3D printing machine is used not just in industry for production but also in school, households and offices. As the price for normal desktop 3D printer has fallen below 1000 euro, affordable price allows unlimited opportunities for individual to print their own customized toys, household appliances and tools.

However, there is always something more than can be done with the current ongoing technology. 3D printed materials can be more flexible and useful, the structures of the material can transform in a pre-programmed way in response to any external stimulus. In general, self-changing structure of 3D printed part after post process is called 4D printing process. (Stratasys, 4D Printing, 2014)

The term 4D printing is developed in a collaboration between MIT´s Self-Assembly Lab and Stratasys education and R&D department. In February 2013, Skylar Tibbits, co-director and founder of the Self-Assembly Lab located at MIT´s International Design Center, unveiled the technology “4D printing” during a talk at TED conference held in Long Beach, California. (TED, 2013) 4D technology is still in the early phase of research and development. This technology has been used only in few labs or prototyping facilities. In current scenario, one can´t just order and buy “4D printer”. As of 2017, MIT´s Self-Assembly Lab, 3D printing manufacturer Stratasys and 3D software company Autodesk are the key players in the development of 4D printing technology.

2.5.1 Smart Materials

Global competition among technological giants and demand for new generation of industrial, commercial, medical, automotive and aerospace applications has fueled research and studies focused on advanced materials and smart structures. Researchers are developing ultimate materials which can be applied in multipurpose scientific and technological applications. Those smart materials or intelligent materials features fibrous polymeric composite materials capable of sensing external command in the form of heat, light, electricity, magnet, water and many other agents. Diverse application and structures of smart materials will certainly revolutionize the current generation. Starting from wooden and stone materials from the Stone Age to copper followed by bronze and Iron Age, human mankind have developed a new age and we can call them Smart Material Age.

Human civilization has been directly influenced by materials technologies and those materials has given mankind to become superior among other living beings in this planet. The timeline of human civilization such as Stone Age, Bronze Age and Iron Age depicts the progress of materials choice and selection. The current synthetic materials featuring plastics and composites, biomaterials represents the new age of materials. Various innovation in diverse field of science including manufacturing, nanotechnology, material science, automation featuring smart materials sill significantly impose positive impact on civilization. The current generation of innovation has already seen some classes of materials such as executing specific functions autonomously in response to changing environmental stimuli, embedded sensory capabilities in order to comply with programmed shape.

Smart materials incorporates with actuators and sensors and are highly integrated within the structure functionality. Characteristics like signal conditioning, signal power amplification and highly integrated control logic in a materials are influenced by mechanical, thermal, optical, magnetic or electric source as shown in Table 2. Light influence smart materials are capable of changing its color, shape and mechanically smart materials are capable of altering mechanical states such as positon, velocity, stiffness or damping. The transition of laminated materials technology which are built up from smaller constitutive elements helps expanding the active element within the structure. Smart ply or piece of composite material can be developed with the capability of carrying actuators, sensors, processers and inter connections. The development of microelectronics, switching circuitry, fiber optic technology and information processing techniques has further advances evolution of smart materials. (Talbot, 2003) Table 2 represents classification of smart materials along with the input force they require and output.

Table 2. Classification of Smart Materials (Kamila, 2013)

Types	Input	Output
Piezoelectric	Mechanical stress	Potential difference
Electrostrictive	Electric field	Deformation
Magnetostrictive	Magnetic field	Deformation
Thermoelectric	Thermal energy	Deformation
Shape memory alloys	Thermal energ	Deformation
Photochromic	Radiation	Color change
Thermochromic	Thermal energy	Color change

Piezoelectric materials

Those materials capable of generating electric charge in response to applied mechanical stress are piezoelectric materials. Not all the smart materials do exhibit a shape change but they do carry significant properties such as electro and magneto theological fluids. Those fluids can change viscosity upon application of external magnetic or electric field. Naturally occurring crystals like quartz and sucrose, human bone, ceramics, Polyvinylidene fluoride (PVDF) are known to have piezoelectric characteristics. Followed by the automotive industry and medical instruments, global demand for these materials have huge application in industrial and manufacturing sector. (Liverpool, 2016)

Researchers from University of Warwick in UK have developed new microstereolithography (MSL) 3D printing technology that can be used to create piezoceramic object. Piezoceramics are special type of ceramic materials that can create electrical response and responds to external electrical stimulation by changing shape. These are very useful materials and applicable all around, sensor in airbag systems, fuel injectors in engines, electric cigarette lighter and electronic equipment. (Alec, 2016)

Light responsive self-changing materials

3D printing technology has a capability of printing objects with multitude of materials. However, these objects are usually fixed geometrically structured, static and not helpful for multifunctional use. 4D printing with light responsive smart material is effective and suitable because light is available easily to work, wireless source, easy control and light energy has ability to create rapid changes in material.

In order to continue with 4D printing process, it is really important to know about the smart materials and their behavior. The relationship between chemical composition of shape changing polymer and its physical properties such as thermal, mechanical, optical and electrical properties.

It is important to understand polymers composition and extrusion process parameter changes the mechanical properties of the object after extrusion process. Altering the extrusion parameters such as temperature, flow rate, cooling time and measuring its properties after extrusion process. The difference between the changes before and after extrusion needs to be analyzed properly.

To measure thermal and optical properties of polymer, processes like UV-Vis spectroscopy, differential scanning calorimetry, and polarizing light microscope are used. Using standard testing bar, stress/strain relationship and hardness measurement can be performed. As the main goal is to identify and study about shape changing behavior of material. Various external sources or energies are applied over the extruded object. Varying thermal energy, magnetic field, electricity, different levels of light intensity and exposing directly towards printed object changes the bending angle, speed, percentage volume contraction, reversibility and mechanical output. Those measuring data helps to gain knowledge in developing 4D printing process. (Org, 2016)

Shape Memory polymers

Shape memory alloy or polymers are emerging smart materials that have dual shape capability. Shape memory alloys go transformation under predefined shape from one to another when exposed to appropriate stimulus. Initially founded on thermal induced dual-shape research, this concept has been extended to other activating process such as direct thermal actuation or indirect actuation. The applications can be found in various areas of our everyday life. Heat shrinkable tubes, intelligent medical parts, self-deployable part in spacecraft are few used area with potential in broad other applications.

The process in shape memory polymer is not intrinsic, it requires combination of a polymer and programmed afterwards. The structure of polymer is deformed and put it into temporary shape. Whenever required, the polymer gains its final shape when external energy is applied. Most of the shape memory polymers required heat as activating agent.

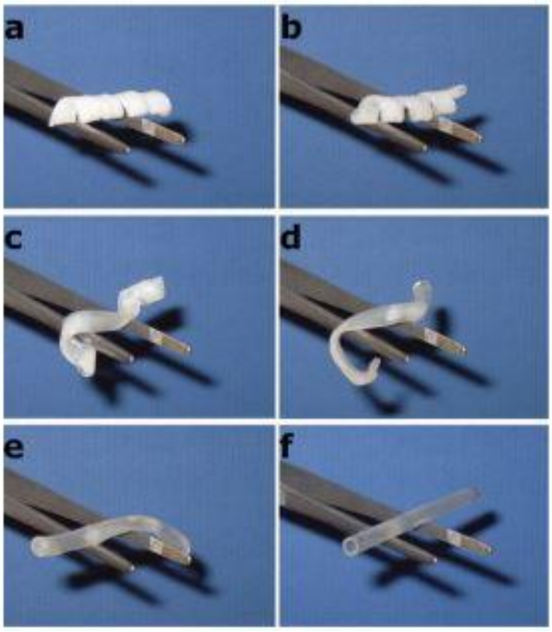


Figure 16. Time line of shape memory tube. (Marc Behl, 2007)

The above figure shows the time series of shape memory tube. The material used in tube is poly dimethacylate polymer. Initially the shape was programmed to form flat helix, using heat energy ranging from 10 degree to 50 degree centigrade, flat helix transformed into tube shape structure.

Magnetostrictive Materials

Similar to piezoelectric and electrostrictive materials magnetostrictive materials uses magnetic energy. They convert magnetic energy into mechanical energy or other way. Iron, terbium, Naval Ordnance Laboratory (NOL) and dysprosium (D) are most common magnetostrictive materials. Those materials can be used as transducers and actuators where magnetic energy is used to cause shape change. The application include telephone receivers, oscillators, sonar scanning, hearing head, damping systems and positioning equipment. The development of magnetostrictive material alloys with better features will certainly help the 4D printing technology. (Talbot, 2003)

2.5.2 4D Printing Process

When Skyalar Tibbits introduced 4D printing technology in 2013, the demonstration of structure folded with only 90 degree transformation and activated when printed specimen was immersed in water. Similar researches were demonstrated with the composite printed materials stretching upon heat activation, light activated materials and electrically activated materials. As the progress is still going on, there still more needed in universality in folding from one shape to another. Further improvement is needed to take control over autonomous transformation rather than human guided energy source.

A major challenge for 4D printing technology is design structure including both hardware section and software section. In order to design hardware part, special measures needs to be addressed. Since, this requires complex and advanced material programming, precise multi-material printing, designing complex joints for folding, expansion, contraction, curling, twisting process. Software section is even challenging that cooperates with hardware design. Sophisticated simulation, material optimization and topology transformation are few of the challenges for software part. Following explanation demonstrates structural transformation regarding its joint angle, folding, curling and bending. (Thomas A. Campbell, 2014)

Fabrication

As the printer deposits UV curable polymer and cures layer by layer using UV light thereby creating complete 3D structure, printers are capable of printing multiple composite materials with various properties such as color pattern, material hardness and transparency allowing creation of complex, multiple composite parts in single process. Digital materials can be printed with this process. The properties can be digitally adjusted and altered with the digital material. The combination of digital material with different proportion and spatial arrangements plays significant role providing additional flexibility. 4D printed parts are generally composed of rigid plastic and digital material that reacts upon external energy source. In case of hydrophilic UV curable polymer, when exposed to water, the structure absorbs and creates hydrogel with upto 150 percentage of original volume. The shape transformation of the structure is linear in this case, but when the polymer structure is combined with different composite material that reacts differently with water, complex geometric transformation occurs. Transformation can be controlled by adjusting pure expandable polymer with digital composite material as per requirement. (Thomas A. Campbell, 2014)

Joint and folding angle strands

For any bending or folding structure, joint plays important role as controlling of joints adjusts the desired shape of structure.

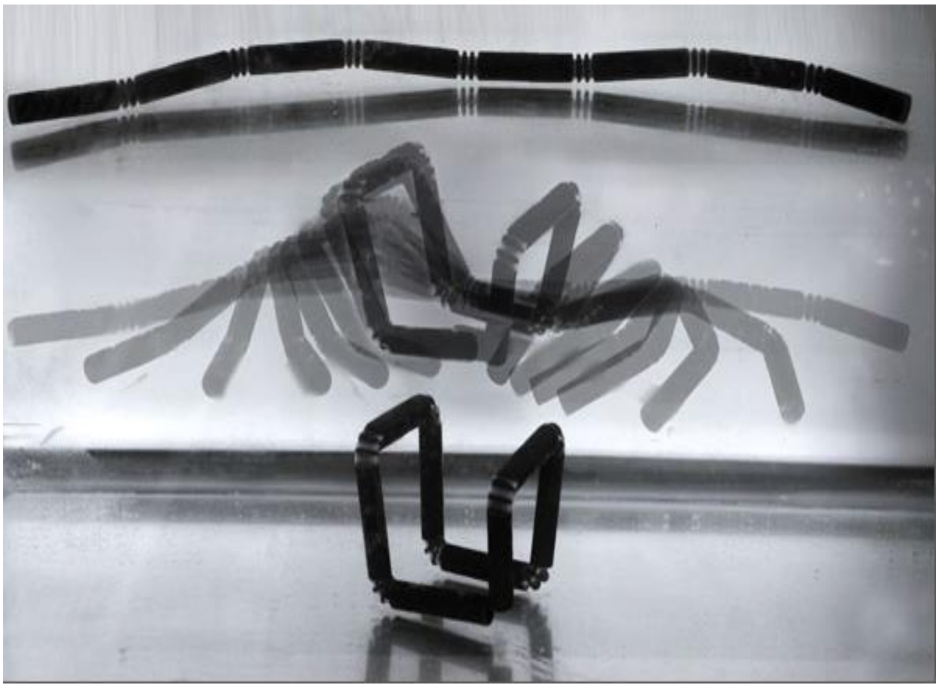


Figure 17. Self-Folding Strand (Self-Assembly Lab, 2016)

Printing 4D joint includes multiple layers of material. Composition of rigid polymer, expanding material and digital material depicts the folding direction and pattern. Those materials are placed above or below of each other depending upon the type of transformation.

If the expanding composite is placed above rigid polymer, the surface will fold downwards and if placed below, the surface will fold upwards. This folding happens due to downward or upward force applied to rigid material. With the digital polymer composite, the control of folding the joints becomes much desirable. The time duration of folding depends upon the expandable material or digital material. If higher expanding composite is used, there will be more folding force increasing folding time. Similarly, less expanding composite will generate less folding force thereby decreasing folding time. The angle of folding can be controlled by printing rigid discs at each vertex. The distance between rigid disc and diameter of disc defines angular variation. Those discs bumps each other when expanding material is activated and stops folding at certain angle. The angle of folding is determined by the distance of rigid disc and its diameter. When the discs are placed further away from each another, angle of folding will increase and when discs are place close to each other, folding angle decreases. Also the increasing diameter of discs decreases the folding angle and vice versa. (Self-Assembly Lab, 2016)

Custom Angle Surfaces

In his research, Skyler Tibbits demonstrated custom angle transformation creating truncated octahedron shape. Similar mechanism as folding strand described previously, series of flat two dimensional structures were generated with edge joints. The position and spacing of materials at each joint specifies the desired fold angle hence positioned accordingly. In such case, folding accuracy can be monitored with the help of code producing custom angle joints and accommodation of date from calibration test. After the digital model was sent to be printed, physical model was immersed in water. The transformation process occurred within certain time with the final desired model having edges aligned perfectly aligned with neighboring edges. With this technique, a two dimensional polyhedral shape was folded and self-transformed into precise three dimensional structure.

Figure 18. Self-Folding Truncated Octahedron (Self-Assembly Lab, 2016)

The advantage of this process includes efficiencies of printing flat shape with quick printing time and minimal resources used. If the final model were to be printed directly, it would have taken longer time consuming more support materials. On the long run, this technology can be effective for logistics operation where flat surface material can be created, shipped and self-transformed into three dimensional structure when required. (Self-Assembly Lab, 2016)

Curved surface Folding

Curved surface folding mechanism is based upon a technique called curved-crease origami, where two dimensional flat sheets are folded along curved creases forming double curved surface with mountain and valley shaped linear pattern. (Figuring, 2016) This mechanism can be further explained with the example of concentric circles made of expanding polymers separated by rigid or less expanding polymer. The position of expanding polymer above or below rigid polymer in each circle with the ring being neutral, creates mountain and valley folds. When the design print is placed in water, after certain time period, the structure transforms itself from two dimensional crease to doubly curved structure. (Erik Demaine, 2016)

Figure 19. Curved-Crease Origami (Self-Assembly Lab, 2016)

Surface Curling

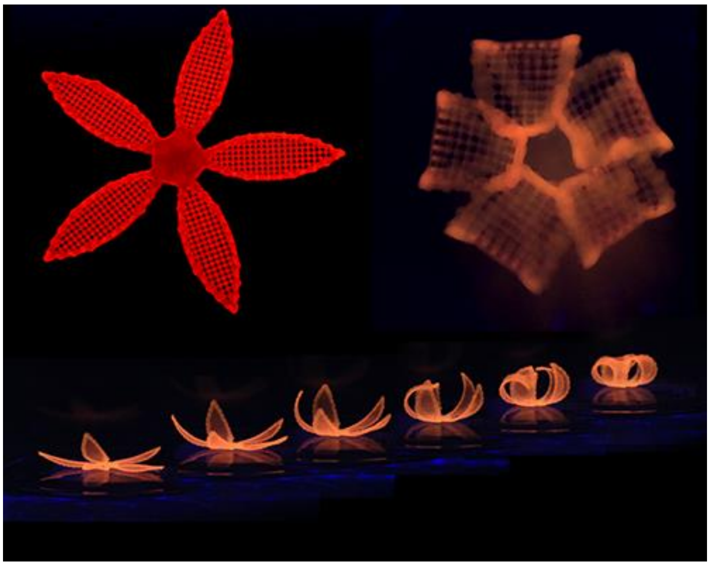
Rather than joints, edger or curve crease folding, similar mechanism can be applied to perform surface curling. With the gradient of material deposition, continuous surface can be achieved. Instead of using expanding material only in the joints or folding section, larger expanding polymer can be used with thin surface in order to have even expansion force. The curling effect is much more visible with increasing length and breadth of surface. Placing expanding material over the top of rigid material gives curved surface with smaller radius towards the rigid surface, similarly placing expanding material below the rigid material results reverse effect. Since there are not any joints and discs for folding process, the quantity of the material distribution and positioning is extremely important for maximum precision. (Thomas A. Campbell, 2014)

2.5.3 4D printing example: Orchid transformation when immersed in water

A team of scientists at Wyss Institute at Harvard University and the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) has developed their microscale three dimensional printing technology to create transformable structure. This method was inspired by natural structures like plants, which reacts and changes their behavior over time according to external environmental stimuli such as water, heat and moisture. In order to process the technology, the team developed 4D printed hydrogel composite structure that changes its shape upon immersion in water as shown in Figure 20. Newly developed hydrogel composite consists of cellulose fibrils derived from wood and their microstructure are similar to the plants that enables shape changes. In general, when the three dimensional composite structure is immersed in water, it swells into certain pattern as programmed. (WYSS Institute, 2016)

Hydrogel cellulose fibril has anisotropic nature which means upon exposed to water, it undergoes different swelling behavior which can be predicted and controlled. To achieve transformable shapes, hydrogel composite needs to be programmed with precise and swelling behavior.

The composite material is liquid state matter that flows through print head and solidifies rapidly once it is printed. Different hydrogel components can be used to achieve different stimuli-responsive characteristics. Conductive fillers, cellulose fillers can be replaced with other anisotropic fillers. This advancement in 4D printing field enables shape changes from the available materials with potential application, establishing new platform for self-assembling structure.



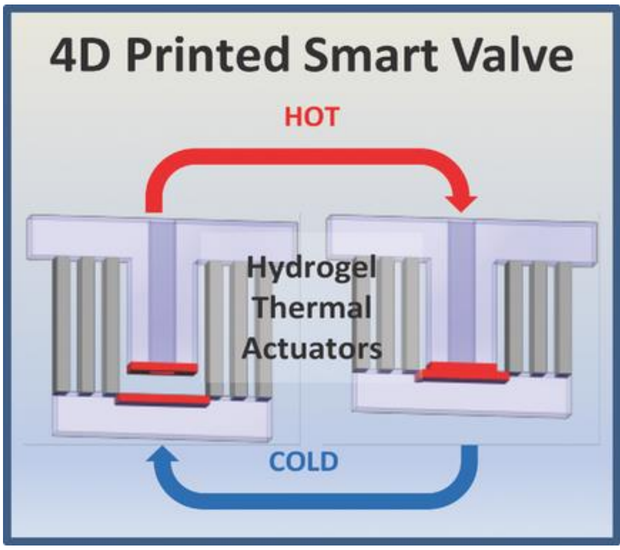


Figure 20. Transformation of 4D printed orchid and Smart Valve (WYSS Institute, 2016) (Shannon E. Bakarich, 2015)

Similar printing technology has been unveiled by researchers at University of Wollongong, Australia. A 4D printed temperature responsive valve shown in figure 20 was designed by combining active hydrogels and three dimensional printing. The hydrogels are made up of alginate and poly (N-isopropyl acrylamide), which are thermally sensitive and expand in volume when heated. This mechanically robust valve expands upon exposure to hot water, subsequently blocking the water flow and closes itself upon flow of cold water. (Shannon E. Bakarich, 2015)

2.6 Application Area and Future Development

4D printing technology has the potential to change the current business environment. Future advancement of this mechanism depends and remains focused on variety of capabilities. For example, current process that allows 4D printed structure to expand when exposed to water and when structure is allowed to dry, it tends to unfold and regain its original shape. However, when similar process is repeated again and again, the material degrades over time and process is not infinitely repeatable. To control directionality and reversibility process, further research and development need to be conducted. This development points towards changing future of education and science. With the study of existing self-changing structures and models, new experiment with new material properties and functional behaviors can be tested.

The self-changing ability of material leads to range of applications in various industries. It is essential for any business to reduce manufacturing cost and increase profit to stay in fierce competitive environment. The concept of 4D printing technology along with 3D printing provides platform for new business ideas that can adapt and compete current market trend by lowering capital requirement, time efficient, less space for holding inventory and increasing efficiency of the business. 4D printing promotes maintaining sustainable environment as the self-transforming capability of 4D printed item allows after use disposition, changing back to original shape.

2.6.1 Medical Research

University of Michigan developed a 3D printed stint that gets absorbed into the body over time. For the patient with weak cartilage in walls of bronchial tubes, the stint was used to open airways for two or three years, which is enough time for bronchial cartilage to form back to the shape. This biomedical splint which was printed using 3D printing technology changes shape and conform over time as the body moves or grows. There has been successful implants of those 4D printed structure, which needs to be biocompatible with patient's immune system and able to adapt the external surrounding tissues within the body.

The process started with virtual model of trachea through CT scan of patient and designing model of virtual stint with medical imaging software called Mimics. Polycaprolactone (PCL), a biomaterial was used to print the stint with the help of Formiga P100 3D printer. (Mearian, 2016)

Most likely, upcoming future of 4D printing technology will include all types of implants and reconstructive surgery. Beyond helping patients with respiratory issues, researchers are exploring their use to correct human skeletal deformation such as facial reconstruction, rebuilding ears.

2.6.2 Aeronautics and Robotics

MIT Research Scientist Skylar Tibbits and Emerging Technology and Concept team from Airbus collaborated together to develop special air inlet component. This collaboration with Airbus developed new air inlet which adjusts automatically to control air flow which is used to cool the engine. As the current air ventilation inlets are static and air flow varies with speed of an airplane. (Group A. , 2016)

Designing roots requires ability to develop responsive and highly sensitive parts. 4D printing will allow those machineries far more advanced adaptive and dynamic ability to perform complex task effectively.

A team of researchers at MIT and Harvard University developed origami robots, which is reconfigurable robots capable of folding themselves into arbitrary shapes and crawling away. The prototype robot was made up of printable parts entirely. (Hardesty, 2014)

2.6.3 Military applications

Programmable matter will have a vast application areas in military sector. US army and Navy are developing three dimensional printed spare parts in the field and developing programmable elements that forms into full building with all the necessary components such as electricity, plumbing and other technical structures. (Laskar, 2017)

As the technology allows the materials to change its shape, military equipment, cars and fabrics could enable them to alter its camouflage. Military advancements with 4D printing technology would develop coating material in automobile that changes its structure to cope with humid environment and corrosion. Similarly, transformation of tires depending upon road and weather condition.

In 2013, US Army Research Office granted $855,000 to researchers at three universities, Harvard's School of Engineering and Applied Science, The University of Illinois and The University of Pittsburgh Swanson School of Engineering. (Sokol, 2013)

2.6.4 Furniture and House appliances

People are much more familiar with IKEA furniture which comes in parts and packed. It takes lots of time and effort for normal customer to assemble and make ready. However, one could imagine the relief when those flat packaged furniture self assembles and the furniture is ready to use without any hassle. Similarly, self-disassembling of furniture while moving from one location is comforting. Along with the time saving, it could help people get rid of complex assembling process and mistakes.

2.6.5 Fashion

The idea of clothes and trainers adjusting their shape and function in response to external environment and comforting the user, sounds fascinating. Fitting perfectly upon pressure being applied or gears becoming water proof itself when raining.

Massachusetts based design studio Nervous System have developed 4D printed wearable which is composed of thousands of unique interlocking component and the dress responds to the wearer's body. (Designboom, 2014)

Experiments involving 4D printing have been few and limited to the date as there are only few major players actively in the field of research. Nevertheless, this technology has been taken seriously because of its constructive and disruptive capability. As the incoming of wide ranges of technologies, new programmable materials, software and design tools, 4D printing mechanism certainly has the potential to become magical and opening new possibilities that were assumed science fiction and seen only in movies.

These technology can be formulated into action for manufacturing and construction idea at extremely large scale and complex environments. Printing small materials and transforming into gigantic shapes in extreme locations such as radiation zone, deep trench, space, war zone. Building materials that are capable of adjusting fluctuating environment, self-healing, maximum shock absorption and mediating moisture, sound, pressure, temperature varying the thickness.

A good example of the potentially inevitable revolution of 4D printing in the field of construction can be smart water pipes, which have the ability to adjust and assemble themselves as per the changing water pressure and temperature. As the pipes adapts and adjust independently, no need of any digging preventing internal damages, this mechanism will help in easy and cost effective maintenance.

3 METHOD

Any emerging technology brings changes both positive and negative. Despite carrying profound implications for construction, industry, military and medical field, the benefits of 3D and 4D printing technology remain offset by many technical and legal challenges. There are concerned areas need to be addressed including design certification and standardization, environmental friendly and sustainable development, patenting and intellectual property law. Since the processes involved in both technologies are very much similar, certain rules and regulations while adopting these technologies remains considerably identical. Along with the benefits, risks including ethical implications, public safety and intellectual property rights need to be handled properly. (Al-Rodhan, 2014)

3.1 SWOT analysis of 3D Printing Technology

A SWOT analysis is carried out for any company, person or product. This process involves specifying objective of any project identifying internal and external factor that are suitable and unsuitable to achieve project goal. Similarly for 3D printing technology, SWOT analysis as shown in Table 3 specifies internal positive and negative factors as well as external positive and negative factors.

Table 1. SWOT analysis of 3D printing

STRENGTHS (internal factors, positive)	WEAKNESS (internal factors, negative)
Low cost Available for all Positive market growth Efficiency of manufacturing process Easy to build custom model High product quality	Some machines are expensive Printing hours are longer i.e. production time Quality differs with the printers used Learning to use of machine and software Create and solve your problem yourself May need post processing Problems printing with smaller details and larger product Material selection limitation Requires controlled environment
OPPORTUNITIES (external factors, positive)	THREATS (external factors, negative)
Customization of existing design Active material development -Recycled plastic garbage -Printing with materials rather than plastic (metals, ceramics, wood, leather, textile) -Smart materials Introduction of advanced machine -High speed and resolution -Multi color print -Multi material print -Printing of micro details -Printing extra-large products 4D printing technology	Machine compatibility and upgrade Public safety Impact on environment Intellectual property rights -Copyright -Patent -Trademark Software problems, hacking & cracking Ethical issues Competitive industry, need to be constantly improving Threat to traditional workforce

3.2 SWOT analysis of 4D Printing Technology

Similar to the SWOT analysis of 3D printing technology as in Table 3, the analysis of 4D printing is useful to identify strengths, weakness, opportunities and threats related components shown in Table 4, for 4D printing technology.

Table 2. SWOT analysis of 4D printing

STRENGTHS (internal factors, positive)	WEAKNESS (internal factors, negative)
Efficiency of material and manufacturing process Positive market growth forecast Multi-color print Multi material print Time efficient Smart material (programmable material) Based upon multi-material 3D printing	New technology in the field of 3D printing Expensive smart material and limited Expensive hardware (printer) that may restrict public from using it Accuracy in shape change, complex shapes Requires specialized personnel and controlled environment
OPPORTUNITIES (external factors, positive)	THREATS (external factors, negative)
Helps logistic problems, transportation Helpful in extreme places i.e. war zone, space Useful for implants in medical field Concept of smart city, buildings & structures 5D printing	Machine compatibility Public safety and health problems Impact on environment Intellectual property rights -copyright, patent, trademark System vulnerable to software hack, piracy Ethical issues

3.3 Comparing global 3D printing market versus 4D printing market

3.3.1 3D printing market analysis

According to Marketsandmarkets, a firm that provides market research reports, 3D printing market is expected to reach 30.19 Billion USD by 2022, at a compound annual growth of 28.5% shown in figure 21.

The market has been analyzed on the basis of printer, software, process, application and geographical location. With the industrial field expecting to take more credits on adopting 3D printing technology, aerospace, defense, health care and consumer products are accounted to hold major share of 3D printing. In 2015, global 3D printing market value was about USD 4.98 billion and North America dominating the market followed by Europe and Asia Pacific. The driving force behind the market growth are supposed to be the benefits of 3D printing, customized goods and government/private investment. (Marketsandmarkets, 2016)

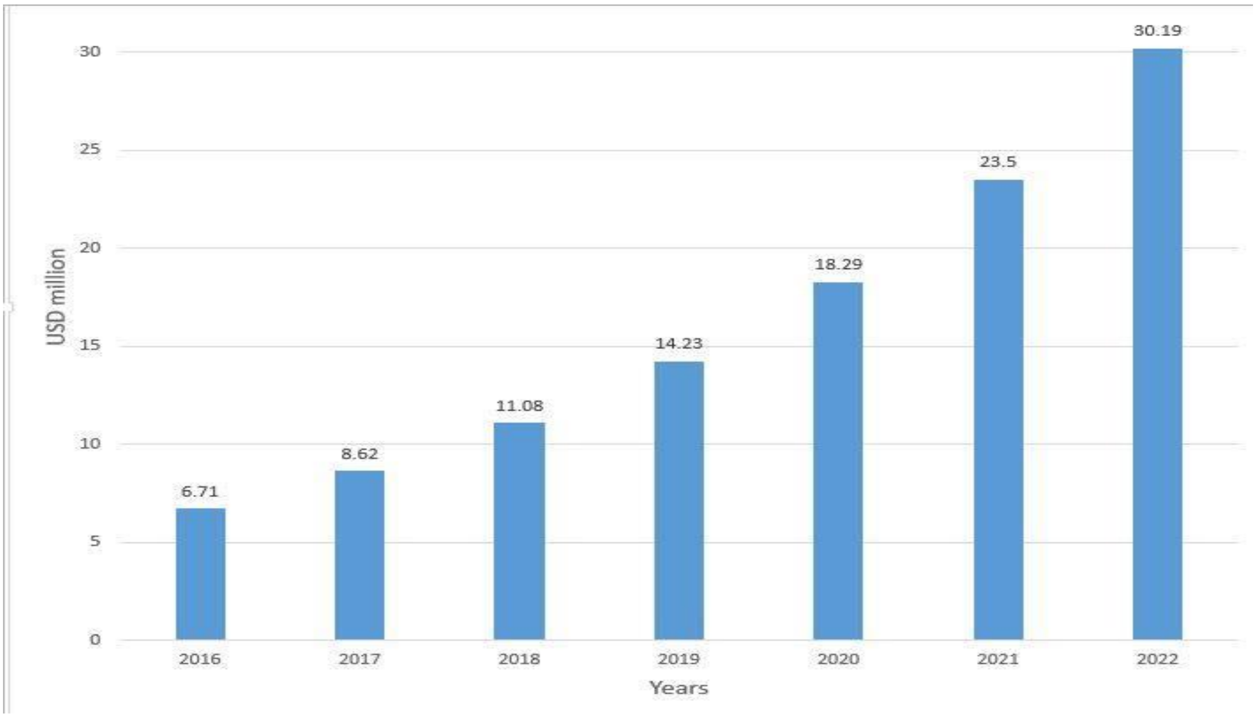


Figure 21. Chart showing 3D printing market (Marketsandmarkets, 2016)

The graph shown in Figure 21 is generated with the given compound annual growth rate of 28.5% and estimated market size of 30.19 billion USD in 2022.

Stratasys Ltd., is one the leading global provider of 3D printing solutions. Some other major companies are 3D systems Corporation (US), Arcam AB (Sweden), EnvisionTEC GmbH (Germany), Autodesk, Inc. (US), Voxeljet AG (Germany) and Concept Laser GmbH (Germany). (Marketsandmarkets, 2016)

3.3.2 4D Printing Market Analysis

Upon analyzing the trends in 4D printing market on the basis of programmable matter, end user industry and future scope, 4D printing market is expected to be commercialized by 2019. As the printing technology is in its initial developing phase, the global market is expected to grow with compound annual growth of 42.5% between 2019 and 2025 reaching USD 537.8 million as shown in Figure 22. As North America expected to hold the majority market size, market development will be driven by the necessity to reduce manufacturing cost, logistic problems and secure sustainable development. Similar to 3D printing technology, 4D printing industry will have major impact into aerospace, military and defense, healthcare, automotive, clothing and construction sector. (Marketsandmarkets, 2016)

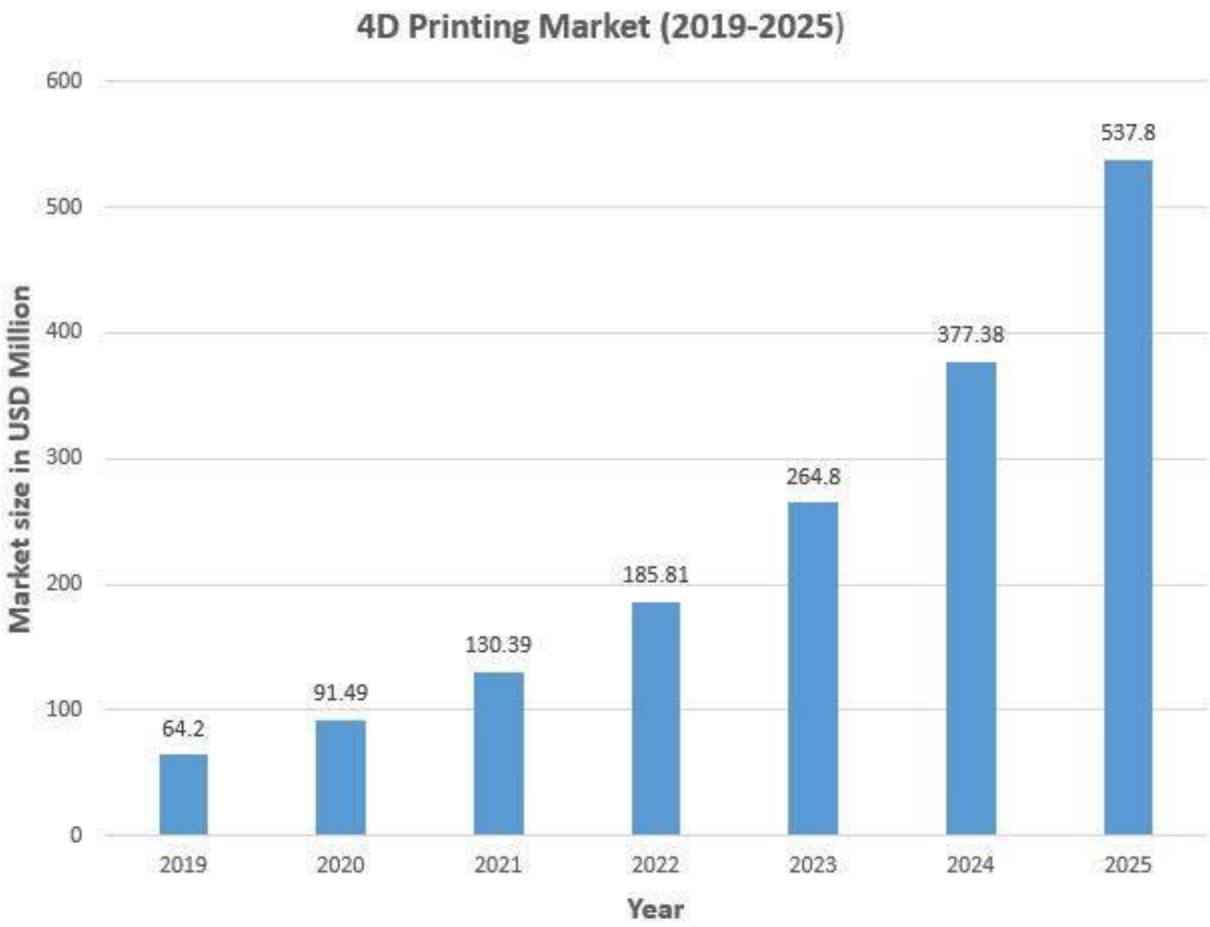


Figure 22. Graph showing 4D printing market (Marketsandmarkets, 2016)

Current key players in 4D printing industry are Stratasys Ltd. (US), Autodesk, inc. (US), HP Corp. (US), ExOne Co. (US), Dassault Systemes SA (France). (Marketsandmarkets, 2016)

3.4 Comparing desktop 3D Printers versus 4D Printer

The following Table 5 shows the comparison between available 3D printers. The brand of printer has been chosen randomly from the website of developer. The table section represents brand of printer, type, build, thickness, speed, filament diameter, price and rating respectively. Based upon user review regarding print quality, ease of use, reliability, failure rate, customer service, price and software, rating of each device is listed at the end of row. Rating 10 being top product to rating 1 as the least performing product, there are few missing information about printing speed. The main reason of comparing different printers is to specify printer types along the technology they rely, analyzing the printing quality and speed as well the price of the printer in the market. This provides better visual specification for individual choose suitable and effective printer.

Table 3. Comparing 3D printers and 4D printer (3Dhubs, 2017) (Aniwaa, 2014), (Stratasys, Overview: Objet260 Connex3 Color and multi-material 3D printing, 2014)

Printer Name	Type	Build volume (cubic cm)	Min layer height (micron)	Speed	Filament diameter (mm)	Price (USD)	Rating (out of 10)
Makegear M2	FDM	25.4*20.3*20.3	25	80-200 mm/s	1.75	1,825	9.2
Ultimaker 2+	FDM	22.3*22.3*20.5	20	30-100 mm/s	2.85	2,499	8.4
Form2	SLA	14.5*14.5*17.5	25	1-3cm/h		3,299	9.0
Monoprice MP Select	FDM	12*12*12	100	55 mm/s	1.75	220	7
ProX 950	SLA	150*75*55	25	-	-	200,000	8
EOS P 396	SLS	34*34*60	106	48mm/h	-	250,000	8.2
Sharebot SnowWhite	SLS	10*10*10	50	25mm/h		10,000-50,000	7
Creator B9	DLP	20.32*10.24*7.68	5	12mm/h	-	4,595	8.1
ProMaker P1000	SLS	30*30*30	100	-	-	50,000-100,000	7.9
SLM 500	SLM	50*28*36.5	20	700mm/h	-	250,000	8.1
Arcam Q10puls	EBM	20*20*18	100	-	-	250,000	7
SD 300Pro	LOM	16*21*13.5	168	-	-	10,000	7
Object260 Connex3	4D	25.5*25.2*20	16	-	-	100,000-250,000	7

4 RESULTS

Comparing SWOT analysis of both 3D printing and 4D printing technology, it is clearer that 3D printing technology has advanced a lot than 4D printing. Nevertheless, 4D printing being new invention opens the door towards endless opportunities in the research field of printing.

Table 6 shows the rating out of 10, (10 being maximum score and 1 minimum score), comparing strength, weakness, opportunity and threat level for both printing technologies from Table 2 and Table 3.

Table 4. Rating of 3D and 4D printing

	Strength	**Weakness**	**Opportunity**	**Threat**	**Average rating**
3D printing	9	7	8	7	7.75
4D printing	7	6	9	7	7.25

The strength of 3D printing is availability of reliable 3D printers widely. Positive market growth, customized parts and common materials strengthens 3D printing industry. 4D printing industry is just in its initial phase with lots of challenges ahead. Considering all those factors, rating 9 is given for 3D printing over 4D printing with 7 points. Any new technologies learn and improve from their existing weakness and flaws. Expensive price, limited material, slow printing time and software problems are few weakness within the printing industry. The column for opportunity includes rating 8 for 3D printing and 9 for 4D printing. The higher rating for 4D printing concludes this new technology as a beginning of whole innovative world of manufacturing with tons of opportunities ahead. Rapid rate of technological and digital advance has always been threat to manufacturing industry. Rating 7 for both 3D printing and 4D printing, represents similar technological and digital threat to the industry.

The table comparing different types of 3D printer helps to identify printer's specifications and its quality. From the table, the price list starts from 199 USD to 250,000 USD. The US manufactured FDM type printer M2 which is fifth generation of MakeGear 3D printer tops the comparison chart with rating 9.2. Although slightly expensive than budget printers, this printers comes with better build quality, precision and reliability. The most affordable 3D printer from the chart is MP Select Mini from Monoprice with price 220 USD. With the build volume of 12*12*12 cubic cm, this machine is capable of printing minimum layer height of 100 micron. (Monoprice, 2016)

Objet260 Connex3 from Stratasys, is polyjet type multi-material color 3D printer. Since Skylar Tibbits' 4D printing project was enabled by Connex multi-material 3D printing technology**,** (Stratasys, 4D Printing, 2014) this printer is listed as 4D printer in the comparison chart. The price for this industrial printer ranges from 100,000 – 250,000 USD with maximum build size 255*252*200 cubic centimeter. (Aniwaa, 2014)

Similarly upon comparing 3D printing market size and 4D printing market size, the market growth of 3D printing industry has compound annual growth (CAGR) of 28.5%, while similar growth rate of 4D printing industry increased with 42.5 %. This annual growth result shows scope of 4D printing market that includes programmable carbon fiber, programmable textiles, woods and grains.

The following graph depicts the market size and growth of 3D printing industry versus 4D printing industry. All the values have been imported from Figure 21 & Figure 22.

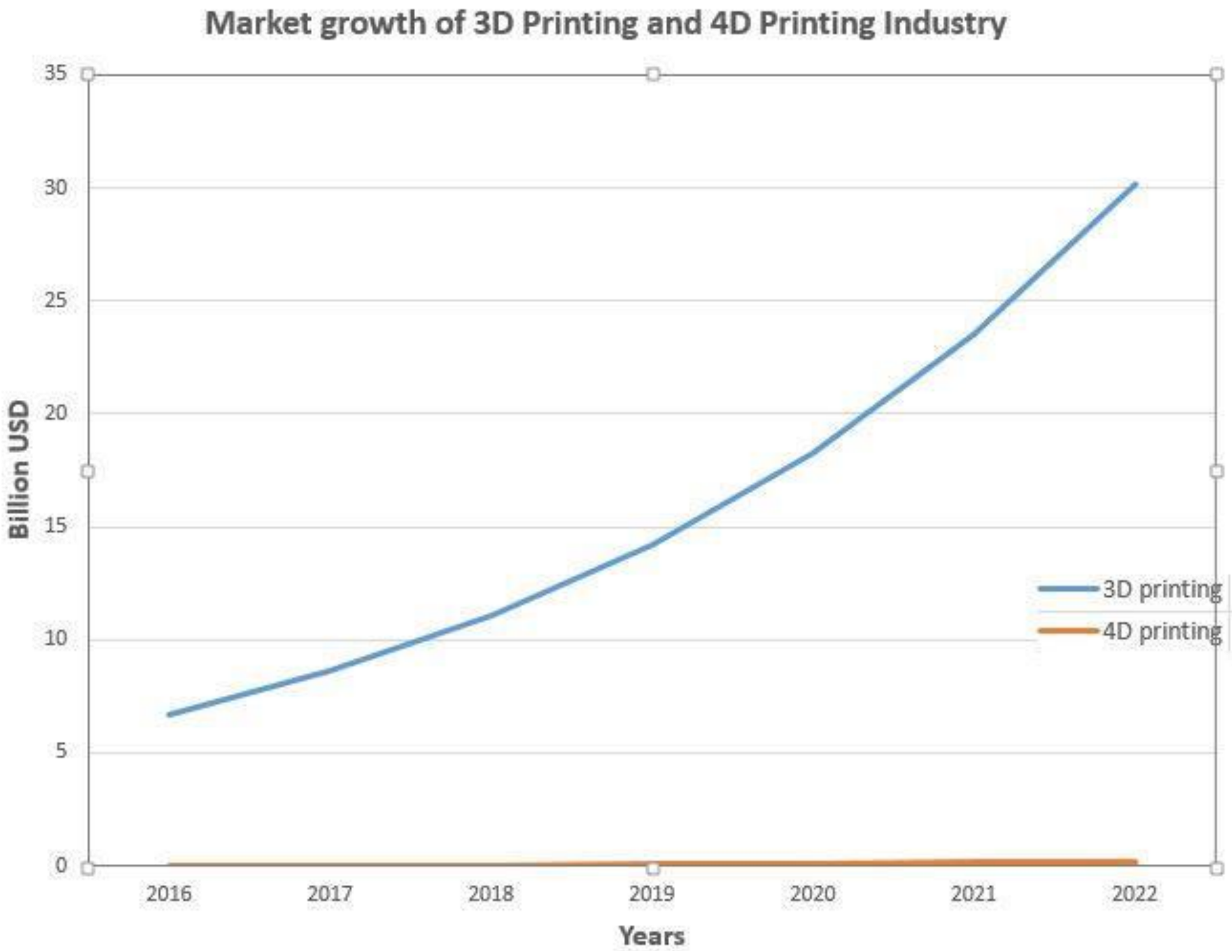


Figure 23. Line chart for 3D & 4D printing market. (Marketsandmarkets, 2016)

Looking through the above graph, the blue line clearly outsizes orange line. The blue line represents the market size of 3D printing industry and orange line represents 4D printing industry. Comparing those graphs, 3D printing industry has huge market size reaching up to astonishing 30.19 billion USD by 2022. However, 4D printing industry is also growing and predicted to be inside industrial market by 2019 and market size will be close to 537 million USD by 2025.

5 DISCUSSIONS

5.1 Challenges while adopting 4D printing and 3D printing

5.1.1 Safety

Fully functional guns and weapons can be printed with the help of 3D printer. The first 3D printed gun was developed and successfully fired by the group called Defense Distributed. (Morelle, 2013) It is absolutely incredible but concerning as well. These 3D printed weapons can easily fall into hands of criminals, children, mentally ill person and convicts which will arise the question regarding public safety and security problems. Health risk related to 3D printed food, printing of human body parts that could impose health risks but also ethical issues concerning testing of those products.

5.1.2 Intellectual Property

Currently, it seems no fixed regulations and recommendations regarding manufacturing implications in 3D printing. Anyone can buy 3D printer and print anything according to their wish. Intellectual properties includes copyright, patents, trademarks, blueprints, design rights. One can design and build exact replica of another product with the help of this technology. In order to avoid intellectual property related issues, there is a need of regulatory framework which could enforce the standard.

Programmable matters or Smart matters brings special concern regarding patenting and intellectual property law. Responsibility debate arises particularly over artificial intelligence and robotics. The key players inside these technologies are manufacturer, programmer, material developer and user. For instance, if any 3D or 4D printed parts fails causing huge loss, which party takes the responsibility? Those concerns need to be integrated into regulatory guidelines and standards. (Thomas A. Campbell, 2014)

5.1.3 Resources

Before processing any task, it is essential to primarily secure enough resources. Most of the 3D printing companies recommend to use their own genuine product and their availability is limited in the market. Also the compatibility of material hinders choosing random product. It is essential to develop mechanism with global standard with materials available globally. The lack of resources causes potential slowdown in research and shortage of supply.

5.1.4 Material Selection

Not all materials are smart materials with the feature of shape changing capabilities. In order to reach its full potential, 4D printing process needs to be able to print nano scale models to mega structures that can undergo more complex transformation. The structure should have ability to change its shape repeatedly and reversing back to its original form. Continuous repetition of transformation degrades the functioning quality of material. Those issues questions about potential problem with long term durability of smart materials. The smart materials or objects required or created during 4D printing process are made up of multi-material components which are not easily available and hard to duplicate at home. (Tibbits, 2016)

5.2 What separates 4D Printing Technology from 3D Printing Technology?

Considering how quickly 3D printing technology prototypes the model and eventually can be used in mass production, this technology is surely a next big thing in the field of manufacturing. But the expansion of this technology even further leads to 4D printing. As explained previously, 4D printing technology involves creating objects with special multi material components that eventually change after reacting with external properties or sometimes on their own without external involvement. In both 3D and 4D printing processes, additive manufacturing is involved to create new product. The only difference is the time with material changing its properties. Time is the extra dimension in 4D printing technology. (Services, 2016)

5.2.1 Time Factor

Time is an element for extra dimension in 3D printing that makes 4D printing. In order to get final structure, it takes time to transform from initial shape. 3D printed object also requires some time in order to heal or cooling time. However, 4D printed parts starts acting only after exposed to external energy. In general, 3D printed parts are ready to use after printed whereas, 4D printed parts are not completely ready for its motive even after print in done.

5.2.2 Material

The most common materials used by 3D printer are Nylon, ABS plastic, Resin, Wax and Polycarbonate. These traditional materials are easily available in the market, hence printing using these materials are easy. However, 4D printing technology uses Smart materials. Smart materials are multi-materials with one or more properties that can undergo transformation in controlled fashion by external energy. Usually Smart material are piezoelectric, electrostictive, magnetostrictive, thermoelectric and shape memory alloys.

Shape memory alloys are strong, hard, tough, very good conductivity but expensive. Cu-Al-Ni alloy, Ni-Ti alloy, Cu-Au-Zn alloy are few list of smart metal alloys. Here, Cu refers to Copper, Al is Aluminum, Ni is Nickel, Ti is Titanium, Au is Gold and Zn refers Zinc metal.

5.2.3 Hardware

After material selection, hardware has the key role in printing process. Depending upon technology and requirement, there are various 3D printing machines available in the market both for home use and production. Form 1+ printer, which is based on Stereolithography process and Mojo from Stratays operates using Fused Deposition Molding technique. Current 3D printers are capable of processing single material. Stratasys' Connex multi-material 3D printer has added capability of embedded transformation from one structure to another. This multi material processing technology allows researchers to map multiple material properties into single structure carrying features of parent material with water absorbing properties to activate self-assembly process. Water acting as external activating factor, this technique promises broad possibilities for embedding programmability for non-electronic based design. Similarly, RoVa4D Full color Blender 3D printer from ORD solutions, (solutions, 2016)allows affordable full-color multi material desktop printing.

5.2.4 Software

Need to say that current software tools are behind hardware capabilities. The new advancement in the field of printing industry has forced researchers and engineers to develop new types of software tools with capabilities that go beyond CAD, CAM, Solidworks or other modeling software. With the emerging new idea such as bio-printing, multi material printing, 4D printing and electronics printing, there is a demand of software which can incorporate all those processes.

Project Cyborg from Autodesk, (Research, 2016) CANVAS software from Mosaic Manufacturing, (Manufacturing, 2017) Foundry, from MIT's Computer Science and Artificial

Intelligence Lab (Etherington, 2016) and Monolith multi material voxel software (Monolith, 2017)are some of the software that makes multi-material 3D printing easier. The complexities are growing with the need to control smart material and stimulate deposition of programmed matter for precise transformation. 4D printing requires further advancement modeling software than the one used for 3D printing.

Product designs in industrial sector are constrained by limitations of the machines. Although the process inside production facility is faster and quicker in comparison to 3D or 4D printing technology. However, 3D printing technology has capability to create complex shape design with a small change in code and allow designers to carry the best part without any huge change. Design freedom with the ability to shape lift physical object from one shape to another leads a step beyond static 3D object. As 3D printing allows material selection process efficiently by selecting the place where it is needed. Selective material placement helps saving excess use of material reducing weight such as creating bone like structures. And with the added dynamics and performance capabilities of material itself 4D printing guides the part to adapt their structure as per the external stimulation.

5.2.5 Simple Manufacturing

The products are directly built from standardized digital file and all the computer controlled processes helps reducing time for expertise as well as human interaction required to create object. While the object is being printed, the process often remains unmonitored allowing objects to be built overnight without human interference. Similar to the process, 4D printing processes are becoming even simpler than 3D printing technology. Simple looking structure can be printed and then with the help of external activating agent, it can transform into complex, large functional structure. Furthermore, self-assembly structure senses and reacts physically with the surrounding environment itself without any human involvement.

5.2.6 Mass production and customization

3D printing technology enables effective design and manufacture of personalized products. Either producing one of a kind design or mass production, the production cost remains relatively similar. The products produced can be customized as per the choice of user with few or no additional cost helps transit mass production to mass customization. Similarly, personally customized items with normal price can be particular positive step for 4D printing. User responsive products, environmentally adaptive structures, weather adjusting products, spare parts and printable consumer electronics proves superiority of 4D printing over 3D printing.

The concept of the products design can be designed and printed anywhere in the world with 3D printer and materials. The Internet bridges and eliminates any gap between the distances to move the digital file within the world. Instead of carrying products increasing logistics cost, design files can be sent immediately from one pole of the earth to another pole and can be printed exactly the same 3D object.

The large piece of final product such as building structure or vehicles can be produced with 3D printing technology in a single process eliminating the cost and time of assembling hundreds of parts produced from traditional manufacturing process. The parts are usually assembled and shipped from various parts of the world that may possibly have been manufactured from external suppliers. This technology eliminates supply chain and assembly line thereby increasing productivity. (Thomas A. Campbell, 2014)

5.2.7 Prototypes and Functioning products

With the improved material properties and effective design prototypes, 3D printing industry has evolved from basic testing idea to fully functional testing of fabricated parts. Creating tooling for molding and casting and finally end user part. Moreover, those end user part created and embedded with dynamic features will inherently boost innovation. Design and fabrication of smart products will dominate production industry enabling users to taste new development that is beyond what exists today.

Engineers and developers will no longer be limited to their design limitation due to existing traditional technology. Elimination of limitation will enhance boosting innovations and disruptive industries along with other application areas will be profound.

The rise of 3D printing and 4D printing is likely to change the field of manufacturing industry. Reinvention of many old products and customization of products into individual's choice will change the consumers' interest over traditional printing process. The representation of physical object with digital file fuels rapid global distribution of products transforming the whole product distribution sector. The very long producer and consumer relationship in industrial production methods including ongoing direct relationship between software engineers and new products has increased interest in the field of production design. Any researchers, engineers and students can imagine the level of multi-functional, multi-material components and then advanced material programming leading into the era of next generation material processing technology. An entirely new field of smart material engineers and material processing researchers may emerge offering current generation entirely different intelligent and smart physical models. Even though it's still too early to predict, but if the current development continues in such a way that we expect it into, a perfect 4D printing technology will show the world a massive shift in the way objects and structures are designed and manufactured. (Matthews, 2016)

6 CONCLUSION

The actual technology resides upon existing contributions over the years. 3D printing technology has been around the field for more than 30 years. From Charles (Chuck) hull's first Stereolithography apparatus (SLA) machine in 1983 to Skylar Tibbits from the MIT self-assembly lab proves the consistent research and contribution on material processing technology over the years. (Industry 3. P., History of 3D Printing, 2016) There has been vast developments in existing 3D printing process with multi-material printing capabilities. With the introduction of 4D printing, the technology will take over wide range of application such as home appliances and consumer goods that can adapt to heat and moisture for added comfort and functionality. Pre-programmed self-deforming materials in health care sector including biocompatible implants inside human body such as cardia tubes will certainly bring revolution in medical research. The introduction of many new companies and competition, quality of the printing has improved surprisingly and price becoming cheaper. The result of priorities and personal choice are forcing developers to work much harder as there are lots of room for improvement. In coming years, it is most likely that those printers will become increasingly available with very low price.

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