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Additive Manufacturing: An Overview of Printing Technologies

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ABSTRACT

Additive manufacturing (AM) is a revolution for the manufacturing industries. The application of these techniques received extensive demand because of their efficient and economical approach. Among AM techniques, 4D printing is an emerging segment in additive manufacturing employing time-responsive programmable materials. Combining 3D printing technologies with materials capable of transforming, possessing shape memory and self-healing abilities, realizes complex structures to be effortlessly constructed for numerous applications. The benefits of using multifunctional materials in 4D printing give possible solutions in demanding environments like outer space and unlikely human interference in severe weather conditions. 5D printing technology is also an innovation in this manufacturing sector and the concept is similar to the 3D printing technique including two axes of rotating head and printing bed. Every technique has some special abilities and drawbacks as well. This review shows the overview of the 3D, 4D, and 5D technologies, the materials used, applications, technical challenges, and the comparative study of these techniques. The conclusion of this review shows that the 5D printing technology is the most reliable and has better output quality and less time-consuming technique compared with the other 3D and 4D techniques.

Keywords:
Fused Deposition Modelling; 3D Printer; Additive Manufacturing; 4D Printing; 5D Printing

1. Introduction

These days, industries are trying to reduce their product's planning, production, and processing time to rapidly enter the market to meet the challenging and competitive demands and expanded needs. The 3D printing technology would make this feasible [1]. This technique are well known for

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their ability in fabricating complex geometries, durable, dimensionally accurate and a wide range of structures [2]. In 1986 Charles Hull developed this technology and named it stereolithography (SLA). Following the consequent developments, numerous techniques developed namely fused deposition modelling (FDM), inkjet printing and contour crafting (CC). Adapting layer by layer technique, the 3D printing develops the products which designed by utilizing the CAD (Computer-aided Design) [3,4]. 3D printing technology has been used in various sectors such as aerospace, automation, electronics, bio-medical, textiles, fashion jewelry and end-use products [5]. The 3D printing technology is typically used to create parts that are rigid and static. However, in the 4D printing technology, the invented object has a dynamic structure, and it can change its shape over time if exposed to heat, water, magnetic field or light. Skylar Tibbit introduced this innovative 4D printing technology with the aid of Statasys™ as printing material and it's manipulated to change over time in response to an external stimulus. The technology used in 3D printing and 4D printing basically are the same, the difference is in the fourth dimension that base on the time rather than the coordinates [6]. Figure 1 denotes the 4D domain representation of intelligent objects that can be activated in simulated and straightforward design with stimuli over time.

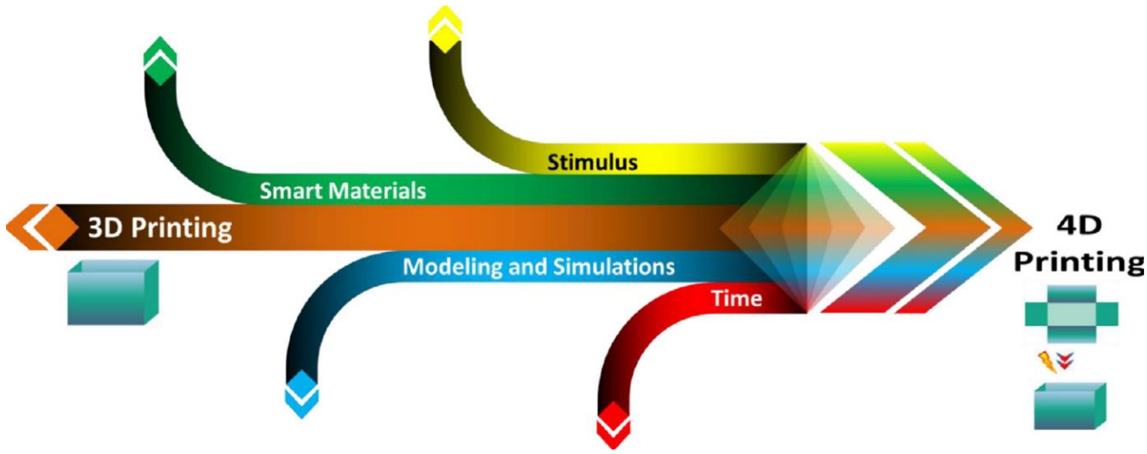

Fig. 1. 4D domain representation of intelligent objects can be activated in simulated and straightforward design with stimuli over time [8]

The 5D printing technology was invented by William Yerazunis, the principle of 5-D printing is supplemented by the addition of two axis through a movable printer bed that, when required, rocks back and forth. In contrast with all regular 3D printers, since 3-D printer heads are able to approach the object from any angle, there are far more possibilities to print – not just in terms of the overall shape of an object [7]. Objects printed on traditional three-dimensional printers which use the layer-on-layer printing method have little structural integrity in their design. In certain conditions, when these objects are placed under pressure, the weak points become visible, and the objects collapse or break down because of their formation. However, 5-D printers allow the designers to consider those anticipated stresses and create a more solid object as the material is positioned from several viewpoints rather than stacked at top of each other to mitigate the weak points. In January of 2018, one of the first 5-D, commercially available printers won a "Best of Innovation" award at the massive Consumer Electronics Show in Las Vegas.

However, each technique has merits and demerits in its applications. for example, 4D printing has the best dynamic shape-changing future compared with other techniques. But compared with the strength of the product, the other techniques have better strength compared with the 4D printing process. This paper aims to briefly review the fundamental aspects of the 3D, 4D and 5D printing technologies material usage, comparative analysis of the techniques and the applications and the technical challenges of those techniques are briefly discussed.

2. Various Technologies

2.1 3D Printing

3D printing is also called Additive manufacturing technique to produce complex geometries and a wide range of structures using 3D model data. A variety of methods for the printing of polymer composites have been employed, among them Stereolithography (SLA), selective laser sintering (SLS), Fused deposition modelling (FDM), Inkjet printing, and 3D plotting are well-established. According to the ASTM standard [9], the range of AM technologies classified into seven categories including material extrusion, material jetting, direct energy deposition, powder bed fusion, sheet lamination, binder jetting and var photopolymerization [10]. The technology categories based on the state of materials used for the process like powder-based materials used in selective laser sintering, selective laser melting (SLM). The liquid-based materials were used in stereolithography (SLA), direct ink writing (DIW), digital light processing (DLP)and the solid-based materials used for the fused deposition modelling process. Thermoplastic polymers are the primary raw material for the 3D printing process. Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA), Polyamide (PA) and Polycarbonate (PC) are the essential materials used in this process [11]. The process of the 3D printing process is established in Figure 2.

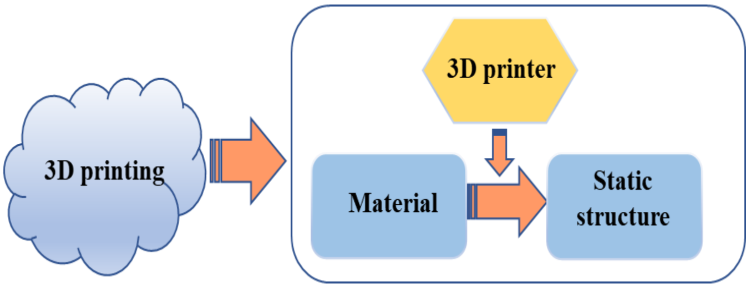

Fig. 2. 3D printing process

2.1 4D Printing

4D printing is an innovative 3D printed structure creation in additive manufacturing of time responsive programmable materials. The integration of 3D printing technology with materials which can transform and have the ability to store shape and self-heal means that complex structures can easily be produced for a myriad application [12]. Figure 3 shows the process flow of 4D printing. The theory of 4D printing is focused mainly on five attributes: Smart materials, 3D printers or equipment, stimuli, interface mechanisms and mathematical modelling [13]. Polymer is the prime working material for the 4D printing process, and the smart polymers are the focusing material on the future of this technique. These kinds of unfixed polymers are not a new technique to combine the 3D print and the dynamic polymers but enable the printed materials to differ across several types along with the appropriate numerical model and chronological stimulus. Popular methods of dynamic polymers are called form memory polymers that activate the predefined form and stimulate outside stimuli when the temperature is changed. Temperature is not only the stimulus for shape memory but also like water or ion strength it serves as stimuli in the hydro gels causing a considerable shift in product amount [14].

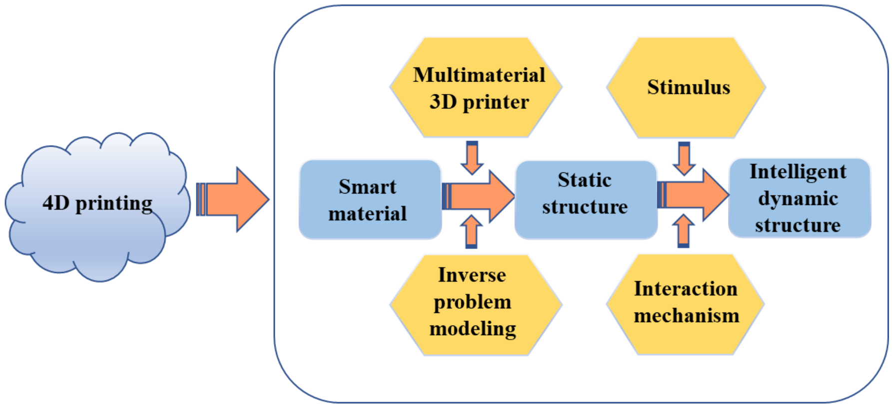

Fig. 3. 4D printing process

2.3 5D Printing

5D printing is a relatively new advancement in the field of 3D printing. This method enables the precise 3D printing of things with concave or curved shapes. The printer process was enhanced by incorporating two extra axes: the rotation of the printing platform and the extruder head. Both 3D and 5D Printing processes utilize comparable technologies, including the utilization of 3D CAD files and same printing materials. William Yerazunis first implemented the 5D printing concept from Mitsubishi Electrical Research Lab (MERL). The printing head and the printing object have five degrees of freedom on this technology. Instead of using 3 axes in 3D printing this 5D printing uses five axes of printing [15]. The 3 axes are same as the 3D printing such as X, Y, Z and the other axes are translation and rotary axes. The main advantage of this 5D printing is that it does not need support structure because instead of flat layers it produces curved layers. Compare with 3D and 4D printing process this this 5D printing technique is capable to make stronger products and the material wastage in this very less [16]. The main advantage of this technique is in 3D printing process the curved joints and the corners are not good. It needs post processing, but in this 5D printing process the corners and the joints are very strong. During the printing process the head and the printing part is also moved. So that the processing time also reduced compared with the other techniques [17]. The standard 5DP methods have three distinct steps: pre-printing, printing, and post-printing. These phases must undergo validation and thorough inspection to guarantee that the model adheres to the expected objectives. Important factors to consider are the necessary specifications, the alignment of the model, the creation of the desired path, the analysis of the printing process, and the adherence to the digital model. In the realm of 5DP, there is potential for using machine learning (ML) and artificial intelligence (AI) to enable the intelligent utilization of materials for the production of multifunctional, environmentally friendly, and biocompatible components [18]. 5D technology, a novel manufacturing process, aims to address limitations in the medical sector by enhancing the hardness of manufactured materials and improving precision in dentistry. Additionally, it has the potential to produce artificial bones with intricate curves and exceptional strength, which can be utilized in surgical procedures [19]. Figure 4 shows the two supplementary axes in the 5D printing process and Figure 5 shows the schematic of 5D printing process.

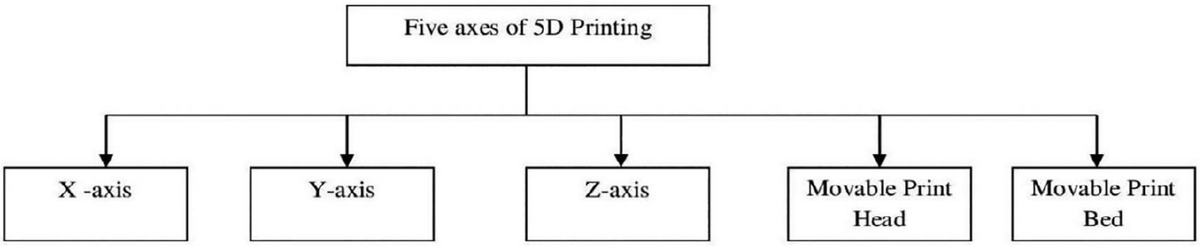

Fig. 4. Diagrammatic summary of two supplementary axes in 5D printing [18]

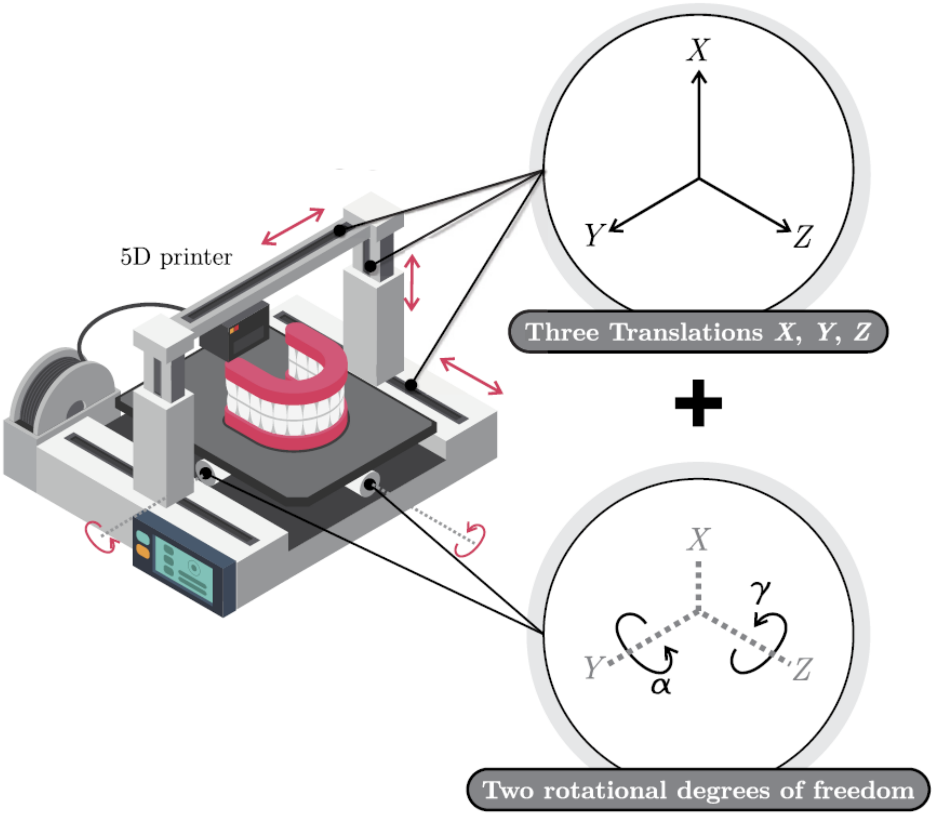

Fig. 5. Schematic of 5D printing process [19]

3. Materials

3.1 Materials Used In 3D Printing Process

The materials used for 3D printing are as varied as the products generated from the process. 3D printing is modular enough to allow manufacturers to decide the form, texture and strength of the component. Best of all, these qualities can be accomplished with much fewer steps than is usually needed by conventional methods of production. In addition, these products can be made from different types of 3D printing materials. 3D printing technology is capable of manufacturing completely usable parts in a wide variety of materials, including ceramic, metallic, polymers and their combinations of hybrid, composite or functional graded materials [19]. Out of all other materials the polymers are the most common materials in 3D printing technique. Polymers are the most flexible material for 3D printed parts. The polymer materials are used in 3D printing process are Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polypropylene (PP), polycarbonates (PC), nylon/ polyamide (PA) and polyethylene (PE)[20]. Later that to improve the properties of the product materials such as Polyetherketoneketone (PEKK), polyetheretherketone (PEEK), polyethyleneimine (PEI), and polystyrene (PS) were used [21]. However, the applications in the various sectors are limited by the limited availability of the materials. So that by adding other materials with the composition of polymers to improve the applications. Composite materials having excellent strength, low weight and customizable properties have revolutionized high-performance industries. Materials such as carbon fiber and glass fiber are reinforced with the polymers. The carbon fiber reinforced polymers having high strength, stiffness, good corrosion resistance, and good fatigue performances are mainly used in aerospace industries [22]. Metal is the second-most popular 3D printing technique which is mainly used in Direct metal laser sintering (DMLS). Metals usage in 3D printing technology will increase the usage in aerospace, automobile, medical and manufacturing industries [23]. The materials such as stainless steel, bronze, gold, nickel, aluminum and titanium are used in this technique [24]. Without any large pours or cacks by using ceramics and concrete 3D printing can produce good mechanical properties products. The ceramic materials are strong, durable and fire resistant and the materials are in fluid state before printing. So that it is easy to print complex geometry and shape in construction sectors. Materials such as alumina, zirconia, bioactive glasses are the common materials of this technique [25]. The resins are the most limited material used in 3D printing technique. The resins have limited flexibility and strength compared with the other materials. Made of liquid polymer, the resin achieves its final state with ultraviolet rays. High detail resins, paintable resins and transparent resins are the common resin types used in this technique [26]. These are the common materials used in this 3D printing technique.

3.2 Materials Used In 4D Printing Process

The 4D printing materials are different from the 3D printing materials, those materials are not applicable in this process. Because the materials used in the 3D printing process are not responsive to the external stimulus. Materials for 4D printing refer to materials that can provide a useful response based on external stimuli such as water, temperature, electrical and magnetic field. This 4D printing materials has two important capabilities: printability and smartness [27]. By the concept of 4D printing, stimulus-responsive materials are the kind of smart materials that are the most widely used materials for 4D printing. The stimulus-responsive materials are usually classified into two types: shape changing materials (SCM) and shape memory materials (SMM) [28,29]. Shape changing materials is a kind of reversible material that can spontaneously modify its shape when stimulus is applied and return to its original shape when stimulus is removed. However, the type of deformation was predetermined by the original material structure [30]. The shape memory materials do not need any preset renovation as prepared, but it need a programming step that allows much more complex and adaptable shape changes for the shape memory materials. This shape memory materials includes two stages. The first step is to program the material so that its structure can be converted from its original forms to its temporary shape. The second stage is the restoration phase, in which the material restores its original form from the temporary form by adding a suitable stimulus. Thus, the ability of the shape memory material to "memorize" its constant forms is referred to as the "shape memory effect". So that this shape memory materials are popular than the shape-changing materials [31]. The main difference is that the shape-changing materials cannot hold on to the temporary form when the stimulus is removed, while the shape memory materials will hold until the proper stimulus has been applied. The shape memory materials are also categorized into two forms: one-way shape memory materials and two-way shape memory materials. When the original form is recovered from the temporary shape, a new programming process is necessary in one way memory materials in every cycle to recreate the temporary shape. In comparison, the two-way form memory materials need not be programmed to restore temporary form. The general used SMM materials are Shape-Memory

Polymers (SMP), Shape-Memory Ceramics (SMC), Shape Memory Alloys (SMA), and Shape-Memory Hydrogels (SMM) [32].

3.3 Materials Used In 5D Printing Process

The 5D printing technique is the same as the 3D printing technique but it contains in addition two axis such as the movable print head and the print bed, other than that the scanning, designing process are same. This 5D printing technology is now under development stage. Ethereal machines, Bengaluru, India, has already created the machine named as “Halo 5D printer”. In this machine extrusion process is used for printing the object as 1.75mm diameter polymer filament [33]. Other than this there is no materials analyzed, by the way the both the 3D and 5D printing techniques are same. So that there is more possible to use all the materials in the 3D printing technique can be used in this 5D printing process.

4. Applications

4.1 Application Of 3D Printing

3D printing technology provides unparallel freedom design in component and production in many sectors. It have ability to print complex geometries, has potential to make lightweight parts in the Aerospace industries which reduces the resources and energy requirement [34], [35]. The same time it reduces the fuel usages in the aircrafts. It also used in some of engine components in spacecrafts [36]. In the automobile industries the 3D printing technology have made big revolution to build lighter and complex structures. Ford is using this technology to produce engine parts and prototypes. Moreover this technique reduce the cost and time so that the it allows the new techniques in very fast and reliable [37], [38]. The creation of custom food for specialist dietary needs including athletes, infants, pregnant women, patients and the like that demands a different amount of nutrients by reducing ingredient levels and improving the presence of healthy ingredients currently exists.

However, it is important to produce custom foods in a very thorough and imaginative way, where 3D-food printing is adopted. Food layer manufacture also known as 3D-food printing generated directly from computer aided design data by deposition of subsequent layers per layer [39]. 3D printing technology is making a big revolution in the medical sector. It is used to print artificial bone, tissue engineering, 3D skin, organs, printing for cancer research and models for visualization [40-43]. 3D printing technology can be used in the construction industry to print whole buildings or to manufacture building components. Building information modelling (BIM) is developed to increase the use of 3D printing technology. It can provide a reliable source of choice during its life cycle, from initial design to demolition for building or renovation. This creative and collaborative technology helps to design, build, and manage the built environment more efficiently [44]. Figure 6 a) shows the First 3D printed house by Dus Architects and b) shows that 3D printed house by WinSun.

(a) (b)

Fig. 6. a) First 3D printed house by Dus Architects b) 3D printed house by WinSun [39]

Nowadays, different 3D printing technologies have already been used in large numbers by incorporating driver into 3D printed items for structural devices such as active electronic materials, electrodes and appliances with mass customization and adaptive design. The 3D electrode production process using the Fused Deposition Modelling of 3D printing technology allows for the production of mass electrode material in a low cost and time efficient manner. The configuration and surface areas of the 3D electrode can be easily modified to a specific application in contrast to commercial electrodes like Aluminum and copper and carbon electrodes [45]. Figure 7 shows the 3D printed carbon black/PCL composite for (a) Piezoresistive sensors (b) Capacitive sensors (c) A macro image of the printed sensor pads.

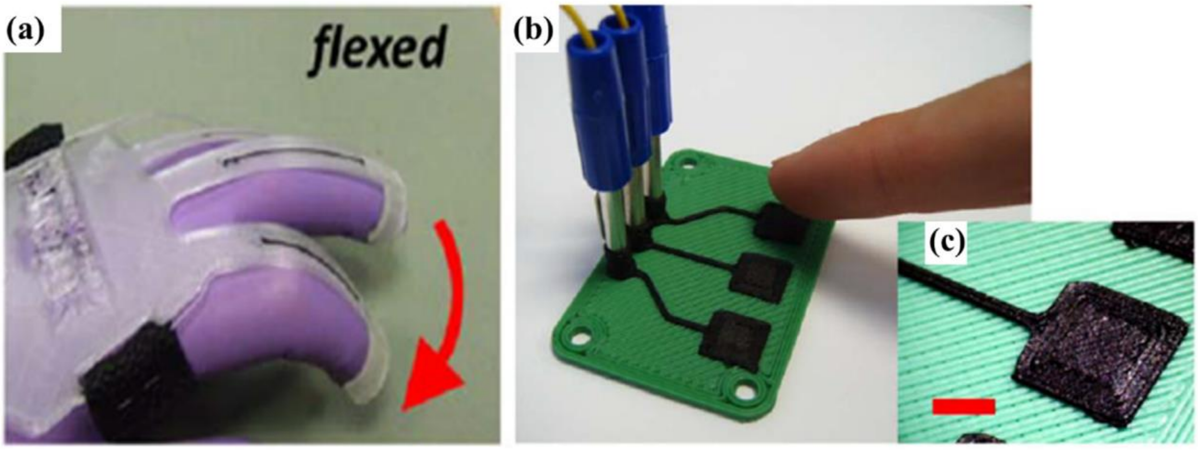

Fig. 7. The 3D printed carbon black/PCL composite for (a) Piezoresistive sensors (b) Capacitive sensors (c) A macro image of the printed sensor pads (scale bar 5 mm) [46]

4.2 Application Of 4D Printing

4D printing technology is currently used in many sectors due to its dynamic changing shape under the relevant stimulus. It involves many fields such aerospace, automobile, biomedical, electronics, self-repair devices etc... With the advanced intelligence of 4D printing technology it is used in biomedical and medical fields from medical implants, splints and stents to medical tissue technology. The possible applications of polymers for pharmaceutical applications range from binders, viscosity enhancer, coating to controlled and targeted drug delivery to intelligent delivery systems where controlled or intelligent delivery has the benefit of improved control of drug concentration, reducing side-effects [47]. The 4D bioprinting can also be used to print hard tissue structures, such as grafts for the bone. The 4D bioprinting will achieve a precise control by self-folding or self-unfolding, encapsulation and release of drugs or cells [48] represents in Figure 8.

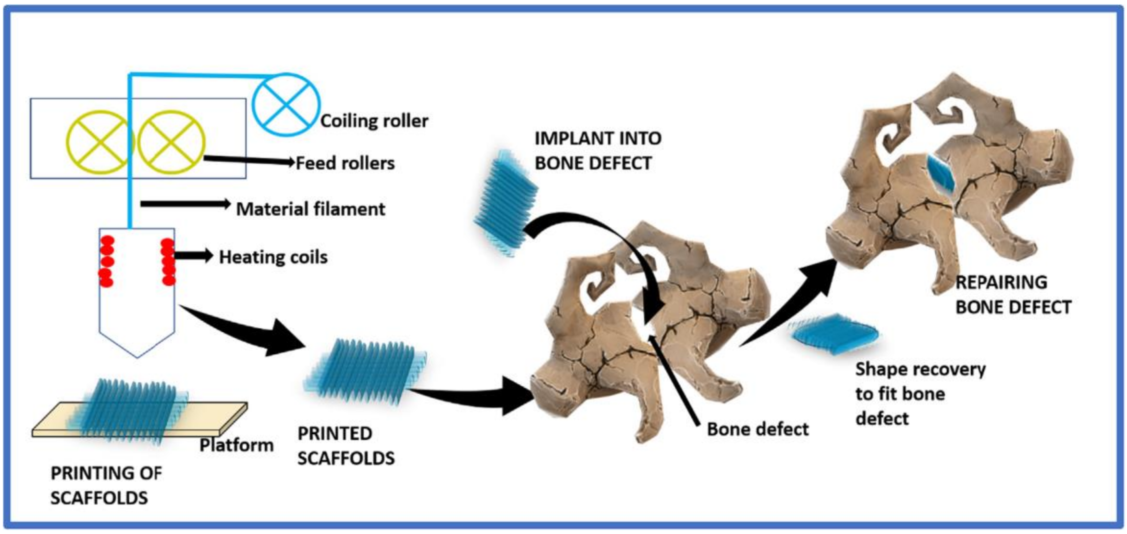

Fig. 8. 4D printing of bone tissue based on shape memory mechanism, where the SMP scaffold transmutes their shape to occupy the void space, repairing the bone defect [32]

Figure 9 a) shows that the self-folding stand and b) stent used for heart surgery. The demand for artificial scaffolds in the biomedical industry has been growing in recent years. Stents are key instruments for the expansion of human vessels or trachea, and examples of artificial 4D printing technology are present [51]. It offers a new approach for the construction of robots and provides extra features for robots. In addition, 4D printing will help to build robots under water [52]. For space station production, the 4D printing technology can be implemented. These parts can be transported to space and then auto assembled to the space station, so that the efficiency can be greatly improved [53]. In general, due to the auto degradations and self-assembly capabilities of 4D printing can be employed for disposal and resource use. The environmental changes, including humidity, temperature, pressure, height or sound, are impressive for 4D print products. Special and highly tuned goods will be generated in entirely new ways in which materials are enabled by environmental energy to unify, reconfigure, mutate and reproduce. 4D printing for the disposal of waste can also be applied [54].

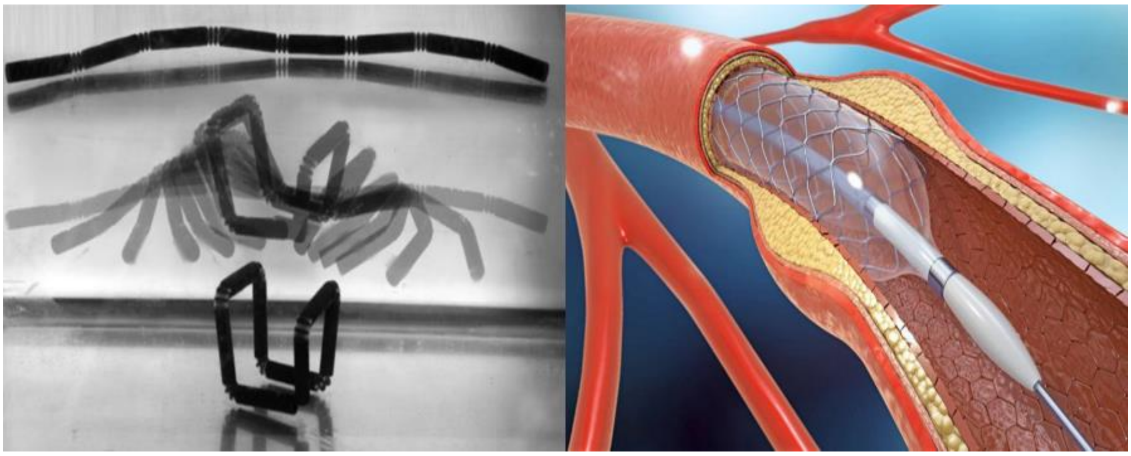

Fig. 9. a) Self-folding stand [49] b) Stent used for heart surgery [50]

4.3 Application Of 5D Printing

The applications of this 5D printing process are limited because this technology is under development stage. Compared with other technologies the parts made up by the 5D printing is 5 times stronger and the material usage also 25% less so that this process is effective. Also, the 3D printing techniques are printing flat layers in the curved edges but in the case of 5D printing the head and the bed are moved to print curves and joints. So that the curves are stronger than the other techniques and the process is relatively quick. So that this 5D printing process can be used in all the sectors such as aerospace, automobile, electronics, biomedical, various industries etc.

5. Comparative Study Of 3D, 4D And 5D Printing Techniques

The world was aware of 3D printing technology until a couple of years ago. It is a great innovation in the printing industry due to its cost effective, complex geometry printing and rapid prototyping. The object becomes stationary in 3d printing, and the printing tool travels along three axes to create an object by using the computerized CAD model. 3D printing technology is highly popular in most industries. It produces goods with low time, good performance, quality and having many benefits. So that the 3D printing technology becomes usual in the world. 4D printing engineering has become a new milestone in recent years. Due to the many applications involved, the use of 4D printing is more important in the medical field. However, 4D printing varies slightly from 3D printing. When in contact with an external medium such as water, heat, the magnetic field, electricity etc., a 4D printed object can change its shape. Compared with the 3D printing technology this 4D printing technology has the capability to achieve multi-functionality, self-repair and self-assembly. But the strength of the product is low compared with the 3D printing products. The main difference between this 3D and the 4D printing technology is the process of printing condition. 3D printing structure is solid so that it does not need anything other than the printing parameters. But in the case of 4D printing it requires mathematics, stimulus and the interaction parts using smart material. These are the main difference between the 3D and 4D printing technique. The 5D printing is different form the 4D printing technique. The process is same as the 3D printing, and it have additional two dimensions such as translation and rotary axes. The strength of the parts made by the 5D printing is 5 times higher than the 3D printing parts. William Yerazunis analyzed the parts strength made by 3D and 5D technique. The 3D printing part withstand the pressure up to 0.1Mpa, but the 5D printed part has withstands the pressure up to 3.4 Mpa [55]. Compared with the other two techniques the 5D printing technique has 25% less material usage. The comparative analysis of this 3D, 4D, 5D printing technique is shown in Table 1. It shows the difference in the design, material usage, machine usage, merits, demerits and the applications of these techniques.

Table 1
Comparison of 3D, 4D and 5D techniques

Category	Design	Materials Used	Machines	Part State	Dynamic Shape Changes	Product Strength	Merits	Demerits	Applications
3D PRINTING	Digital 3d information (scanning, designing)	• Polymers • Polymer blends • Polymer composites • Ceramics • Metals composites • Fiber-reinforced composites • Nanocomposites	• 3D printers. e.g.: • Fused deposition modeling (FDM), • Stereolithography (SLA), • Selective laser sintering (SLS).	Static	No	Good	• Process efficiency is high. • Ability to print complex geometry. • Product quality is high. • Materials can be recycled. • Easy to handle. • Rapid prototyping. • Fast design and production. • Cost-effective products.	• Production time is high. • Limited materials. • Not suitable for batch production. • Products are limited in size. • Some processes are very expensive.	• Aerospace • Automobile • Art & Jewelry • Biomedical • Constructio n • Education • Electronics • End-user products • Food processing • Prototypes • Toys.
4D PRINTING	Digital 3D information (smart design)	• Smart materials: • (Shape memory polymers (SMP), • Shape memory alloys (SMA), • Shape memory ceramics (SMC), • Shape memory hydrogels (SMH) • Self-assembled materials	• Multi-material smart 3D printer • 3D printer-stereolithography (SLA)	Dynamic, smart structure	Change its shape, function, color, and other properties over time when external stimuli are imposed on it. e.g.: • Water • Thermal • Electrical • Light • Magnetic • pH-responsive	Less compare d with 3D printed objects	• Efficient process. • Dynamic changing structure. • Increased capability of printed products. • Manufacturing cost is less. • New applications from adaptive materials.	• Limited material availability • Product strength is low. • The initial cost is very high. • Requires skilled labors. • Production time is high.	Dynamically changes in configuration involve applications. e.g.: • Aerospace • Automotive • Electronics • Consumer applications • Medical

5D PRINTING	Digital 3d information (scanning, designing)	Same as 3D printing • Polymers • Polymer blends • Polymer composites • Ceramics • Metals composites • Fiber-reinforced composites • Nanocomposites	• 5D printer e.g.: • Halo 5D printer	Static	No	5 times higher strength compared with 3D printed objects.	• Fast and reliable. • Easy to be handling. • Printed parts had high strength compared with other processes. • Curved and complex shapes can easily be printable. • Less material wastage.	• The initial cost is very high. • Products are limited in size. • Under development.	Under development stage, expected all the sectors due to its printing ability in complex geometrical structures and the strength of the product.

6. Technical Challenges

Moreover, from the advantages of these techniques such as smart printing, low price, ease of access, innovation in the industrial field all the techniques have some drawbacks. In 3D printing technology the applications in various sectors were limited due to the limited materials availability because of the inconsistencies in material properties (integrity, strength, aesthetics). Initial cost of the machines, manual post-processing requirements, high time period to achieve fine and accurate finishing. These are the important limitations in 3D printing process. Smart materials are used for the design and transformation of structural functions for 4D printer technology. The use of 4D printing technology in the biomedical field has fulfilled the needs. The 4D printing also have some issues in the process such as limited material availability, and the initial cost is too high. The main limitation of this technique is the process time because the initial mathematical calculation for the process will take more time. The shape memory materials are changed their shape with limited stimuli, poor properties (mechanical, thermal, electrical). Compared with these problems the 5D printing is essential to make high quality product and high-speed process. But the main drawback of this process is the initial cost of the machine is too high and it requires highly skilled resources to develop and to maintain the 5D printer. These are the main technical challenges of the various printing techniques. In the future to overcome these problems will make the additive manufacturing process is a revolution in the manufacturing industries.

7. Conclusions

This paper presents a detailed review of the 3D, 4D, and 5D printing technology. This review shows the detail about the three printing techniques, materials used, applications, technical challenges and the comparative analysis. Compared with the three techniques every technique has the unique advantage by the way the techniques also have the major limitations. The 3D printing process is easy to access, have the ability to print complex shapes but the part quality and the process time is poor compared with 5D process. The 4D printing have some unique features of dynamic shape changing but the limitation of materials and the poor part quality compared with the 3D printing process. By the way the 5D printing process is relatively quick and the 5 times better part quality compared with the 3D printing process. 25% Less material usage compared with the other processes, better quality in curved edges and joints. From this data the 5D printing technique is best compared with the other 3D and 4D printing techniques, but the technique needs more development to move into the manufacturing sector.

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