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SHORT FORAY INTO THE STAGES OF CONVERSION FROM 2.5D TO VOLUMETRIC PRINTING

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ABSTRACT: Additive manufacturing gained popularity in the 2000s and is now considered a new or emerging technology of the 21st century. However, the origin of the process is much older and has existed for several decades, more precisely since the 20th century, when it appeared in small science fiction novels. In addition to these layer-by-layer approaches, there are also additive tomographic or volumetric approaches that allow the 3D object to be printed in a single step. These approaches are not so popular and consequently not fully understood or utilised. Thus, the paper briefly outlines the history of the transition from classical 2.5D printing, to 3D or non-planar printing, to 4D printing (with smart materials), to 5D printing (on equipment with more than three degrees of freedom), to 6D printing (a combination of 4D and 5D printing) and finally to volumetric and tomographic printing. The future perspectives of this technology are briefly presented with some applications and examples.

KEY WORDS: *2.5D printing, 4D printing, 5D printing, 6D printing, volumetric printing, tomographic printing, 3D objects, review*.

1. INTRODUCTION

According to various reports in 2022 (Ritchie & Roser, 2022; Organisation for Economic Co-operation and Development [OECD], 2022) global annual plastics production increased from two million tonnes in 1950 to 360.5 million tonnes in 2018 and respectively 459.75 million tonnes in 2019. According to assessments by the European Environment Agency (EEA) and the European Commission, global

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annual plastic production is expected to further increase by up to 1.2 billion tonnes by 2050 (European Environment Agency [EEA], 2019; European Commission, 2020). The dependence on these products is also reflected in the value of the global plastics market, estimated at 593 billion USD in 2021 (Statista Research Department [SRD], 2023) and 609.01 billion USD in 2021 (Grand View Research [GVR], 2022). By 2030, growth is estimated to reach 824.46 billion USD, with a CAGR (Compound Annual Growth Rate) of 3.98 % (SRD, 2023; GVR, 2022).

High annual consumption is due to the transformation of plastics into a wide range of products using primary manufacturing technologies such as injection (accounted of the largest market share of over 43.38 % in 2022 (GRV, 2022)) and extrusion moulding. In comparison, additive manufacturing is mostly used in prototyping application and less widely in industry. Other processing technologies, namely extrusion, atomization, sputtering, grinding, centrifugal disintegration, electronic deposition, calendaring, crushing, and chemical reactions are required to produce the raw material for additives processes (Fraunhofer, 2023). The most common forms of these raw materials are filaments, powders, rods, sheets, plates, foils, gels, pastes, liquids and fibres. Thus, similar to thermoforming (Throne, 2008), additive manufacturing can be considered a secondary processing technology.

Even so, a 2019 study shows that the global 3D printing market was estimated at 12.1 billion USD (SRD, 2020) and 15.2 billion USD in 2021 (Valuates, 2022) with a 25 % year-on-year growth from 2014 to 2019 (Jemghili et al., 2021). Due to a CAGR of 21.6 % from 2023 to 2033, the global additive manufacturing market size is estimated to reach between 76.16 and 77.83 billion USD by 2030 (Persistence, 2023; Strategic, 2021). This estimate includes revenues from 3D printing systems (equipment), software, materials, accessories, and services. 3D printing is one of the fundamental elements of the latest industrial revolution, known as Industry 4.0 (Jemghili et al., 2021).

In the literature, a number of papers can be identified that show the connection and transition from 3D to 4D (Zhou et al., 2015; Mallakpour et al., 2021), nonplanar approach (Nayyeri et al., 2022; Nisja et al., 2021), 5D printing (Anas et al., 2022), 6D printing (Georgantzinos et al., 2021), transition from 3D to 6D printing (Vasiliadis et al., 2022), volumetric 3D printing (Rodríguez-Pombo et al., 222). Yet, none of these provides a complete overview of the history of additive manufacturing and the stages of the transition from an idea in a fiction novel to volumetric printing.

Therefore, in the following chapters a brief review of the transition from 2.5 to volumetric printing as well as a brief overview of the history of additive manufacturing is given.

2. TRANSITION FROM 2.5D PRINTING TO VOLUMETRIC PRINTING

2.1 Short history of additive manufacturing

Additive Manufacturing (AM) is also known by other, more or less common names, such as 3D printing, Rapid Manufacturing, Rapid Prototyping or Rapid Tooling, Digital Manufacturing, Digital Fabrication or Desktop Manufacturing and Layered Manufacturing. Unlike the formative and subtractive approaches, the common characteristic of additive manufacturing processes is the formation of a three-dimensional solid object by depositing material or binder in successive layers until the desired final shape is obtained.

Based on a partnership agreement between ISO/TC261 (Additive Manufacturing) and ASTM Committee F42 (Additive Manufacturing Technologies), a common set of rules, classification and information on additive manufacturing has been created. Hence, based on the revised standard ISO/ASTM52900-2021 (Additive manufacturing - General principles – Fundamentals and vocabulary), the different 3D printing processes can be grouped into seven categories: Material Extrusion (ME), VAT Photopolymerisation, Binder Jetting (BJ), Material Jetting (MJ), Powder Bed Fusion (PBF), Directed Energy Deposition (DED) and Sheet Lamination (SL) (ISO/ASTM52900, 2021).

Long before this collaboration, Blanther J.E., Birdseye S.H. and Tyler M.C. (1956) proposed a manual method (Blanther, 1892) as well as an apparatus (Birdseye & Tyler, 1956) for producing topographic maps with three-dimensional graphics using a layering method.

Meanwhile additive manufacturing was just an imaginary technology in small science fiction novels. In the 1945s and 1950s, the science fiction authors Murray Leinster (in the short story “Things Pass By”) and Raymond F. Jones (in the work “Tools of the Trade”) described a fictional but similar manufacturing technology to the concept of 3D printing (Haines, 2022; McIntosh, 2022). Murray Leinster (1945) describes a robotic arm capable of taking his 2D designs and using molten plastic to create 3D models and Raymon Jones calls his technology Molecular Spray (Historydraft, 2023). Only 26 years later, Johannes F. Gottwald is granted the right for patent US3596285A- *Liquid metal recorder* (Gottwald, 1969), the application originally filed on 11/07/1969. He envisioned a device like a normal desktop printer but printing 3D objects from molten metal rather than printing ink text on a page.

Starting from this point, a long series of papers has been published in the literature, and new equipment, materials, patents or ideas ensued, as follows:

- The first attempt to create solid objects using photopolymers and a laser was made in the late 1960s at the Battelle Memorial Institute (Mouzakis, 2018). The experiment aimed to polymerize a liquid resin by intersecting two laser beams of different wavelengths in the middle of a tank;
- In 1968, based on a similar dual laser beam approach, Wyn K. Swainson of Denmark applied for a patent for his invention, entitled “Method of Producing a three-dimensional figure by *Holography*” (Swainson, 1968);

- In October 1974, David E.H. Jones (under the pseudonym Daedalus) published a satirical article jokingly describing a single UV laser curing process (Daedalus, 1974) in an article in the New Scientist. Dr. Adrian Bowyer (future founder of the RepRap movement) later stated that Daedalus had jokingly invented what we now call stereolithography SLA;
- Clyde O. Brown, Edward M. Breinan, Bernard H. Kear, as part of Raytheon Technologies Corp. (U.S.A.), filed an application for a patent entitled "*Method for fabricating articles by sequential layer deposition*" (Brown et al., 1979) on 29 November 1979. The rights to patent US4323756A are given on 6 April 1982 and contain information for the use of hundreds or thousands of layers of metal powder and a laser energy source to fabricate a 3D object on a substrate acting as a base or printing plate. Also, in the late 1970s, Dynell Electronics Corp. (New York, USA) was awarded several patents for making *3D solid photographs*. The method involves cutting cross-sections of plywood (using CNC equipment, a conventional milling machine or a laser) and stacking them to form the 3D object (Dariah, 2023);
- In April 1980, Dr. Hideo Kodama of the Municipal Industrial Research Institute in Nagoya, Japan, describes the first layer-by-layer approach called by himself *rapid prototyping*. In 1981, he received the rights for the XYZ plotter patent (Kodama, 1981c) and published a series of papers in which he described the fabrication of three-dimensional objects from thermoset polymer (photo-sensitive resin/photo-polymers) by preferential solidification using a UV light source and a pattern acting as a mask or a scanning fibre transmitter (Kodama, 1981a; Kodama, 1981b; McIntosh, 2022).
- The patent "Pulsed droplet ejecting system" (Zoltan, 1970) of the inventor Steven I. Zoltan published in 1972 and the patent US4336544A - "Method and apparatus for *drop-on-demand ink jet printing*" (Donald et al., 1980) would form the basis for the development and refinement of *3D material-jet printers* in the coming years.
- In July 1984, American entrepreneur and engineer William Edward Masters applied for a patent describing his computer automated manufacturing process and system- US 4665492A (Masters, 1984). In the years that followed he was granted over 40 more patents of which the most important are US 5134569A- "System and method for computer automated manufacturing using fluent material" (Masters, 1989a) and US 5216616A- "System and method for computer automated manufacture with reduced object shape distortion" (Masters, 1989b). In July of the same year, Alain Le Mehaute, Olivier de Witte and Jean Claude André filed an application to patent the *stereolithography* process (FR 2567668A1- "Dispositif pour réaliser un modèle de pièce industrielle"; André et al., 1984) in which they used UV light to cure photopolymers. Similar to the earlier cases of Gottwald J. F. and Kodama H., the ideas and patents of the three French inventors were abandoned or expired due to lack of interest from the public or the companies they were working for and lack of any significant commercial potential. At the same time, three weeks later, in 1984, 'Chuck' Hull

filed his own patent for stereolithography and also described elements such as the STL file and the digital slicing/stratification approach (Hull, 1984). His contributions form the basis of modern additive manufacturing technologies. Thirty years after 3D Systems (a company founded by Charles Hulls) kick-started the additive manufacturing industry with its SLA-1 equipment, it was declared a landmark in mechanical engineering by the American Society of Mechanical Engineers- ASME (ASME, 2016).

- In 1986, Carl R. Deckard filed a patent (Deckard, 1986) for an additive technology in which he replaced UV light with a beam of light from a laser to draw and solidify successive layers of powdered polymers (a technology known today as *Selective Laser Sintering SLS)*;
- Precision Optical Manufacturing, Inc. has revolutionized the field of additive manufacturing by developing *Direct Metal Deposition- DMD* (Dutta et al., 2011), a laser beam metal powder coating process used in the production and repair of three-dimensional parts;
- In 1989, Steven Scott Crump patented the *Fused Deposition Modeling FDM* process, introduced Prodigy, a machine that produces ABS components (Crump, 1989; Haines, 2022) and together with his wife (Lisa Crump) founded Stratasys Ltd.;
- On 04/08/1992, R. Helinski was granted the patent US5136515A (Helinski, 1989), which describes the method of fabricating a 3D object layer-by-layer by droplet-by-droplet deposition and heat solidification of two materials (base material for the main component and the second one as a support);
- In 1993, Soligen Technologies, Inc. (Texas, U.S.A.) began marketing a *Direct Shell Production Casting- DSPC* equipment (Soligen, 2023) used to manufacture ceramic moulds or shells (alumina, silicon carbide, aluminium oxide, etc.). Z Corp. launches the Z402 3D printer which is based on a 2D inkjet printer but uses powdered materials (starch and gypsum based) and a water-based binder to print 3D objects (technology known today as *Binder Jetting- BJ*) (Masaeli, 2012);
- In the mid-90s, new technologies such as *SDM- Shape Deposition Manufacturing* or *Microcasting* (Amon et al., 1998), *Mold SDM* and *SSD- Spray Shape Deposition* (Beck et al., 1992) were developed at Stanford University (California, USA) and Carnegie Mellon (Pittsburgh, USA) (Masaeli, 2012; Merz et al., 1994);
- In 1995, German scientists at the Fraunhofer Institute (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V.) began the development of a technology (DE19649865C1) for fusing thin layers of metal powders using a high-power laser beam in an inert gas atmosphere (Meiners, 1996);
- In 1996, Dr Behrokh Khoshnevis patented *CC- Contour Crafting*, one of his ideas to use large printing layers to make huge parts (aircraft engines, sand moulds, etc.) on an industrial scale (Henke et al., 2016; Khoshnevis, 2006);

- In 1997, the AeroMet company developed the additive process with high-power lasers and titanium alloys in powder form called *Laser Additive Manufacturing LAM* (Ding et al., 2015; Wohlers & Gormet, 2015). During the same year the first manufacturer of *EBM (Electron Beam Melting)* 3D printers appeared (Markfoged, 2023) and used a stream of electrons guided by a magnetic field to melt successive layers of metal powders. Arcam AB (Mölndal, Sweden) developed *Direct Energy Deposition- DED* technology at Sandia National Laboratories, with equipment marketed by Optomec (New Mexico, USA) (Kumar, 2021). Although the operating principle is similar, diverse other variations of the process can be found under different names (Treutler & Wesling, 2021): *EBAM- Electron Beam Additive Manufacturing* (Sciaky Inc., USA), *LENS- Laser Engineered Net Shaping* (Optomec, Inc., New Mexico, USA), RPD- Rapid Plasma Deposition (Norsk Titanium AS Inc., Norway) or *WAAM- Wire Arc Additive Manufacturing*, *CMT- Cold Metal Transfer* (Fronius GmbH, Austria);

- WAAM has its origins as far back as the 1920s', thus making it the oldest additive technology (Dash et al., 2023; Twi, 2023) when R. Baker proposed to manufacture metal ornaments by using an electric arc as heat source and metal wire as base material. The WAAM technique can also be divided (Binato et al., 2018; Northeastern University [NU], 2020) into *GMAW- Gas Metal Arc Welding* (Ding et al., 2011), *GTAW- Gas Tungsten Arc Welding* (Dickens et al., 1992) and *PAW- Plasma Arc Welding* (Spener et al., 1998), *SAW- Submerged Arc Welding* and *SkAW- Skeleton Arc Welding* (Treutler & Wesling, 2021);

- In 1999 scientists at the Wake Forest Institute for Regenerative Medicine [WFIRM] successfully implanted a human bladder (WFIRM, 2023). The synthetic structure was made using a 3D printer and then coated with cells from the patient's own tissue to reduce the risk of the body rejecting the new organ. Three years, later they 3D printed a miniature human kidney. Although it was not full-size, this was a key advance in *3D bio-printing*, and later (in 2021) the institute received 2 awards in the NASA Vascular Tissue Challenge (WFIRM, 2023);

- In 2000, Objet Geometries Ltd. (Rehovot, Israel, later to become one of the Stratasys brands) announced the launch of the Quadra, an inkjet 3D printer that deposits and cures photopolymers using 1536 nozzles and a UV light source, giving birth to *PolyJet 3D printing* technology (Wohlers & Gormet, 2015);

- Dr. Behrokh Khoshnevis and his team at the University of Southern California develops the *Selective Inhibition Sintering- SIS* process of a metal, plastic or ceramic material without the use of a laser beam (Torabi et al., 2014; Khoshnevis et al., 2003);

- Since February 2004, a new revolution in the history of additive manufacturing has begun (Irwin et al., 2014), when Prof. Dr. Adrian Bowyer of the University of Bath, started an open initiative called RepRap (Replication Rapid Prototyper), offering free access to 3D printing to the general public. Another major consequence was the emergence of *Fused Filament Fabrication- FFF* technology;

- In 2008, the Thingiverse website, launched by MakerBot Industries, LLC, started to provide an easy way for the online community (home/private/independent makers and businesses) to access and use thousands of easily 3D printed models for free. It reached the top 700 most popular websites in the U.S. in 2021, hosting over 2.5 million 3D models today (Lind & Bertasius, 2023);
- In 2009, Scott Crump loses his patent for FDM technology and in 2014, the same happened to Carl Deckard's patent for SLS technology. In both cases, the doors were opening for many companies to expand by bringing equipment and materials to the market at much cheaper prices for independent users or companies. Thus, in January 2009 the BfB RapMan, the first affordable desktop 3D printer ($700 USD) is launched on the market, followed in April by the Cupcake CNC ($750 USD) of the much better known Makerbot brand (Kraft, 2009; Schneider, 2009);
- In 2011, KOR Ecologic produced the Urbee, the first hybrid car built using FDM technology (O'Neal, 2018) and Cornell University (U.S.) brought the first 3D printer for food manufacturing to public attention (Haines, 2022);
- In June 2012, five years after the original SLA patent expired, the B9Creator (Digital Light Processing- DLP printer) and Form 1 (SLA printer), the first two affordable 3D printers, were launched (Ouajjani, 2018);
- In 2013, Joseph and Philip DeSimone (from the Carbon® Company), inspired by the film Terminator 2 (Devlin, 2015), developed *Continuous Liquid Interface Production- CLIP* technology. Two years later, they announced the launch of revolutionary new printers (with print speeds up to 100 times faster than competitors' printers) that allow continuous printing of photopolymerizing resin objects. The new technology can be found today as *Carbon DLS*™ (*Carbon Digital Light Synthesis*™ (Carbon, 2023). Similarly, the company Nexa3D Inc. was developing and patenting (US20170129175A1) its own technology called *LSPc*®- Lubricant Sublayer Photocuring (Zitelli et al., 2015);
- In 2014, Dr. Benjamin S. Cook and Dr. Manos M. Tentzeris developed the first multi-material integrated printed electronics additive manufacturing platform *VIPRE* (*Vertical integration of inkjet-printed RF circuits and systems*) at the Georgia Institute of Technology, which enables functional 3D printing of electronic components for radio frequency communication systems operating up to 40 GHz (Stassen, 2014);
- In 2015-2016, two new innovations emerge in the medical field when CELLINK, as part of the BICO Group (Sweden) announces the first commercially available bio-ink material used in human tissue 3D printing and Trinity College Dublin [TCD] announces the printing of human bone or cartilage (TCD, 2016; Haines, 2022);

- In 2016, Hewlett-Packard Company- HP, began commercializing 3D printers with its patented *MJF- Multi Jet Fusion* technology (Kauppila, 2023). The company has also made its first foray into 3D binder metal printing with the *MJ- Metal Jet system*;
- Since 2016, the company Local Motors (Arizona, U.S.) has launched the first two 3D printed autonomous vehicles, named Olli, running on the Sacramento State University campus (Boissonneault, 2018). Their printing was made possible with the help of Thermwood company (Indiana, U.S.A.) and *Large Scale Additive Manufacturing- LSAM* technology (Aysha, 2020), the world's largest facility dedicated to additive manufacturing;
- In 2017, the first generation of FFF continuous belt printers (O'Connell, 2021) was launched with the release of Blackbelt 3D printer. Replacing the print bed capable of limited movement along the Z or X-Y axis with a belt capable of "infinite" movement (by continuously rotating it) and tilting the print head allows for an "infinite Z axis". In the same year, Prof. John Hart and Jamison Go, from MIT, succeeded in developing a dedicated *FastFFF* equipment that achieves a volumetric printing rate of up to 282 cm^3/h while conventional systems offer the possibility of printing at 10- 20 cm^3/h (Go & Hart, 2017);
- Over the period from 2016 to 2018, the use of 3D printers in civil construction became popular, materializing in the construction of artisanal structures, statues, bridges, houses and even some plans have been made for skyscrapers/office buildings in Dubai (Javelosa, 2017; Ramirez, 2020);
- Using SLM technology, Orbex, a UK spaceflight company, 3D printed a one-piece rocket on SLM 800 equipment (Davies, 2019). Similarly, Launcher Inc (California, USA) and AMCM GmbH (Additive Manufacturing Customized Machines, Starnberg, Germany), as part of the EOS GmbH group, have announced the successful production of a one-piece additively manufactured copper alloy liquid propellant rocket. The Engine-2 liquid rocket engine chamber was created on an AM4M M4K 3D printer (O`Neal, 2019);
- At the same time, additive manufacturing is already integrated into the U.S. Navy and Army supply chain (Metal, 2019; Suits, 2019) and in the production of five new warships for the Spanish Navy (Vialva, 2019).
- In 2020, due to the growing interest in metal printing, *Joule Printing*™ technology emerged and parts are made by melting a metal wire and depositing it in successive layers (Digital, 2023);
- In 2022, a manufacturing process patented by BCN3D, called *Viscous Lithography Manufacturing- VLM*™, enables the layer-by-layer production of 3D components by using a UV light and transparent films over which thin laminates of high-viscosity resin are deposited (BCN3D, 2022). In order to develop *Direct Sound Printing– DSP* a group of researchers, from Concordia University (Montreal, Canada) have moved away from classical approaches in which energy sources,

such as light and heat, are used to chemically or physically transform the polymers. The sono-chemiluminescence phenomenon, which underlies the technology, is utilized to create a hotspot (with high temperature and pressure) in cavitation bubbles directed into an enclosure containing a monomer (Habibi et al., 2022);

- On 24 March 2023, Northann Corp (California, USA) was granted a European patent for *DSE- Embossing Technology*. They use a combined positive and negative embossing method for 3D printing decorative panels/plates (Keane, 2023a). The same month also sees the release of AMULIT (Additive Manufacturing at Ultra-Low Interfacial Tension) technology, developed by a team of researchers at the University of Florida (Madeleine, 2023; Keane, 2023b). They use silicone-based elastomers, due to their biocompatibility and resistance (to heat, moisture and chemicals), in precise 3D printing of blood vessels (up to 4 µm in size) (Madeleine, 2023; Duraivel et al., 2023). In the same period but in the field of nanotechnology, researchers at the Chinese University of Hong Kong developed DH-TPL Digital Holography- based Two Photon Litography (Balena et al., 2023). This three-dimensional laser nanoprinting technology enables the fabrication of complex nano-sized structures at submicron resolution (Ouyang et al., 2023).

The latest research indicates a continuous development of the additive manufacturing industry not only through the development of new equipment dedicated to improve existing technologies but also through the emergence of new materials or 3D printing technologies. Thus, more than 75 (Boca et al., 2022) layer-by-layer or volumetric approaches (described in later chapters) for macroscopic and microscopic 3D printing can be identified.

2.2 Misconceptions related to the actual 3D printing

Although it is ingrained and used globally in a strict sense, 3D printing is in reality 2.5D printing (Gebhardt, 2003) because 2D layers or contours are made strictly in one plane (in most cases X- Y plane) and movement along the Z-axis is gradual, with a height corresponding to the height of the layer. Also, in a more simplified way the slicing software (CAM software required for all additive technologies) converts the 3D model into 2D layers along the transverse axis Z (Georgantzinos et al., 2021).

One way to take advantage of the Z-axis in conjunction with the X- and Y-axes is a technique called non-planar printing (Ahlers, 2018), Curved Layer Fused Deposition Modeling- CLFDM/CLFFF or non-horizontal printing (Chakraborty et al., 2008; Singamneni et al., 2012; Llewellyn-Jones et al., 2016), active-z printing (Khurana et al., 2017) and 'true 3D printing' (O'Connell, 2021).

One of the first papers addressing the aspects of the transition from flat to slightly curved layers is that of Chakraborty and collaborators in 2008. They use 3-axis CNC equipment dedicated to the FDM process in which the control method of the movements (printing table and printhead) is converted from *2C,P* (material deposition due to the movement along the X and Y axis and a point-by-point along the Z axis) to *2C,L* (similar

X and Y axis control but a linear interpolation control of the Z axis). They and Huang & Singamneni (2015) also recommend alternating the printing direction, for the upper curved layers, to reduce intrinsic porosity between layers and to increase isotropy of the continuous material string.

In 2012, Singamneni et al. presented research for the deposition of curved FDM printed ABS layers, for the fabrication of thin shell-shaped parts. Their CLFDM approach includes (Singamneni et al., 2012) the generation of surface points data using G&M code processing in a Computer Aided Manufacturing (CAM) module or through processing the part.stl file and subsequently, using of this point cloud data and an offsetting algorithm to generate curved layers. Two years, later Huang & Singamneni continue previous research focusing only on.stl file processing. They divide the FDM printed part domain into two distinct regions: adaptive curved layer on top and the flat layers at the bottom of the part. By using the mixed-layer approach (Huang & Singamneni, 2015), they obtained a scaled portion of an aircraft wing with improved surfaces and internal micro-structures and increased printing time compared to the classical flat-layer approach.

In 2016, Llewellyn-Jones et al. use an automated method for the generation of concave and convex layer to produce 3D printed components, such as vehicle body panel, shoe insole and dished sandwich panel. Similar to the previous cases, using a script written in MATLAB, they take the.stl file of the part and generate separate G-code files for each component (Llewellyn-Jones et al., 2016) of the printed part (e.g., scaffold structure which is printed with conventional static z layers and upon which the curved layer (buffer layers, or model skins) model will be printed using dynamic z-values). The difference is that they use and recommend a Delta printer instead of a Cartesian printer to combat speed differences along the X and Y axis versus the Z axis.

In the same year, Micali & Dornfeld (2016) come up with a different approach to the ones presented above. Their work also focuses on eliminating the stair-stepping artifacts in FFF technology on standard 3-axis equipment. To do so, they generate an inverse toolpath offset that can follow wavy/free surfaces and predict collision. Thus, the nozzle geometry also allows entrance into narrower regions, steeper inclines and a smoother surface due to nozzle sliding on the printed perimeters.

In 2017, Khurana et al., use active z-printing to get stiffer and stronger parts. They use (Khurana et al., 2017) two STL files (one for the main part and another with curved profile) and the open-source Bread slicing software (Parker, 2018) to generate the 3d printhead paths. They use a script in MATLAB to eliminate some of the problems (e.g. unnecessary travel movements that increased printing time and caused collisions) caused by the early stage of Bread slicer software development.

A major contribution to this non-planar printing took place in 2018, in Daniel Ahlers' master thesis from the University of Hamburg in Germany (Ahlers, 2018). The first step in achieving these curve profiles is to modify the FFF 3D printers to allow the print head to move freely up/down and right/left during material extrusion. Avoiding collision of the printing head components (nozzle, fans, air ducts, heating block, bed level sensor) with existing printed sections can be achieved by using a longer hot end and/or a nozzle (Kupol, 2020) longer than conventional ones (the height of the outer cone is increased and its angle is reduced). Since active cooling of the printed raster is still required, the fans and air ducts must be readjusted. Ramírez-Gutiérrez et al (2020) propose even a unique adaptable base which brings advantages to the fabrication of curved-layered structures. It should be mentioned, however, that the printing is done using the 2.5D method to obtain a base and the first curved surface of the part (Ahlers, 2018; O'Connell, 2021). Therefore the stair-stepping effect is still to be expected. Only after that, the actual free printing on the previously obtained structure can begin. The second and equally important step is to generate the toolpath in the altered version of the Slic3r slicing software on Linux (O'Connell, 2021).

At the beginning of the process of creating collision-free nonplanar surfaces, information about the printer configuration (nozzle angle and the height of the printhead hardware) must be added, regardless of whether or not the printer has been modified. Since this entire project is public, all the information and files required are available online on the Github platform, under the name: Slic3r NonPlanar Slicing (Ebert, 2017).

Due to the open source nature of the project, all data can be used as is or modified as preferred. Some versions of the slicing software capable of non-planar printing for Windows have also been released due to the interest of some independent developers (Mbartlett, 2019). A similar phenomenon occurred with the introduction of the Creality CR-30 belt printer, also known as Naomi Wu's 3DPrintMill (Sink 2021). First launched as a Kickstarter project in November 2020 (Creality, 2021), the design of the 3d printer was created as a result of collaboration between Shenzhen Creality 3D Technology Co, Ltd. and three online community members.

In all the above papers and few others (McCaw & Cuan-Urquizo, 2018; Nisja et al., 2021), this printing method is available for 3-axis equipment dedicated to FFF/FDM technology. However, in the literature there is also a way to obtain curved layers using LOM technology. Klosterman et al. (1999) named the Curved Layer Laminated Object Manufacturing- CLLOM process and use materials such as monolithic ceramic and ceramic matrix composites to create shell-type objects.

2.3 How materials and equipment brought three new dimensions in additive manufacturing

The first way to implement a new dimension in 3D printing is through the materials selection rather than the equipment. Three-dimensional models are thus printed on regular 2.5D printers and designed to change shape, property and functionality over time. 4D printing is characterized by the ability of the parts to self-transformation, self-assembly (Tibbits & Cheung, 2012), self- sensing, self-adaptability (Khoo et al., 2015) or self-healing (Wang et al., 2018)/ self-regeneration. Shape changes manifest themselves through folding, expansion, shrinkage, twisting while self- healing through rebuilding of the polymer chains of the printed parts. Therefore, *time* is considered that the 4th dimension (Georgantzinos et al., 2021; González-Henríquez et al., 2019).

These so-called smart materials (SMs) or stimulus-responsive material (SRM) (Tzo et al., 2004) are able to respond in a reversible way to external stimuli variations (Roy & Gupta, 2003; Leist & Zhou, 2016) such as temperature, light, humidity, pressure, pH, magnetic field, electrical current, electrostatic interaction, solvents, Ca^{2+}, Mg^{2+}, radiation (UV and IR), ultrasound, etc. SMs can be classified into (Maheswari et al., 2022; Kamila 2013) piezoelectric materials, shape memory materials (SMM), magnetostrictive and magnetorheological materials, electrorheological fluids, chromoactive materials, optical fibres and photoactive materials. The most popular and common SMs in additive manufacturing are those with shape memory. These SMM can be divided (González-Henríquez et al., 2019), also, into shape memory alloy (SMA), polymer (SMP), hybrid (SMH), ceramic (SMC), gel (SMG) and of course, composite (SMc). Although SMPs first appeared in 1984 in Japan, they have experienced accelerated growth and increased interest from the research community. By using laminate form polymers, by combining two polymeric materials or combining the resulting polymer matrix with additive material, multiple controllable and reversible shape changes (Multi-Way Shape Memory Effects MW- SME or two way shape memory effects 2W- SME) can be achieved (Basit et al., 2013; Scalet, 2020). Due to the thorough design of the shape memory composition a dual shape changes or a response to multiple stimuli is enabled (Fu et al., 2018; Roy & Gupta, 2003). Dual-Stimuli-Sensitive Polymers can respond to a combination of stimuli such as light and temperature (Kurihara et al., 1998), pH and temperature (Gan et al., 2000), Ca^{2+} and acetonitrile or temperature.

Shape memory polymer blends typically (Kurahashi et al., 2012) consist of a network polymer containing physical or chemical crosslinks for the permanent phase, and the other amorphous or crystalline polymer playing the role of fixing the reversible/switching phase. In practice filaments such as Facilan™ PCL 100 Filament (3D4Makers, 2023) can be found on the market but it is more common to produce them. Such SMP blends are: polylactide PLA70/ thermoplastic poly(ether)urethane TPU30/CB (Qi et al., 2017), PLA85/poly(ether)urethane PU15/CB (Xiu et al., 2016), poly(ethylene vinyl acetate) EVA60/ poly(ε-caprolactone) PCL40/CNT (Zhang et al., 2016), poly(propylene carbonate) PPC70/PLA30/MWCNTs and PPC50/PLA50/MWCNTs (Qi et al., 2016), Poly(methyl methacrylate) PMMA/ poly(ethylene glycol) PEG (Liu et al., 2005), poly(vinyl chloride) PVC+PCL/TPU (Jeong et al., 2001) etc. The most popular nano-fillers (Ni et al., 2007; Mather et al., 2009) are carbon nanotubes (CNTs), carbon black (CB) nanoparticles, carbon nanofibers (CNFs), multiwalled carbon nanotubes (MWCNTs) but also nano-silica dioxide SiO_2 (Yan et al., 2013), silicon carbide (SiC) nano-particles (Gall et al., 2004) and magnetite (Fe_3O_4) (Razzaq et al., 2007) can be used.

In order to achieve dynamic rather than static structures, 4D printing diverges from classical printing (2.5D or non-planar) through the mandatory use of multi-materials, external stimulus and mathematical models and/or finite element analysis FEA (González-Henríquez et al., 2019). SMs multi-materials are the fundamental element underlying the change in shape because the differences in the materials physical properties. The stimuli provide the energy needed to trigger phase/morphological/structures changes and the mathematical model predict the changes in the final part. Such a mathematical model and FEA is presented by Ge et al. (2014) and Mao et al., (2015), and serves as guidance for the selection of process and design parameters required for 4D prototyping. They use it to print flat polymer sheet with active composite hinges and apply it for self-assemble active origami structures (e.g. a box, a pyramid, and three or five hinge airplanes). With thoughtful design, multi-material assemblies capable of responding to different sensors can be achieved. One such example is the artificial insect controlled by multi-stimulus (magnetic waves, light and electric field) of Khare et al (2017).

The concept of *4D printing* was first introduced by Professor Skylar Tibbits (Founder and co-director of the Self-Assembly Lab at Massachusetts Institute of Technology- MIT) (Ly & Kim, 2017) in 2013. He initially worked with Stratasys Comp. to introduce two composite materials capable of changing shape when placed in water (one chain like object spelled MIT while the other morph into a wire frame cube).

Over time, this approach has been used in printing with electroactive polymers EAPs of dielectric elastomers or membrane actuators DEAs (Bar-Cohem, 2010; Rossiter et al., 2009) for soft-robots, printing of planar electronics that can electronically transform into nonplanar geometries at room temperature (Sundaram et al., 2017), 4D printing of SMPs self-interlocking components (Yu et al., 2015) which can react rapidly to a thermal stimulus and precisely change back the shape, 3D printing of piezoelectric device which can response to a finger-tap (Bodkhe et al., 2017; Chen et al., 2016), fabrication of parts able to mechanically (stretching, pressure) or chemically (pH) activate a chemical reaction which enable a colour change in the mechanochromic material (Peterson et al., 2015; Weder, 2011), smart valve able to respond to a hot/cold flow (Bakarich et al., 2015) or an acidic/basic flow (Nadgorny et al., 2016) proposed a 4D computed tomography approach which aim to reduce the exposure to radiation of patients, 4D food printing (Ghazal et al., 2022), 4D bio-printing of vascular endoprosthesis (stents) implant (Zhou et al., 2021; Wang et al., 2022a) and tracheal stent with thermal responsive material (Zarek et al. 2016), pH and thermosensitive medical device used for drug delivery (carrying and releasing) application (Gazzaniga et al., 2023; Sheikh et al., 2022).

The high interest in these applications is not only from the research community but also from companies and institutions such as (Reddy & Devi, 2018): U.S. Army Research Center, Stratasys, Ltd., Dassault Systemes S. A., NASA, Airbus SAS (France), Materialise NV, Massachusetts Institute of Technology, Hewlett-Packard, Inc., Briggs Automotive Company Ltd. (U.K.) and 3D Systems Corporation.

Unlike the non-planar approach and 4D printing, *5D or 5-axis printing* is more related to the type of movements the equipment can make. The method was first proposed by William Yerazunis, Ph.D., Senior Principal Research Scientist at Mitsubishi Electric Research Labs- [MERL] (Haleem & Javaid, 2019). The aim of this project was to obtain stronger components (on the whole surface of the part or where it is necessary), with a more complex design (including obtaining curved surfaces) and all this with a lower material consumption compared to traditional approaches. All this was achieved by adding two additional movements (rotations) of the printing platform of a FFF dedicated 3D printer.

Therefore, usually in addition to the three linear movements around the X- Y- Z-axis, a rotation A around the X and a rotation B around the Y-axis is also possible. These rotations make it possible to print curved layers more easily and without the need for or with a minimum amount of support structures (printing over an already printed surface can be facilitated considerably). At the same time, by using interwoven layers and eliminating the printing of flat layers, it is possible to obtain parts that are stronger (especially in the case of tensile forces with directions perpendicular to the printing direction), more aesthetic (with complex shapes and intricate geometries) and with reduced material consumption.

Similar to the configuration of conventional equipment and in the case of 5D printing, different approaches of displacements and rotations can be considered: either the printing platform is “fixed” and the print head performs the Z-axis displacement and the A and B rotations or the print head is “fixed” and the printing table (implicitly the printed part) rotates around the X and Y axis.

This technology is expected to bring new innovations and new users from dentistry (dental implants, crows, aligners, orthodontic braces and models) (Haleem & Javaid, 2019; Haleem et al., 2018), aerospace industry and medicine (surgical aids, gauges and implants) (Vshaper, 2023a).

Objects with steep overhangs can be printed (without the need of support structure) using multi-direction toolpath planning (Ahlers, 2018) or multi-axis material extrusion by curved layer slicing CLS (Kubalak et al., 2017). Such multi-direction slicing of CAD models were generated by Ding et al. (2015) for a five-axis robotic wire-feed additive manufacturing. The strategies presented in their study (volume decomposition and sub-volume regrouping) were implemented by programs written in Matlab.

Other algorithms capable of automatically slicing 3D models in multi-direction layers (without or with min. support structure and collision-free) for Layered Manufacturing technologies are: silhouette edge projection and offset slicing (concepts implemented in C++) (Singh & Dutta, 2001; Singh & Dutta, 2008), Multi-Orientational Deposition MOD algorithm (implemented using C++) (Yang et al., 2003), centroid axis computation (implemented in VC++ using and ACIS geometry kernel) (Ruan et al., 2006), normal marching algorithm (for 5 axis Laser Aided Manufacturing Process- LAMP) (Zhang & Lio, 2001), skin generation algorithm (Kubalak et al., 2017), skeleton method (for Laser-Based Direct Metal Deposition) (Eiamsa et al., 2001), adaptive spatial decomposition (enhance the performance of the centroidal axis method) (Ren et al., 2008) and adaptive slicing (for Hybrid Plasma Deposition and Milling- HPDM technology) (Xiangping et al., 2014).

In 2018, Ethereal Machines Halo, a 3D printer and milling machine that operates on 5-axes, received a CES award for the Best of Innovation Honoree in the category of 3D printing (Haleem et al., 2018). Other 5 axis hybrid printer on the market are 5AxisMaker’s CNC (a desktop machine that offers both milling and 3D printing, launched on Kickstarter in 2014) (5AXISWORKS, 2023), CY1000 (robotic manufacturing cell for insulated wire deposition, bare wire deposition, polymer deposition, printing of electronic components and pick and place operations) (Q5Technologies, 2023), 5AX Machine (5 axis industrial FFF printer with a rotary-tilt heated-vacuum- building platform, actively heated chamber and additional finishing and probing tool) (Vshaper, 2023b), University of Oslo's Pentarod 5 axis FFF printer (a modified version of the RepRap Ormerod, developed by a master student named Øyvind Kallevik Grutle) (Grutle, 2015) and Opex5x (an open-source project started by a team at Imperial College London, dedicated to converting the Prusa i3 3D printer into a 5-axis FFF printer) (Hog et al., 2022).

Still a domain waiting to be developed to its full potential, so far the only limitations of this technology are the extra cost of equipment (purchase, manufacturing, maintenance) and the need for skilled operators (Haleem & Javaid, 2019). W. Yerazunis stated in an interview that "5D printing does require a lot of analysis and it does require knowing how the part will be used. But when you can make a part that's five times stronger, that really changes how you think about 3D printed parts." (MERL, 2017).

As a natural next step in the evolution of additive manufacturing, the concepts of 4D and 5D printing are being combined into one, to take the advantages of both approaches. Georgantzinos et al. describe the idea of *6D printing* for the first time (Vasiliadis et al., 2022) in 2021 and refers to it as "a child born from the marriage between a five-axis printer of FDM technology and SMs" (Georgantzinos et al., 2021).

Since 4D printing is performed on conventional 3-axis printers, some of the limitations of the layer-by-layer planar approach are inherited by the resulting intelligent components. However, the addition of two additional degrees of freedom (specific to 5D printing) allows the manufacture of SMs components with more complex shapes the use of less raw material, shorter processing/printing time and increased structural integrity, flexibility in design and part functionality.

The printing method also allows the use of intelligent raw materials with nano-inclusions, nano-fillers and nano-reinforcements. These special composite materials (presented above, in the 4D section of this sub-chapter) already offer the possibility of obtaining parts with dual shape modifications. Due to the advantages of 5D printing and an optimal design, it is expected to manufacture SMs with the possibility of at least three shape transformations.

Involving smart materials into 6D printing, can lead to custom-made orthopedic casts that are capable of providing mechanical corrections of the arm or foot. There will be no need of weekly cast replacement because the smart material will change the shape over time, becoming tighter or looser according to the affected limb condition. As an example, the "smart cast" (Vasiliadis et al., 2022) can be a great solution for the most common congenital orthopedic foot deformity also known as clubfoot (Ganesan et al., 2017). By using this dual approach innovations will emerge in areas such as medicine (prosthetics, orthopedics, dental, custom-made implants) construction (pipes capable of changing their diameter and shape as a result of the introduction of a fluid), aerospace engineering, food sector and manufacturing.

Similar to 5D and 6D printing can be achieved by introducing more degrees of freedom at the detriment of using smart materials. By using this approach, the printer head has the ability to move around from six different angles or less, and the additional moves an rotation, at defined angles, are done by the mobile printing platform (including the printed part).

To achieve the required 6 degrees of freedom, modifying a conventional 3-axis printer can be an arduous, costly and time-consuming problem (ZHAW, 2016), which is why 6-axis CNCs or robotic arms and adapters for printing heads are preferred (e.g. Trumph 1000W CW laser and a coaxial powder head mounted on Kuba robot (Pinkerton, 2010) and 6- axis robotic-end effector and KUKA robot arm for ABS printing (Shi, 2014)). Especially, robotic arms have the benefits of speed, agility and flexibility in printing (Ding et al., 2015; Vasiliadis et al., 2022; Kubalak et al., 2018) and their control is already known before the advent of 3-, 5- or 6D printing concepts.

In practice (at industrial level) technologies such as Direct Metal Deposition DMD™, Laser Engineered Net Shaping LENS™, Laser Powder Fusion LPF™, AREVO polymer Directed Enerrgy Deposition DED, Continous Fiber Coextrusion CFC system are performed on 5 or 6-axis systems (with or without an additional rotary axis for the printing platform), and with the help of a 6-axis comprehensive CAM software (Dutta et al., 2011; Aero, 2023; Anisoprint, 2023). Such examples of printing systems are the DMD 105D/505D (5-axis equipment on CNC platform), DMD 44R/66R and DMD IC106 (6-axis industrial robot), LENS® 860 (rugged CNC platform with til-rotate printing platform), LENS 850R (5-axis gantry system coupled with a tilt-rotate platform), HP- 115 and HP- 205 (fully automated 5-axis powder deposition systems), AREVO® AQUA System (6-axis robotic arm), Anisoprint PROM PT (a 6-axis robot arm Continuous Carbon Fiber- CCF Printing system in development) etc.

2.4 Elimination of the layer-by-layer approach

The necessity to overcome the problems associated with the layer-by-layer approach led the scientific communities, along with some companies to develop new concepts, namely volumetric (holographic printing or multi-beam AM) (Rodríguez-Pombo et al., 2022) and tomographic printing. These new approaches allow the fabrication of macro-, mico- or nano- scale 3D components in a much shorter time by free deposition and/or dispensing of droplets or strands/ribbon of liquid/paste/ink material, (Parupelli & Desai, 2019) or by projecting a hologram, patterns or several laser beams inside an enclosure or VAT with photosensitive material. The first methods referring to the sequential manufacture of a product by direct deposition (Direct Writing DW) of material are presented below. Later new concepts emerge into volumetric and tomographic additive methods, which allowed parts to be produced “at once” (Hoeben, 2022), namely by selectively solidifying/curing voxels (the 3D equivalent of a 2D pixel) (Kety, 2021) inside a vat filled with photosensitive resin.

Early means of rapidly manufacturing components:

- *Matrix Assisted Pulsed Laser Evaporation*-MAPLE DW: A pulsed laser is induced through a ribbon (double layer material made of a laser transparent material coated with a viscous material of interest/ink) to eject/transfer the ink onto the substrate (Piqué et al., 2003). Also, micro-machining is possible by allowing a direct interaction between the laser and the substrate) (Parupelli & Desai, 2019);
- *Laser Chemical Vapor Deposition* LCVD: A guided laser beam is used to induce a chemical reaction in a reactant in order to deposit thin films of various materials (metals, ceramics, insulators, semi-conductor etc.) on the surface of a substrate (Elliott, 1995). Three-dimensional parts can be obtained in two ways, depending on the mechanism that triggers the chemical reaction. Consequently LCVD technology can be separated into two categories, namely (Duty et al., 2001; Piqué & Christey, 2001) pyrolytic (thermal energy of the laser beam is used to heat the substrate surface to the temperature necessary to initiate the chemical reaction) and photolytic (photons from the laser beam are used to break the chemical bond within the reactant gas).
- *Dip-pen Nanolithography* DPN: is the first macroscopic DW- SPL (Scanning probe Lithography) technology involving the use of an atomic force microscopy mechanism to deposit molecular patterns (from certain inks, e.g. alkanethiols, biological molecules like DNA, viruses, and proteins, polymers, and nanoparticles) on the surface of a substrate (Krivoshapkina et al., 2016; Piner et al, 1999). Other variations of SPL technologies are 3D nanoprinting Atomic Force Microscopy AFM or AFM Nanolithography (Ventrici de Souza et al., 2018; Obermair et al., 2011), 3D nanoprinting Scanning Tunneling Microscopy STM (Liu et al., 2016; Plank et al., 2020), 3D nanoprinting Scanning Probe Microscopy SPM (Garcia, 2020; Dietrich et al., 2019), 3D nanoprinting Focused Electron Bean Induced Deposition 3D-FEBID (Seewald et al., 2022; Plank et al., 2019), electrochemical probe microscopy SEPM (Oswald et al., 2022), Fountain-pen Nanolithography FPL (Lewis et al., 1999; Kkim et al., 2005), Fluidic- Enhanced Molecular Transfer Operation FEMTO (Vengasandra et al., 2005), thermochemical Nanolithography TCNL (Szoszkiewicz et al., 2007), Polymer-Pen Lithgrophy PPL (Huang et al., 2010; Huo et al., 2008);
- *Solvent-Cast Direct Writing SC- DW*: being a method based on Direct Writing extrusion principle, the thermoplastic material is extruded through a nozzle and deposited on a substrate. The major difference between this technology and those presented above is that the base material is mixed with a evaporable solvent which allows the ink to solidify quickly (Balani et al., 2021). Thus it is possible to print parts without the need for a support structure for bone and tissue engineering (Dong et al., 2020; Omidia-Anarkoli et al., 2019), from PLA for Isotropic thin film fabrication (Singh et al., 2019), from and for intelligent materials applications

(Wan et al., 2019), polycaprolactone PCL based ink for biomedical and prosthesis applications (Camacho et al., 2019; Geisendorfer & Shah, 2019) and for electronic or electric applications (Hardin et al., 2019).

A new printing concept, developed by researchers at North Carolina State University, emerged in 2013 in the field of micro-component manufacturing called *Direct-Write 3D Liquid Metal- DW 3D LM* (Ladd et al., 2013a; Neumann & Dickey, 2020). In contrast to *Laser based Direct Writing- LDW* (Arnold et al., 2011; Schiele et al., 2010), manufacturing is carried out at room temperature and does not require auxiliary systems or laser sources to melt the metal. DW 3D LM enable the formation of stable structures (using a syringe) in a liquid medium due to the passive oxide layer/film (~1 nm thick) on the surface of the low-viscosity liquid metal (gallium alloy). Thus wires with a diameter of 270 µm and a height of 8 mm can be obtained as well as complex or free-standing shapes with a size ranging up to 10 µm (cylinders, 3D drop arrays, arcs, spheres, etc.) (Ladd et al, 2013b).

Both before and after, variations of direct printing with liquid metal has proven to be an effective method in various applications such as: printing of wireless wearable flexible microfluidic device (Koh et al., 2016) capable of capturing, measuring and storing quantitative values for sweat rate, total sweat loss and colorimetric readouts (pH, concentration of lactate, glucose, chloride and hydronium ions), epidermal heat flux sensors for continous noninvasive measurement of core body temperature, electronic skins e-skins (Wang et al., 2015) with liquid metal circuits- LMCs (Guo et al., 2018a) (wearable electrocardiogram ECG for physiological signals monitoring), omnidirectional printing of flexible, stretchable and spanning silver (silver nanoparticle ink) microelectrodes for electronic and optoelectronic devices (Ahn et al., 2009), multi-layer highly-stretchable strain sensors with integrated readout liquid metal paste circuitry (Votzke e tal., 2019), wireless wearable healthcare monitors (puls wave measurement) using directly-printed Ni-GaIn amalgams (Guo et al., 2018b), multylayer microstrip patch antenna (Hayes et al., 2012) (multilayer liquid eutectic gallium-indium- Ega-In encased in an elastomer), conformal printed hemispherical small antennas (tapered liquid silver meander line affixed to patterned cooper feed lines on a low-loss laminate substrate) (Adams et al., 2011), and many other flexible/stretchable wearable electronics (Lin et al., 2023; Bao et al., 2016; Gao et al., 2012; Boley et al., 2014).

Later, truer and more complex volumetric and tomographic technologies emerge on the market and between the research community. In 2017, as a result of the collaboration between MIT (MIT's Self-Assembly Lab) and Steelcase Inc. (Michigan, U.S.A.), a new process of rapid additive manufacturing in liquid/gel environment was born, named *RLP Rapid Liquid Printing* (Charbauski, 2023; Rapid, 2023). It is used to produce components (especially furniture parts) on a large scale ("with a large enough tank, the process can create objects of any size"- Simon-Lewis, 2017) with high precision, with quality industrial materials in minutes (Rapid, 2023). The major difference between classical additive manufacturing technologies and RLP (is that the part is produced in a liquid suspension (gel with the consistency of a hand sanitizer or hair gel) by direct extrusion/injection of the material (plastic, metal, ceramic, elastic materials, etc.) to form composites rather than the classical layer-by-layer approach (Simon-Lewis, 2017; Hajash et al., 2017).

However, the technologies that are best known or have attracted the most attention are Readily3D S.A.'s 3D tomographic printing and Xolo3D's volumetric printing called Xolography. Emerged in 2017 and developed by researchers from the Ecole Polytechnique Fédérale de Lausanne (the future founders of Readily3D S.A.) the tomographic approach allows 3D photo-polymerization (using shaped light beams from multiple angle) for direct printing of a desired part. Simultaneous illumination of the entire building volume allows for build times in the order of seconds and parts as small as a few centimetres (Readily, 2023; Hoeben, 2022) without the need for support structures. Xolography or linear volumetric 3D printing (Regehly et al., 2020), originally developed in 2019, allows a material with photoswichable molecules, to be accurately solidified at the intersection of two light rays of different colours. The difference between this technology and conventional ones such as SLA/DLP/LCD is that the planar printing area is moved continuously and at speed inside a vat of material as opposed to the slow movement of material inside the tank followed by the exposure of layers (Kety, 2021).

Other volumetric, toographic and DW technologies available on the market or under development are: *Computed Axial Lithography* (University of California) (Kelly et al. 2019; Wang et al., 2022b), *Stanford 3D printing* (developed at Stanford University and Harvard University) (Sanders, 2022), *Ultrafast volumetric 3D bioprinting* (University Medical Center Ultrecht and École polytechnique fédérale de Lausanne) (Bernal et al., 2019), FluidForm's *FRESH™ 3D bioprinting* (Fluidform, 2022), *Scaffold-free 3D bioprinting* (University of Illinois at Chicago) (Jeon et al., 2019), *FabRx Volumetric printing system with DLP projector* (colaboration between University College London, University of Santiago de Compostela, MERLN Institute for Technology-Inspired Regenerative Medicine, and pharmaceutical 3D printing specialist FabRx Ltd.) (Rodríguez-Pombo et al., 2022), *micro-CAL* (Lawrence Livermore National Laboratory and University of California) (Toombs et al., 2022), *tomographic volumetric additive manufacturing* (Madrid-Wolf et al., 2022), *Continous Inkjet CJ- DW manufacturing process* (Desai & Lovell, 2012), *Aerosol Jet DW* (Rosker et al., 2020), *Digital Holography- based TPL- Two Photon Litography or Ultrafast 3D nanofabrication via digital holography* (Ouyang et al., 2023), *Two-Photon-Polymerization Direct Laser Writing TPP- DLW* (Gissibl et al., 2016), *Micropen by Exxelia* (Exxelia, 2023) and *Beam Based DW- Focused Ion Beam FIB* (Edinger, 2002).

3. CONCLUSION

In the present paper, a short review of AM techniques has been conducted, along with applications and materials specific to some of them. Since its origin, additive manufacturing has undergone an accelerated evolution from short stories in science fiction novels or timid and unsuccessful attempt to create a three-dimensional object, to development of over 75 technologies, to being part of the latest industrial revolution, known as Industry 4.0.

The production and global market value of plastics has reached its peak in recent years and is expected to grow exponentially in the coming decades. Although injection moulding holds the largest market share (43.38% in 2022, followed by extrusion moulding) of plastics processing techniques, 3D printing is also growing with increasing interest from companies. As opposed to classical technologies, due to the low cost of equipment and materials dedicated to additive technologies, both the research community and independent/home/hobbyist users have come up with their own ideas and ways of improvement that have massively contributed to the growth and development of 3D printing (e.g. Creality CR-30 belt printer with “infinite X-axis”, thousands of free 3D models ready to print on dedicated websites, non-planar printing, RepRap open source initiative etc.).

Although it is ingrained and used globally in a strict sense, 3D printing is in reality 2.5D printing, since the slicing software converts the 3D model into 2D layers along the transverse axis Z (hence the name layer-by-layer). Approaches that can benefit from all 3 axes are called ‘true 3D printing’, non-planar printing, Curved Layer Fused Deposition Modelling- CLFDM/CLFFF, non-horizontal printing and active-z printing. Such applications can be achieved by using a 3-axis CNC machine and converting the Z-axis point-to-point movements into linear movements either by using special algorithms designed to separate the part into individually sliced components, or by using CAM software capable of allowing planar slicing of the part followed by a non-planar coating of the upper surfaces.

Unlike non-planar printing, 4D printing with smart materials (especially shape memory material) received a huge interest from the research community and is used for a multitude of applications in different field. In many of these cases the actuation or shape change triggering is done without any additional equipment such as wires, batteries, or electric motors. In addition to components capable of transforming themselves in response to external stimuli, adding new dimensions to 3D printing is achieved using multi-axis equipment. This has resulted in 5D printing and, as a final evolution, 6D printing (which can also result from combining 5D and 4D printing).

The problems (high printing times, surface quality, structural integrity and mechanical properties) associated with the deposition of material or adhesives layer by layer associated with conventional printing can be overcome with the help of direct writing concepts and in particular by implementing volumetric or tomographic approaches. They allow the fabrication of components all-at-once by projecting a hologram, patterns or several laser beams inside an enclosure or VAT with photosensitive material or by free deposition and/or dispensing of droplets or strands/ribbon of liquid/paste/ink material.

Given the rapid developments and changing trends (increased interest in plastics followed by an increase in additive manufacturing methods with metallic materials, printing with smart materials, development of bioprinting, increasing sustainability of processes) over the years it is hard to predict what will happen to 3D printing or what form it will take in 10, 5 or even a year. Despite these advances, there are still some challenges to be overcome but it is clear that: 3D printing which started as a means of prototyping has become a tool for either mass production or for unique or customized products, new faster and more reliable equipment, materials and accessories will come onto the market, multi-dimensional printing will gain popularity due to the high levels of flexibility in design, efficiency and structural integrity of components, implementation in even more biomedical applications (manufacturing of stretchable-flexible-wearable medical devices and tissue deposition for organs printing) etc.

REFERENCES

Adams, J.J., Duoss, E.B., Malkowski, T.F., Motala, M.J., Ahn, B.Y., Nuzzo, R.G., Bernhard, J.T., & Lewis, J.A. (2011). Conformal Printing of Electrically Small Antennas on Three-Dimensional Surfaces. *Advanced Materials*, *23*(11), 1335–1340. https://doi.org/10.1002/adma.201003734

Ahlers, D. (2018). *3D Printing of Nonplanar Layers for Smooth Surface Generation*. https://www.researchgate.net/publication/335542650_3D_Printing_of_Nonplanar_Layers_for_Smooth_Surface_Generation

Ahn, B.Y., Duoss, E.B., Motala, M.J., Guo, X., Park, S., Xiong, Y., Yoon, J., Nuzzo, R.G., Rogers, J. A., & Lewis, J.A. (2009). Omnidirectional Printing of Flexible, Stretchable, and Spanning Silver Microelectrodes. *Science*, *323*(5921), 1590–1593. https://doi.org/10.1126/science.1168375

Amon, C.H., Beuth, J., Weiss, L., Merz, R., & Prinz, F.B. (1998). Shape Deposition Manufacturing With Microcasting: Processing, Thermal and Mechanical Issues. *Journal of Manufacturing Science and Engineering-transactions of the Asme*, *120*(3), 656–665. https://doi.org/10.1115/1.2830171

Anas, S., Khan, M.S., Rafey, M., & Faheem, K. (2021). Concept of 5D printing technology and its applicability in the healthcare industry. *Materials Today: Proceedings*, *56*, 1726–1732. https://doi.org/10.1016/j.matpr.2021.10.391

André, J. (1984, July 16). *FR2567668A1 - Dispositif pour realiser un modele de piece industrielle*. https://patents.google.com/patent/FR2567668A1/fr

Anisoprint. (2023). *Desktop Anisoprinting*. https://anisoprint.com/solutions/desktop/

Aero. (2023). *Arevo*. https://arevo.com/products/aqua?lang=en

Arnold, C.B., Serra, P., & Piqué, A. (2007). Laser Direct-Write Techniques for Printing of Complex Materials. *Mrs Bulletin*, *32*(1), 23–31. https://doi.org/10.1557/mrs2007.11

ASME. (2016). *3D Systems' First 3D Printer named Historic Mechanical Engineering Landmark by ASME*. https://www.asme.org/about-asme/media-inquiries/press-releases/3d-systems-first-3d-printer-named-historic-mechani

Aysha, M. (2020). *Thermwood develops a process for large format vertical 3D printing*. https://www.3dnatives.com/en/thermwood-010920206/

Bakarich, S.E., Gorkin, R., Panhuis, M.I.H., & Spinks, G.M. (2015). 4D Printing with Mechanically Robust, Thermally Actuating Hydrogels. *Macromolecular Rapid Communications*, *36*(12), 1211–1217. https://doi.org/10.1002/marc.201500079

Balani, S.B., Ghaffar, S.H., Chougan, M., Pei, E., & Şahin, E. (2021). Processes and materials used for direct writing technologies: A review. *Results in Engineering*, *11*, 100257. https://doi.org/10.1016/j.rineng.2021.100257

Balena, A., Bianco, M., Pisanello, F., & De Vittorio, M. (2023). Recent Advances on High-Speed and Holographic Two-Photon Direct Laser Writing. *Advanced Functional Materials*, 2211773. https://doi.org/10.1002/adfm.202211773

Bao, Z., & Chen, X.D. (2016). Flexible and Stretchable Devices. *Advanced Materials*, *28*(22), 4177–4179. https://doi.org/10.1002/adma.201601422

Bar-Cohen, Y. (2010). Electroactive polymers as actuators. In *Elsevier eBooks* (pp. 287–317). https://doi.org/10.1533/9781845699758.1.287

BCN3D. (2022). *BCN3D: Viscous Lithography Manufacturing (VLM) 3D printing technology*. https://vlm.bcn3d.com/

Basit, A., L'Hostis, G., Pac, M., & Durand, B. (2013). Thermally Activated Composite with Two-Way and Multi-Shape Memory Effects. *Materials*, *6*(9), 4031–4045. https://doi.org/10.3390/ma6094031

Beck, J.D., Prinz, F.B., Siewiorek, D.P., & Weiss, L.E. (1992). Manufacturing Mechatronics Using Thermal Spray Shape Deposition. *1992 International Solid Freeform Fabrication Symposium*. https://doi.org/10.15781/t23n20x5t

Bernal, P.N., Delrot, P., Loterie, D., Li, Y., Malda, J., Moser, C., & Levato, R. (2019). Volumetric Bioprinting of Complex Living-Tissue Constructs within Seconds. *Advanced Materials*, *31*(42), 1904209. https://doi.org/10.1002/adma.201904209

Birdseye, S.H. (1956). *US2961772A - Apparatus for making three-dimensional reliefs*. https://patents.google.com/patent/US2961772A/en

Blanther J.E. (1892, May 3). *US473901A - Manufacture of contour relief-maps.*. https://patents.google.com/patent/US473901A/en

Boca, M., Sover, A., & Slătineanu, L. (2022). Use of the 3-Level Idea Diagram Method to Identify Constructive Solutions for the Development of a Thermoforming Mould. *Bulletin of the Polytechnic Institute of Iași. Machine Constructions Section*, *68*(4), 9–22. https://doi.org/10.2478/bipcm-2022-0031

Bodkhe, S., Turcot, G., Gosselin, F.P., & Therriault, D. (2017). One-Step Solvent Evaporation-Assisted 3D Printing of Piezoelectric PVDF Nanocomposite Structures. *ACS Applied Materials & Interfaces*, *9*(24), 20833–20842. https://doi.org/10.1021/acsami.7b04095

Boissonneault, T. (2022). *Local Motors installs massive LSAM composite 3D printer to manufacture autonomous Olli shuttle*. https://www.voxelmatters.com/local-motors-lsam-3d-printer-autonomous-olli/

Boley, J.W., White, E.B., Chiu, G.T., & Kramer, R.K. (2014). Direct Writing of Gallium-Indium Alloy for Stretchable Electronics. *Advanced Functional Materials*, *24*(23), 3501–3507. https://doi.org/10.1002/adfm.201303220

Brown, C.O. (1979). *US4323756A - Method for fabricating articles by sequential layer*. https://patents.google.com/patent/US4323756A/en

Camacho, P.S., Busari, H., Seims, K.B., Schwarzenberg, P., Dailey, H.L., & Chow, L.W. (2019). 3D printing with peptide–polymer conjugates for single-step fabrication of spatially functionalized scaffolds. *Biomaterials Science*, *7*(10), 4237–4247. https://doi.org/10.1039/c9bm00887j

Carbon, Inc. (2022). *DLS 3D Printing Technology - Carbon*. https://www.carbon3d.com/carbon-dls-technology

Carolo, L. (2020). *5-Axis 3D Printer: The Latest Advancements*. https://all3dp.com/2/5-axis-3d-printer-the-latest-advancements/

Chakraborty, D., Reddy, B.A., & Choudhury, A. (2008). Extruder path generation for Curved Layer Fused Deposition Modeling. *Computer-Aided Design*, *40*(2), 235–243. https://doi.org/10.1016/j.cad.2007.10.014

Charbauski, R. (2017). *MIT Lab + Steelcase Yield 3D Printing Breakthrough*. https://www.steelcase.com/eu-en/research/articles/topics/culture-talent/mit-lab-steelcase-yield-3d-printing-breakthrough/

Chen, Z., Song, X., Lei, L., Chen, X., Sun, L., Chiu, C., Qian, X., Ma, T., Yang, Y., Shung, K.K., Chen, Y., & Zhou, Q. (2016). 3D printing of piezoelectric element for energy focusing and ultrasonic sensing. *Nano Energy*, *27*, 78–86. https://doi.org/10.1016/j.nanoen.2016.06.048

Cook, B.S. (2014). *Vertical integration of inkjet-printed RF circuits and systems (VIPRE) for wireless sensing and inter/intra-chip communication applications*. https://repository.gatech.edu/entities/publication/27ecfd4d-e701-447d-950b-817b86917ef4

Creality. (2021). *Creality 3DPrintMill(CR-30)- Belt 3D Printing For Everyone*. https://www.kickstarter.com/projects/3dprintmill/creality-infinite-z-axis-build-volume-printer-3dprintmill/description

Crump, S.S. (1989). *US5121329A - Apparatus and method for creating three-dimensional objects*. https://patents.google.com/patent/US5121329

Daedalus, (1974) “Ariadne”. *New Scientist*. 64 (917): 80. ISSN 0262-4079.

Dash, A., Squires, L., Avila, J., Bose, S., & Bandyopadhyay, A. (2023). Influence of active cooling on microstructure and mechanical properties of wire arc additively manufactured mild steel. *Frontiers in Mechanical Engineering*, *9*. https://doi.org/10.3389/fmech.2023.1130407

De Souza, J., Liu, Y., Wang, S., Dorig, P., Kuhl, T.L., Frommer, J., & Liu, G. (2018). Three-Dimensional Nanoprinting via Direct Delivery. *The Journal of Physical Chemistry B*, *122*(2), 956–962. https://doi.org/10.1021/acs.jpcb.7b06978

Deckard, C.R. (1986).*Method and apparatus for producing parts by selective sintering*. https://patents.google.com/patent/US4863538A/en?inventor=Carl+Deckard&oq=Carl+Deckard&sort=old

Desai, S., & Lovell, M.R. (2012). Modeling fluid–structure interaction in a direct write manufacturing process. *Journal of Materials Processing Technology*, *212*(10), 2031–2040. https://doi.org/10.1016/j.jmatprotec.2012.05.006

Devlin, H. (2017). *Scientists create Terminator 2-inspired 3D printer*. https://www.theguardian.com/science/2015/mar/19/scientists-create-terminator-2-inspired-3d-printer

Dickens, P., Pridham, M.S., Cobb, R., Gibson, I.R., & Dixon, G. (1992). Rapid Prototyping Using 3-D Welding. *1992 International Solid Freeform Fabrication Symposium*. https://doi.org/10.15781/t2zw1990v

Dietrich, P., Göring, G., Trappen, M., Blaicher, M., Freude, W., Schimmel, T., Hölscher, H., & Koos, C. (2020). 3D-Printed Scanning-Probe Microscopes with Integrated Optical Actuation and Read-Out. *Small*, *16*(2), 1904695. https://doi.org/10.1002/smll.201904695

Digital, A. (2023). *Joule Printing^{TM} - A radically simple new technology for fast, low-cost metal additive manufacturing*. https://www.digitalalloys.com/technology/

Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). Wire-feed additive manufacturing of metal components: technologies, developments and future interests. *The International Journal of Advanced Manufacturing Technology*, *81*(1–4), 465–481. https://doi.org/10.1007/s00170-015-7077-3

Ding, J.L., Colegrove, P.A., Mehnen, J., Ganguly, S., Almeida, P.M.S., Wang, F., & Williams, S.W. (2011). Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts. *Computational Materials Science*, *50*(12). https://doi.org/10.1016/j.commatsci.2011.06.023

Domadraghi. (2021). *Creality CR-30 3D Printer Review: Batch Printing on a Conveyor Belt*. https://www.tomshardware.com/reviews/creality-cr-30-3d-printer

Donald, D.K. (1980). *Method and apparatus for drop-on-demand ink jet printing.* https://patents.google.com/patent/US4336544A/en?q=(Steven+Zoltan)&oq=Steven+Zoltan&sort=old&page=2

Dong, J., Li, Y., Lin, P., Leeflang, M., Van Asperen, S., Yu, K. M., Tümer, N., Norder, B., Zadpoor, A.A., & Zhou, J. (2020). Solvent-cast 3D printing of magnesium scaffolds. *Acta Biomaterialia*, *114*. https://doi.org/10.1016/j.actbio.2020.08.002

Duraivel, S., Laurent, D., Rajon, D.A., Scheutz, G.M., Shetty, A., Sumerlin, B.S., Banks, S.A., Bova, F.J., & Angelini, T.E. (2023). A silicone-based support material eliminates interfacial instabilities in 3D silicone printing. *Science*, *379*(6638), 1248–1252. https://doi.org/10.1126/science.ade4441

Dutta, B., Palaniswamy, S., Choi, J., & Mazumder, J. (2011). Additive Manufacturing by Direct Metal Deposition. *Advanced Materials and Processes*, *169 (5),* 33-36

Duty, C.E., Jean, D., & Lackey, W.J. (2001). Laser chemical vapour deposition: materials, modelling, and process control. *International Materials Reviews*, *46*(6), 271–287. https://doi.org/10.1179/095066001771048727

Eiamsa-Ard, K. (2001). *Skeleton-Based Geometric Reasoning for Adaptive Slicing in a Five-Axis Laser Aided Manufacturing Process System*. https://scholarsmine.mst.edu/mec_aereng_facwork/1830/

Elliott, D. (1995). UV Materials Research. In *Elsevier eBooks* (pp. 95–121). https://doi.org/10.1016/b978-0-12-237070-0.50008-x

European Commission. (2020). *Leading the way to a global circular economy: state of play and outlook*. https://ec.europa.eu/environment/pdf/circular-economy/leading_way_global_circular_economy.pdf

European Environment Agency [EEA]. (2019). *Preventing plastic waste in Europe*. https://www.eea.europa.eu/publications/preventing-plastic-waste-in-europe

Ebert, E (2017). *Slic3r_NonPlanar_Slicing: Slic3r with integrated electronics and Nonplanar slicer*. https://github.com/DrEricEbert/Slic3r_NonPlanar_Slicing

Fang, N.X., Dunn, C.K., Qi, H.R., & Dunn, M.L. (2014). Active origami by 4D printing. *Smart Materials and Structures*, *23*(9), 094007. https://doi.org/10.1088/0964-1726/23/9/094007

Fu, X.,Hosta-Rigau, L., Chandrawati, R., & Cui, J. (2018). Multi-Stimuli-Responsive Polymer Particles, Films, and Hydrogels for Drug Delivery. *Chem*, *4*(9), 2084–2107. https://doi.org/10.1016/j.chempr.2018.07.002

Fraunhore. (2023). *Powder for additive manufacturing*. https://www.umsicht-suro.fraunhofer.de/en/Our_Solution/Powder-for-additive-manufacturing1.html

FluidForm. (2022). *Technology*. https://www.fluidform3d.com/technology

Gall, K., Dunn, M.L., Liu, Y., Stefanic, G., & Balzar, D. (2004). Internal stress storage in shape memory polymer nanocomposites. Applied Physics Letters, 85(2), 290–292. https://doi.org/10.1063/1.1769087

Ganesan, B., Luximon, A., Al-Jumaily, A., Balasankar, S., & Naik, G.R. (2017). Ponseti method in the management of clubfoot under 2 years of age: A systematic review. *PLOS ONE*, *12*(6), e0178299. https://doi.org/10.1371/journal.pone.0178299

Gao, Y., Li, H., & Liu, J. (2012). Direct Writing of Flexible Electronics through Room Temperature Liquid Metal Ink. *PLOS ONE*, *7*(9), e45485. https://doi.org/10.1371/journal.pone.0045485

Gazzaniga, A., Foppoli, A., Cerea, M., Palugan, L., Cirilli, M., Moutaharrik, S., Melocchi, A., & Maroni, A. (2023). Towards 4D printing in pharmaceutics. *International Journal of Pharmaceutics: X*, *5*, 100171. https://doi.org/10.1016/j.ijpx.2023.100171

Gebhardt, A. (2003). Rapid Prototyping. In *Carl Hanser Verlag GmbH & Co. KG eBooks*. https://doi.org/10.3139/9783446402690

Geisendorfer, N.R., & Shah, R.N. (2019). Effect of Polymer Binder on the Synthesis and Properties of 3D-Printable Particle-Based Liquid Materials and Resulting Structures. *ACS Omega*, *4*(7). https://doi.org/10.1021/acsomega.9b00090

Georgantzinos, S., Giannopoulos, G., & Bakalis, P. (2021). Additive Manufacturing for Effective Smart Structures: The Idea of 6D Printing. *Journal of Composites Science*, *5*(5), 119. https://doi.org/10.3390/jcs5050119

Ghazal, A.F., Zhang, M., Mujumdar, A.S., & Ghamry, M. (2022). Progress in 4D/5D/6D printing of foods: applications and R&D opportunities. *Critical Reviews in Food Science and Nutrition*, 1–24. https://doi.org/10.1080/10408398.2022.2045896

Gissibl, T., Thiele, S., Herkommer, A., & Giessen, H. (2016). Two-photon direct laser writing of ultracompact multi-lens objectives. *Nature Photonics*, *10*(8), 554–560. https://doi.org/10.1038/nphoton.2016.121

Go, J., Schiffres, S.N., Stevens, A., & Hart, A. (2017). Rate limits of additive manufacturing by fused filament fabrication and guidelines for high-throughput system design. *Additive Manufacturing*, *16*, 1–11. https://doi.org/10.1016/j.addma.2017.03.007

Go, J. & Hart, A.J. (2017). Fast desktop-scale extrusion additive manufacturing. *Additive Manufacturing*, 18, 276–284. https://doi.org/10.1016/j.addma.2017.10.016

González-Henríquez, C.M., Sarabia-Vallejos, M.A., & Rodríguez-Hernández, J. (2019). Polymers for additive manufacturing and 4D-printing: Materials, methodologies, and biomedical applications. *Progress in Polymer Science*, *94*, 57–116. https://doi.org/10.1016/j.progpolymsci.2019.03.001

Gottwald, J.F. (1969). *US3596285A - Liquid metal recorder*. https://patents.google.com/patent/US3596285A/en

Grand View Research [GRV].(2022). *Plastic Market Size, Share & Trends Analysis Report By Product (PVC, PET, ABS, PBT), By End-use (Packaging, Construction), By Application (Injection Molding, Calendering), By Region, And Segment Forecasts 2023 - 2030*. https://www.grandviewresearch.com/industry-analysis/global-plastics-market

Grutle, Ø.K. (2015). 5-axis 3D Printer. *Uio*. https://www.academia.edu/15736899/5_axis_3D_Printer

Guo, R., Wang, X., Chang, H., Yu, W., Liang, S., Rao, W., & Liu, J. (2018). Ni-GaIn Amalgams Enabled Rapid and Customizable Fabrication of Wearable and Wireless Healthcare Electronics. *Advanced Engineering Materials*, *20*(10), 1800054. https://doi.org/10.1002/adem.201800054

Guo, R., Wang, X., Yu, W., Tang, J., & Liu, J. (2018). A highly conductive and stretchable wearable liquid metal electronic skin for long-term conformable health monitoring. *Science China-technological Sciences*, *61*(7), 1031–1037. https://doi.org/10.1007/s11431-018-9253-9

Habibi, M., Foroughi, S., Karamzadeh, V., & Packirisamy, M. (2022). Direct sound printing. *Nature Communications*, *13*(1). https://doi.org/10.1038/s41467-022-29395-1

Haines, J. (2022). *History of 3D Printing: When Was 3D Printing Invented?* https://all3dp.com/2/history-of-3d-printing-when-was-3d-printing-invented/

Hajash K., Sparrman B., Guberan C., Laucks J., & Tibbits S. (2017). Large-Scale Rapid Liquid Printing. *3D Printing and Additive Manufacturing*, *4*(3), 123–132. https://doi.org/10.1089/3dp.2017.0037

Haleem, A., & Javaid, M. (2019). Future applications of five-dimensional printing in dentistry. *Current Medicine Research and Practice*, *9*(2), 85–86. https://doi.org/10.1016/j.cmrp.2019.03.002

Haleem, A., Javaid, M., & Vaishya, R. (2019). 5D printing and its expected applications in Orthopaedics. *Journal of Clinical Orthopaedics and Trauma*, *10*(4), 809–810. https://doi.org/10.1016/j.jcot.2018.11.014

Hardin, J.W., Grabowski, C.A., Stone, M.B., Durstock, M.F., & Berrigan, J.D. (2019). All-printed multilayer high voltage capacitors with integrated processing feedback. *Additive Manufacturing*, *27*, 327–333. https://doi.org/10.1016/j.addma.2019.02.011

Hayes, G.J., So, J., Qusba, A., Dickey, M.D., & Lazzi, G. (2012). Flexible Liquid Metal Alloy (EGaIn) Microstrip Patch Antenna. *IEEE Transactions on Antennas and Propagation*, *60*(5), 2151–2156. https://doi.org/10.1109/tap.2012.2189698

Helinski, R. (1989). *Method and means for constructing three-dimensional articles by particle deposition.* https://patents.google.com/patent/US5136515A/en

Henke, K., Talke, D., & Winter, S. (2016). Additive Manufacturing of Building Elements by Extrusion of Wood Concrete. *World Conference on Timber Engineering*.https://www.researchgate.net/publication/328538383_Additive_Manufacturing_of_Building_Elements_by_Extrusion_of_Wood_Concrete

Hermann, S. (2022). Non-Planar 3D Printing by Bending G-Code–CNC Kitchen. *CNC Kitchen*. https://www.cnckitchen.com/blog/non-planar-3d-printing-by-bending-g-code

Historydraft. (2023). *3D printing- Tools of the Trade*. https://historydraft.com/events/tools-of-the-trade/16384

Hoeben, J. (2022). *Volumetric resin 3D-printing explained.* https://www.liqcreate.com/supportarticles/volumetric-resin-3d-printing-explained/

Hong, F., Hodges, S., Myant, C., & Boyle, D.L. (2022). Open5x: Accessible 5-axis 3D printing and conformal slicing. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. https://doi.org/10.1145/3491101.3519782

Huang, B., & Singamneni, S. (2013). Curved Layer Fused Deposition Modeling with Varying Raster Orientations. *Applied Mechanics and Materials*, *446–447*, 263–269. https://doi.org/10.4028/www.scientific.net/amm.446-447.263

Huang, B., & Singamneni, S. (2015). A mixed-layer approach combining both flat and curved layer slicing for fused deposition modelling. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *229*(12), 2238–2249. https://doi.org/10.1177/0954405414551076

Huang, L., Braunschweig, A.B., Shim, W., Qin, L., Lim, J.S., Hurst, S.J., Huo, F., Xue, C., Jang, J.E., & Mirkin, C.A. (2009). Matrix-Assisted Dip-Pen Nanolithography and Polymer Pen Lithography. *Small*, *6*(10), 1077–1081. https://doi.org/10.1002/smll.200901198

Hull, C.W. (1984). *US4575330A - Apparatus for production of three-dimensional objects by stereolithography*. https://patents.google.com/patent/US4575330A/en

Huo, F., Zheng, Z., Shao, Z., Giam, L.R., Zhang, H., & Mirkin, C.A. (2008). Polymer Pen Lithography. *Science*, *321*(5896), https://doi.org/10.1126/science.1162193

Irwin, J.L., Pearce, J.M., Anzalone, G.C., Douglas, M., & Oppliger, E. (2014). The RepRap 3-D Printer Revolution in STEM Education. *360 of Engineering Education.* https://hal.science/hal-02119683/

ISO/ASTM 52900:2021(en) *Additive manufacturing — General principles — Fundamentals and vocabulary.* https://www.iso.org/obp/ui/#!iso:std:74514:en

Javelosa, J. (2017). *Dubai is Going to Be Home to the World's First 3D Printed Skyscraper*. https://futurism.com/dubai-is-going-to-be-home-to-the-worlds-first-3d-printed-skyscraper

Jemghili, R., Aittaleb, A.A.T., & Mansouri, K. (2021). *Additive Manufacturing Progress as a New Industrial Revolution*. https://www.researchgate.net/publication/349168024_Additive_Manufacturing_Progress_as_a_New_Industrial_Revolution

Jeon, O., Lee, Y.B., Jeong, H.J., Lee, S.Y., Wells, D., & Alsberg, E. (2019). Individual cell-only bioink and photocurable supporting medium for 3D printing and generation of engineered tissues with complex geometries. *Materials Horizons*, *6*(8), 1625–1631. https://doi.org/10.1039/c9mh00375d

Jeong, H.M., Song, J.H., Lee, S.Y., & Kim, B. (2001). Miscibility and shape memory property of poly(vinyl chloride)/thermoplastic polyurethane blends. *Journal of Materials Science*, *36*(22), https://doi.org/10.1023/a:1012481631570

Kamila, S. (2013). Introduction, classification and applications of smart materials: an overview. *American Journal of Applied Sciences*, *10*(8), 876–880. https://doi.org/10.3844/ajassp.2013.876.880

Keane, P. (2023a). *Patent Granted for 3D Printing Embossing Technology*. https://3dprinting.com/news/patent-granted-for-3d-printing-embossing-technology/

Keane, P. (2023b). *Researchers Use Silicone to 3D Print Accurate Brain Models*. https://3dprinting.com/news/researchers-use-silicone-to-3d-print-accurate-brain-models/

Kelly, B., Bhattacharya, I., Heidari, H., Shusteff, M., Spadaccini, C.M., & Taylor, H. (2019). Volumetric additive manufacturing via tomographic reconstruction. *Science*, *363*(6431), 1075–1079. https://doi.org/10.1126/science.aau7114

Khare, V., Sonkaria, S., Lee, G., & Ahn, S. (2017). From 3D to 4D printing – design, material and fabrication for multi-functional multi-materials. *International Journal of Precision Engineering and Manufacturing-Green Technology*, *4*(3), 291–299. https://doi.org/10.1007/s40684-017-0035-9

Khoo, Z.X., Teoh, J.E.M., Liu, Y., Chua, C.K., Yang, S., An, J., Leong, K.F., & Yeong, W.Y. (2015). 3D printing of smart materials: A review on recent progresses in 4D printing. *Virtual and Physical Prototyping*, *10*(3), 103–122. https://doi.org/10.1080/17452759.2015.1097054

Khoshnevis, B. (2005). *US7814937B2 - Deployable contour crafting*. https://patents.google.com/patent/US7814937B2/en?inventor=Behrokh+Khoshnevis&sort=old&page=1

Khoshnevis, B., Asiabanpour, B., Mojdeh, M., & Palmer, K. (2003). SIS – a new SFF method based on powder sintering. *Rapid Prototyping Journal*, *9*(1), 30–36. https://doi.org/10.1108/13552540310455638

Khoshnevis, B., Zhang, J., Fateri, M., & Xiao, Z. (2014). Ceramics 3D printing by selective inhibition sintering. *ResearchGate*. https://www.researchgate.net/publication/264548226_Ceramics_3D_printing_by_selective_inhibition_sintering

Khurana, J.B. (2017). *Active - Z Printing: A New Approach to Increasing 3D Printed Part Strength*. https://repositories.lib.utexas.edu/handle/2152/89971

Kim, K.N., Moldovan, N., & Espinosa, H.D. (2005). A Nanofountain Probe with Sub-100 nm Molecular Writing Resolution. *Small*, *1*(6), 632–635. https://doi.org/10.1002/smll.200500027

Klosterman, D.A., Chartoff, R.P., Osborne, N., Graves, G., Lightman, A., Han, G., Bezeredi, A., & Rodrigues, S. (1999). Development of a curved layer LOM process for monolithic ceramics and ceramic matrix composites. *Rapid Prototyping Journal*, *5*(2), 61–71. https://doi.org/10.1108/13552549910267362

Kodama, H. (1980). *JPS56144478A - Stereoscopic figure drawing device*. https://patents.google.com/patent/JPS56144478A/en

Kodama, H. (1981). Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer. *Review of Scientific Instruments*, *52*(11), 1770–1773. https://doi.org/10.1063/1.1136492

Koh, A., Kang, D., Xue, Y., Lee, S., Pielak, R.M., Kim, J., Hwang, T., Min, S., Banks, A., Bastien, P., Manco, M., Wang, L., Ammann, K.R., Jang, K.L., Won, P., Han, S., Ghaffari, R., Paik, U., Slepian, M.J., Rogers, J.A. (2016). A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat. *Science Translational Medicine*, *8*(366). https://doi.org/10.1126/scitranslmed.aaf2593

Kraft, C. (2009). *CupCake CNC Kit*. https://hackaday.com/2009/03/16/cupcake-cnc-kit/

Kety, S. (2021). *Volumetric 3D printing: From research to commercialization*. https://3dadept.com/volumetric-3d-printing-from-research-to-commercialization/

Krivoshapkina, Y., Kaestner, M., & Rangelow, I.W. (2016). Tip-based nanolithography methods and materials. In *Frontiers of nanoscience* (pp. 497–542). Elsevier BV. https://doi.org/10.1016/b978-0-08-100354-1.00015-6

Kubalak, J.R., Wicks, A.L., & Williams, C. (2018). Using multi-axis material extrusion to improve mechanical properties through surface reinforcement. *Virtual and Physical Prototyping*, *13*(1), 32–38. https://doi.org/10.1080/17452759.2017.1392686

Kumar, S., Goel, S., Sharma, A., & Pandey, C. (2021). *Direct Energy Deposition*. https://www.researchgate.net/publication/350411708_Direct_Energy_Deposition

Kurahashi, E., Sugimoto, H., Nakanishi, E., Nagata, K., & Inomata, K. (2012). Shape memory properties of polyurethane/poly(oxyethylene) blends. *Soft Matter*, *8*(2), 496–503. https://doi.org/10.1039/c1sm06585h

Ladd, C., So, J., Muth, J.F., & Dickey, M.D. (2013a). 3D Printing of Free Standing Liquid Metal Microstructures. *Advanced Materials*, *25*(36), 5081–5085. https://doi.org/10.1002/adma.201301400

Ladd, C., So, J., Muth, J.F., & Dickey, M.D. (2013b). Microstructures: 3D Printing of Free Standing Liquid Metal Microstructures. *Advanced Materials*, *25*(36), 4953. https://doi.org/10.1002/adma.201370225

McIntosh, M.A. (2022). *Leaping from the Page: A History of 3D Printing, Types, and Applications since 1940*. https://brewminate.com/leaping-from-the-page-a-history-of-3d-printing-types-and-applications-since-1940/

Leinster, M. (1945). *Things Pass By* http://www.troynovant.com/Franson/Leinster/Things-Pass-By.html

Leist, S.K., & Zhou, J.G. (2016). Current status of 4D printing technology and the potential of light-reactive smart materials as 4D printable materials. *Virtual and Physical Prototyping*, *11*(4), 249–262. https://doi.org/10.1080/17452759.2016.1198630

Lewis, A., Kheifetz, Y., Shambrodt, E., Radko, A., Khatchatryan, E., & Sukenik, C.N. (1999). Fountain pen nanochemistry: Atomic force control of chrome etching. *Applied Physics Letters*, *75*(17), 2689–2691. https://doi.org/10.1063/1.125120

Lin, S., Zhang, L., & Cong, L. (2023). A micro-vibration-driven direct ink write printing method of gallium–indium alloys. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-31091-z

Liu, G., Ding, X., Cao, Y., Zheng, Z., & Peng, Y. (2005). Novel Shape-Memory Polymer with Two Transition Temperatures. *Macromolecular Rapid Communications*, *26*(8), 649–652. https://doi.org/10.1002/marc.200400640

Liu, X., Carbonell, C., & Braunschweig, A.B. (2016). Towards scanning probe lithography-based 4D nanoprinting by advancing surface chemistry, nanopatterning strategies, and characterization protocols. *Chemical Society Reviews*, *45*(22), 6289–6310. https://doi.org/10.1039/c6cs00349d

Llewellyn-Jones, T.M., Allen, R.J., & Trask, R.S. (2016). Curved Layer Fused Filament Fabrication Using Automated Toolpath Generation. *3D Printing and Additive Manufacturing*, *3*(4), 236–243. https://doi.org/10.1089/3dp.2016.0033

Ly, S.T., & Kim, J. (2017). 4D printing – fused deposition modeling printing with thermal-responsive shape memory polymers. *International Journal of Precision Engineering and Manufacturing-Green Technology*, *4*(3), 267–272. https://doi.org/10.1007/s40684-017-0032-z

Madrid-Wolff, J., Boniface, A., Loterie, D., Delrot, P., & Moser, C. (2022). Controlling Light in Scattering Materials for Volumetric Additive Manufacturing. *Advanced Science*, *9*(22), 2105144. https://doi.org/10.1002/advs.202105144

Madeleine, P. (2023). *Silicone 3D Printing Allows for More Accurate Models of Blood Vessels in the Brain*. https://www.3dnatives.com/en/silicone-3d-printing-blood-vessels-brain-280320234/#

Maheswari, A.U. (2022). Smart Materials- Types & Applications. *International Journal for Research in Applied Science and Engineering Technology*, *10*(1), 1752–1755. https://doi.org/10.22214/ijraset.2022.40147

Mallakpour, S., Tabesh, F., & Hussain, C.M. (2021). 3D and 4D printing: From innovation to evolution. *Advances in Colloid and Interface Science*, *294*, 102482. https://doi.org/10.1016/j.cis.2021.102482

Mao, Y., Yu, K., Isakov, M., Wu, J., Dunn, M.L., & Qi, H.R. (2015). Sequential Self-Folding Structures by 3D Printed Digital Shape Memory Polymers. *Scientific Reports*, *5*(1). https://doi.org/10.1038/srep13616

Markforged. (2021). *What is Electron Beam Melting (EBM)?*. https://markforged.com/resources/learn/3d-printing-basics/3d-printing-processes/what-is-electron-beam-melting-ebm

Masaeli, M.M. (2012). *Robot Mechanisms And Mechanical Devices Illustrated.* https://www.researchgate.net/publication/245543196_Robot_Mechanisms_And_Mechanical_Devices_Illustrated_-_McGraw_Hill

Masters, W.E. (1984, July 2). *US4665492A - Computer automated manufacturing process and system*. https://patents.google.com/patent/US4665492A/en

Masters, W.E. (1989a). *US5134569A - System and method for computer automated manufacturing using fluent material*. https://patents.google.com/patent/US5134569A/en?oq=US+5134569A-+%E2%80%9ESystem+and+method+for+computer+automated+manufacturing+using+fluent+material%E2%80%9D

Masters, W.E. (1989b). *US5216616A - System and method for computer automated manufacture with reduced object shape distortion.* https://patents.google.com/patent/US5216616A/en?oq=US+5216616A-+%E2%80%9ESystem+and+method+for+computer+automated+manufacture+with+reduced+object+shape+distortion

Mather, P.T., Luo, X., & Rousseau, I.A. (2009). Shape Memory Polymer Research. *Annual Review of Materials Research*, *39*(1), 445–471. https://doi.org/10.1146/annurev-matsci-082908-145419

Mbartlett. (2019). *Builds for Windows*. https://github.com/Zip-o-mat/Slic3r/issues/6#issuecomment-528333989

McCaw, J.A., & Cuan-Urquizo, E. (2018). Curved-Layered Additive Manufacturing of non-planar, parametric lattice structures. *Materials & Design*, *160*, 949–963. https://doi.org/10.1016/j.matdes.2018.10.024

Meiners, W. (1996). *DE19649865C1 -Shaped body especially prototype or replacement part production*. https://patents.google.com/patent/DE19649865C1/en

Metal, AM. (2019). *Marines employ mobile hybrid metal Additive Manufacturing solution*. https://www.metal-am.com/marines-employ-mobile-hybrid-metal-additive-manufacturing-solution/

Micropen. (2023). *About Us | Exxelia Micropen*. https://micropen.com/about/

Mitsubishi Electric Research Labs (MERL). (2016). *Five Axis Additive Manufacturing* [Video]. https://www.youtube.com/watch?v=Fomi0V_xl4k

Mouzakis, D.E. (2018). *Advanced Technologies in Manufacturing 3D-Layered Structures for Defense and Aerospace.* https://doi.org/10.5772/intechopen.74331

Nadgorny, M., Xiao, Z., Chen, C., & Connal, L.A. (2016). Three-Dimensional Printing of pH-Responsive and Functional Polymers on an Affordable Desktop Printer. *ACS Applied Materials & Interfaces*, *8*(42), 28946–28954. https://doi.org/10.1021/acsami.6b07388

Nayyeri, P., Zareinia, K., & Bougherara, H. (2022). Planar and nonplanar slicing algorithms for fused deposition modeling technology: a critical review. *The International Journal of Advanced Manufacturing Technology*, *119*(5–6), 2785–2810. https://doi.org/10.1007/s00170-021-08347-x

Neumann, T.V. (2020). *Liquid Metal Direct Write and 3D Printing: A Review*. https://www.semanticscholar.org/paper/Liquid-Metal-Direct-Write-and-3D-Printing%3A-A-Review-Neumann-Dickey/f70b7add6a0a9d502bf4af436363d953fc558294

Ni, Q., Zhang, C., Fu, Y., Dai, G., & Kimura, T. (2007). Shape memory effect and mechanical properties of carbon nanotube/shape memory polymer nanocomposites. *Composite Structures*, *81*(2), 176–184. https://doi.org/10.1016/j.compstruct.2006.08.017

Nick-Parker. (2018). *GitHub - nick-parker/Bread: An experimental slicer for FFF 3D Printers*. https://github.com/nick-parker/bread

Nisja, G.A., Cao, A., & Gao, C. (2021). Short review of nonplanar fused deposition modeling printing. *Material Design & Processing Communications*, *3*(4). https://doi.org/10.1002/mdp2.221

Obermair, C., Wagner, A., & Schimmel, T. (2011). The atomic force microscope as a mechano–electrochemical pen. *Beilstein Journal of Nanotechnology*, *2*, 659–664. https://doi.org/10.3762/bjnano.2.70

O'Connell, J. (2021). *Non-Planar 3D Printing: All You Need to Know.* https://all3dp.com/2/non-planar-3d-printing-simply-explained/

Omidinia-Anarkoli, A., Rimal, R., Chandorkar, Y., Gehlen, D.B., Rose, J., Rahimi, K., Haraszti, T., & De Laporte, L. (2019). Solvent-Induced Nanotopographies of Single Microfibers Regulate Cell Mechanotransduction. *ACS Applied Materials & Interfaces*, *11*(8), 7671–7685. https://doi.org/10.1021/acsami.8b17955

O'Neal, B. (2019). *Launcher & AMCM Develop Largest Known 3D Printed DMLS Rocket Engine Part.* https://3dprint.com/236779/launcher-amcm-develop-largest-known-3d-printed-dmls-rocket-part/

Oswald, E., Palanisamy, K., & Kranz, C. (2022). Nanoscale surface modification via scanning electrochemical probe microscopy. *Current Opinion in Electrochemistry*, *34*, 100965. https://doi.org/10.1016/j.coelec.2022.100965

Ouajjani, K. (2018). *The History of 3D Printing*. https://www.engineeringclicks.com/history-of-3d-printing-2/

Ouyang, W., Xu, X., Lu, W., Zhao, N., Han, F., & Chen, S. (2023). Ultrafast 3D nanofabrication via digital holography. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-37163-y

Pan, Z., Ding, D., Cuiuri, D., Li, H., Xu, J., & Norrish, J. (2018). A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement. *Journal of Manufacturing Processes*, *35*, 127–139. https://doi.org/10.1016/j.jmapro.2018.08.001

Persistence. (2023). Global Market Study on Additive Manufacturing: Commercial Revolution to drive the market. Persistence Market Research. https://www.persistencemarketresearch.com/market-research/additive-manufacturing-market.asp

Peterson, G.M., Larsen, M., Ganter, M.A., Storti, D.W., & Boydston, A.J. (2015). 3D-Printed Mechanochromic Materials. *ACS Appl. Mater. Interfaces*, *7*(1), 577–583. https://doi.org/10.1021/am506745m

Piner, R.D., Zhu, J., Xu, F., Hong, S., & Mirkin, C.A. (1999). "Dip-Pen" Nanolithography. *Science*, *283*(5402), https://doi.org/10.1126/science.283.5402.661

Pinkerton, A.J. (2010). *Laser direct metal deposition: theory and applications in manufacturing and maintenance*. https://doi.org/10.1533/9781845699819.6.461

Piqué, A., & Chrisey, D.B. (2001). Direct-Write Technologies for Rapid Prototyping Applications: Sensors, Electronics, and Integrated Power Sources. *Academic Press; Illustrated edition*. ISBN-10: 0121742318

Piqué, A., Arnold, C.B., Wartena, R.C., Pratap, B., Shashishekar, B., Swider-Lyons, K.E., Weir, D.W. & Kant, R.A. (2003). *Laser direct-write of miniature sensor and microbattery systems.* https://www.researchgate.net/publication/237548965_Laser_direct-write_of_miniature_sensor_and_microbattery_systems

Plank, H., Winkler, R., Schwalb, C.H., Hütner, J., Fowlkes, J.D., Rack, P.D., Utke, I., & Huth, M. (2019). Focused Electron Beam-Based 3D Nanoprinting for Scanning Probe Microscopy: A Review. *Micromachines*, *11*(1), 48. https://doi.org/10.3390/mi11010048

Q5Technologies. (2023). *Manufacturing cell*. https://q5d.com/haas/technical-details/

Ramirez, V. B. (2021). *World's Biggest 3D Printed Building Opens in Dubai*. https://singularityhub.com/2020/01/27/worlds-biggest-3d-printed-building-opens-in-dubai/

Ramírez-Gutiérrez, D.L., Cuan-Urquizo, E., & Gómez-Espinosa, A. (2020). Adaptable Bed for Curved-Layered Fused Deposition Modeling of Nonplanar Structures: A Proof of Concept. *3D Printing and Additive Manufacturing*, *7*(4), 198–201. https://doi.org/10.1089/3dp.2019.0086

Rapid. (2023). *Process-Rapid Liquid Printing Process*. https://www.rapidliquidprint.co/home/#process

Razzaq, M.A., Anhalt, M., Frormann, L., & Weidenfeller, B. (2007). Mechanical spectroscopy of magnetite filled polyurethane shape memory polymers. *Materials Science and Engineering A-structural Materials Properties Microstructure and Processing*, *471*(1–2), 57–62. https://doi.org/10.1016/j.msea.2007.03.059

Readily3D. (2023). *Readily3D*. https://readily3d.com/

Reddy, P.R. & Anjani, D. (2018). Review on the Advancements to Additive Manufacturing-4D and 5D Printing. *International Journal of Mechanical and Production Engineering Research and Development*, *8*(4), 397–402. https://doi.org/10.24247/ijmperdaug201841

Regehly, M., Garmshausen, Y., Reuter, M., König, N., Israel, E., Kelly, D.P., Chou, C., Koch, K., Asfari, B., & Hecht, S. (2020). Xolography for linear volumetric 3D printing. *Nature*, *588*(7839), 620–624. https://doi.org/10.1038/s41586-020-3029-7

Ren, L., Sparks, T.E., Ruan, J., & Liou, F.W. (2008). Process planning strategies for solid freeform fabrication of metal parts. *Journal of Manufacturing Systems*, *27*(4), 158–165. https://doi.org/10.1016/j.jmsy.2009.02.002

Valuates, R. (2022). *Additive Manufacturing Market Size to Grow at a CAGR of 21.75%*. https://www.prnewswire.com/in/news-releases/additive-manufacturing-market-size-to-grow-at-a-cagr-of-21-75-valuates-reports-852729280.html

Shi. J. (2014). *Robotic Extrusion (6-Axis KUKA+ABS 3D Printing)*. https://www.behance.net/gallery/22536831/ROBOTIC-EXTRUSION(6-Axis-KUKAABS-3D-Printing)

Ritchie, H. & Roser, M. (2018). *Plastic Pollution*. https://ourworldindata.org/plastic-pollution

Rodríguez-Pombo, L., Xu, X., Seijo-Rabina, A., Ong, J.R., Alvarez-Lorenzo, C., Rial, C., Garcia, D.F., Gaisford, S., Basit, A., & Goyanes, A. (2022). Volumetric 3D printing for rapid production of medicines. *Additive Manufacturing*, *52*, 102673. https://doi.org/10.1016/j.addma.2022.102673

Rossiter, J., Walters, P., & Stoimenov, B. (2009). Printing 3D dielectric elastomer actuators for soft robotics. In *Proceedings of SPIE*. SPIE. https://doi.org/10.1117/12.815746

Vshaper. (2022a). *VSHAPER 5AX - Professional 3D Printing five axis gamechanger.* https://vshaper.com/3d-printers/vshaper-5ax-machine

Vshaper. (2022b). *VSHAPER - Professional 3D Printing solutions for medicine*. https://vshaper.com/industries/medicine

Roy, I., & Gupta, M. N. (2003). Smart Polymeric Materials. *Chemistry & Biology*, *10*(12), 1161–1171. https://doi.org/10.1016/j.chembiol.2003.12.004

Ruan, J., Sparks, T.E., Panackal, A., Eiamsa-Ard, K., Liou, F., Slattery, K., Chou, H.N. & Kinsella, M. (2006). *Automated Slicing for a Multi-Axis Metal Deposition System.* https://www.researchgate.net/publication/235063477_Automated_Slicing_for_a_Multi-Axis_Metal_Deposition_System_Preprint

Sanders, S.N., Schloemer, T.H., Gangishetty, M.K., Anderson, D.G., Seitz, M., Gallegos, A., Stokes, R.C., & Congreve, D. N. (2022). Triplet fusion upconversion nanocapsules for volumetric 3D printing. *Nature*, *604*(7906), 474–478. https://doi.org/10.1038/s41586-022-04485-8

Scalet, G. (2020). Two-Way and Multiple-Way Shape Memory Polymers for Soft Robotics: An Overview. *Actuators*, *9*(1), 10. https://doi.org/10.3390/act9010010

Schiele, N.R., Corr, D.T., Huang, Y., Raof, N.A., Xie, Y., & Chrisey, D.B. (2010). Laser-based direct-write techniques for cell printing. *Biofabrication*, *2*(3), 032001. https://doi.org/10.1088/1758-5082/2/3/032001

Schneider, D. (2009). *Bits From Bytes INVOICE*. https://edutechwiki.unige.ch/mediawiki/images/9/9a/Invoice490DanielSchneider.pdf

Schwaar, C. (2023). Multi Jet Fusion (MJF 3D Printing) – The Ultimate Guide. *All3DP Pro*. https://all3dp.com/1/multi-jet-fusion-mjf-3d-printing-simply-explained/

Seewald, L.M., Sattelkow, J., Brugger-Hatzl, M., Kothleitner, G., Frerichs, H., Schwalb, C.H., Hummel, S., & Plank, H. (2022). 3D Nanoprinting of All-Metal Nanoprobes for Electric AFM Modes. *Nanomaterials*, *12*(24), 4477. https://doi.org/10.3390/nano12244477

Sheikh, A., Abourehab, M.A., & Kesharwani, P. (2022). The clinical significance of 4D printing. *Drug Discovery Today*, *28*(1), 103391. https://doi.org/10.1016/j.drudis.2022.103391

Simon-Lewis, A. (2017). *3D printing is yesterday's news. Rapid liquid printing is the future*. https://www.wired.co.uk/article/rapid-liquid-printing-mit-steelcase

Singamneni, S., Roychoudhury, A., Diegel, O., & Huang, B. (2012). Modeling and evaluation of curved layer fused deposition. *Journal of Materials Processing Technology*, *212*(1), 27–35. https://doi.org/10.1016/j.jmatprotec.2011.08.001

Singh, M., Haring, A.P., Tong, Y., Cesewski, E., Ball, E., Jasper, R., Davis, E.M., & Johnson, B.W. (2019). Additive Manufacturing of Mechanically Isotropic Thin Films and Membranes via Microextrusion 3D Printing of Polymer Solutions. *ACS Applied Materials & Interfaces*, *11*(6), 6652–6661. https://doi.org/10.1021/acsami.8b22164

Singh, P., & Dutta, D. (2001). Multi-Direction Slicing for Layered Manufacturing. *Journal of Computing and Information Science in Engineering*, *1*(2), 129–142. https://doi.org/10.1115/1.1375816

Singh, P., & Dutta, D. (2008). Offset Slices for Multidirection Layered Deposition. *Journal of Manufacturing Science and Engineering-transactions of the Asme*, *130*(1). https://doi.org/10.1115/1.2783217

Soligen. (2023). *DSPC Capabilities*. http://www.soligen.com/about/dspc_capabilites.shtml

Spencer, J.D. (1998). *Rapid prototyping of metal parts by three-dimensional welding*. https://www.semanticscholar.org/paper/Rapid-prototyping-of-metal-parts-by-welding-Spencer-Dickens/4ed07c41358af75d19de75522d9a208ff7142a85

Statista Research Department [SRD]. (2023). *Plastic market size worldwide 2030 | Statista*. https://www.statista.com/statistics/1060583/global-market-value-of-plastic/

Strategic S.M. (2021). *3D Printing Market Growth, Global Industry Size | Report 2030*. https://www.strategicmarketresearch.com/market-report/3d-printing-market

Suits, D.L. (2019). *3D printing technology enhancing logistics for Army*. https://www.army.mil/article/217433/3d_printing_technology_enhancing_logistics_for_army

Sundaram, S., Kim, D.H., Baldo, M.A., Hayward, R.C., & Matusik, W. (2017). 3D-Printed Self-Folding Electronics. *ACS Applied Materials & Interfaces*, *9*(37), 32290–32298. https://doi.org/10.1021/acsami.7b10443

Swainson, W.K. (1967). *GB1243044A - Method of producing a three-dimensional figure by holography*. https://patents.google.com/patent/GB1243044A/en

Szoszkiewicz, R., Okada, T., Jones, S., Li, T., King, W.P., Marder, S.R., & Riedo, E. (2007). High-Speed, Sub-15 nm Feature Size Thermochemical Nanolithography. *Nano Letters*, *7*(4), 1064–1069. https://doi.org/10.1021/nl070300f

Throne, J.L. (2008). *Understanding Thermoforming*. Hanser Verlag.

Tibbits, S., & Cheung, K. (2012). Programmable materials for architectural assembly and automation. *Assembly Automation*, *32*(3), 216–225. https://doi.org/10.1108/01445151211244348

Toombs, J., Luitz, M.P., Cook, C., Jenne, S., Li, C., Rapp, B.E., Kotz, F., & Taylor, H. (2022). Volumetric additive manufacturing of silica glass with microscale computed axial lithography. *Science*, *376*(6590), 308–312. https://doi.org/10.1126/science.abm6459

TorabiPayman, PetrosMatthew, & KhoshnevisBehrokh. (2014). Selective Inhibition Sintering: The Process for Consumer Metal Additive Manufacturing. *3D Printing and Additive Manufacturing*, *1*(3), 152–155. https://doi.org/10.1089/3dp.2014.0017

Treutler, K., & Wesling, V. (2021). The Current State of Research of Wire Arc Additive Manufacturing (WAAM): A Review. *Applied Sciences*, *11*(18), 8619. https://doi.org/10.3390/app11188619

Trinity College Dublin. (2016). *3D bioprinting technology could provide alternative bone graft options*. https://www.tcd.ie/news_events/articles/3d-bioprinting-technology-could-provide-alternative-bone-graft-options/

Tzou, H., Lee, H., & Arnold, S.R. (2004). Smart Materials, Precision Sensors/Actuators, Smart Structures, and Structronic Systems. *Mechanics of Advanced Materials and Structures*, *11*(4–5), 367–393. https://doi.org/10.1080/15376490490451552

Twi. (2023). *Wire Arc Additive Manufacturing (WAAM)*. https://www.twi-global.com/technical-knowledge/job-knowledge/arc-based-additive-manufacturing-137

Vasiliadis, A.V., Koukoulias, N.E., & Katakalos, K. (2022). From Three-Dimensional (3D)- to 6D-Printing Technology in Orthopedics: Science Fiction or Scientific Reality? *Journal of Functional Biomaterials*, *13*(3), 101. https://doi.org/10.3390/jfb13030101

Vengasandra, S.G., Lynch, M., Xu, J., & Henderson, E. (2005). Microfluidic ultramicroscale deposition and patterning of quantum dots. *Nanotechnology*, *16*(10), 2052–2055. https://doi.org/10.1088/0957-4484/16/10/012

Vialva, T. (2019). *Navantia and Ministry of Defense to construct warships using additive manufacturing*. https://3dprintingindustry.com/news/navantia-and-ministry-of-defense-to-construct-warships-using-additive-manufacturing-154374/

Votzke, C., Daalkhaijav, U., Menguc, Y., & Johnston, M.L. (2019). 3D-Printed Liquid Metal Interconnects for Stretchable Electronics. *IEEE Sensors Journal*, *19*(10), 3832–3840. https://doi.org/10.1109/jsen.2019.2894405

Wan, X., Zhang, F., Liu, Y., & Leng, J. (2019). CNT-based electro-responsive shape memory functionalized 3D printed nanocomposites for liquid sensors. *Carbon*, *155*, 77–87. https://doi.org/10.1016/j.carbon.2019.08.047

Wang, X., Dong, L., Zhang, H., Yu, R., Pan, C., & Wang, Z.L. (2015). Recent Progress in Electronic Skin. *Advanced Science*, *2*(10), 1500169. https://doi.org/10.1002/advs.201500169

Wang, X., Zhang, Y., Shen, P., Cheng, Z., Chu, C., Xue, F., & Bai, J. (2022a). Preparation of 4D printed peripheral vascular stent and its degradation behavior under fluid shear stress after deployment. *Biomaterials Science*, *10*(9), 2302–2314. https://doi.org/10.1039/d2bm00088a

Wang, B., Engay, E., Stubbe, P.R., Moghaddam, S., Thormann, E., Almdal, K., Islam, A., & Yang, Y. (2022b). Stiffness control in dual color tomographic volumetric 3D printing. *Nature Communications*, *13*(1). https://doi.org/10.1038/s41467-022-28013-4

Wang, Y., Adokoh, C.K., & Narain, R. (2018). Recent development and biomedical applications of self-healing hydrogels. *Expert Opinion on Drug Delivery*, *15*(1), 77–91. https://doi.org/10.1080/17425247.2017.1360865

Weder, C. (2011). Mechanoresponsive Materials. *Journal of Materials Chemistry*, *21*(23), 8235. https://doi.org/10.1039/c1jm90068d

Weiss, L.E., Merz, R., Prinz, F.B., Neplotnik, G., Padmanabhan, P., Schultz, L., & Ramaswami, K. (1997). Shape deposition manufacturing of heterogeneous structures. Journal of Manufacturing Systems, 16(4), 239–248. https://doi.org/10.1016/s0278-6125(97)89095-4

Wake Forest Institute for Regenerative Medicin [WFIRM]. (2023). *A Record of Firsts*. https://school.wakehealth.edu/research/institutes-and-centers/wake-forest-institute-for-regenerative-medicine/research/a-record-of-firsts

Wohlers, T., & Gornet, T. (2015). *History of Additive Manufacturing History of additive manufacturing*. https://wohlersassociates.com/wp-content/uploads/2022/08/history2015.pdf

Xiangping, W. (2014). *Adaptive Slicing for Multi-axis Hybrid Plasma Deposition and Milling*. https://www.semanticscholar.org/paper/Adaptive-Slicing-for-Multi-axis-Hybrid-Plasma-and-Xiangping-Haiou/807df64fc358c689a402bb7effc809cb794a3491

Yan, B., Gu, S., & Zhang, Y. (2013). Polylactide-based thermoplastic shape memory polymer nanocomposites. *European Polymer Journal*, *49*(2), 366–378. https://doi.org/10.1016/j.eurpolymj.2012.09.026

Yang, J., Yang, Y., He, Z., Chen, B., & Liu, J. (2015). A Personal Desktop Liquid-Metal Printer as a Pervasive Electronics Manufacturing Tool for Society in the Near Future. *Engineering*, *1*(4), 506–512. https://doi.org/10.15302/j-eng-2015042

Yang, Y., Fuh, J.Y.H., Loh, H.H., & Wong, Y.J. (2003). Multi-orientational deposition to minimize support in the layered manufacturing process. *Journal of Manufacturing Systems*, *22*(2), 116–129. https://doi.org/10.1016/s0278-6125(03)90009-4

Yanyi, Z., Zhou, D., Cao, P., Zhang, X., Wang, Q., Wang, T., Li, Z., He, W., Ju, J., & Zhang, Y. (2021). 4D Printing of Shape Memory Vascular Stent Based on *β* CD- *g* -Polycaprolactone. *Macromolecular Rapid Communications*, *42*(14), 2100176. https://doi.org/10.1002/marc.202100176

Yu, K., Ritchie, A., Mao, Y., Dunn, M.L., & Qi, H.R. (2015). Controlled Sequential Shape Changing Components by 3D Printing of Shape Memory Polymer Multimaterials. *Procedia IUTAM*, *12*, 193–203. https://doi.org/10.1016/j.piutam.2014.12.021

Zarek, M., Mansour, N., Shapira, S., & Cohn, D.H. (2017). 4D Printing of Shape Memory-Based Personalized Endoluminal Medical Devices. *Macromolecular Rapid Communications*, *38*(2), 1600628. https://doi.org/10.1002/marc.201600628

Zhang, J., & Liou, F.W. (2001). *Adaptive Slicing for a Five-Axis Laser Aided Manufacturing Process*. https://doi.org/10.1115/detc2001/dac-21157

Zhang, Y., Webb, R.I., Luo, H., Xue, Y., Kurniawan, J., Cho, N.H., Krishnan, S., Li, Y., Huang, Y., & Rogers, J.A. (2016). Theoretical and Experimental Studies of Epidermal Heat Flux Sensors for Measurements of Core Body Temperature. *Advanced Healthcare Materials*, *5*(1), 119–127. https://doi.org/10.1002/adhm.201500110

ZHAW. (2016). *Masterstudenten entwickeln neuartigen 3D-Drucker*. https://www.zhaw.ch/de/ueber-uns/aktuell/news/detailansicht-news/event-news/zhaw-masterstudenten-entwickeln-neuartigen-3d-drucker/

Zhou, Y., Huang, W., Kang, S., Wu, X., Lu, H., Fu, J., & Cui, H. (2015). From 3D to 4D printing: approaches and typical applications. *Journal of Mechanical Science and Technology*, *29*(10), 4281–4288. https://doi.org/10.1007/s12206-015-0925-0

Zitelli, G. (2015). *US20170129175A1 - Method and apparatus for photo-curing with displaceable self-lubricating substratum for the formation of three-dimensional objects*. https://patents.google.com/patent/US20170129175A1/en

Zoltan, S. I. (1970). *US3683212A - Pulsed droplet ejecting system*. https://patents.google.com/patent/US3683212A/en?inventor=Steven+I+Zoltan

5AXISWORKS. (2023). *Desktop cnc machines*. https://5axismaker.co.uk/