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ADVANCES IN 3D PRINTING: AN EXTENSIVE OVERVIEW OF TECHNOLOGIES AND DIVERSE USES

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Abstract
The coming of 3D printing innovation has started a transformation in different fields, going from assembling and medical care to aviation and craftsmanship. This complete survey paper digs into the complex scene of 3D printing, giving an exhaustive investigation of its development, present status of-the-workmanship strategies, and various applications. Starting with an outline of the verifiable improvement of 3D printing, this audit explains the central standards and cycles supporting this innovation. It investigates the heap of materials used in 3D printing, highlighting their special features and applications. The paper carefully looks at the different 3D printing techniques, including Stereolithography (SLA), Selective laser sintering (SLS) and Fused Deposition Modelling (FDM), examining their benefits, constraints, and arising developments. Moreover, the audit researches the boundless uses of 3D printing across ventures, exhibiting its effect on custom prosthetics, engineering plan, auto assembling, and even space investigation. In synopsis, this survey paper gives a far reaching and exceptional analysis of 3D printing innovation, underlining its development, strategies, materials, and different applications. This paper investigates the promising crossing point of 3D printing and artificial intelligence, revealing insight into the future extent of this powerful collaboration. It explores through the present status of artificial intelligence applications in 3D printing, featuring headways in plan improvement, material advancement, and cycle robotization. Furthermore, the paper explores metrology-related topics, emphasizing the use of precise measurement methods in determining part variations and verifying compensation schemes. The study emphasizes the importance of metrology in maximizing the performance and quality of additive manufacturing processes through in-depth research and testing.
Keywords: 3D printing, Additive Manufacturing, Stereolithography, Industry 4.0, AI Integration, Metrology

1. Introduction

Manufacturing can be stated precisely as a process of making goods and providing services in order to satisfy human needs. The series of all the manufacturing processes put together is what we know as an entire manufacturing system. Any process through which a raw material can be converted into a useful desired product which adds to its value economically would be classified as a manufacturing process[1]. It can be of the four following types: - Subtractive, Additive, Forming and Casting. Subtractive manufacturing is the one in which a product is derived out of an existing model. It involved material removal with turning, grinding, milling, drilling etc. Forming is the metal work done to reshape by plastic deformation. No material is added or subtracted from it. Casting is the strategy wherein a metal is softened, filled an ideal shape and permitted to solidify. Added substance Assembling or 3D printing is the freshest structure wherein material is being kept layer by layer. A crucial hardware for this is a 3-Dimensional printer that creates a 3D prototype from a digital file[2]. This digital file is drafted on a Computer Aided Designing (CAD) Software that get read by a slicer software. The process flow of 3D manufacturing begins from conceptualisation and right dimensional information of the required model and tracing it out on a CAD software[3]. It allows the user to sketch out a design and create a prototype. The final design is put out on a slicer software, which gives a preview of the desired 3D print [4].Various alterations can be made such as the layer thickness or the build plate adhesion. The 3D printer browses through the file and once the model is printed, necessary machining process is done if required. Charles Hull presented the first commercialised 3D printing process in year 1980. The first technology introduced was layer by layer fabrication technology from computer aided design[5].3D printing has emerged over the years. It has a wide range on application proving its versatility. It revolutionizes the industry and the production line [3]. Aerospace and automotive industry were the early embracers of 3D printing technology. It made the availability of complex figures easier. A variety of 3D printed aircraft parts are now manufactured successfully. Medical sector has also received its benefits. 3D printed dental fixtures and hearing aids are being customised as per the customer's need with this technology. With style and food industry, 3D printed items legitimize the imagination and innovation [6]. To summarize, 3D printing innovation has arisen during the years and chips away at the rule of quick prototyping. This paper showcases the outline of 3D printing innovation and the extensive variety of utilization in different fields. It also comprises of the variety of print settings and how each factor affects the other, the material used and its application.

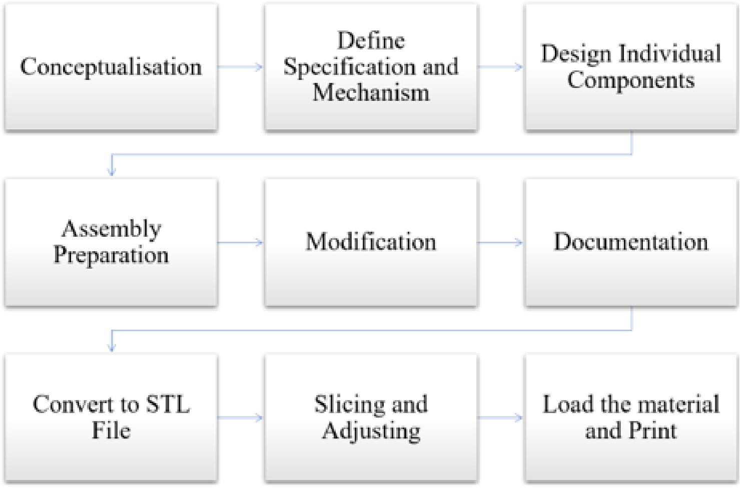

Figure 1: Printing Procedure

2. Processes in 3D printing

Intricate 3D models get printed with high resolution through AM. However different processes give different output. It is necessary to understand how the printer reads a CAD model. The CAD model is first transfigured into an STL file which is a file format commonly operated for 3D printing [7]. The acronym stands for stereolithography or standard tessellation language or standard triangle language. Each file is made up of triangles that are associated together to form the geometry of a model. It uses an .stl extension [8]. There exist a variety of processes for 3D printing. According to ASTM (American Society for Testing and Materials), the technologies can be grouped into seven categories that includes directed energy deposition, sheet lamination, vat photopolymerization, material jetting, material extrusion binder jetting, and powder bed fusion. Each of these processes have their own significance, since all of them are targeted to a specific application [2].

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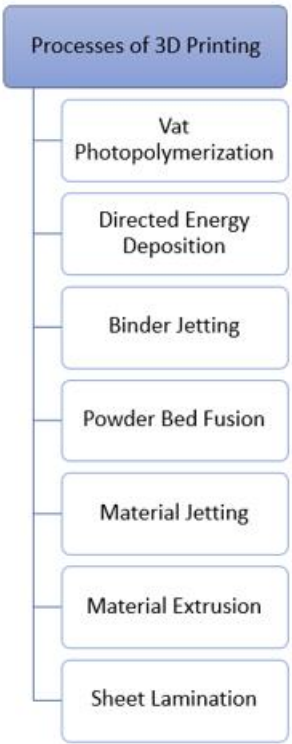

Figure 2: Processes of 3D Printing

2.1 Vat photopolymerization

It requires a light head that cures the surface of a vat loaded with liquid photopolymer resin stratified [9]. Since it transforms into a different structure upon putting of external stimuli such as light and heat, it shifts its itself to 4D printing. It offers high dimensional accuracy and better resolution [10] [11].

2.2 Directed Energy Deposition

Directed Energy Deposition (DED) works like a super-focused energy beam, sort of like a laser, that carefully hits a specific spot. In that spot, tiny metal powders get heated up and then melted together in a very controlled way [12]. The strength of the electron beam really affects how good the final print looks, especially the small details. And how quickly the DED process happens depends on how fast things are getting deposited [13]. DED process maintains a constant supply of metal powder throughout. Noteworthy metal powders such as aluminum, titanium, copper, tin, cobalt, nickel and stainless steel find practical utility within the realm of DED applications [14] [15].

2.3 Binder Jetting

Binder jetting stands as a swift 3D printing method where liquid binding substance joins powdered particles selectively [16]. This method uses chemical sprays on a layer of powder to raise things one layer at once. It's useful for making moulds, solid objects that haven't been fully heated, and big things made from sand-like material [17]. Metals, hybrids, sands, ceramics and polymers can all be printed via binder jetting, with certain materials such as sand needing no added treatment. Beyond its simplicity, speed, and affordability rooted in particle adhesion, this process excels in producing substantial prints [18] [19].

2.4 Powder Bed Fusion

Powder Bed Fusion is a common way to create detailed parts from different materials. In this process, we use laser beams to melt a lean layer of powder that we've put down, and it sticks to the layers below it [20]. This method ensures things happen quickly and can easily adapt. However, when we use lasers to scan quickly, it creates heat and pressure in the area where the work is being done [21]. Observing the actions of individual particles within the powder bed during this process has remained a challenge. In a recent study, high-speed imaging was harnessed to monitor the movements of these particles during Powder Bed Fusion, unveiling their actions [22]. Interestingly, tiny particles move towards the hot, melted area, causing changes in how the powder is spread out. This movement shows that there's

a strong flow of gas happening all the time while this is going on. This gas flow could be because the metal turns into vapor when the laser heats it up, or it could happen because the temperature and pressure are very high in the area where the work is being done, even if there's no vapor [23].
2.5 Material Jetting
Material jetting works much like a 2D inkjet printer, forming objects. Here, material is sprayed onto a building area via continuous or Drop on Demand (DOD) techniques. This material is then projected onto the build surface, gradually solidifying as the model takes shape layer by layer [24]. The substance is released through a nozzle that glides horizontally covering the platform. Machine intricacies and material deposition control methods differ. To finalize the layers, ultraviolet (UV) light is employed for curing and solidification [25].
2.6 Material Extrusion
Fused Deposition Modelling (FDM) is a popular way to make things with melted material. It works like this: the material gets heated and pushed out through a small hole, and then it's carefully placed layer by layer. The secret sauce is how the nozzle moves side to side and how the platform oscillates vertically for each new layer [26]. This method, commonly used in affordable 3D printers for personal use, works well when we handle its various aspects properly. Unlike some other 3D printing methods that build layer by layer, FDM (Fused Deposition Modelling) keeps pushing material steadily through a nozzle, ensuring a consistent flow and pressure [27]. Keeping the pressure steady and moving smoothly is really important for being accurate. [28]Temperature control or special chemicals can stick the material layers together. Usually, the material comes from a spool, like the picture shows, and it goes into the machine [29].
2.7 Sheet Lamination
Sheet lamination techniques encompass innovative methods like Laminated Object Manufacturing (LOM) and Ultrasonic Additive Manufacturing (UAM) [30]. UAM is a process where metal sheets or ribbons are co-joint together using high-frequency vibrations. After this, extra metal that didn't get attached needs to be removed, which is often done at the same time as the joining process using CNC machining [31]. On the flip side, LOM works similarly, but instead of using metal and welding, it uses paper and glue. When doing LOM, it uses a crisscross pattern while printing, making it easy to remove things after they're made [30].

3. Processing Techniques for 3D Print

Using the FDM technique, a 3D printer employs thermoplastic filaments that are extruded in a controlled manner. A single or dual extruder head nozzle is present, which heats the polymeric filaments to a semi-liquid state. This enables the creation of successive object layers as the fused filaments are extruded onto a build platform [32]. As the material cools and hardens, it affixes with the previously deposited material [33]. The printer's nozzle or base plate moves horizontally (x-y plane) while depositing molten material onto the build surface. Additionally, the base plate descends or the nozzle ascends vertically (z-direction) based on the filament height, effectively building up layers [34]. By adjusting filament type, printer settings (e.g., temperature, flow, layer thickness), and other parameters, the FDM method allows control over mechanical strength and surface finish. The quality of adhesion between layers is influenced by temperature changes at interfaces, impacting the diffusion and arrangement of polymer chains [35] [36].
3.1 Advantages of Fused Deposition Modelling (FDM) 3D Printing
1. Economical Advantage: FDM flaunts a financial savvy approach, making it open for a great many applications and clients. The affordability of the materials and technology contributes to democratizing the world of 3D printing.
2.Rigidity and Strength: The resulting prints from FDM exhibit notable stiffness and impressive mechanical strength. This structural integrity makes FDM-printed objects suitable for functional prototypes, end-use parts, and a plethora of engineering applications [37].

3. Precision in Dimensions: FDM demonstrates an exceptional ability to maintain dimensional accuracy throughout the printing process. This accuracy is crucial when creating intricate designs or components that require exact specifications.
4. Extended Shelf Life: Objects created through FDM possess a favourable shelf life, thanks to the properties of the thermoplastic materials used. This durability ensures that FDM-produced items remain structurally sound and reliable over extended periods [38].

4. Materials used

The world of 3D printing is used in many different areas like making food, clothes, and buildings. It's used for lots of things, from designing a first version of something to making the final product. Each area needs a special kind of material to work best. For example, think about making a fancy ring. When using 3D printing, a designer might use a special type of plastic to shape the ring. But if they were making a strong part for a machine, they would use metal instead. In the food industry, picking the right material is super important. So, the material used has to match what they're making.

4.1 Poly Lactic Acid (PLA)

PLA is a well- known material for 3D printing, particularly with the FDM strategy. Individuals like it since it's eco-accommodating and can separate normally. However, it has some problems. It can easily break under pressure, and it dissolves quickly in water [39]. But in the last ten years, researchers have been working on making new kinds of PLA that are better, and this has gotten a lot of attention from both universities and companies [29].
Lactic acid-derived polymers, known as poly (lactic acid) or polylactide, are commonly abbreviated as PLA. Over the past two decades, it has emerged as the key thermoplastic resource in 3D printing [30]. PLA's eco-friendliness is evident as it's predominantly sourced from renewables like corn, sugar cane, wheat, and rice, with a notable uptake of carbon dioxide during production. PLA boasts multiple benefits, including biodegradability, recyclability, and facile thermal processing [28].

Property	Value
Full Name	Polylactic Acid (PLA)
Melting Point	150° -160° C
Tensile Strength	60 N mm^{-2}
Printing Temperature	180° -230° C
Injection Mold Temperature	178 to 240 °C
Elongation at break	7 %
Glass Transition	60 °C – 65 °C

Figure 3: Properties of PLA

PLA stands as a semi-crystalline polymer characterized by a relatively modest melting point of 170-180°C, setting it apart from the higher ranges of 200-260°C found in ABS filament. This selection, while challenging complexities, doesn't compromise on performance [40] [41].
When it comes to 3D printing materials like ABS and PETG, PLA is not as strong and can break more easily. This means that things made with PLA are better for looking nice rather than being really tough and strong [42].
While regular PLA containers are safe for food, PLA containers might not be as safe. When we 3D print things, tiny gaps and holes can form in the layers. These small spaces can trap moisture and food bits, which can lead to the growth of bacteria and mold. So, it's important to be cautious when using 3D-printed PLA containers for food [43]. When PLA filament gets too hot, it can drop out of the 3D printer's nozzle when it's not supposed to. This creates unwanted strings between different parts of the print, making it look messy. To fix this, you can use a cooling fan to keep the temperature down and prevent the dripping [44].

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4.2 Polyethylene Terephthalate- Glycol (PETG)

PETG stands as the Glycol modified Polyethylene Terephthalate (PET)[45] , also used in the creation of water bottles. PETG is a type of plastic that's kind of like what water bottles are made from. It's not too flexible and can handle hits pretty well, but it's a bit softer on the surface, so it can show some wear. What's really cool about it is that it can cool down quickly after being heated [46]. Among the different types of plastic available, PETG is one of the best, and there are also similar ones like PETE and PETT, each with their own special features [46].

In terms of printing settings, when working with PETG, it's proposed to set the extrusion temperature within the limit of 220°C to 260°C. Utilizing a heated print bed within the temperature range of 75°C to 90°C is also advised [28]. For optimal results, a printing speed of 40 to 60mm/s is considered ideal. It's worth noting that using supports with PETG is not recommended, as the material tends to adhere quite strongly to itself, which can lead to challenges in removing them post-printing [47]. Nevertheless, PETG is a material that offers a poise between ease of printing and desirable properties, though it might present slightly more challenges compared to PLA [48] [49].

A heating plate is imperative to prevent the potential warping effects associated with PETG, even when the warping rate is minimal. For added assurance of material adherence, employing a BuildTak sheet is advisable. Additionally, PETG is more susceptible to scratching compared to PLA. Moreover, it has a tendency to absorb moisture rapidly, necessitating storage in a cool, dry setting. It's important to acknowledge that due to its high viscosity, PETG has the potential to cause clogs in print heads [50].

4.3 Acrylonitrile Butadiene Styrene (ABS)

ABS (acrylonitrile butadiene styrene) is the most used material for 3D printing. It's known for making strong plastic parts that can handle different temperatures. People usually use it with FDM 3D printers[51]. Comprising a thermoplastic polymer, ABS amalgamates three monomers: butadiene, acrylonitrile, and styrene. Originating in 1940s, this material rapidly gained widespread acclaim through its patent. In contemporary times, ABS's versatility, malleability, and resilience have secured its role across various industries [52]. Notable for its superior attributes relative to many budget-friendly polymers, ABS exhibits considerable flexibility, formidable heat resistance, and ease of machining. Within the realm of 3D printing, ABS garners appreciation for its swift printing capabilities and heightened durability, setting it apart from numerous alternatives [53].

Available in both filament and resin forms, ABS finds its most common application within the FFF 3D printing domain. ABS is offered in filament variations with diameters of either 1.75 mm or 2.85 mm, spanning a diverse array of colors [7]. Despite the fact that it presents a more noteworthy printing challenge in contrast with PLA, ABS stays a sought-after decision among 3D printing experts because of its praiseworthy impact resistance and its ability to endure elevated temperatures going from - 20°C to 80°C [54]. This material has a opaque quality, presents smooth matte finish, and can be upgraded with acetone treatment to accomplish a polished appearance [55].

ABS plastic melts at around 200 degrees Celsius, so when we're 3D printing with it, we regularly use temperatures somewhere in the range of 230 and 260 degrees Celsius. Additionally, we need to use a warmed print bed that's set between 80 and 130 degrees Celsius. This is necessary because ABS has a tendency to shrink when it cools down. Without a heated print bed, the material can warp and come off the printing surface [56]. For big parts, it's a good idea to use special glues like Kapton or adhesive lacquer. Also, it's best to use a 3D printer that has an enclosed space around it. This is important for two main reasons: first, to keep you safe because ABS material can release harmful particles, and second, because it's really important to control the temperature precisely when working with ABS. Having a closed space around the printer is crucial for successful printing. It helps prevent problems like the part bending, breaking, or layers not sticking together properly. The heated space also keeps the temperature steady, which makes sure your 3D prints turn out just right [57].

S. No	Material	Advantages	Disadvantages	References
1.	PLA	1. The filament adapts with rapid printing speeds with well-defined contours, contingent upon effective cooling measures. 2. The resultant components exhibit minimal susceptibility to deformation. 3. The filaments exhibit a shelf life of no less than a year under appropriate storage conditions, specifically within the temperature range of 15 to 25°C.	1. PLA doesn't work well in really hot situations, so it's not good for high-temperature stuff. When it gets too hot, PLA can change shape quickly, especially when it's under pressure	[58][59][60]
2.	PET-G	1. Exquisite Gloss and Smoothness in Surface Texture: One special thing about this material is that it makes things look really shiny and smooth when you use it for 3D printing. This smooth and glossy finish makes the printed objects look fancy and more attractive 2. Exceptional Bed Adhesion with Minimal Warping: One of the great things about PETG is that it sticks really well to the printing surface when you're making something. This makes sure that what you're creating doesn't get all bent out of shape. This helps the whole printing process work smoothly, so you get things that are just the right size and shape like you want them. 3. Virtually Odourless Throughout Printing: Another good thing about PETG when you're using it for 3D printing is that it doesn't give off strong smells. This means you can work comfortably without being bothered by any strong odours, so you can concentrate better on your creative work.	1. Not-So-Good at Bridging: One of the things this material isn't great at is making bridges. When it tries to make something like a bridge to cover empty spaces while printing, it might have some trouble. This could mean the thing it's making might not be very strong or stable. 2. Potential for Surface Imperfections: Another thing to think about is how likely it is for thin stringy bits to form on the surface of the print. These stringy bits can make the printed object look less nice and might need some fixing after printing to make it look better.	[49][61][62][63]

3.	ABS	1. Affordability: One of the notable benefits lies in its cost-effectiveness. ABS material stands out as a low-cost option, making it an attractive choice for those seeking economical 3D printing solutions. 2. Robust Impact and Wear Resistance: ABS showcases commendable durability, excelling in both impact resistance and wear resistance. This characteristic renders ABS-printed objects more resistant to the rigors of everyday use and environmental stressors, contributing to their extended longevity. 3. It can handle high temperatures without getting damaged easily. This makes it a good choice for things that need to be near heat, but only up to a certain point. ABS can be used for many different things, like making test versions of products or parts that need to handle a little bit of heat.	1. ABS has a habit of warping, which means the things you print might end up bent or twisted when they cool down. This can make it tricky to get the shape you want. 2. One needs a special heated bed or a heated box to print ABS properly. So, it's not as simple as just putting it in a regular 3D printer. When the material cools down after 3D printing, it can shrink and sometimes come off the printing surface, making it stick poorly and messing up the quality of the print. 3. It produces a strong and unique smell while printing, which can be unpleasant, especially indoors or in small spaces. 4. ABS can also shrink as it cools, making the printed object slightly smaller than it should be. This can affect how well different parts fit together and how accurately the final product turns out.	[64][65][62][66][67]

Figure 4: Advantages and Disadvantages of PLA, PET-G, ABS

5. Parameters contributing in FDM printing

After finalizing the design, the next step involves inputting the model into a slicer software. This sophisticated tool not only provides a visual representation of the anticipated output but also offers a range of customizable parameters that significantly influence the printing process. Within the slicer, the user gains the ability to fine-tune several critical elements. First and foremost, the thickness of each individual layer that constitutes the final print can be adjusted. This parameter is pivotal as it directly influences the intricacy of the object's details and the overall printing time. Furthermore, the slicer permits the manipulation of interior space allocation for each material. This feature is particularly crucial when dealing with multi-material or multi-component designs. By determining how much space different materials occupy within the print, users can seamlessly integrate complex structures or amalgamations. Another integral aspect that can be personalized is the build plate adhesion strategy, particularly pertinent for ensuring a well-adhered bottom layer. Various options are available, including brims, rafts, and supports, each catering to specific design and material characteristics. This customization is pivotal in addressing concerns related to print stability, warping prevention, and overall adhesion quality. These adjustable print settings assume an even greater significance when it comes to troubleshooting common printing challenges such as shrinkage and scaling discrepancies.

By fine-tuning parameters such as layer thickness and material allocation, users can mitigate potential distortions and inaccuracies in the final printed object.

In essence, the slicer software functions as a control hub, allowing creators to tailor their printing process to meet the unique demands of their design. This level of customization empowers users to address potential issues, optimize printing outcomes, and bring their envisioned models to life with precision and accuracy.

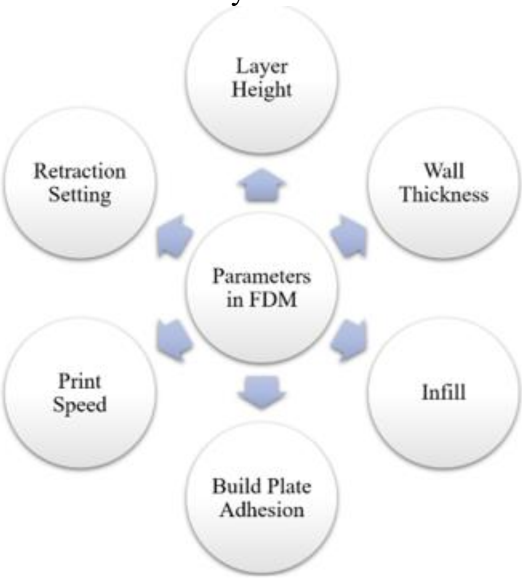

Figure 5: Parameters in FDM

5.1 Layer Height

The thickness of the material layer being put down is really important. Many sources agree that making this layer thinner makes the final product stronger [68]. The thickness of each layer you choose affects how smooth your 3D-printed thing looks when it's done. If you want it to look really nice, pick a smaller layer thickness because it makes the surface smoother. But if you're making something that doesn't need to look perfect, like a practical object, it's better to choose a thicker layer [69]. This way, it'll be made faster and cost less, and it will also be stronger. For example, if you're using FDM to print in PLA and you choose a layer thickness of 300 µm, your thing will be about 20% stronger than if you picked 100 µm [70].

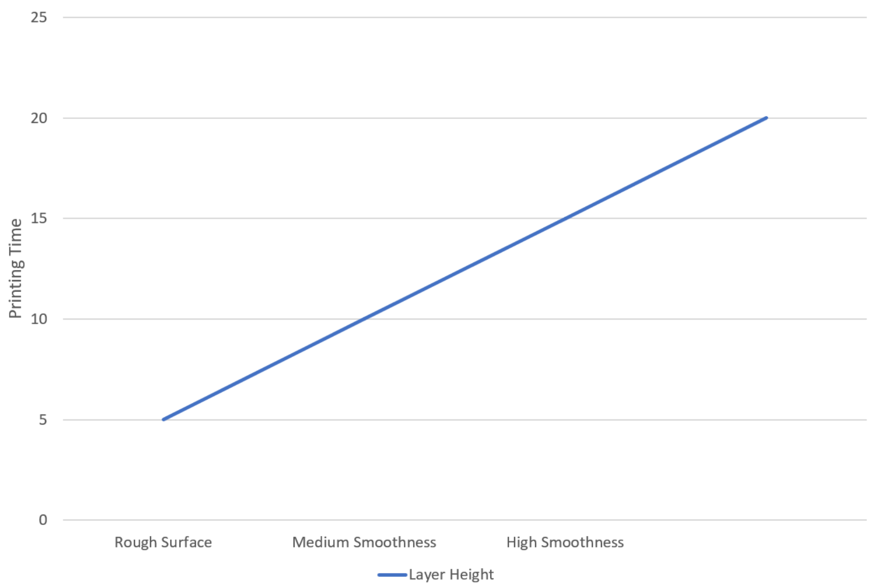

Figure 6: Variation of Layer Height with Printing Time

5.2 Wall Thickness

When we use 3D printing and we need to make the walls thicker to support the object, there's a limit to how thick we can make them. This is especially important when we're working with metal materials. If we ignore this limit and make the walls too thick, it can cause problems like stress inside the object, cracks, or even make it break. Think about making a phone case, for example. If we make it too thick, it won't be flexible, and that's not what we want for a phone case. Hence, it's important to calculate the right balance between thickness and flexibility while using 3D printing [71]. Recommended wall thickness in case of PLA, ABS and Nylon is 1.5 whereas for rubber like it goes up to 2.0 [72] [73].

5.3 Infill

The infill assumes a significantly more dynamic role, profoundly influencing a component's strength, weight, structure, buoyancy, and other attributes. Within the realm of 3D printing, you possess the freedom to specify diverse variables that dictate the infill employed for a given element. These parameters are configured within a slicer program, which translates a 3D model into G-code instructions. Among these parameters, two pivotal facets stand out: infill density and infill pattern [74] [75].

5.3.1 Infill Pattern

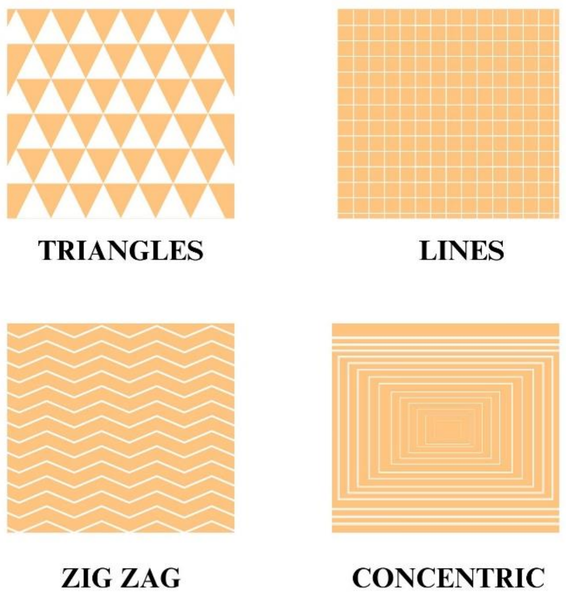

Figure 7: Types of Infill Pattern

Quick 2D infill: The Lines infill pattern is fast, uses little material, and suits decorative prints. It creates a grid with alternating layers of unidirectional lines. Strong 2D infill: Triangles infill, an option in Cura, is like a triangle-based grid. It's sturdy and shear-resistant in all directions but has flow interruptions at intersections, similar to the Grid pattern [76]. Other patterns that exist are gyroid, cubic, zig zag, concentric, octet etc. Gyroid is considered one of the best infill patterns as it provides the maximum strength [77].

5.3.2 Infill Density

The infill percentage determines the density of the structure and is denoted as a percentage. To illustrate, a 3D print featuring 100% infill will exhibit a completely solid interior, whereas a model with 0% infill will be produced as a hollow shell. Essentially, a greater infill percentage augments the volume of material within the 3D printed part [78].

5.4 Build Plate Adhesion

When printing small or low-surface area objects, they might not stick well to the build plate, leading to print failures. To fix this, enhance build plate adhesion using a brim or a raft. A brim creates a thick outline alongside the first layer, allowing the initial layer to attach better. For stronger adhesion, a raft can be used, which adds a plastic layer below the object, enabling it to print directly on additional plastic support [79].

6. Application of 3D printing

Certainly, earlier in our conversation, we touched upon the various domains where 3D printing finds its valuable applications. This inventive manufacturing technology has demonstrated its utility across a large number of fields and businesses, displaying its flexibility and versatility [80]. From aviation and auto enterprises to medical services, fashion, engineering, and even workmanship, 3D printing has cut a critical specialty for itself [81]. Its capacity to change computerized plans into substantial items layer by layer has opened up new roads for customization, fast prototyping, and, surprisingly, the creation of complicated calculations that were once challenging to accomplish through conventional assembling techniques [82]. This assembly of innovation and imagination has smoothed out creation processes as well as prompted novel arrangements and leap forwards in different areas. As we dive further into the particular uses of 3D printing, its effect turns out to be significantly more obvious and entrancing.

6.1 Medical Industry

Current applications involve creating patient-specific implants and anatomical models for surgical planning and education. In cardiac surgery, 3D models of hearts with hereditary defects are useful for training and preoperative planning [83]. For instance, in cases with specific heart defects, these models can assist in locating collateral arteries and making decisions about connecting them to the main pulmonary artery or ligating them [84]. These models are also valuable for complex interventional procedures like TAVR or LAA closure, where the intricate anatomy and device interaction pose challenges for even advanced imaging methods [85] [86].

6.2 Fashion Industry

3D printing (3DP) is utilized in fashion for creating prototypes, haute couture pieces, and customizable products, offering users an interactive choice-driven involvement. Nike employed Selective Laser Sintering (SLS) to produce prototypes and craft lightweight plates for their Vapour Laser Talon and Vapour High Agility football cleats. Nike noticed minor slippage during athlete Michael Johnson's 40-yard dash in the Vapour Laser Talon cleat, leading to design adjustments [87].

6.3 Aerospace Industry

Significant advantages apply to common 3D printing uses like crafting jigs and fixtures. In aircraft manufacturing, firms create numerous 3D printed guides, templates, and gauges per plane, cutting costs and production time by around 60 to 90 percent compared to traditional methods [88]. Substitutes are stand-in components in production, standing for parts later placed in the final product. They're primarily for training and are frequently seen at NASA and Air Force bases during production [89].

6.4 Food Industry

The prevalent technology utilizes food ingredients with moderate viscosity to ensure that the material maintains its intended shape when extruded. The food is incrementally constructed through layering until the entire form is achieved. The 3D printers don't involve cooking the food; instead, they shape it into the desired form. Subsequently, an oven might be required to cook the printed food after the printing process concludes. Certain foods, such as sugar or chocolate, can be directly consumed immediately following the printing process [90].

6.5 Industry 4.0

Industry 4.0 has recently come to the forefront as a means to achieve more efficient mass production of high-quality products while reducing both time and development [91]. The idea of a 'smart factory' has given rise to Industry 4.0, which serves as a broad term encompassing the Internet of Things (IoT) built upon cyber-physical systems (CPS) [92]. These systems effectively connect the digital and physical realms [93]. Industry 4.0 can be condensed into 9 key pillars, which encompass cybersecurity, advanced robotics, augmented reality, industrial internet, additive manufacturing, simulation, horizontal and vertical integration, cloud technology, and big data and analytics [94]. Despite the

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growing acceptance of additive manufacturing as a valuable educational tool in biomedical schools, engineering education has paid relatively little attention to additive manufacturing and Industry 4.0. This lack of attention can be attributed to the misconception that these concepts are relevant solely to automation and mechanical engineering. Furthermore, there is a shortage of knowledge regarding the various pillars of Industry 4.0. However, some universities are taking steps to incorporate Industry 4.0 into their teaching and research endeavors [95]. The countless advantages of 3D printing, including remote accessibility, digital data transfer, minimal human intervention, the capacity to create intricate shapes and intelligent materials, reduced waste, and decreased post-processing needs, are composed to play a pivotal role in realizing the objectives of Industry 4.0 [96].

7. AI-Driven Optimization for Customized 3D Printing Solutions

In the beginning, "artificial intelligence" meant making machines smart like humans, solving tricky problems by learning and reasoning. But now, some AI researchers see intelligence as being rational, which means it's not just about copying humans but having a wider perspective. Smart machines can think on their own and make decisions without making mistakes, following their design or a preset plan [97] [98]. Recently, companies have made AI part of computer-aided design (CAD) systems. This has sped up the design process a lot and created smart design spaces where machines learn from experience.

In health care, AI is making CAD even more useful. It's helping organize medical images and making the workflow smoother in places like hospitals. People also want to use AI in things like green manufacturing and sustainable development to make processes smarter. Recognizing the need for AI in design happened early on in CAD development. Back in 1965, Mann had some early ideas about intelligent design. All of these, show how AI is becoming a big part of different industries, making things work better and solving problems smarter [99].

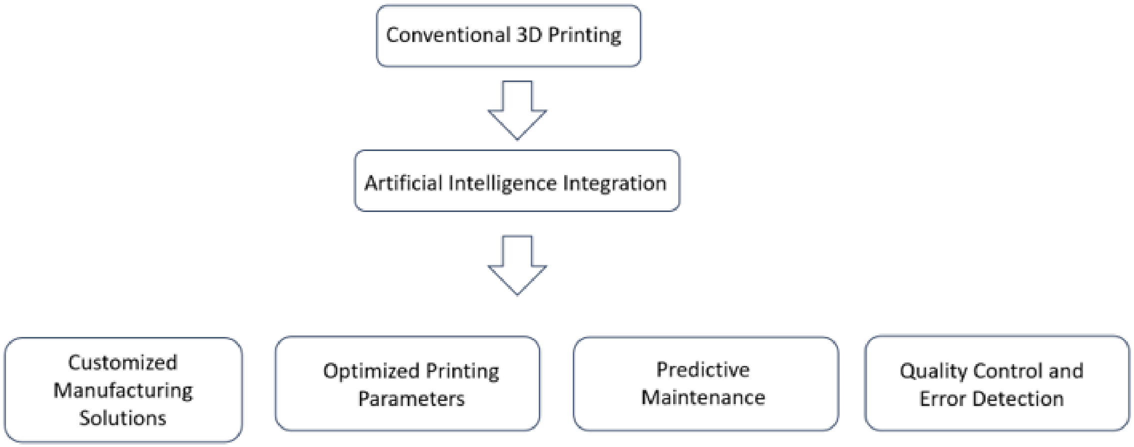

Figure 8: AI integration

Ever since the introduction of CAD systems, we gained the ability to view a product in three dimensions before actually making it. Nowadays, CAD models go beyond just 3D modeling; they help simulate effects and plan work schedules. CAD also allows us to check things like how parts move together and avoid colliding. But, there's still a gap because regular CAD apps don't provide a fully immersive experience like what we see in Mixed Reality (MR), Augmented Reality (AR), and Virtual Reality (VR) [100].

In the real world, many complex products need careful planning before they're created. Using traditional CAD tech, it's challenging to replicate the real 3D world accurately. This is where extended reality technologies come in. With MR, AR and VR, the models created in CAD software can be loaded into these platforms, offering immersive simulations and detailed planning. It's like stepping into a virtual world where you can interact with and visualize your designs in a more realistic way [101].

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8. Metrology

The achievement of exact geometric dimensions is one of the main issues with 3D printing. This disparity frequently results from warping and shrinking that happens during the printing process. Shrinkage is caused by a number of variables, such as the extruder's temperature settings, the material composition, and the surrounding conditions. As a result, these factors have the potential to cause notable variations in dimensions, especially with regard to internal elements like slots and holes [102]. Moustapha Jadayel et al. [103] proposed a three-dimensional geometric compensation method that may be used to improve the geometric correctness of 3D printed parts. The method works by morphing the part's original surface mesh model by the inverse of the systematic deviations, hence removing systematic deviations. By 3D scanning several produced sacrificial components and calculating an average deviation vector field across the model, these systematic deviations are quantified. Tong et al. [104] suggested an approach for reducing geometric mistakes that was modeled after machine tool techniques. This involved generating a parametric error model of the machine's volumetric errors and adjusting the machine's movement appropriately. An artifact that was printed was measured in order to derive the error model.

A number of statistical error models were put out by Huang et al. [105], [106] to forecast the printed part's in-plane shrinkage and out-of-plane deviation. Subsequently, by processing the 3D model layer by layer and accounting for the influence of layers on previously printed layers, they developed a convolution model to more correctly represent the deformation of 3D printed objects. An inspection phase is usually included in an AM workflow to confirm print quality and evaluate dimensional tolerances. Because of the shortcomings of existing geometrical metrology techniques, this phase is carried out after printing. For instance, ionizing radiation precautions make X-ray computed tomography (CT) [107] impractical for in-situ application.

8.1 Deviation Analysis

Farbod Khameneifar et al. [103] compared the original parts with the compensated parts. The compensated components exhibit notable improvements in average absolute error, standard deviation, and 99th percentile values when compared to the original parts.

	Average Absolute Error (µm)	Standard Deviation (µm)	99th Percentile (µm)
Sample Part	53	60	318
Compensated Part	52	48	221
Improvement	No change	20%	31%

Figure 9: Deviation Analysis

In particular, compared to the original components, the compensated parts show improvements of 68% in the 99th percentile, 65% in standard deviation, and 55% in average absolute error.

8.2 Tolerance Analysis

Tolerance Feature	Specified Tolerance (µm)	Deviation (µm)
Cylindricity (Cylinder A)	5	Out of tolerance
Position (Hole Group B)	10	Out of tolerance
Angularity (Plane C to D)	0.2	Out of tolerance

Figure 10: Tolerance Analysis

For each of the three characteristics, the original parts (A–E) are out of tolerance.

- Due to random variability, the compensated component based on part B is out of tolerance for two characteristics.
- All characteristics are brought within tolerance by compensation depending on the original components' average deviation.
- Cylindricity deviation is effectively reduced by 51%, position deviation by 61%, and angular deviation by 15% by compensation.

Conclusion

In conclusion, this complete survey has investigated the multifaceted view of 3D printing, revealing insight into its authentic development, the different types of materials and methods it envelops, and its broad applications across different enterprises. We have seen the extraordinary force of 3D printing as it reforms creation processes as well as opens up new frontiers in customization, plan development, and maintainability.

As we explore the steadily developing domain of 3D printing, it is pivotal to recognize the difficulties it presents, including intellectual property concerns, regulatory framework, and the requirement for standardized practices. Additionally, the coordination of 3D printing into instructive educational programs and the scattering of information to sustain future ability in this field are fundamental undertakings.

Looking forward, the proceeded with collaboration among examination and industry will drive further advancements, pushing the limits of what can be accomplished with 3D printing. Joint effort across disciplines and the tenacious quest for greatness will be vital in outfitting this innovation's maximum capacity.

In this dynamic landscape, 3D printing isn't only a device however an impetus for change, molding the fate of assembling, medical services, design, and beyond. With each layer it adds, 3D printing builds an extension to a more flexible, reasonable, and innovative future.

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