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Additive Manufacturing Technology Development: A Trajectory Towards Industrial Revolution

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Abstract: With the recent advancement in complexity of various technological products and the need for faster production, the quest for inventing new manufacturing technologies to reduce the design limitations such as the costs involved in purchasing and maintaining machines, the need for a trained operator, and increase in waste produced during machining in conventional manufacturing methods, has received significant boost in recent time with the advent of additive technology (AM) or 3D printing within various experts in industry, research & development institutes and universities, which invariably has not only enhanced deliverable on time and on budget of products, as well as ability to fabricate complex geometry with high precision and weight reduction. Several types of additive manufacturing (AM) that use different technologies and materials have emerged, in which the 3D systems are used to produce objects through adding rather than subtracting materials, transforming essentially detailed design files to fully functional products, to directly or indirectly alleviate the burden associated with convectional manufacturing and assembly methods. In this paper, an extensive review has been done on several methods adopted in 3D printing. Example include: Fused Filament Fabrication (FFF), Selective Laser Sintering (SLS), Continuous Filament Fabrication (CFF), Stereolithography (SLA), Atomic Diffusion Additive Manufacturing (ADAM) and Selective Laser Melting (SLM). The various steps involve in operation and working principle of 3D printing technology was also stated. The paper also presents the applicable areas of 3-D printing focusing on tooling, aviation/aerospace, medical/biomechanical and city planning.

Keywords: Additive Manufacturing, Fused Filament Fabrication, Selective Laser Sintering, Continuous Filament Fabrication, Stereolithography, Atomic Diffusion and Selective Laser Melting

1. Introduction

The increasing demand for innovation in new manufacturing and assembly technologies is to provide extensive high precision, good quality, high production rates and low production costs to improve the efficiency and high level of autonomy in manufacturing process that minimize product time to market. Additive manufacturing (AM), also known as 3D printing is an emerging technology in which computer 3D designs model data are used to produce objects through adding, usually in layer upon layer by deposition, rather than subtracting materials as in traditional manufacturing processes [1] such as milling, turning, drilling and welding etc. This technology can create parts of very intricate and complex geometries that are difficult to manufacture traditionally, from varieties of materials, including metals, thermoplastics, carbon fiber and even ceramics with near zero material waste [2].

Since the inception of 3D printing in 1976 when the inkjet printer was invented, 3D printing technologies have grown substantially in size over the years. In 1984, Charles Deckard Hull, the co-founder of 3D Systems Corp, invented stereolithography and obtained a patent for the technique in 1986, a printing process that enables a tangible 3D object to be created from digital data. The 3D system advances the inkjet concept and morphed the technology from printing with ink to printing with materials. The technology is used to create a 3D model from a picture and allows users to test a design before investing in a larger manufacturing program. Later in 1990's other companies developed 3D printers. In 2005, Z Corp launched first high definition color 3D printer and ever since, additive manufacturing (AM) continues to grow as an advanced manufacturing technique. The following names have been used to refer to 3D printing: Rapid prototyping, rapid manufacturing, laminated object manufacturing and additive manufacturing (AM) [3]. The latter involves the whole process of making 3D solid objects from computer-generated files, or digital files.

The actual 3D printing process is only one part of the entire procedure as depicted in a nutshell in Figure 1, it works like inkjet printers. Instead of ink, 3D printers deposit the desired material in successive layers to create a physical object from a digital file.

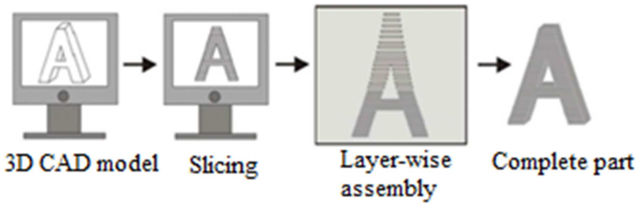

Figure 1. *Additive manufacturing process in a nutshell [4].*

The process involves creation of three-dimensional object in a computer using commercial Computer Aided Design (CAD) software such as Solidworks and saving the object in STL file format or other 3D printer readable format such as ". thing". The 3D design model is then exported to a slicing software that translate 3D design files into instructions by analysing this model, taking a series of layer slices and working out the tool path (G-codes) within each layer for the 3D printing machine via USB drive, USB cable, or local network. For example, for the FFF systems, the extruder head will melt the printing material and squeeze it out onto the build plate in thin lines to build the object layer by layer. Once each layer is complete, the build plate is lowered by a fraction of a millimeter and the construction of the next layer begins and lastly, when all the layers have been completed to make the model part, any excess material such as the raft and support structure are cleaned away to reveal the finished object.

As at today, plastic products are the most commonly used 3D printing materials. In the last few years, there is a significant trend towards the use of other substances which include metals, ceramics and even bio-materials. The present percentages of the use of different materials that are enabling new applications in a range of industries are represented in Figure 2.

The tangible and intangible benefits of AM technology are the driver in the research and development. The multiple benefits it offers include distribution of manufacturing, increased production speed, lower cost, reduced part count including reduction in tooling and fixtures for complex geometries, product specialization and customization in designs and variants, and the ability to produce parts that could not be manufactured easily with traditional manufacturing methods.

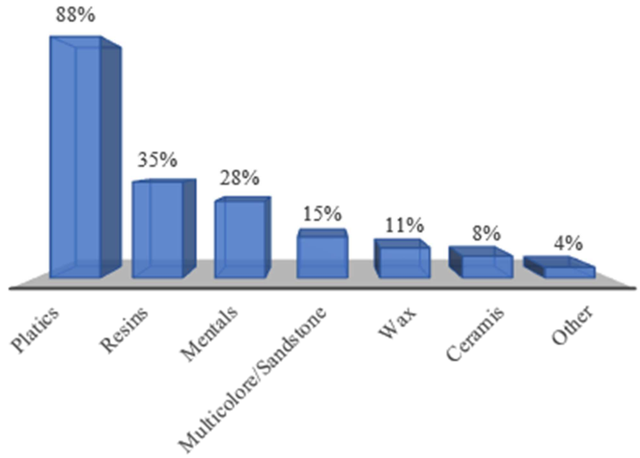

Figure 2. *Most used 3D printing materials [5].*

In order to realize the full benefits of Additive Manufacturing, one of the greatest challenges is producing repeatable and consistent quality parts. Part quality is driven by the variation from the "as manufactured" part. Variation stems from several factors, including the additive system, material, build information, part information, and process parameters. As a result, parts need to be rigorously qualified, which is a costly and time-consuming process that results in reduced realized benefits from additive manufacturing [6].

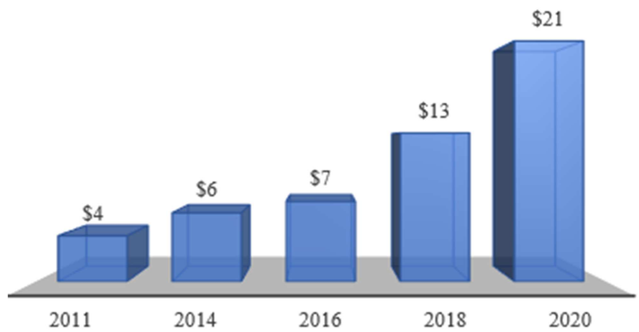

Figure 3. *3D Printing is a Multi-Billion Dollar Market and Growing [7].*

The transformation from conventional processes of manufacturing industrial products to Additive Manufacturing (AM) techniques continues the enormous growth it has enjoyed during recent decades in terms of application and market share, spreading into various manufacturing divisions, such as automotive, medical, aerospace and defense. The most current industry progress report showing in Figure 3 represents $7.3 billion in revenue from primary market which include 3D printing systems, materials, supplies and service in 2016 which indicates at least 30% growth each from 2012 to 2014. This is expected to grow to more than $13 billion by 2018 and to $21 billion by 2020 [7], only two years from now. This heavy growth is expected to continue over the next few years.

Sculpteo recently conducted a research with 1000 respondents from 62 different countries [8], 28% are mainly using 3D printing technology to accelerate product development, 16% to offer customized products and 13% to increase the production flexibility. Moreover, Figure 4 (a) clearly indicates the present percentages of 3D applications, in which prototyping as the leading use today (34%) and proof of concept (23%) are still the leading uses quoted by the respondents. This is clearly correlated to the massive adoption of 3D Printing by Research and Development departments (62%) in Figure 4 (b).

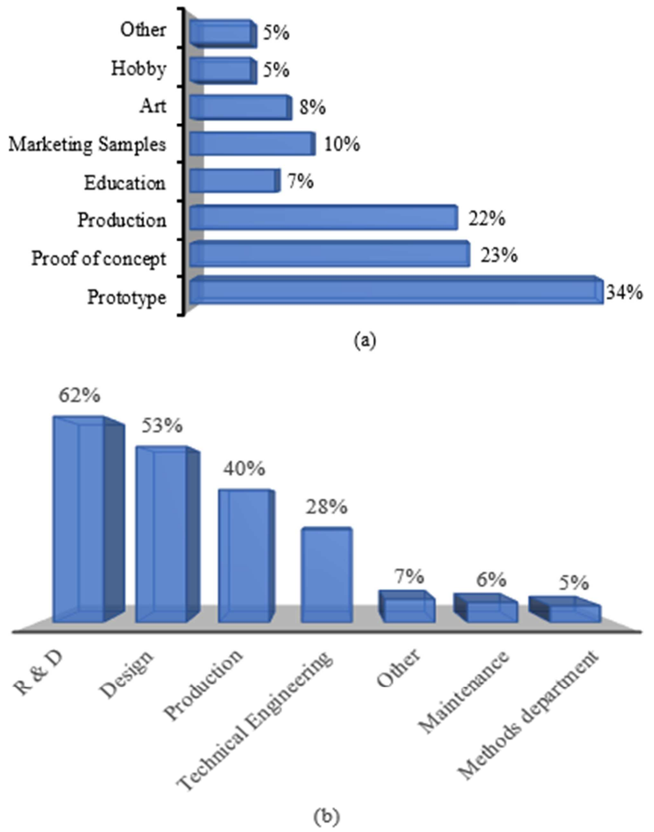

Figure 4. *(a) 3D printing applications and (b) 3D Printer users by departments [8].*

Despite this significant growth, there is still a wealth of untapped potential in 3D printing. In fact, 3D printing represents only 0.04% of the global manufacturing market [9] Wohler's and Associates believes 3D printing will eventually capture 5% of the global manufacturing capacity, which would make 3D printing a $640 billion industry. Much of the opportunity lies in parts and structural components production, mainly in areas, such as aerospace, biomedical and automobile applications, that could benefit from significant weight savings – the fastest-growing 3D printing application. The use of 3D printing for parts and structural components production grew from virtually zero in 2003 to 43% ($1.8B) of global 3D-printed product and service revenue in 2014, as a lot of effort is being made on making those AM processes faster and more reliable. This is a market ripe for disruption. Technology adopters that move beyond prototyping to use 3D printing in supporting and streamlining production can achieve new manufacturing efficiencies. Plus, there is an enormous opportunity for companies that get it right.

2. Methods for Additive Manufacturing

Several Additive Manufacturing processes are currently existing; they only differ in the way layers are deposited to create an object, in the mode of operation and in the materials been fed to the system. Some methods melt or soften materials (thermoplastics, composites, photopolymers and metals) to produce the layers, e.g. Fused Filament Fabrication (FFF), Selective Laser Sintering (SLS), Composite Filament Fabrication (CFF), Atomic Diffusion Additive Manufacturing (ADAM), Selective Laser Melting (SLM), while others cure liquid materials, e.g. Stereolithography (SLA). Each method has its own pros and cons, and some companies consequently offer a choice between powder form, chopped fibers, plastic and liquid polymers for the material that the object is built from. The main considerations made for choosing a machine are, the cost of the printed prototype, the cost and range of materials as well as its colour capabilities [10]. Nowadays, there is a significant tendency towards AM of structural, load-bearing and lightweight structures, by taking advantage of the inherit design freedom of such a process. Those structures need to be built from metal and composites; therefore, focus is given to processes, such as FFF, SLS, CFF, ADAM, and SLM for educational and industrial uses.

2.1. Thermoplastics Material

Thermoplastics are some of the most common materials in additive manufacturing. Thermoplastic 3D printing processes involve heating a plastic material until it is semi-formable to create a shape. Common thermoplastics are often tough, deforming rather than fracturing under stress, but they have a relatively low melting point along with low chemical and abrasion resistance.

2.1.1. Fused Filament Fabrication (FFF)

Fused Filament Fabrication (FFF) similar equivalent to Fused Deposition Modeling (FDM) is the most widespread 3D printing technology. In this process, a thermoplastic material (such as plastic, wax, or metal) is heated and extruded through a nozzle, as depicted by the schematic diagram in Figure 5. As the nozzle of the printer moves, it deposits a cross-section of the model being printed.

This process is repeated layer by layer until the model is completed. Printed models can be hollow or low density with designated internal fill percentages. Thermoplastic Fused Filament Fabrication is most commonly used with low-fidelity prototypes and models. This method has pros: simple, affordable and accessible technology and lightweight. Also, with cons: limited materials, weak parts, anisotropic, prone to wear and poor surface finish.

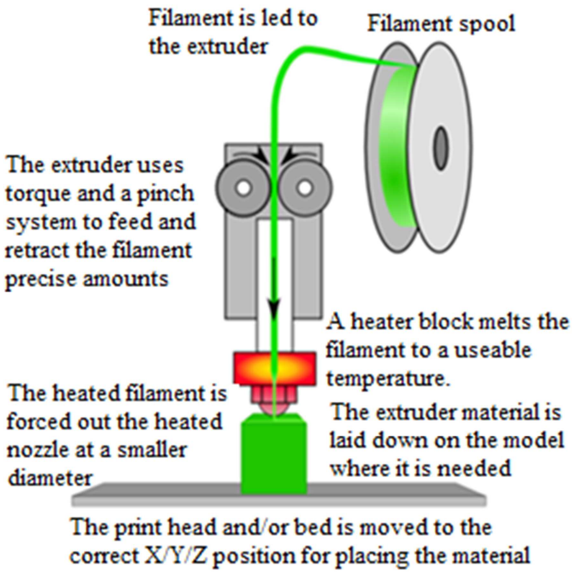

Figure 5. *Fused Filament Fabrication (FFF) AM process schematic [11].*

2.1.2. Laser Melting (LM)

The Laser Melting (LM) 3D printing process utilizes a laser to melt and bind powdered thermoplastics into a given shape. The parts are printed in a chamber of plastic powder. Each layer, a roller sweeps new powder over the chamber, a laser selectively melts a cross-section of the part within the powder, and the chamber recesses to make room for the next powder layer. This process is shown in Figure 6.

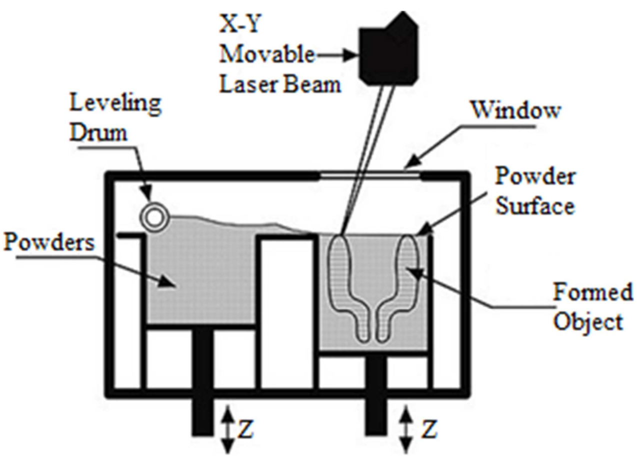

Figure 6. *Laser melting AM process schematic [11].*

Pros: high detail, full density parts, isotropic properties, and wide range of materials. Also, with cons: costly and respiratory protection required.

2.2. Composites Material

Traditionally, composite materials are highly valuable because of their material properties. Well known and heavily utilized composites like carbon fiber deliver high strength to weight ratios for automotive and aerospace industries. With the recent innovation of 3D printing composite materials, parts can be made strong enough for use in engineering applications where the material properties of more common printing methods would not be sufficient. In 3D printing, composite materials can effectively replace traditionally machined aluminum components because they combine the strength and stiffness of metal with the ease of additive manufacturing.

2.2.1. Fused Filament Fabrication (FFF)

Some composite materials can be 3D printed using FFF methods. These materials are composed of chopped fibers (commonly Carbon, Glass and Aramid fibers) mixed with traditional thermoplastics like Nylon and PLS.

While the FFF process remains unchanged, the chopped fibers increase the stiffness, strength, and surface finish of the model, and greatly improve dimensional stability and precision. PROS: improved dimensional stability, heat deflection, part precision, and part strength. CONS: limited materials, weak parts, anisotropic, and prone to wear.

2.2.2. Continuous Filament Fabrication (CFF)

The Continuous Filament Fabrication (CFF) 3D printing process is a cost-effective solution for replacing metal parts with 3D printed parts. CFF 3D printers lay continuous strands of composite fibers (usually Carbon fiber, fiberglass, or Kevlar) within or alongside FFF extruded thermoplastics during the printing process as shown below in Figure 7.

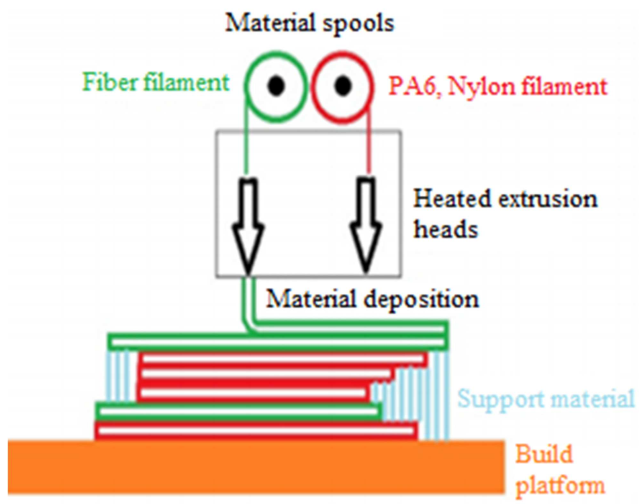

Figure 7. *Continuous Filament Fabrication (CFF) AM process schematic [12].*

The reinforcing fibers form the backbone of the printed part to achieve exceptional stiffness and strength. Pros: stronger than 6061 aluminum and 20x stronger than thermoplastic FFF. CONS: lower surface hardness and corrosion resistance than ADAM

2.3. Photopolymers Material

Photopolymer materials are liquid polymers that change structure when exposed to a light source. When catalyzed with UV radiation, these liquid resins become solid.

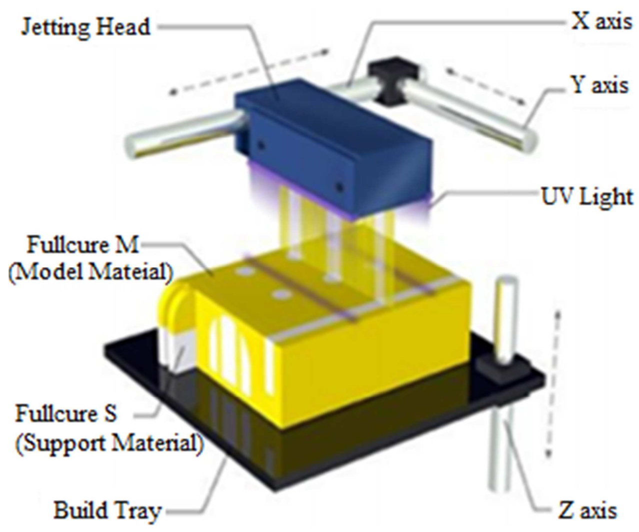

Figure 8. *Object Polyjet 3D printing [13].*

Unlike thermoplastics, photopolymers cannot be melted as the polymerization process is a molecular change, Figure 8 shows the principle of the object polyjet 3D printing. Due to the specific properties that enable photopolymerization, resins are often brittle and not as long lasting as thermoplastics because they degrade over time from continued UV exposure.

2.4. Stereolithography (SLA)

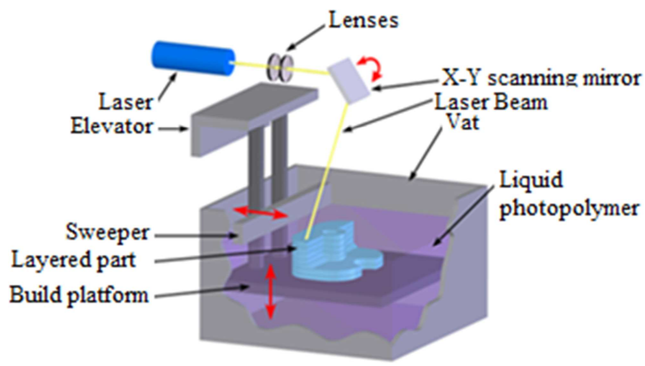

Figure 9. *Stereolithography (SLA) AM process schematic [11].*

The Stereolithography (SLA) printing technologies make use of photopolymers by selectively curing photopolymers with a UV laser. A laser selectively cures the resin to form a hardened layer and repeats the process to build up the model layer by layer. Figure 9.

Because of the chemical bonding process induced by photopolymerization, printed parts are fully dense and isotropic. SLA 3D printers often have a relatively small build volume but can achieve exceptional detail and surface finish with precise control of the laser beam. PROS: Isotropic, highly detailed, smooth surface finish. CONS: small build volume, brittle parts and chemical protection necessary.

2.5. Metal Material

3D printing metal has been a longstanding goal in additive manufacturing, but has often been limited by cost, complexity, and material constraints until recently. Metals cannot be extruded as easily as thermoplastics and require high heat and power to achieve a formable state. In order to implement metal additive manufacturing, most solutions start with the metal in powder form and use various heating techniques to fuse the powders together. Many metal printing methods include post processing steps to fully strengthen or finish the printed parts.

2.5.1. Atomic Diffusion Additive Manufacturing (ADAM)

Atomic Diffused Additive Manufacturing (ADAM) is a unique and cost-effective metal 3D printing process that combines concepts from 3D printing and Metal Injection Molding. The metal powder common to SLM methods is encased in a plastic binder, which gets deposited layer by layer on a print platform by an extruder, very similar to FFF processes. After printing, the part is washed and sintered in an oven, melting away the binder and allowing the metal powders to fuse and form an isotropic metal part. The ADAM process can be applied at an industry level to manufacture metal tooling like injection molding and can produce complex metal parts cost effectively. PROS: cost effective, variety of materials, and similar to FFF. CONS: longer lead time to strong part than CFF.

2.5.2. Selective Laser Melting (SLM)

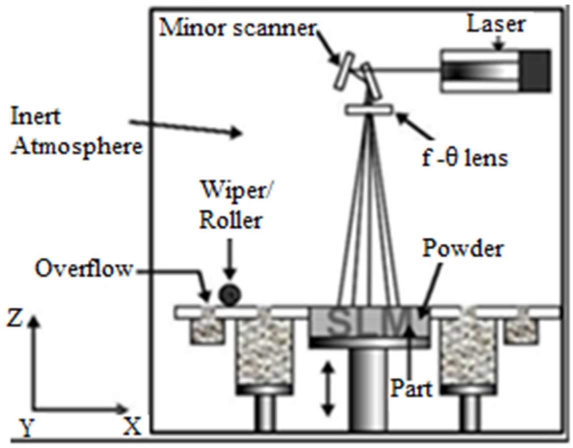

Figure 10. *Selective Laser Melting (SLM) AM process schematic [11].*

The process of Selective Laser Melting (SLM) involves melting fine metal powders in an inert gas chamber to build up a metal part. Layers of metal powder are distributed and then selectively melted with a high-power laser to fuse the metal powders together as presented in Figure 10. Like SLS, this is a layer by layer process, but parts can easily deform or warp due to high heat concentrations within the chamber.

As a result, the SLM process has some geometry limitations but can be used for functional metal parts that would be too costly or impossible to machine like medical implants and weight-optimized parts. This process also requires multiple post processing operations to remove supports and clean off the part, and specific facility requirements are necessary for handling loose powder. PROS: Variety of metals, intricate detail level and metal-strength parts. CONS: part failure due to heat buildup, very costly, many post processing steps, many facilities requirements necessary and long lead time to finished part.

3. Basic Steps of Additive Manufacturing Technology Process

Figure Additive manufacturing parts are made through the following basic steps:

Step 1. Create a CAD model of the design
Step 2. Convert the CAD model to STL format
Step 3. Slice the STL file into thin cross-sectional layers
Step 4. Layer by Layer construction
Step 5. Clean and Finish

These basic steps are further indicated in Figure 11.

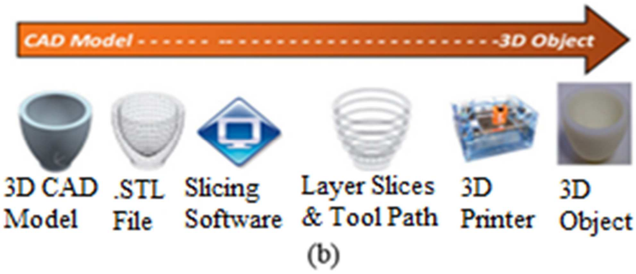

Figure 11. *Steps in creating a 3D printing model Part.*

3.1. Create a CAD Model of the Design

Computer-aided design (CAD) is the use of computer systems to assist in the creation, modification, analysis, or optimization of a design 3D parts for 3-D printer. A 3-D printing or additive manufacturing machine needs a computational description of what you wish to build. Initial designs may start with a hand sketch or drawing that will give information needed to develop a model in Computer-Aided Design (CAD) commercial software, so that either complex or simple three-dimensional computer model of the part can be made as shown in Figure 12.

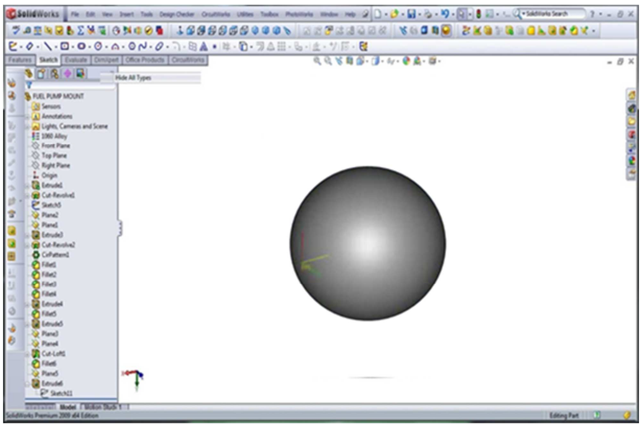

Figure 12. *Solid CAD model of a sphere.*

The most widely used interchangeable mesh file format is . STL or . OBJ files are important because, they are used by CAM tools to generate G-code. OpenSCAD, FreeCAD, HeeksCAD PTC Creo (formerly PTC Pro/Engineer), Dassault Solidworks, Autodesk Inventor, Auto CAD are some examples of CAD packages.

3.2. Convert to STL File Format

Most CAD programs can generate an STL or OBJ file automatically. An STL file is way of storing files geometry (shape) in a series of triangles. It was first used with 3-D Systems' Stereolithography machines from which the abbreviation is derived. The 3-D Systems' were the first commercial machines available and this file format is the standard for driving virtually all 3-D printers.

The STL file's description of the item to be 3-D printed is based on boundary representation of the original CAD object as a series of numerous triangular facets shown in Figure 13. Objects can be scaled easily and the size of the triangles is usually chosen to be just slightly smaller than the resolution of the printer which makes them invisible in the final object.

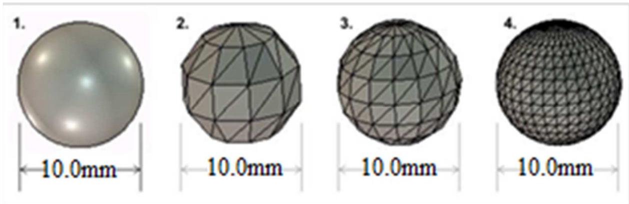

Figure 13. *Conversion of a CAD model of a sphere to STL. The more triangles the more accurate the model [14].*

3.3. Create the Layers Using a Slicing Software and Send to the 3-D Printer

Once the STL file has been generated and after any possible corrections to the model, it must be sent to Computer Aided Manufacturing (CAM) software tools handle the intermediate step of translating CAD files into a machine-friendly format used by the Microcontroller board. CAM software needs a . STL file format from CAD software to generate machine friendly G-CODE that will run the 3-D printer. As illustrated in Figure 14, this software has sophisticated user interfaces that allow you to manipulate, scale, slice and position the STL file within the build chamber on the build plate of the printer.

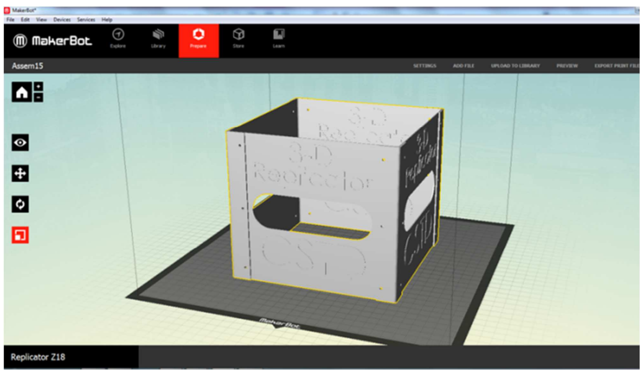

Figure 14. *MakerBot Desktop in scaling mode [15].*

For low cost systems this is typically a two-step process.

(1) One program is used to manipulate the STL file

(2) A second to issue commands to the machine in the form of so-called G-codes

G-codes provide very basic commands such as those used for actually positioning motors and for various settings. These are the same G-codes used in CNC lathes, and milling. The amount of code required can be very large for complex parts and writing this manually would take too long.

It can take quite a bit of time for the software to process the STL file before the printer can make something. Twenty minutes is not unusual and an hour or more is possible for a not so large object at higher resolutions. That processed file is then sent to the printer and it can finally get to work.

3.4. 3D Print and Remove the Part

It can take hours and, in some cases, days, to make a print. Assuming all goes well and the print is finally completed as shown in Figure 15, the object can be removed from the machine.

Figure 15. *MakerBot print preview [16].*

It may be necessary to work with various hand tools to free the object from a base upon which it was built and to which it is firmly attached, and you may have to refurbish the build surface before the next part is printed if you damage it, or it has reached the end of its life.

3.5. 3D Clean and Post-Process

With some 3-D printing methods some finishing is required to remove and recycle powder or clean surfaces with solvents. It may be necessary to cut away support structures or dissolve them away if soluble support materials were used. Technologies that produce objects from light sensitive polymers (photopolymers) may require exposure to light for several hours to fully cure them like the one shown in Figure 16.

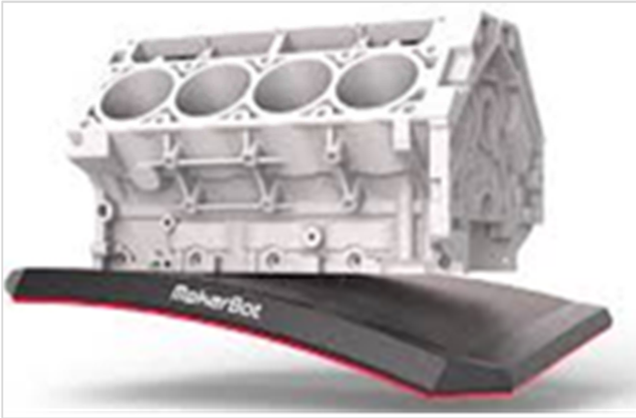

Figure 16. *MakerBot print with bendable Flex Build Plate [16].*

3-D printed parts may also require additional finishing or processing to ensure the part looks like the intended finished object. This can include sanding to improve the surface finish, filing and painting or electroplating before the part can be used. An example is displayed in Figure 17.

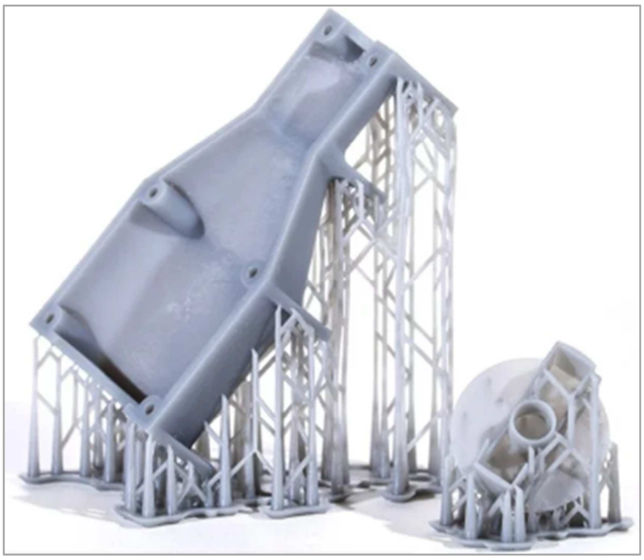

Figure 17. *3D printing part supports material to be removed later [17].*

4. 3D Printing Machine Working Principle

4.1. X, Y and Z Movements

In order to be able to print a physical object, i.e. an object in 3-dimensions, a 3D printer needs to be able to move on 3 coordinate axes X, Y and Z (i.e. most commonly referred to as length, width and height).

There exist three directions movement in order to achieve the linear motion of each axis, the linear rail assembly is connected to each axis which is capable of load carriers and allow linear motion in each axis. The controlled motion in each axis is achieved directly by controlling the rotation of the stepper motor connected to each axis. In Figure 18, letters X, Y and Z are used to identify each direction of the table movement. Each axis is perpendicular to each other and this can be explained by using the right-hand rule in Figure 19 to indicate each axis direction.

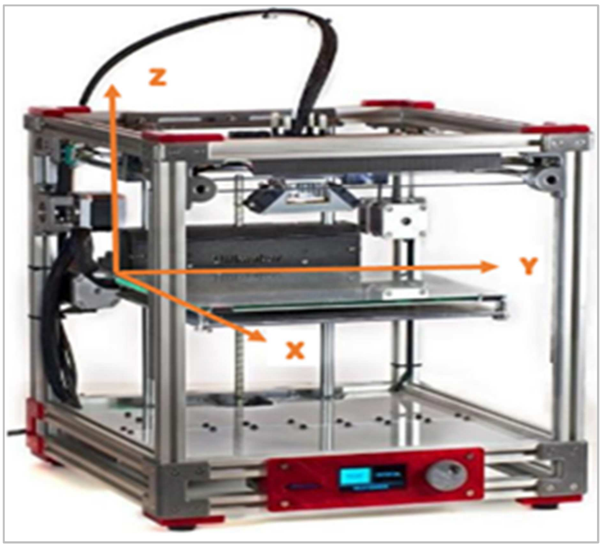

Figure 18. *3D printer Cartesian coordinate system [18].*

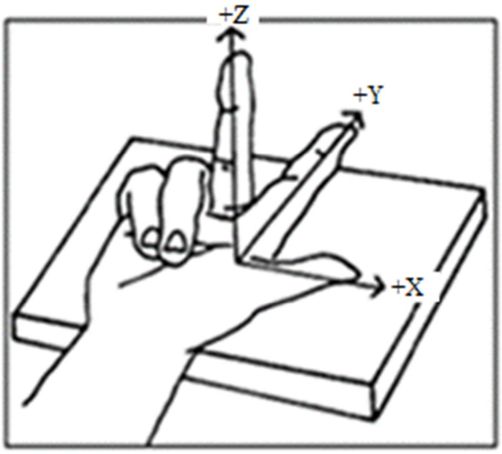

Figure 19. *Right hand rule.*

(1) A movement in the +Z direction is upwards, a -Z movement is downwards
(2) A movement in the X direction is horizontal. This is usually the longest movement or table travel
(3) A movement in the Y direction is also a horizontal movement.

4.2. Stepper Motors

Stepper motors are direct current (DC) motors that move in discrete steps. They have multiple coils that are organized in groups called "phases". When energized each phase in sequence, the motor will spin certain number of degrees at each step, this determine the precision motion control of the stepper motors. Stepper motor are common in 3d printers as shown in Figure 20.

Figure 20. *Stepper Motor [19].*

With a computer controlled stepping you can achieve very precise positioning and/or speed control. The stepper motor driver receives step and direction signals from the microcontroller and converts them into rated high voltage electrical signals to run the step motor.

While choosing the motors one should take into account the physical size of the machine, the weight each axis will carry. Another important criterion is the precision of the motors – the number of degrees it spins at each step. A few more parameters are the physical size of the motor (NEMA23, NEMA32...) and its power rating.

Stepper motors are good for:

(1) Positioning – Since steppers move in precise repeatable steps, they are used in applications requiring precise positioning such as 3-D printers, CNC, and X, Y Plotters.
(2) Speed Control – Precise increments of movement also allow for excellent control of rotational speed for process automation and robotics. They can turn part of a revolution or run continuously.
(3) Low Speed Torque - Normal DC motors don't have very much torque at low speeds. A Stepper motor has maximum torque at low speeds, so they are a good choice for applications requiring low speed with high precision.

4.3. G Codes

G-code is a Computer Numerical Control (CNC) language used mainly for Computer Aided Manufacturing (both subtractive and additive manufacturing). It is a language which tells a machine how to move. G-code firmware is the Brain of the machine which is responsible for tool path control. G-code firmware is a program code implemented in optimized C/C++ code language which interprets/compile the G-codes basic command G0, G1, G2, G3.... G-code Firmware reads each line of the G-code file received and generates the actual electronic signals (electrical pulses) to the motors and thus motion is controlled over the three axes depending how the pulses are sent. Figure 21 gives a good illustration of the G-code.

```
G01 Z-1 F80
G01 X40 Y35
G02 X35 Y40 R5
G01 X-35 Y40
G02 X-40 Y35 R5
G01 X-40 Y-35
G02 X-35 Y-40 R5
G01 X35 Y-40
G02 X40 Y-35 R5
G00 Z15
G00 G28 X0 Y0
M05
G04 X5
G21
M63
G04 X5
```

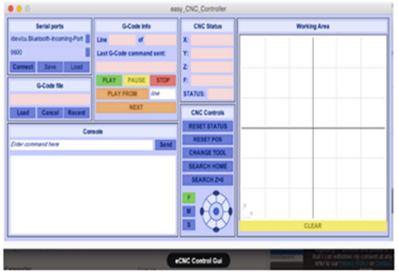

Figure 21. *G-code and CNC control software GUI. [20].*

Without G-code there would be no way for the computer to communicate where to deposit, cure or sinter a material during the fabrication process. Programs such as Slicer are required in order to convert 3-D model files into G-code. Once the G-code is created it can be sent to the 3-D printer, providing a series of stepped movements to create the layers. These steps all add up to the complete fabrication of a physical object.

4.4. Extruder Head

The printer head for filament extrusion should be considered as a good example of engineering design. Examples are displayed in Figure 22.

(1) The feed mechanism is driven by a stepper motor and controlled by G-Code.
(2) This feeds the filament through the head at the correct speed and into the hot end.
(3) This hot-end contains a heater that heats the material just above its melting temperature, Tm, so that it can have plastic flow.
(4) The polymer is laid down in layers as the table is moved around by the stepper motors on the X and Y axis controlled by the G-Code.
(5) The head is moved up (or the table is moved down) by the stepper motor on the Z axis so the next layer can be started.

Figure 22. *Extruder head [21].*

4.5. Filament

3D printing filament is the consumable for your 3D printer. It is the thermoplastic feedstock for Fused Deposition Modeling 3D printers. These plastic materials used by 3D FDM/FFF printers come in the form of a plastic filament as shown in Figure 23.

Figure 23. *PLA rolls [22].*

These filaments are usually sold in spools and generally provided by the machine manufacturers, even though there are more and more generic filament manufacturers.

There are many types of filament available with different properties, requiring different temperatures to print. Filament is available in two standard diameters; 1.75 and 2.85 mm/3 mm. Most common among these filaments are PLA (Poly Lactic Acid) and ABS (Acrylonitrile Butadiene Styrene).

5. The Future of 3-d Printing: Examples

Additive manufacturing or 3D Printing is a disruptive technology as it opens up new possibilities and is revolutionizing engineers approach to design and manufacture. Early adopters of Additive Manufacturing are demonstrating the technology's potential in a variety of industries and services. It is ready for takeoff in areas like tooling, aerospace and defense, printing services, medical, automotive aviation/aerospace, and city planning as shown in Figure 24.

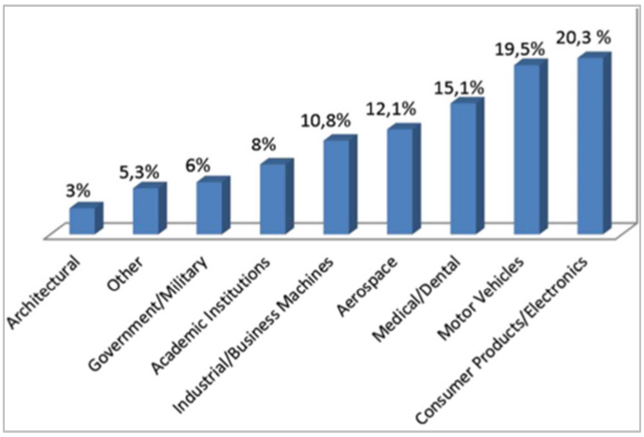

Figure 24. *Breakdown of the percentage of the industrial sectors using AM [23].*

Figure 25. *Steering column switches [24].*

5.1. Tooling

3D printing technology is commonly used for rapidly prototyping parts and developing custom shop-floor tools. Seuffer, a German automation company, saved more than $50,000 in 50 days by switching from traditional fabrication to a Stratasys PolyJet 3D printing system. In the years ahead, tooling in poised to have the largest year-over-year growth among AM applications. Figure 25 shows Steering column switches.

5.2. Aviation/Aerospace

In manufacturing of parts for aviation, it is not uncommon for 95% of the material to be machined away to create the final part as depicted in Figure 26 a, b, c, and d.

(1) A 3-D printed part may only have 95% of the material.
(2) Weight reduced by 30 to 50% by changing the design.
(3) Structural stiffness increased by 30%

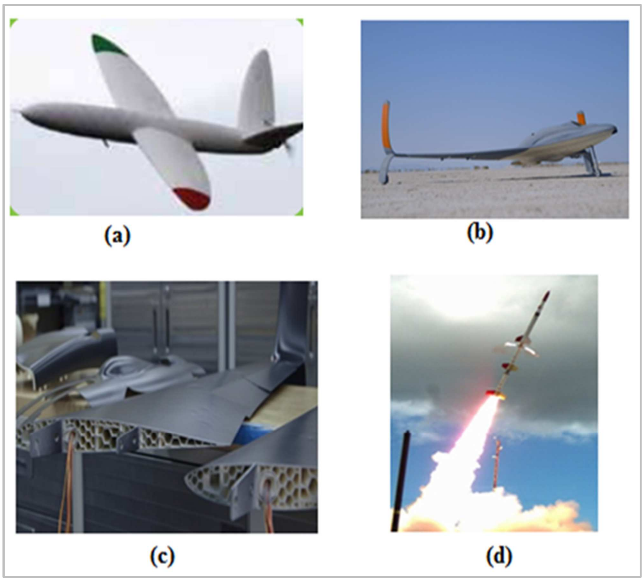

Figure 26. *3D printed (a) World's first robotic aircraft, (b) Aurora Flight Sciences' UAV is 80% 3D printed to take flight, (c) 33-lb aircraft with a 9-ft. wingspan leveraged multiple printing materials to produce a stiff, lightweight structure and (d) Hypersonic engine combustor successfully tested [25].*

5.3. Medical/Bio Mechanical

3D printers offer many advantages for medical and Bio-mechanical applications. Each person is unique and the opportunity to make custom made parts for patients in areas such as prosthetics and implants is growing. 3D printing can also be used to make jigs and fixtures to hold and guide tools and instruments during surgery.

Surgeons now view 3D printing models of hearts before surgery so that they can plan their approach to complex problems efficiently. This helps to develop techniques for difficult situations or to even show the patient before surgery what the procedure will entail. Figure 27a, b and c give models of 3d printed human leg, spine and jaw.

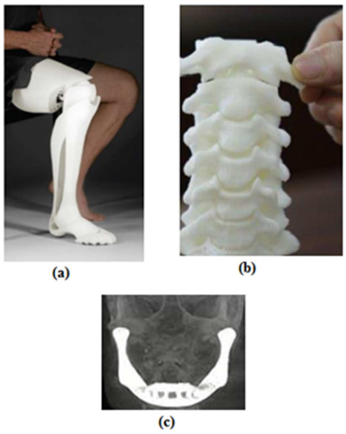

Figure 27. *3D printed (a) Prosthetic leg (b) model of a spine and (c) Implanted prosthetic jaw [26].*

5.4. City Planning

3D printing of city and landscapes allow planners, architects or developers to visualize the effect of changes of new building on the landscape. For example, demolishing one building and replacing it with another building can now be planned and knowing the effect these changes will have on the surrounding areas.

One of the first cities to have a model created was San Francisco as shown in Figure 28 below. The model was created to aid real-estate developer Tishman Speyer in telling the story of urban development in the rapidly changing SOMA neighbourhood. It can help with urban planning and building construction decisions that are better understood with the kind of physicality that only real-world 3D replica offers compared to digital images or digital models.

Figure 28. *3D printed model of a cityscape [27].*

6. Conclusion

Additive manufacturing opens the door to new design possibilities and also helps free designers and engineers from the design for manufacturability rules of traditional manufacturing methods that aims to optimize all functions in the manufacturing process which include: fabrication, assembly, test, procurement, shipping, service and repair that invariably minimize total cost, time to stable production and improve product quality. Production without tooling makes it possible to produce more complex geometries, organic shapes, hollow interiors and negative draft, opening up many possibilities and reducing cost. Companies should embrace new ways of thinking to fully leverage the benefits of 3D printing. Manufacturers should take advantage of additive manufacturing to increase functionality, combine multiple components into one design, reduce weight and see their product's full potential. The future is bright for 3D printing applications across the supply chain

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