

Analysis of Implementation Factors of 3D Printer: The Key Enabling Technology for making Prototypes of the Engineering Design and Manufacturing

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ABSTRACT

3D printer technology employs the Additive Manufacturing (AM) process which is very popular method of layered manufacturing. 3D printer has huge application to manufacture small amount of fresh, customized & durable prototypes in a short time thus the concept of 3D printing technique is also referred to as rapid prototyping (RP) technique. 3D printer is one of the most promising fabrication tools to meet the criteria of increased flexibility and empower low cost small scale production. 3D printing supports solid freeform fabrication (SFF) process as it has also the ability to create parts with locally controlled composition. In this paper we discuss the in-depth study of implementation issues of 3D printer, cost benefit of low to medium production (additive manufacturing) with mass production. We also provides the required mathematical theorem and statements which supports the fact that 3D printer can replicate any physical object. Finally, we analyze the root cause implementation factors & the possible modified way to produce the next generation 3D printer.

General Terms

Additive manufacturing, rapid prototyping, solid-freeform technology, rapid manufacturing

Keywords

3D printing, slicing software, CAD image, filament, extruder assembly, print bed

1. INTRODUCTION

3D printer is emerging as a promising additive manufacturing (AM) [6]-[7]-[15]-[22] technology to improve low volume production. Additive manufacturing process can be defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer” [3]-[21]. Different technologies like fused deposition modeling (FDM), selective laser sintering (SLS), 3D printing etc obey the principle of AM process[5]. These technologies have prominent differences in spite of several similarities among each other [19]. In [2], the authors showed that the benefits can be captured in low to medium production volume through the AM process. In this paper, cost benefits are compared by producing the landing gear aircraft assemblies, through high pressure die casting (HPDC) and selective laser sintering (SLS). Authors also illustrated the brake even analysis which is showed in fig.1.

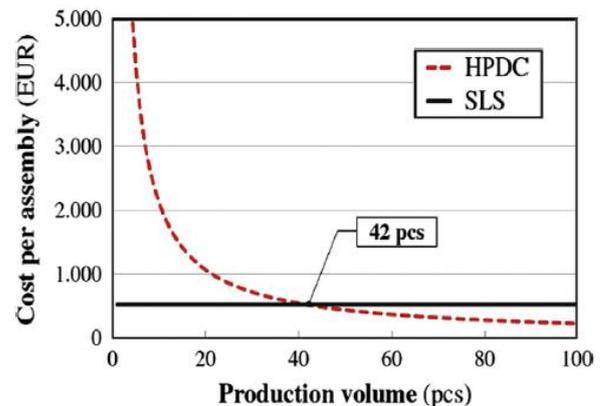


Fig1: Comparing HPDC and SLS processes, Break even analysis is performed in [2]

The technology of 3D printing, also referred to as additive manufacturing, are applied mainly for the designing of prototypes, and the process also known as Rapid Prototyping (RP). In the early 1980s, the concept of 3D printing was developed by Charles Hull with the aim to improve the existing techniques to develop the prototype. Hull obtained his first patent for stereolithography in the year of 1986, and in the same year he developed the .STL file format to represent 3d models and which could build the electronic handshake between CAD software and 3D printer. Based on Hull's work, in 1990, Scott Crump developed the advanced concept of fused deposition modeling (FDM). Finally, in 1993, 3D printer, this very term has been coined by MIT professors Michael Cima and Emanuel Sachs which is the first patented apparatus termed by this name & can print plastic, metal, and ceramic parts.

Flexibility is increased by using this technology in Jewelry, footwear, industrial design, architecture, engineering, construction, automotive, dental and medical education, and several other fields those are directly or indirectly is benefited by the application of the 3D printing.

In this paper, we focus on the implementation factors of 3D printing technology. The major contributions of this paper are defined as follows. Firstly, we derive the mathematical formulation of 3D printing technology. The rest of the paper is described as follows. Section 3 presents working principle of 3D printer. In Section 4, we discuss the integral parts of 3D printer. Section 5 provides the application areas of 3D printer. Finally, in Section 6 and VI, we provide future scope of 3D printer and discuss some concluding remarks.

2. MATHEMATICAL FORMULATION OF 3D PRINTING TECHNOLOGY

Mathematics empowers us to construct any real life three dimensional objects by joining of materials layer-upon-layer basis [23]. One thing we need to remember that 3D models are generated by CAD program then it is converted to an.STL file format which stores the information of the each surface of the 3D model using a list of triangle vertices. Now, we need to discuss the mathematical theorem and statements by using those it is possible to print any real life three dimensional object. Famous Italian mathematician Guido Fubini (1907) introduced Fubini's theorem, a popular theorem in mathematical analysis which gives the conditions by using iterated integrals it is possible to derive a double integral. Fubini's theorem also states that an object having 'n' dimensions which can be represented as a spectrum of layers of shapes of 'n - 1' dimensional layers. Hence, any 3 dimensional real world objects can be represented as layers of 2 dimensional shapes. 3D printing technology adopts this concept to construct any 3 dimensional objects as layers of 2 dimensional planes. Here the authors provide only the theorem as its proof is not relevant for this paper. Consider, A and B are complete measure spaces. Assume $f(x, y)$ is

$A \times B$ measurable. If

$$\int_{A \times B} |f(x, y)| d(x, y) < \infty, \quad (1)$$

Here the integral is taken with respect to a product measure on the product space $A \times B$, then

$$\int_A \left(\int_B f(x, y) dy \right) dx = \int_B \left(\int_A f(x, y) dx \right) dy = \int_{A \times B} f(x, y) d(x, y) \quad (2)$$

The first two integrals are iterated integrals with respect to two measures, respectively, and the third is an integral with respect to the product measure. If the above integral of the absolute value is not finite, then the two iterated integrals may actually have different values. Now if we also consider $f(x, y) = g(x)f(y)$ for some functions g and h, then

$$\int_A g(x) dx \int_B h(y) dy = \int_{A \times B} f(x, y) d(x, y) \quad (3)$$

The integral on the right side being with respect to a product measure on the product space $A \times B$. Hence it is proved that using Fubini's theorem any real life objects is possible to print. Slicing resolution and achieving physical stability during layering are the practical limitations in 3D printing process.

3. WORKING PRINCIPLE OF 3D PRINTER

Mainly, 3D printing techniques are of two types, FDM (Fused Deposition Modeling) and PBP (Powder Binder Printing). Among the various AM processes FDM is a most popular process in making 3D objects. Fused deposition modeling (FDM) is a method of Rapid Prototyping [9]-[13]-[14] is the most commonly used additive technology. It includes 1. nozzle ejecting molten material (plastic), 2. deposited material (modeled part), 3. controlled movable tab. FDM process is shown in fig.2.

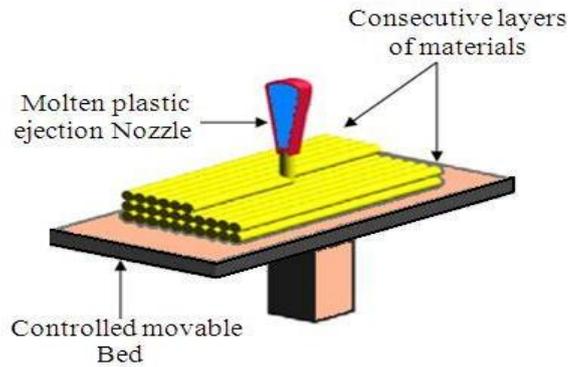


Fig2: FDM Process

First we have to create the virtual 3D design. This virtual design can be made using CAD (computer aided design) [11]-[12] or with 3D scanner to copy an existing object. A 3D scanner makes a copy of the existing object into CAD format. 3D scanner uses different technologies such as time of flight, structured/modulated light, and volumetric scanning. Many companies like Microsoft, Google has introduced a hardware to perform 3D scanning, such an example is Microsoft's Kinect. This is a sign that future hand-held devices like smart phones will be integrated 3D scanners to scan objects of any kind. Price of 3D scanners ranges from very expensive industrial devices to DIY (do it yourself) devices that anyone can make at home. After the virtual 3D object is created by CAD, save the virtual created object in .STL format. 3D models is taken as .STL format by the slicer software which then "slices" the designed object into layers for printing based on layer height or resolution of the desired object and some other parameters that is previously set from within the slicer. The object is saved in G-code format when sliced. Depending on the type of plastic used in the melting chamber starts heating up to the desired temperature on the initialization of the print command. The extruder, almost touching the build platform moves to its starting point. Printing process will start when the extruder is hot enough to melt the plastic filament. According to the instruction (gcode), the extruder will move relative to the build platform to deposit plastic layer after layer. The first layer is generally pressed against the print bed due to the extruder's proximity to the build platform. One thing we need to remember that layer height of the 3D printer is its resolution and it is measured in microns, or a millimeter. Typical resolutions range is between 100 and 250 microns or 0.0039 to 0.0088 inches.

The extruder will generally move away from the printed object on the completion of the printing and until next printing, the printer will remain idle. It is very much challenging to remove the printed object from the heat bed. We can use few drops of water for soften the glue that hold the printed object to the heat bed & with care the object is removed from the heat bed. Now 3D printer is more portable by using wireless communication technology to print 3D objects without any requirement of connecting computers to the 3D printer using wires. So, to print an object, the .STL file will be simply transferred to the printer motherboard containing SD card to store the data and then to execute the process of 3D printing. In [17], different stages are described to produce 3D products (see fig.4).

4. INTEGRAL PARTS OF 3D PRINTER

In diagram 3, different components of 3D printer are depicted.

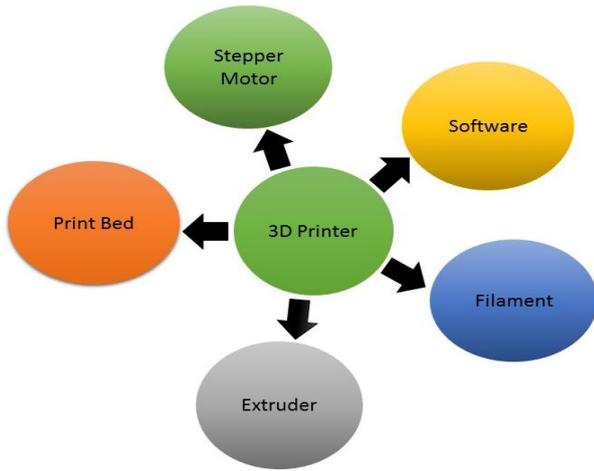


Fig3: Components of 3D printer

4.1 Software

3D printers are generally computer mediated and require a number of programs like Slic3r and a print control program like pronterface. The programs are often bundled by 3D printer makers to optimize the package for their models. 3D models are taken in STL format by the slicer software (see fig. 3, 4 & 5) which then "slices" the designed object into layers for printing based on layer height or resolution of the desired object and some other parameters that is previously set from within the slicer. STL (stereolithography) is a file format innate to the stereolithography cad software. Many software packages support this format. It is mainly used for Rapid prototyping, 3D printing and computer-aided manufacturing. The object is saved in G-code format when sliced. The extruder gets heated up and the temperature gets controlled by the print control software which also moves the extruder in 3 dimensions. The minimum possible distance between the

build platform and the extruder is set with the help of it.

4.2 Filament

PLA and ABS are the most frequently used plastic raw material as fused filament for 3D printing. PLA filament is a biodegradable corn based polymer [16] [24] filament which needs to be preheated to about 1850C (3650F) before its extruding and bonding well. (Temperatures in 3D printing are given in Celsius.) ABS (acrylonitrile butadiene styrene) is a thermoplastic that requires a higher temperature (~2400C, or 4640F) for use in 3D printing. It tends to be smooth and strong. While melted PLA may smell slightly sweet, melted ABS can give off a burnt plastic odor, and has been known to cause headaches, so it's best used in a well-ventilated area.

Recently, filament Maker can be used to make filament which will reduce the cost of buying readymade filament from the shop which costs 2000 in Indian rupee per spool of 1kg weight.

4.2.1 Working principle of filament maker

As we just mentioned the term Filament Maker, now we need to discuss the working principle of the Filament Maker. Filament Maker is divided into two zone and they are, the Crushing zone and the Melting zone. Filament Maker uses plastic pellets of any kind having melting temperature below 350 degrees centigrade. Stepper motor is connected to the spiral bit using a connector called coupler (As shown in figure no-5). The circular rubber is used to hold the spiral bit in place. Heat Insulator (wood) is used to prevent the crushing zone getting heated up thus dividing the crushing and melting zone. Pellets are kept in a funnel and are poured down into the filament maker through a small hole underneath. Then the pellets are crushed into small pieces as it moves forward by pressing the pellets against the wall of the pipe. As it entered into the melting zone the pellets get melted and is then comes out of the small hole as filament. The production speed of making filament is controlled by the stepper motor controller.

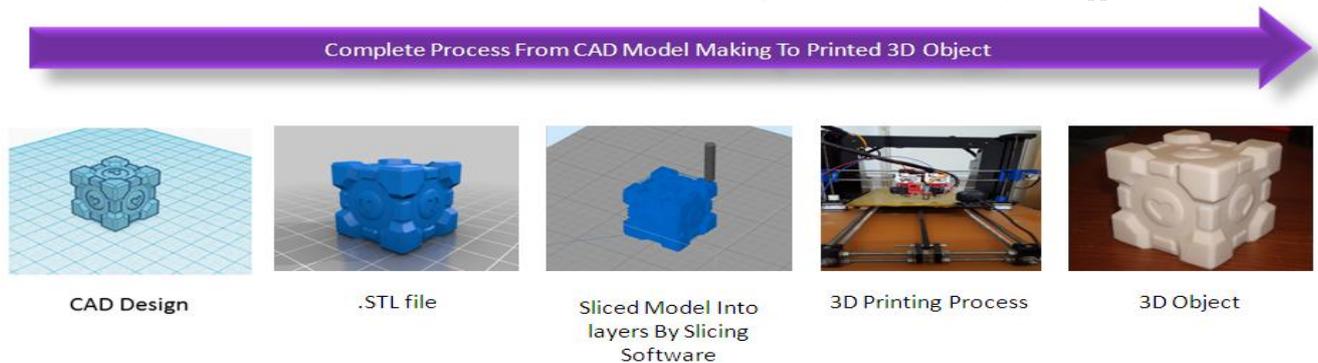


Fig4: Complete 3D printing Process

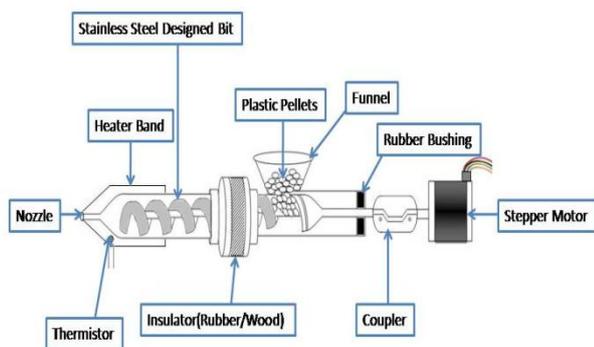


Fig5: Filament maker

Now as different plastic has different melting temperature, the temperature can be controlled and adjusted by the PID controller connected to the thermistor (to check the temperature) and the heater. The thermistor is placed near the nozzle. The nozzle is completely made of copper as copper is a very good conductor heat. A circular heat belt is used for heating up the nozzle and is clamped near the nozzle. Except the nozzle (which is made out of copper) everything is made out of stainless steel as stainless steel is rust free, strong and is bad conductor of heat. The Continuous working period for this filament maker is 4day at Maximum temperature but require some additional cooling such as fan near the stepper motor to keep it cool. This reduces the manufacturing cost of the filament. (1kg Abs spool of filament= 25\$ whereas 1kg Abs pellets= 5\$).

4.3 Extruder assembly

The convectional printer's print head is an analogue to the 3D printer and is known as extruder (see fig. 6). At the extruder's bottom, nozzle is placed which is found adhered to it. After few researches on extruder, a modified form is being introduced in 3D printer category. The single and dual extruder can be replaced with multi-color extruder having single nozzle to extrude the filaments. Modifications are as follows:

- Decrease the size of the extruder.
- Decrease the load on the x-axis thus stepper motor can now perform with great speed without any issue.
- Increase portability
- Reduce the price as one extruder is extruding different kinds of filaments.
- Only one stepper motor is being used for extruding multiple filaments unlike dual extruder which uses two stepper motor to extrude two different color only.

4.3.1 Working principle of extruder

Feed roller consists of a stepper motor with drive gear (connected to the shaft of the stepper motor) to push the filament into the extruder with the help of a bearing (as shown in the figure 6). With the help of the feed roller the filament is pushed into the extruder. Extruder is made up of aluminum to decrease the weight on the y axis so that stepper motor can move the extruder at high speed along y-axis without missing steps. Extruder consists of aluminum fins where small fan can be connected to cool down the upper part of the extruder. The extruder is connected to an aluminum block consisting of heater and a thermistor (to check the temperature). Before extrusion of the filament, the temperature is raised up to the melting point of the plastic [25]. As the filament proceeds into the heated block it starts to melt and is then poured out through the nozzle (made out of copper/brass as they are good conductor of heat). The molten extruder plastic solidifies as soon as it comes in contact with the substrate. The amount of flow is controlled by the stepper motor controller according to the G-code. Once the layer is completed the build platform (z-Axis) rises up and the deposition of the next layer begins. A secondary material (support material) may also be deposited (which can be removed) in order to support overhanging/bridging construction.

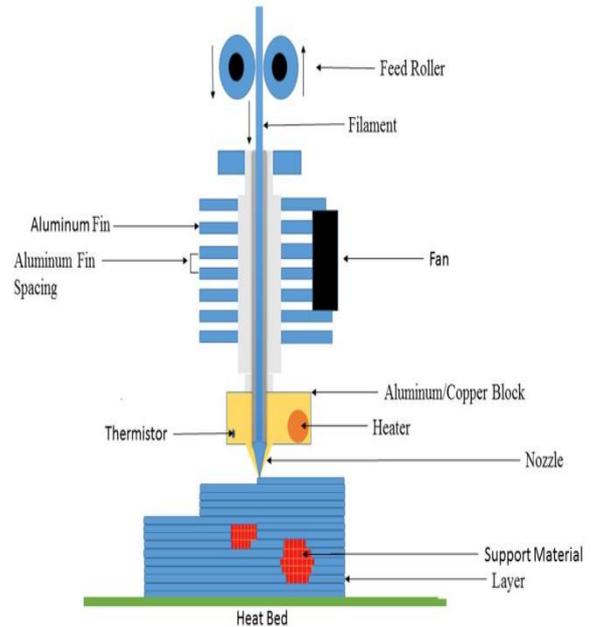


Fig6: Design of extruder

4.4 Print bed

The print bed or build platform is the surface on which the object is printed. It will be at least as large as the width and depth of the printer's build area (the size of the largest object it's capable of printing). It is often treated to allow the object to adhere to it while printing. You need to apply glue before each printing to the Printer's build platform, and then rinse it under running water to soften the glue when the job is finished. The readymade 3D printer bed is not efficient in terms of money as well as the power consumed by the bed. This readymade bed took lot of time to get heated up to reach 100 degrees in isolated place, so printing abs on this heat bed is difficult as heat bed should reach minimum of 100 degrees centigrade to stick abs material on the bed. It can be replaced with aluminum or copper (costly but best conductor heat) with heat resistor of 10k ohm to heat the heat bed (see fig. 9(d)). Again the numbers of resistor to be attached to the aluminum or copper clad depend on the size and the thickness of the clad.

4.5 Stepper motor

According to the diagram (see fig.7) the Extruder carriage move up (when both the stepper motors of (A) move clockwise) and down along Z -axis (when both the stepper motors of (A) move anticlockwise) with the help of each of the two stepper motors connected to the 8mm threaded rod via

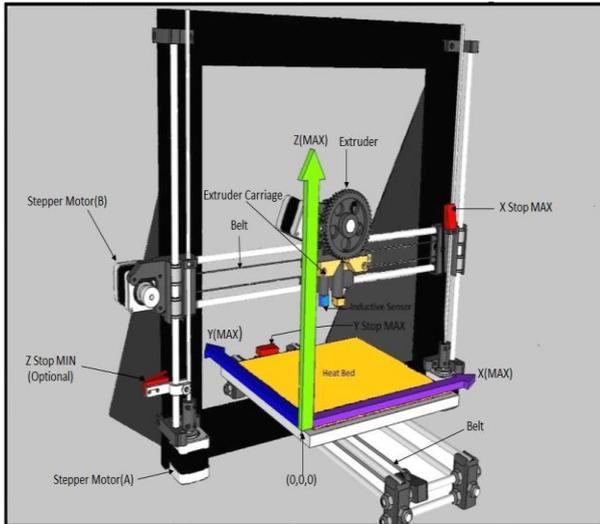


Fig7: Movement of 3D printer using stepper motor

a coupler. The Extruder carriage move left (when the stepper motor (B) moves anticlockwise) and right (when stepper motor (B) moves clockwise) along Y-axis with the help of the stepper motor (B) and the belt. The X-axis movement is made by a stepper motor with the help of the belt attached to the bed underneath. The heat bed moves forward (when the stepper motor moves clockwise) and backward (when the stepper motor moves anti-clockwise) according to the movement of the stepper motor shaft. During 3D printing, the printer moves all the coordinates simultaneously according to the .STL code, to form the complete 3D object.

4.5.1 Inductive sensor in-place of Z-Axis end-stop
Z-axis end-stop is used to mark the minimum position of the Z axis. Further if the stepper motor of Z-axis tries to move down the end-stop will trigger which will stop the stepper motor for further moving downward. In such case for each printing one has to adjust the adjustment screw of the heat bed and to see that the heat bed is not tilted in any direction by tiny little bit else extruder nozzle might crushed the print bed (shown in figure 8) during printing which may destroy the nozzle or the 3D printing object. So to prevent such problem inductive sensor is used in place of the Z-axis end-stop. Here we are going to replace the Z-axis end stop with the inductive sensor that detects if and how much the heat bed is tilted in any direction. If one of the adjustment screw is moved by tiny or a larger bit, printer's firmware then automatically tilt the printed model according to compensate for that which gives you perfect first layer and good adhesion without never had to manually adjust the heat bed ever again after the initial setup is done perfectly.

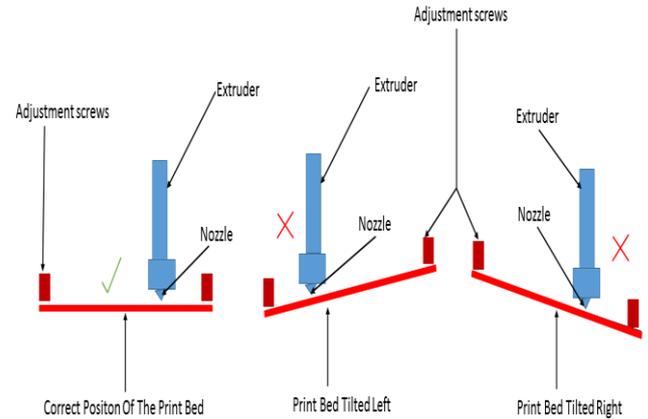


Fig8: Different tilt position of the Heat-Bed

Here in following diagram (fig.9) we have given the actual implemented pictures of 3D printer & its various components, based on the prescribed designing method.

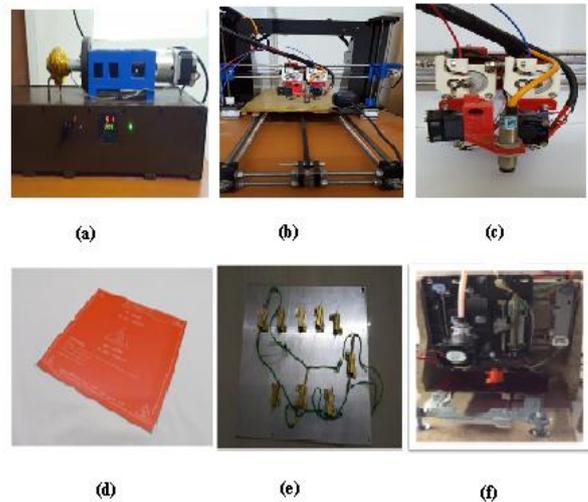


Fig9: A photo of actual implementation of 3D printer based on described design, (a) filament maker frame, (b) advanced dual head extruder 3D printer, (c) Dual head extruder with inductive sensor for z-axis and extruder head with cooling fan, (d) heat bed, (e) advanced heat bed, (f) implementation of 3D printer using waste electronic devices

5. APPLICATION AREAS OF 3D PRINTER

3D printer is very user friendly and it takes very less time to print any kind of object with accurate resolution. The following fields are the main application areas of 3D printer [1] [4] [10] [14].

- **Automotive industry**

The use of 3D printing in automotive is to manufacture models for design verification, vehicles, engines, and platforms.

- **Biotechnology & Medical science**

3D printing technology has been studied by biotechnology firms & medical science institutes [21] for possible use in tissue engineering application and other fields of medical science where organs and body parts are built using 3D

technique.

- **Aerospace & aviation industries**

Utilization growth of 3D printing technology in the aerospace and aviation industries is huge. 3D printing technology is used in Aerospace & aviation industries to manufacture engines, model and for design verification.

6. THE FUTURE OF 3D PRINTER

3D printer can develop low demand parts quickly and cost effectively. 3D products are now getting popularity due to its low cost, accuracy and strength of the product. Moreover, the additive manufacturing (AM) technology is considered as the most attention seeking technology. From fig. 10, it is clear to us the growth of AM products and services throughout the entire world. However, 3D printer is considered a bit of costly, due to the materials are used to construct it and all the electronic parts in it. But this device can widely be available to everyone if it can be built using electronic waste devices (see fig.9(f)) [13] [20] such as scanner, CD drives.

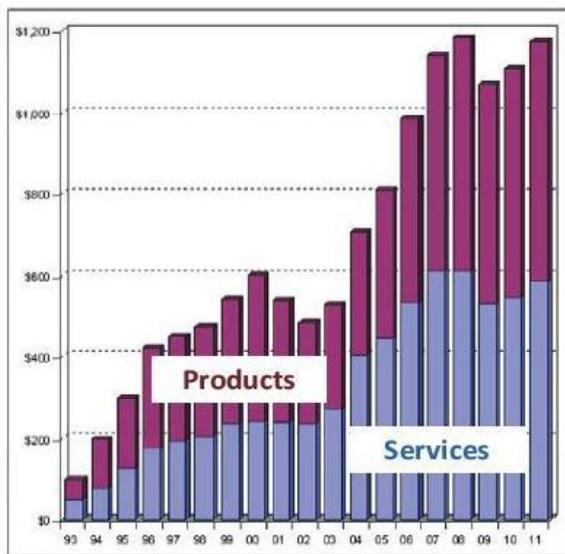


Fig10: Annual estimated revenues ((in millions of US dollars)) from additive manufacturing products and services worldwide, source-Wohlers Report 2010 [17]

7. CONCLUSION

3D printing is an expanding technology as any virtual designed object can be printed into physical object with ease. Such technology has a blooming prospect and will soon start an industry in which everyone will have a possibility of being a manufacturer. This method is cost effective and time saving. 3D printer has lots of possible benefits that will help in the progress of society.

8. ACKNOWLEDGMENTS

The authors deeply acknowledge the support from the department of ECE, Bengal Institute of Technology (A unit of Techno India Group) & the department of EIE, Techno India College of Technology (A unit of Techno India Group). The authors also wish to express appreciation to Prof. Debanshu Ray, Director, Bengal Institute of Technology, Prof. (Dr.) Bibek Chakraborty, Principal, Bengal Institute of Technology & Prof. (Dr.) Sanjib Sil, Techno India College of Technology for their continuous support and inspiration.

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