Tutorial: Rapid Prototyping Technologies

1. Introduction

Rapid prototyping (RP) is a new manufacturing technique that allows for fast fabrication of computer models designed with three-dimension (3D) computer aided design (CAD) software. RP is used in a wide variety of industries, from shoe to car manufacturers. This technique allows for fast realizations of ideas into functioning prototypes, shortening the design time, leading towards successful final products.

RP technique comprise of two general types: additive and subtractive, each of which has its own pros and cons. Subtractive type RP or traditional tooling manufacturing process is a technique in which material is removed from a solid piece of material until the desired design remains. Examples of this type of RP includes traditional milling, turning/lathing or drilling to more advanced versions - computer numerical control (CNC), electric discharge machining (EDM). Additive type RP is the opposite of subtractive type RP. Instead of removing material, material is added layer upon layer to build up the desired design such as stereolithography, fused deposition modeling (FDM), and 3D printing.

This tutorial will introduce additive type RP techniques: Selective Laser Sintering (SLS), StereoLithography Apparatus (SLA), FDM, Inkjet based printing. It will also cover how to properly prepare 3D CAD models for fabrication with RP techniques.

2. Advantages and disadvantages of rapid prototyping

Subtractive type RP is typically limited to simple geometries due to the tooling process where material is removed. This type of RP also usually takes a longer time but the main advantage is that the end product is fabricated in the desired material. Additive type RP, on the other hand, can fabricate most complex geometries in a shorter time and lower cost. However, additive type RP typically includes extra post fabrication process of cleaning, post curing or finishing.

Here is some of the general advantages and disadvantages of rapid prototyping [1]:

Advantages:

- Fast and inexpensive method of prototyping design ideas
- Multiple design iterations
- Physical validation of design
- Reduced product development time

Disadvantages:

- Resolution not as fine as traditional machining (millimeter to sub-millimeter resolution)
- Surface flatness is rough (dependant of material and type of RP)

3. Rapid Prototyping Process

The basic process is similar across the different additive type RP technologies. We will use a ball as an example here. It begins with using a CAD software such as Solidworks to design a 3D computer model. Figure 1 is a golf ball designed in Solidworks.

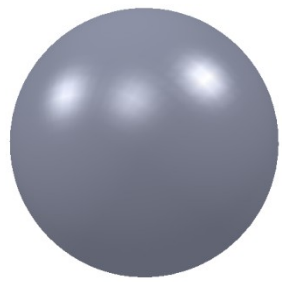

Figure 1 – CAD of a ball.

This 3D CAD model is next converted into a Stereolithography or Standard Tessellation Language (STL) file format. The STL file format only describes the surface geometry of a 3D CAD model. It does not contain any information on the color, texture or material. STL file format can be saved in either ASCII or binary versions, with the latter as the more compact version. The surface geometry is described with triangular facets. Each triangle facets uses a set of Cartesian coordinates to describe its three vertices and the surface normal vector using a right-hand rule for ordering. An example of how an ASCII STL file format is show in Fig. 2.

```
solid print
  facet normal 0.00000e+00 1.00000e+00 0.00000e+00
    outer loop
      vertex 0.00000e+00 0.00000e+00 2.00000e+01
      vertex 0.00000e+00 0.00000e+00 0.00000e+00
      vertex 1.00000e+00 0.00000e+00 2.00000e+01
    endloop
  endfacet
   :
endsolid print.stl
```

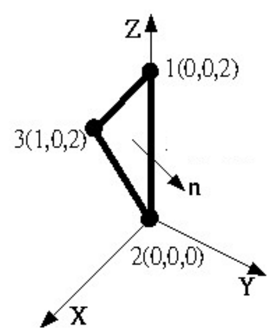

Figure 2 – ASCII STL file format.

To convert a CAD model to STL in Solidworks,

File →Save as →Change 'Save as type' to .STL

Select 'Options' for more advance export options. Figure 3 shows a printscreen of the STL export option.

As shown in Fig. 3, one can select to export the STL as Binary or ASCII file format in millimeter, centimeter, meter, inches or feet depending on the unit used in the CAD model.

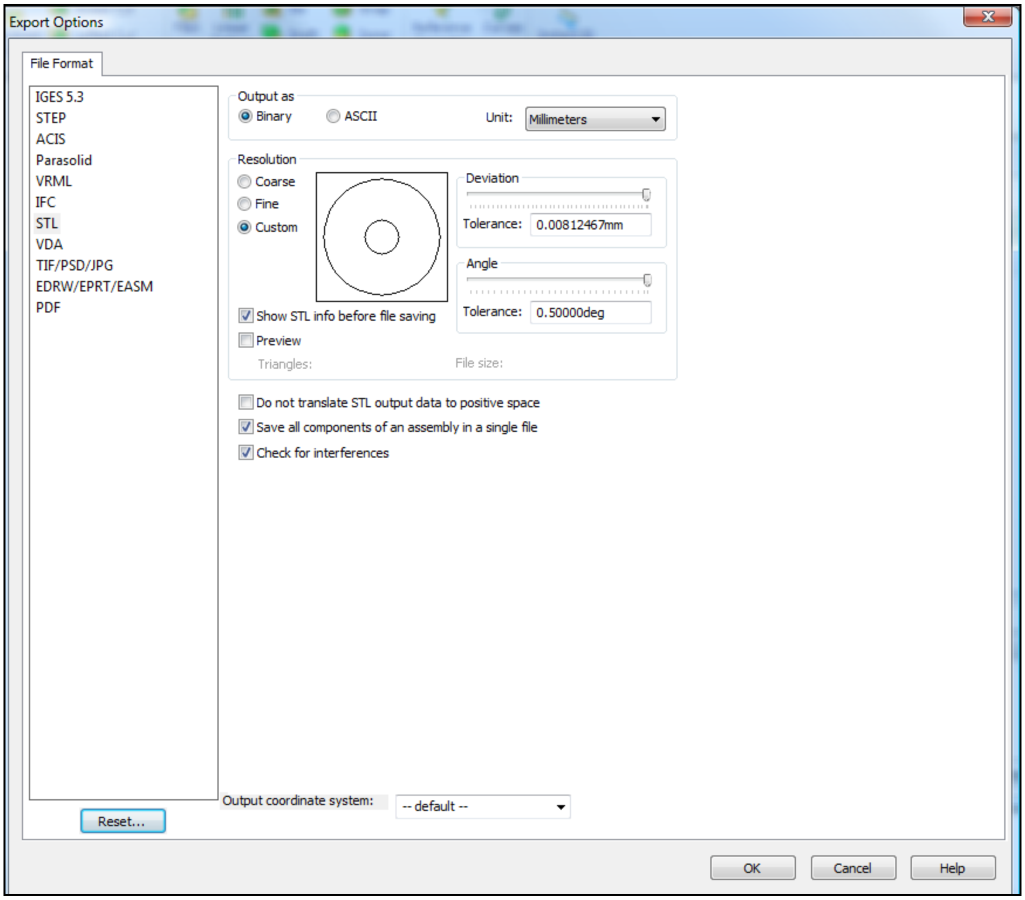

Figure 3 – Solidworks STL export option.

The resolution options allow a user to control the tessellation of non-planar surfaces. There are two preset resolutions of 'Coarse' and 'Fine'. The 'Custom' setting allows one to adjust the deviation and angle tolerances. Lower deviation tolerance sets tighter accuracy to the tessellation where as smaller angle deviation sets smaller detail tessellation [2]. The caveat is that tighter tolerances create more triangle facets to describe the 3D CAD model's surface more finely which causes the file size to be large. Figure 4 shows a CAD model exported to a coarse resolution STL (114KB), fine resolution STL (300 KB), and a very fine resolution STL file (1.51 MB). A more complicated design with complicated features would also result in a large STL file size. Figure 5 shows an exaggerated view of how the export STL tolerance option affects how the 3D CAD model's surface is described. Furthermore, depending on how fine the tolerances are set, computation power to export the CAD model and process the file for fabrication could be an issue. Once the appropriate STL file has been generated, this is then loaded into the individual RP company's proprietary software to be processed into 2D slices for fabrication.

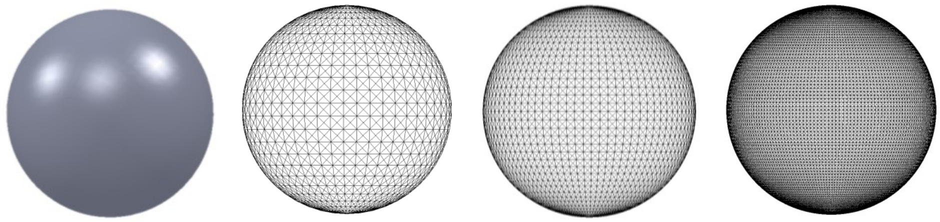

Figure 4 – CAD model to a coarse STL, fine STL, and a very fine STL file.

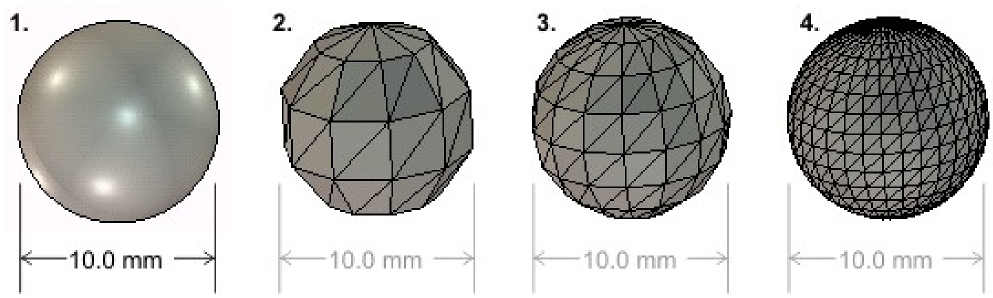

Figure 5 – Exaggerated view of different STL tolerances.

4. Additive Rapid Prototyping

The different types of additive RP technologies can be categorized into three types: liquid based (SLA and Inkjet based Printing), solid based (FDM), and powder based (SLS). These are just a few examples of the different RP technologies in existence. Regardless of the different types of RP technologies, all of them require the 3D CAD model's STL file for fabrication. These STL files are then used to generate to 2D slice layers for fabrication.

4.1 Liquid base - StereoLithography Apparatus (SLA) and Inkjet based printing

4.1.1 StereoLithography Apparatus (SLA)

SLA RP technology has three main parts: a vat filled with ultraviolet (UV) curable photopolymer, a perforated build tray, and an UV laser, Fig. 6. Figure 7 shows a production level SLA system by 3DSYSTEMS. The fabrication process starts with positioning the build tray a slice layer depth below the surface of the photopolymer. A slice layer is cured on to the build tray with the UV laser. The pattern of the slice layer is "painted" with the UV laser with the control of the scanner system. Once the layer is cured, the tray lowers by a slice layer thickness allowing for uncured photopolymer to cover the previously cured slice. The next slice layer is then formed on top of the previous layer with the UV laser, bonding it to the previous layer. This process is repeated until the entire 3D object is fully formed. The finished 3D object is removed and washed with solvent to remove excess resin off the object. Finally, the object is placed in a UV oven for further curing. During the fabrication process, support scaffolding can be fabricated to support overhangs or undercuts of the 3D object. These can be cut off after fabrication.

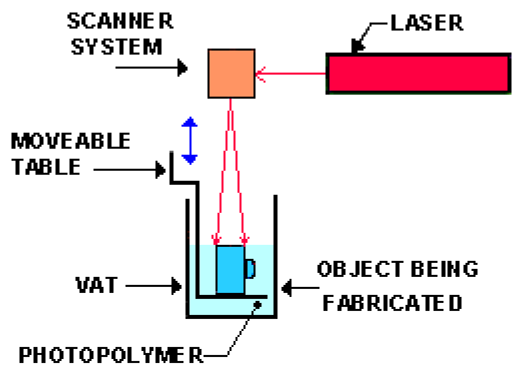

Figure 6 - StereoLithography apparatus (SLA) [3].

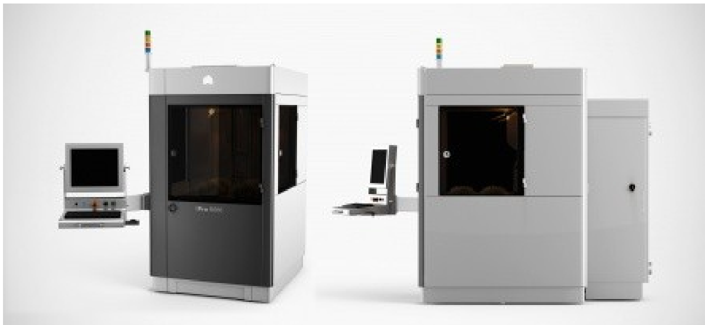

Figure 7 – 3DSYSTEMS SLA production RP printers [4].

4.1.2 Inkjet based Printing

This RP technology is similar to the SLA technology, both of which utilize UV curable photopolymer as the build material. Two types of UV curable photopolymer materials are used: model that act as the structure and support material acting as scaffolding to the object. The technology is based on inkjet systems as shown in Fig. 8 where it has 'ink' cartridges and a print head.

During fabrication, a thin layer of photopolymer is jetted on to the build tray. The jetted photopolymer is cured by UV lamps mounted to the side of the print heads. Next, the tray lowers by precisely one layer's thickness, allowing for the next slice to be jetted on to the previous slice. This process repeats until the 3D object is formed. Once completed, the support material is removed with a high pressure washer. A commercially available inkjet based RP printer by Stratasys is shown in Fig. 9.

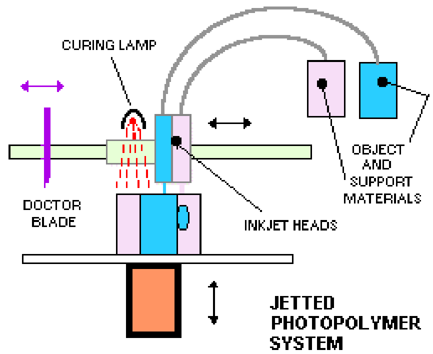

Figure 8 – Inkjet based printing [3].

Figure 9 – Stratasys inkjet based RP printer [5].

4.2 Solid based: Fused Deposition Modeling (FDM)

FDM RP technologies use a thermoplastic filament, which is heated to its melting point and then extruded, layer by layer, to create a three dimensional object, shown in Fig. 10. Two kinds of materials are used: a model material which acts as the structure and a support material which acts as a scaffolding to support the object during the fabrication process.

During the fabrication process, the filaments are fed to an extrusion nozzle unwounded from a coil. This nozzle is heated to melt the filament which is then extruded on to a build tray forming a slice of the 3D object as cools and hardens. Next, the build tray is lowered or the extrusion nozzle is raised, by a thickness of an extruded layer, for the next slice layer to be extruded on top of the previous layer. As the extruded thermoplastic cools, it also binds to the previous layer. This continues until all the slices are printed to finally form the full 3D object. After the fabrication process, the support build material is typically dissolved by water if water-soluble wax was used or broken off if polyphenylsulfone was used. An affordable desktop version by 3DSYSTEM is shown in Fig. 11.

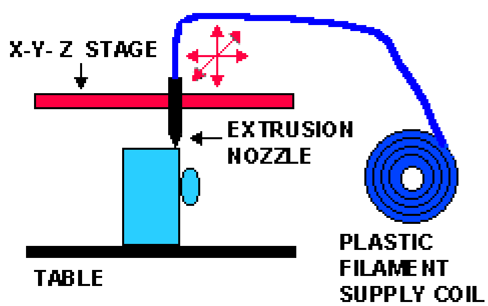

Figure 10 – Fused deposition modeling [3].

Figure 11 – 3DSYSTEMS FDM desktop RP printer [6].

4.3 Powder Base: Selective Laser Sintering (SLS)

SLS is similar to SLA in which it also uses a laser and build tray except instead of using a vat of liquid photopolymer as the build material it uses a powder build material. The powder used can be plastic nylon, ceramic, glass or metal. A schematic of this system is shown in Fig. 12. This RP technique can be used to create both prototypes as well as final products. Figure 13 shows a production level SLS system by 3DSYSTEM.

A high power laser is used to heat the powder build material to just below its boiling point (sintering) or above boiling point (melting) to fuse it together to form the 3D object's slice layers. Once a slice layer is formed, the build tray lowers by a slice layer's thickness. Next, the roller spreads more powder build material over the previously fused slice layer for the next slice layer to be sintered. This repeats until the 3D object is formed. Another difference to the SLA RP technique is that it does not require any support scaffolding as it is supported by the powder build material surrounding the object.

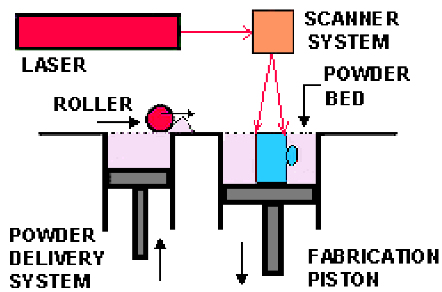

Figure 12 – Selective Laser Sintering [3].

Figure 13 –3DSYSTEMS production SLS RP printer [5].

4.4 Comparison of different RP technology

Comparison from [3].

	Stereolithography Aparatus (SLA)	Inkjet Based	Fused Deposition Modeling (FDM)	Selective Laser Sintering (SLS)
Build tray size (inches)	20 x 20 x 24	12 x 6 x 9	24 x 20 x 24	27.5 x 15 x 23
System price range	$75K-800K	$46K-80K	$10K-300K	$200K-1M+
Speed	Average	Poor	Poor	Average to good
Accuracy	Very good	Excellent	Fair	Good
Surface Finish	Very good	Excellent	Fair	Good to very good
Strengths	• Large part size • Accuracy	• Accuracy • Finish	• Price • Materials	• Accuracy • Materials
Weaknesses	• Post processing • Messy liquids	• Speed • Limited materials • Part size	• Speed • Part size	• Size and weight • System price • Surface finish
Typical applications	• Very detailed parts and models for fit & form testing • Trade show and marketing parts & models • Rapid manufacturing of small detailed parts • Fabrication of specialized manufacturing tools • Patterns for investment casting • Patterns for urethane & RTV molding	• Most detailed parts and models available using additive technologies for fit & form testing • Patterns for investment casting, especially jewelry and fine items, such as medical devices • Patterns for urethane & RTV molding	• Detailed parts and models for fit & form testing using engineering plastics • Detailed parts for patient- and food-contacting applications • Plastic parts for higher-temperature applications • Trade show and marketing parts & models • Rapid manufacturing of small detailed parts • Patterns for investment casting • Fabrication of specialized manufacturing tools • Patterns for urethane & RTV molding	• Slightly less detailed parts and models for fit & form testing compared to photopolymer-based methods • Rapid manufacturing of parts, including larger items such as air ducts • Parts with snap-fits & living hinges • Parts which are durable and use true engineering plastics • Patterns for investment casting

	Stereolithography Aparatus (SLA)	Inkjet Based	Fused Deposition Modeling (FDM)	Selective Laser Sintering (SLS)
Available build material	• Acrylics (fair selection) • Clear and rigid • ABS-like • Polypropylene-like (PP) • Flexible or elastomeric Water-resistant	• Polyester-based plastic • Investment casting wax	• ABS • Polycarbonate (PC) • Polyphenylsulfone Elastomer	• Nylon, including flame-retardant, glass-, aluminum-, carbon-filled and others providing increased strength and other properties • Polystyrene (PS) • Elastomeric • Steel and stainless steel alloys • Bronze alloy • Cobalt-chrome alloy Titanium

5. Rapid Prototyping Optomechanics

Additive RP technologies can be useful with fabricating the optomechanics in an optical system. Figure 14 shows a CAD design of a spectral image classifier and the fabricated system with an inkjet based RP printer shown in Fig. 15. New RP technology has allowed for optical systems to have an integrated design and be fabricated directly. One can design an optical system with a ray tracing program then easily design a 3D CAD model to match the optimization performed previously by the ray tracing program. The choice of additive RP technology would depend on fabrication time, cost, and build material requirements.

Typical 3D CAD design considerations that would need to be taken into account includes:

- RP fabrication tolerances – fitting and alignment
- Optical fine adjustment ability
- Stiffness of material to support heavy optical devices
- Fasteners
- Adhesion

Figure 14 – CAD model of optical system.

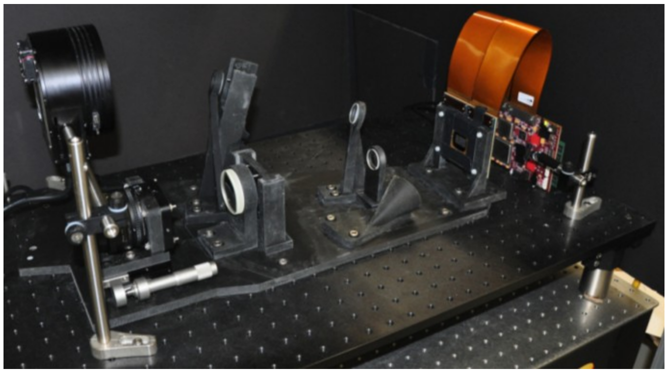

Figure 15 – Fabricated CAD model of optical system, Fig. 15 with inkjet based RP technology.

6. References

[1] Chua, Chee Kai, Kah Fai Leong, and C. Chu Sing Lim. *Rapid prototyping: principles and applications*. World Scientific, 2010.

[2] Solidworks help files.

[3] http://www.additive3d.com

[4] http://www.3dsystems.com

[5] http://www.stratasys.com

[6] http://www.cubictechnologies.com