The Types of 3-D Printing

Abstract

Chapter 2 of Library Technology Reports *(vol. 50, no. 5) "3-D Printers for Libraries" describes in detail the predominant type of 3-D printing, fused deposition modeling (FDM). The chapter also covers stereolithography, selective laser sintering, and laminated object manufacturing.*

In chapter 1 I described the most common type of 3-D printing as a sort of robotic hot glue gun. This process, only one of multiple kinds of 3-D printing that are available, is usually referred to as *fused deposition modeling*. In this chapter we'll take a look at not only fused deposition modeling, but also selective laser sintering, stereolithography, laminated object manufacturing, and electron beam melting. While many of them are well outside the price point for most libraries, prices go down dramatically as soon as patents expire on the core technologies behind the printing methods. This is the central reason that fused deposition became inexpensive so quickly over the last five years, and most people that follow 3-D printing believe that laser sintering will follow suit shortly because a key patent for that technology expired in January 2014.

I'll start with the printing technology most central to libraries at the current time, fused deposition modeling, and then, after we wrap our heads around how that technology works, we'll take a look at other options that may be coming for us to use in the next three to five years.

Fused Deposition Modeling Printing

Fused deposition modeling (FDM) is what most people understand to be 3-D printing, as this technology is by far the most common and in many ways the simplest of the possibilities. FDM uses a variety of plastics that fall within a range of melting points and that fuse when melted and resolidified, the most common of which are ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid). We'll discuss the specifics of these and other print substrates below.

The most common arrangement for an FDM printer is called a Cartesian print engine because it uses basic Cartesian coordinates (*X*, *Y*, *Z*) to create the printed objects. There are multiple types of printers even within this general category, although two are more common than others: the MakerBot style (see figure 2.1), which relies on a fixed plane *X* and *Y* printhead and movable *Z* print bed, and the so-called "RepRap" style, which relies on a fixed plane *X* axis, while the *Y* axis is controlled by moving the print bed itself and the Z axis is accomplished by moving the whole printhead system vertically upwards (see figure 2.2).

There is at least one other significantly different geometry for an FDM printer, the layout that is called a delta printer. In this instance, the printhead is suspended from three arms that are controlled along vertical supports while the print bed is completely stationary. This arrangement allows the printhead to "float" above the print bed and be located at any physical point in three dimensions simply by altering the relation of each of the three arms to the other. This is the same sort of control geometry at work in the flying cameras used in NFL games, applied to a robot. I will discuss two examples of a delta printer in chapter 5.

The Mechanics of Printing

Regardless of the control geometry used, the method of printing is the same for both types of FDM printers.

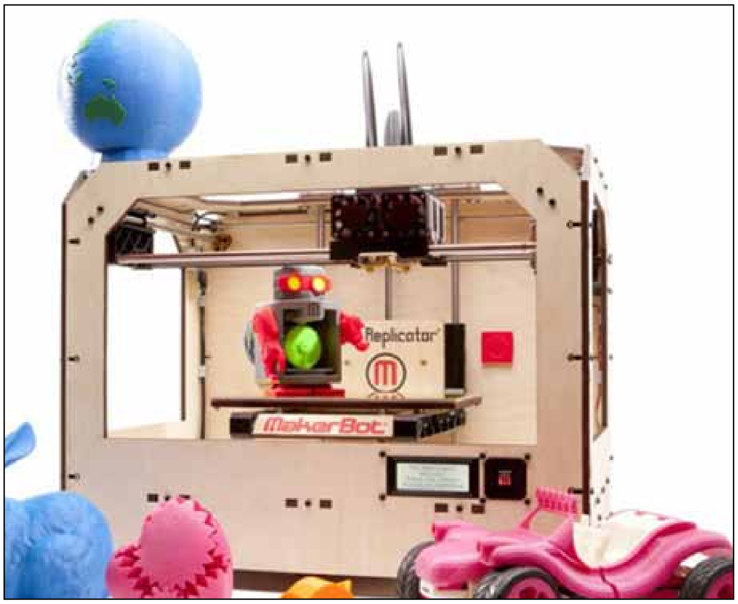

Figure 2.1
MakerBot Replicator

The printhead is a metal tube with a heating element and thermistor to control the temperature. The plastic substrate is melted by the heat of the printhead, and pressure is applied by forcing more plastic in, causing some of the liquid plastic to extrude through a small nozzle that ranges from .2 mm to .5 mm in size.

A print from an FDM printer begins with a single layer of plastic applied very thinly to the print bed, the nozzle moving across the print bed and depositing the plastic in the shape of the object it's creating. This initial layer is the base layer of the object, and the second layer will be deposited directly on top of the first and will fuse due to the properties of the plastic involved. Once the second layer is completed, the third, fourth, and so on will be done, building the object over time along the Z axis. You can think of layer height as the equivalent of the DPI (dots per inch) of a printed page. It's the resolution of the object in the vertical dimension, and the smaller the layer height, the smoother the final product will appear. It will also take significantly longer to print since as you reduce the layer height, you're adding layers to the overall build.

For example, let's imagine you're printing a 5-cm-tall cube. If you print that cube at what would be considered a fairly rough layer height of .3 mm, you'll print a total of 167 layers. If you print that same cube at a fine resolution (around .1 mm for most printers), then you'll print 500 layers, tripling the number of overall layers and the time necessary to print the object.

Because FDM printers rely on building objects vertically in the open air, they have issues with specific geometries of objects. If you imagine a thing being printed slowly from the bottom up, if the thing has a significant overhang or free-hanging part like a wide doorway or something like a stalactite, it won't be printable without supports on an FDM printer. The plastic has to be deposited on something: otherwise the print won't work.

All FDM printer software has the built-in ability to include supports for printing when issues like this arise. Printing an object with supports means that the software builds vertical towers whose only purpose is to give the object a structure upon which to print. In the best case, a support structure would be easily removable from the rest of the model, either by just peeling them apart or, in a slightly more advanced process, by printing the supports in a type of plastic that is soluble in a solvent, while printing the object itself in a plastic that is insoluble. The most popular of these support structures (discussed in more detail below) is high impact polystyrene, or HIPS, which allows a printer with dual extruders to print support structures that can be dissolved off the actual print.

Terminology

As with any sort of specialty product, there's a vocabulary that has built up around 3-D printing, and if you're new to looking at these printers, some of the specific terms are inscrutable without research. One example would be the terms for the two types of extruder setups found on FDM printers. The extruder is the part of the FDM printer that forces the plastic filament into the hot-end and through the nozzle onto the build plate. One is simply called a *direct extruder*, while the other is known as a *Bowden extruder*. On a direct extruder FDM printer, the moving print assembly includes the hot-end and the nozzle, and a motor pulls filament off the spool and drives it directly into the hot-end. The majority of FDM printers have a direct drive extruder. The Bowden extruder removes the motor assembly from the moving printhead. In a Bowden setup, the motor pushes the filament from the spool through a tube connected to the hot-end and nozzle. The advantage to the Bowden is that it significantly reduces the weight of the moving print assembly, which means that it can move more quickly and can change directions without serious jitter problems. The disadvantage is that it is, in some sense, pushing a rope, and the more flexible the filament is, the harder a time the Bowden setup will have with pushing it into the print assembly.

A few other helpful FDM-specific terms (and some of these I've already used without explaining, forgive me, dear reader) are *hot-end*, *build plate*, *nozzle*, and *spool*. The hot-end of an FDM printer is the metal piece that contains the heating element and melts the filament when the filament reaches it. These are normally some form of nonreactive metal, either aluminum, brass, or stainless steel. The *nozzle* is the very small diameter (.2 mm to .5 mm) that the melted plastic is forced through under pressure on its way to the build plate. There is a relationship between the nozzle diameter and the possible layer height of the output from the printer. Because you are extruding tubes of melted plastic and they need to be pressed together in order to fuse, the layer height can't be any larger than the diameter of the nozzle. If it were, you would be extruding into thin air, without the new layer pressing into the old layer. To help visualize this, if the width of your extruded plastic is .3 mm and you attempt to print at a .4 mm layer height, there's .1 mm between the plastic and the layer below it—not good. In practice, a good rule of thumb is that the maximum layer height is somewhere between 75 and 80 percent of the nozzle diameter. So for a .4 mm diameter nozzle, your maximum layer height would be around .3 mm. Generally speaking, the goal is to have lower and lower print heights, as that makes for a smoother and smoother final product. But for rough prints, or demos, having a higher maximum layer height can speed up prints tremendously.

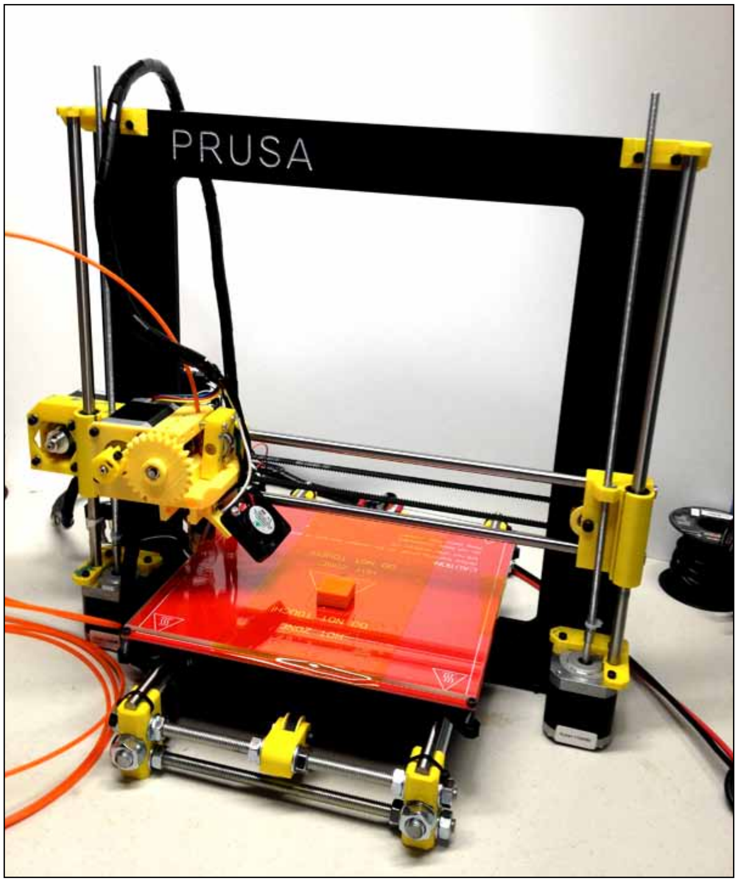

Figure 2.2
RepRap style 3-D printer. Photo credit: https://www.flickr.com/photos/jabella/8965235630 by John Abella

The last couple of FDM-specific pieces of terminology are *build plate* and *spool*. Spool is easy, as it's the way that filament is generally purchased and used. A typical purchase of ABS or PLA would be a kilogram (2.2 pounds) of plastic, wrapped onto a plastic or cardboard spool that hangs on the printer and plays out filament as needed. In an FDM printer, the build plate is the surface upon which the plastic is extruded. The specifics of the build plate vary widely but fall into a few basic categories, the primary of which is *heated* or *nonheated*. A heated build plate adds cost to the printer but is absolutely necessary for printing with certain types of filament (ABS, nylon, and others).

Another aspect of the build plate is what it's made of and whether you print directly onto the plate, onto some tape or other covering, or onto a glue or other adhesive. Heated build plates are usually made of either aluminum or tempered glass, although occasionally stainless steel shows up. Unheated build plates can be composed of the same things, as well as acrylic. The important thing with build plate construction is that you want something that will not warp or deform over time, since if the plate itself isn't flat, it's impossible to level it appropriately to the printheads. Glass is a very popular build plate material for this reason, although many FDM printers ship with aluminum plates that are then covered with a replaceable printing surface of some kind, most commonly PET tape or Kapton tape for a heated bed, or painter's tape for a nonheated bed.

Factors in Pricing

The price points for FDM printers are typically determined by size, more specifically print volume or the size of the print bed, and a variety of upgrades that make specific kinds of printing or printing with specific plastics more easily done. Print bed sizes range from very small (no more than 3 inches by 3 inches or so) to massive (over 12 inches by 12 inches). The print volume determines the maximum size of a single object that you can print or, conversely, the number of smaller objects that you can print at the same time. Printing larger objects is also more difficult because as you print larger things, there's more opportunity for a small error to creep into the print due any number of common 3-D printer issues.

Challenges with Fused Deposition Modeling

Most of the issues with FDM printing are related to the fact that it's a very mechanical process, and tuning the printer is key. The most sensitive aspect of the process is the relationship between the extruder/nozzle and the build plate. Because the printhead has to extrude an even layer of plastic onto the build plate, it's necessary that the build plate be perfectly flat relative to the nozzle. If there is any warp or unevenness, you'll get uneven attachment to the plate or other forms of print failure. This is the most common issue with FDM printing, especially with new operators. The first question that should always be asked if a print fails is, "Is my build plate level?"

And prints will fail. FDM printing is a complicated mechanical process, and while you can tune a FDM printer to be very reliable, at some point you will have a failure and will come back to a print that looks like someone poured plastic spaghetti on your build plate. This is normal. Recalibrate, relevel, and try again.

Stereolithography

While FDM printing is by far the most common inexpensive method of 3-D printing, we are starting to see stereolithography (SLA) printing move down-market into the affordable-for-libraries zone. I'm aware of a couple of libraries that have already purchased stereolithography printers, so it is starting to trickle into our midst. What is stereolithography? It's a method of 3-D printing that involves a light-sensitive resin and lasers. A liquid resin is contained in the body of the printer, with a build plate that moves up and down inside the resin. The resin solidifies when exposed to a specific wavelength of light, usually in the UV spectrum, and the printer has a laser or lasers that are tuned to that specific wavelength. The build plate starts near the top of the resin, and the lasers sweep across, solidifying the resin in the appropriate areas. The build plate then lowers, and the lasers repeat their sweep, building layer after layer, one after the other, as the object is built. You can also have this process occur upside down, as in the Formlabs Form 1 printer, where the build plate is actually above the resin, and as layers are added, it pulls the completed layer out of the resin.

This type of printing has several advantages over FDM printing. First, because the print is always encased in liquid resin as it prints, it is much more forgiving as to geometry of design. Not completely, as there still has to be some connection to the base layer (you couldn't print a "floating" horizontal piece, for instance). But in general, the resin provides substantially more support for designs than you are capable of printing with FDM printers. The other major advantage is that the detail level is limited by the crystallization of the liquid and the size of the lasers, which means that you can have very, very fine details in an SLA print. It's possible to achieve .025 mm (25 microns) layer heights with SLA prints.

Stereolithography printing is limited in some ways as well. The first is that the resin is available only in a very limited number of colors, generally clear or translucent and white. When compared to the rainbow of colors available for FDM printing with ABS or PLA, it feels limiting. The second, and far more worrisome, limitation is that most vendors of this type of printer manufacture their own resin, and it's possible to tune the wavelength of the lasers involved to the specific resin they sell, thus making it very difficult for anyone to compete with them on consumables for the printer. This would be the equivalent of buying a printer from HP and having to then buy paper and toner from HP as well in order to use the printer.

Small SLA printers are just beginning to hit the market, available in the $2,500 to $3,500 range. The consumable for printing, the photosensitive resin, is more expensive than filament for FDM printing, too. The most popular of consumer-grade SLA printers, the Formlabs Form 1, has resin that sells for $149 per liter.

Selective Laser Sintering

Simultaneously, the most flexible and the most expensive type of 3-D printing commonly used, selective laser sintering (SLS), is similar to stereolithography in that it uses lasers to solidify a loose substrate. But in SLS the printing substrate is a powder and you use high-energy lasers rather than UV ones. The high-energy lasers selectively fuse sections of a powder together, a new layer of powder is deposited on top of the sintered layer as the entire print bed drops, and the lasers do another pass, fusing the single layer of powder to the already solid layer below. Thus prints are completed layer by layer, exactly as in the other printing technologies that we have covered, except the end product is a solid object that's been drawn by lasers, encased in all of the powder that wasn't fused.

This method provides total support for the print in question, so nearly any imaginable geometry can be printed using SLS printing. It is also possible to use any material for SLS that is capable of being powdered and fused with heat, including most of the previously mentioned thermoplastics as well as steel, aluminum, titanium, and other metals and alloys. Prints produced in this way are very nearly as strong as solid-cast parts, which means that it's possible via SLS printing to 3-D print mechanical parts that are directly usable in engineering projects.

Layer height and resolution in SLS printing are completely determined by the resolution of the powder being fused, but they are typically on par with

SLA printing, averaging around .1 mm layer heights. Another similar technology is electron beam melting (EBM), which uses high-energy electron beams to melt powdered metals in order to produce 3-D objects. The use of electron beams allows for even higher precision than lasers, as small as .05 mm layer heights, which is nearly unheard of by any other method.

Laminated Object Manufacturing

The last specific type of 3-D printing that I'd like to describe is, in my opinion, particularly clever. Laminated object manufacturing takes thin materials like paper or plastic sheets, cuts them to a specific shape, and then uses adhesive to glue one layer to the next. The best known of these types of printers is manufactured by a company called Mcor Technologies. Its printer uses normal, ordinary copy paper as its substrate, cutting one sheet at a time into the appropriate shape for the given layer and then using paper glue to laminate the individual layers together. The high-end Mcor printer includes a full-color ink-jet printhead inside to allow the creation of full-color 3-D prints from very inexpensive raw materials—literally paper, ink, and glue.

Other 3-D Printing Types

There are numerous other 3-D printing technologies in existence, especially those that are patented and limited to a single company. For example, 3D Systems uses a type of 3-D printing methodology it calls ColorJet Printing (CJP), which uses two different materials that are combined using a sort of high-end ink-jet printer in order to create the solid end product. This patented process allows 3D Systems to print in materials like food-grade ceramic. 3D Systems also makes a 3-D printer that is capable of printing in sugar, called the ChefJet, and the high-end model, the ChefJet Pro, can print edible 3-D models in full color.