An Evaluation of Some Low-cost Rapid Prototyping Systems for Educational Use

Wayne Helmer, Damon Mobbs
Arkansas Tech University, Arkansas Tech University,

Abstract

Rapid Prototyping (RP) technology and methods have been around for over twenty years. As this technology has matured the base price of these units has decreased as well. RP are now cost effective in graduate schools, technical schools, secondary and primary educational facilities. New improvements in the technology have made RP units available to almost any school in our country. This paper evaluates some of the current low cost RP units available and provides recommendations for those schools seeking to implement such technology in the class room.

Introduction and Background

RP technology and systems have been around for a number of years. This technology has found application in industry, governmental engineering laboratories, manufacturing facilities and all types of schools. As the sophistication of this technology has increased the base price of these units has decreased. RP are now cost effective in graduate schools, technical schools and secondary and primary educational facilities. New improvements in the technology have made RP units available to almost any school in our country.

The terminology used in the rapid prototyping industry is not completely consistent. Some differentiate "RP" from "3D Printing" Theoretically RP includes more expensive machines and manufacturing staff. "3D printing" is thus focused on lower-cost systems and technologies. In this paper RP will include both definitions. Various summaries of RP technology and methods are given in references [1,2,3].

In a RP process an object or model is first created electronically in a CAD file. The CAD file is then converted to a STL file format. The RP machine or some intermediate computer slices the STL file to generate the object electronically in layers. Finally the RP machine physically produces the model in layers from the layered "slice" file. The layers may be produced by build material in filaments, droplets, or laminates.

RP build materials include paper laminates, powders, thermo-plastics, photopolymers, and other special materials. All of these materials are solidified, joined, melted, welded, or hardened by one of a number of specific methods. The main RP types are: Selective Laser Sintering [SLS], Laminated Object Manufacturing [LOM], Stereolithography [SLA], or Fused Deposition Modeling [FDM]. See table 1. All of the technologies are "additive" methods rather than “subtractive” methods. In additive methods the material is added to existing material to the build the parts. In subtractive methods material is taken away from the existing material to make the final product. CNC is a typical subtractive build method (but not usually considered a RP method).

Build material needs to be differentiated from support material. Build material is the actual material that makes up main RP part. Support material is necessary to support or hold up the build material as the part is being made; for example in an overhang. An RP system is usually capable of generating both such materials.

Rapid prototyping Methods	Build Materials
Selective Laser Sintering [SLS]	Metal powers, thermoplastics
Laminated Object Manufacturing [LOM]	Special paper
Stereolithography [SLA]	Photopolymer
Fused Deposition Modeling [FDM]	Thermoplastics

Table 1. Main Rapid Prototyping Methods and Build Materials.

Selective Laser Sintering

Selective Laser sintering [SLS] was developed at the university of Texas in the 1980s. In this process a high power laser is used to fuse material (e.g. plastics, metal, ceramic) in layers. See Figure 1. The new backed bed of material for each layer is deposited on the previous fused material from a roller and a bin of unprocessed powder. Support material is not required in the SLS process. Due to the materials used the final object built by this method can be stronger than from other RP methods.

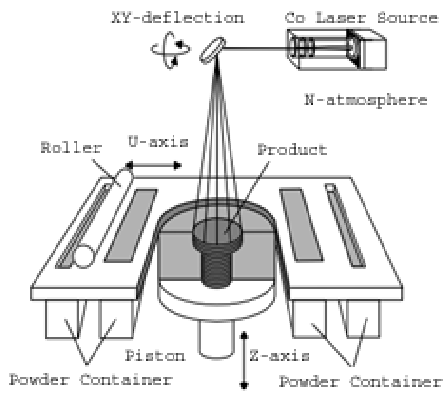

Figure 1. Selective Laser Sintering [4].

Laminates/Paper systems

In this method layered paper is first adhered to a moveable base. A CO_2 laser cuts out the outline of the first layer of the object, the support material is cut in cross-hatch fashion. The table translated down and new paper (or plastic) is adhered over the previous layer. See Figure 2. The laser then cuts out the next layer of the object. After completion the support material can be removed with a pick. The final object has the look and feel of wood. LOM may be less expensive than other methods but the final object may be susceptible to shrinkage/warpage if the exterior surfaces are not sealed.

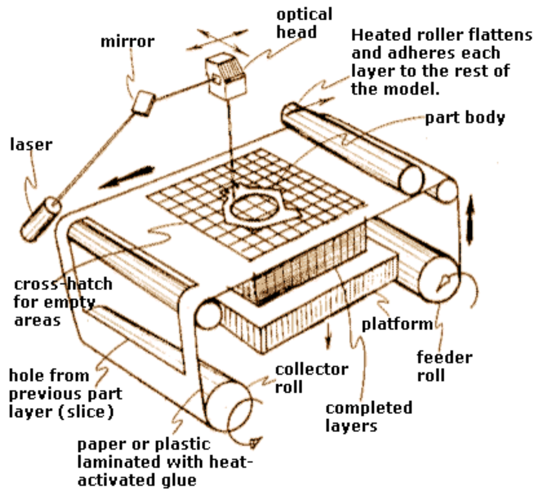

Figure 2. Laminated Object Manufacturing [5]

Stereolithography

Stereolithography (or SLA**)** was coined and developed by Chuck Hull in about 1985. This method is widely used today. In this method a light – sensitive resin in a vat is photo-cured by a UV laser. The table in the vat moves downward as each layer is built. Each layer is about 0.001 to - 0.007 inch. Ventilation of the vat is usually required due to the adverse resin vapors. Accuracy in the z-direction may suffer if there is no milling in this direction.

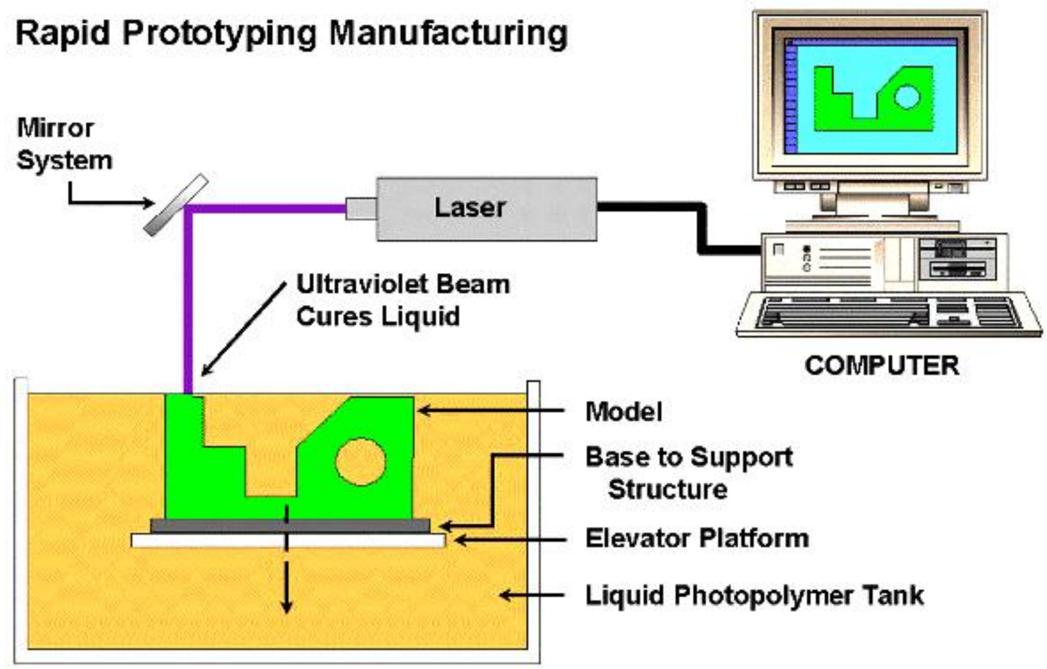

Figure 3. Stereolithography [6]

Fused Deposition Modeling (FDM). This process was invented and developed by *Stratasys*. In the FDM procedure a filament of thermoplastic is metered through a heated injection head to lay down a cylinder of hardening plastic on a build-plate. The heated head follows a tool path as prescribed by the software. Support structure may be required. See Figure 4. This is much like a “hot glue gun“ technique.

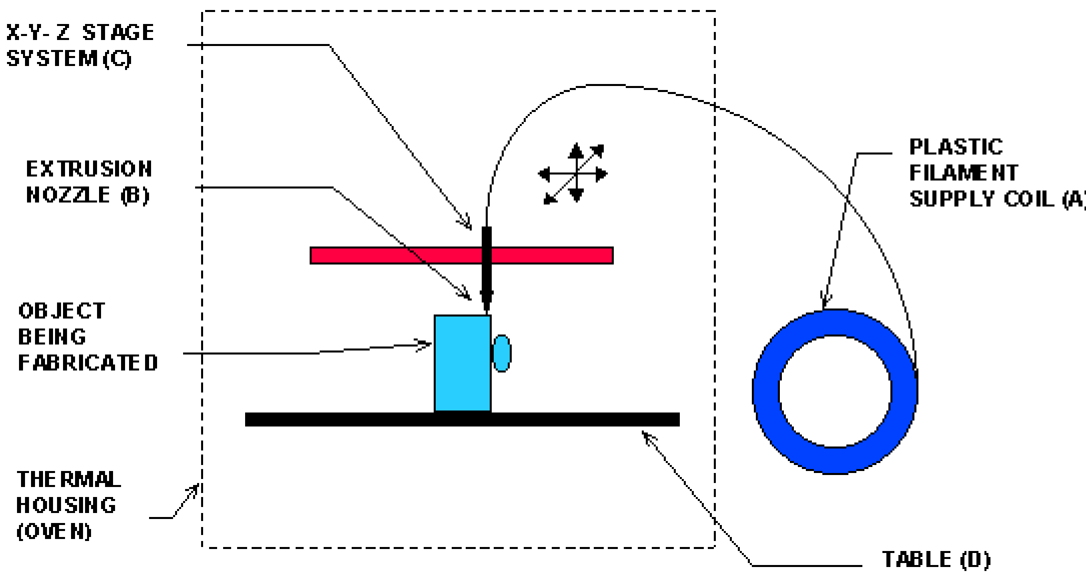

Figure 4. Fused Deposition Modeling process[7]

Low-end RP Machines

While there are numerous high-quality, high-end machines there still exists a market for less-expensive medium-quality RP units. Several such units have surfaced on the market during the last few years. Upon review of that literature and commercial information the following RP machines were selected for further evaluation as quality low-cost units.

1. Dimension
2. V-Flash
3. RepRap
4. Rapid PRO
5. MakerBot.
6. Rapman

V-Flash. These units by produced by 3D Systems. V-Flash is one of their high-quality, low-end RP units. UV laser striking a photopolymer resin converts the liquid to a hard plastic solid. See Figure 5. The liquid resin is contained in a vat below the computer-controlled laser. The part is usually built upside down and thus it tends not to need support material. A low-cost cleaning and final curing system is available with the unit. The build layer thickness is 0.004 inch. The build volume is 9 inch by 6.75 inch by 8 inch. The modeler size itself is 26 inch by 27 inch by 31 inch. This RP modeler produces hard plastic parts suitable for functional testing. The basic unit lists for $9900. A separate cleaning and curing system for post-processing is about $1800. This increases the final price to about $12,000. It has been mentioned that the uncured resin can be harmful.

Figure 5. V-Flash Models [8]

Dimension U-Print. *Stratasys* was the company that invented and developed FDM (Fused Deposition Modeling) in 1988 [9]. Dimension U-Printers is one of their lower cost RP product lines. This system prints parts in ABSplus™ ivory material. The FDM Layer thickness is 0.010 inch. The build volume is 8 inch by 6 inch by 6 inch. The modeler size is 25 inch x 26 inch x 31.5 inches. *Stratasys* says that the RP parts are capable of being sanded, machined, and painted. The models are acceptable for proof-of-concept replicas and vacuum forming molds. Post-processing is by either manual removal of the support material or accomplished by the support material being dissolved away in a solution of warm sodium hydroxide bath. The U-Print systems start at $14,900. The cleaning vat and system is about $2500. In its support for education *Stratasys* has donated thousands of dollars to underwrite these units at Project Lead The Way high schools in the USA.

Figure 6. Dimension Uprint[10]

RepRap is a 3D printer that is also called a "self-replicating machine" - one that anyone can build (and duplicate). The RepRap project was conceived and developed by Dr. Adrian Bowyer, a senior lecturer in engineering at the University of Bath, UK. It has been described as a "small manufacturing plant in your own home." The plans for the RepRap 3D printer and detailed tutorials are available for free on their web site. The RP unit again uses the FDM method. See Figure 7. The parts cost about $750. It can make about 50% of its own parts to reproduce itself. It is open-sourced with no big company is financially supporting it. The philosophy is to give the technology away so that other people, even third- world countries, can make parts, equipment, devices that they did not have available to them. The RepRap unit is more a "home" system rather that a university educational system. They have their own user forum at *reprap.org/wiki/RepRapWiki:Community_portal*. Unlike other machines this unit has the extrusion head move in the x and z-direction while the bed moves in the y-direction.

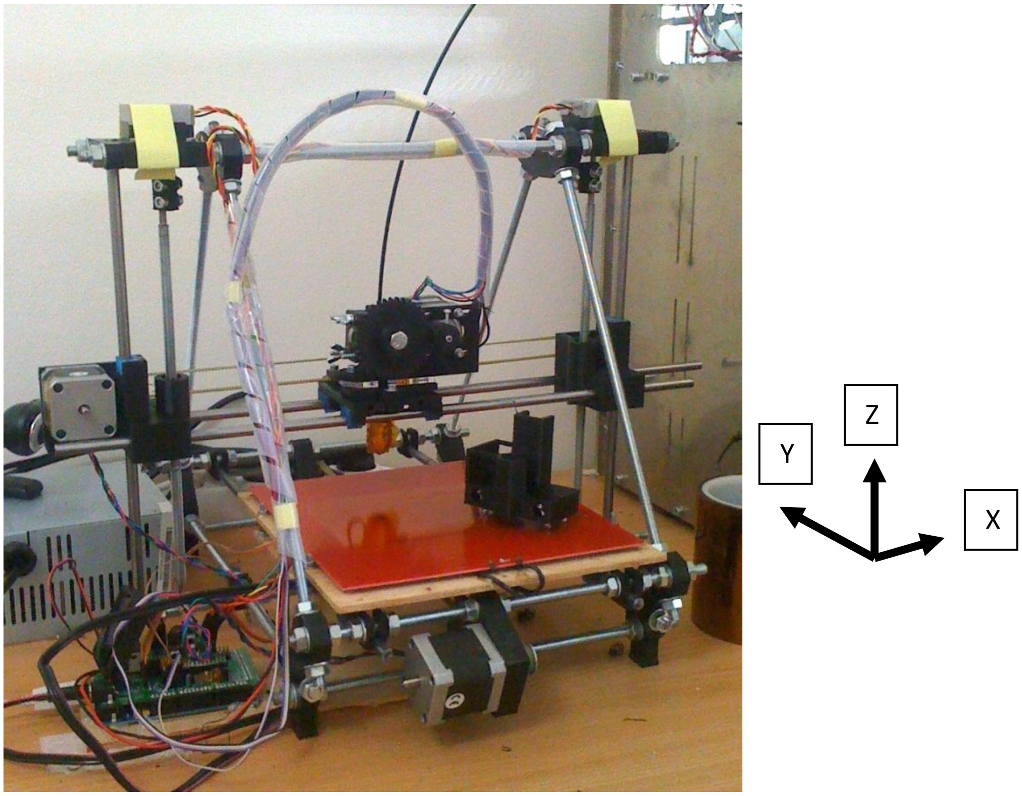

Figure 7. RepRap Modeler [11]

Rapid PRO [12] provides educational systems by Boxford industries-UK. This RP device makes the part out of layers of sticky-backed paper rather than plastic from droplets or filaments. See Figure 8. The paper is cut out in the appropriate shape as determined from the slice file with a special cutter/printer. These sheets are then aligned with pegs on a register and stacked together to form a solid part. Final sanding can yield a hard object adequate for molds for low-pressure injection molding. No price on the system has been received from contact with the company. No price was listed on their web page but it is assumed to be less than $3000.

Figure 8. Rapid PRO [12]

Makerbot. Makerbot is a company started by three men in January 2009. They shipped their first RP machine in September 2010. Their first RP unit was called a “Cupcake” and this system has improved and is now called the “Thing-O-Matic”. Their purpose was to create an open-source 3-D printer to “democratize” the industry. This company seems to focus more on the home or hobby RP market. Their “Thing-O-Matic” RP machine prints in ABS and PLA plastic using the FDM process. Their units come in kit or completely-assembled form.

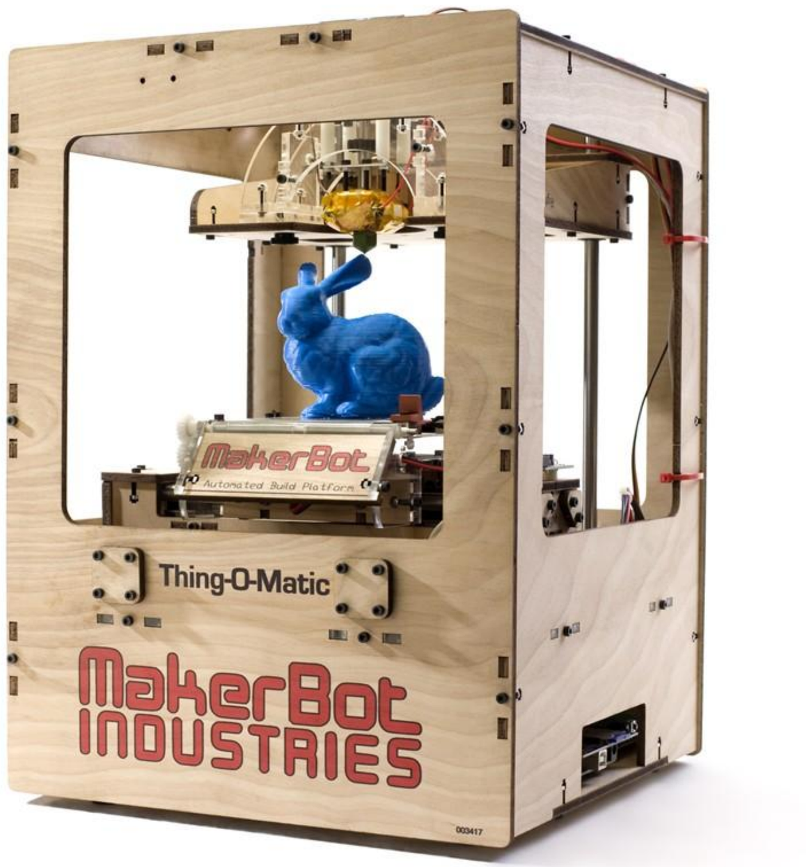

Figure 9. Makerbot/Thing-O-Matic [13]

The RP unit is housed in a wooden-laminate box. Metal rods (3/8inch diameter) form the frame and positioning slide-rods for the head and platform. MakerBot has its own users forum at *Thingiverse.com*. The enclosure and other parts are produced in laser-cut form. See Figure 10.

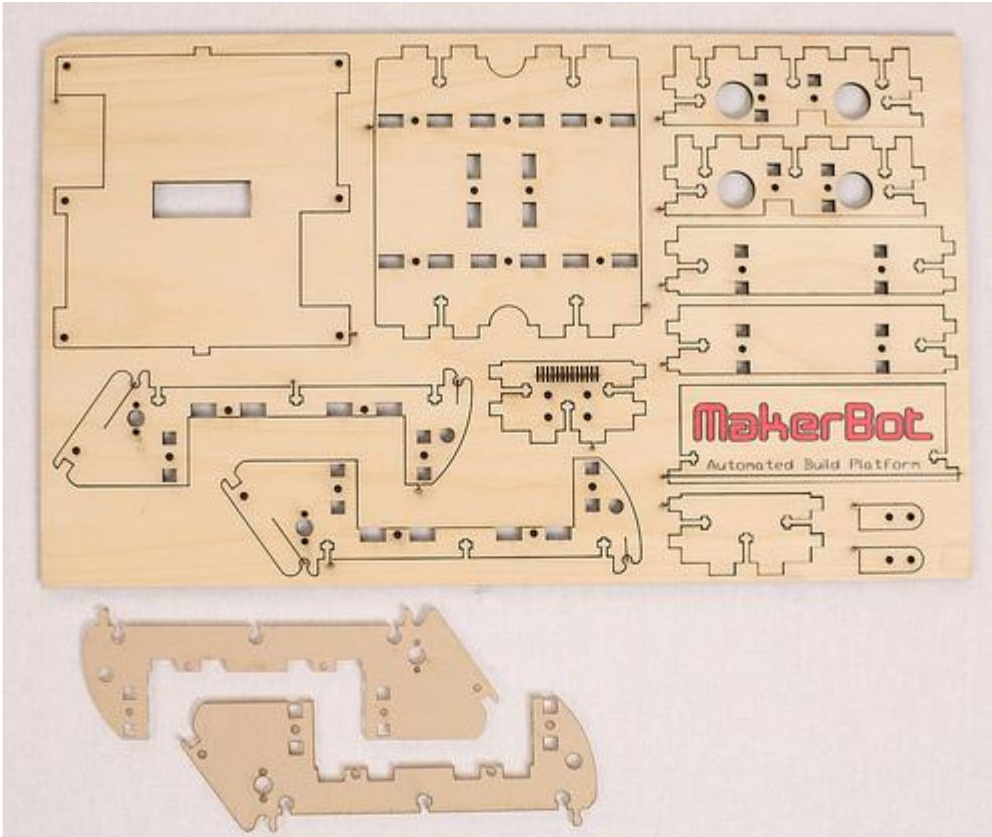

Figure 10. Thing-O-Matic Parts Sheet [13]

RapMan 3.1

Rapman 3.1 is produced by Bits from Bytes [BFB] [14]. They actually make two machines: Rapman 3.1 and BFB 3000 that are similar. The BFB is basically an assembled version of the Rapman 3.1 with a few modifications. Both units use the FDM process that focus on the education and hobby market. The Rapman 3.1 is more for demonstration in that it has basically open-form construction so that spectators can see all of the moving parts. The positioning of the head and table is done by the slide rod and Plexiglas frame. See Figure 11.

Figure 11. Rapman 3.1[14]

BFB 3000

The completed assembly-version of the Rapman 3.1 is called the BFB 3000. However the BFB 3000 has some upgrades: the exterior envelope is more enclosed. It seems that the frame and enclosure are stronger and more rigid thus giving a more professional look; practically and esthetically. See Figure 12. Interestingly enough, *3D Systems* now owns Rapman 3.1 and BFB 3000 as well as their own SLA product line.

Figure 12. BFB 3000 [14]

Most schools will be using RP machines for demonstration and for design projects at a price les than $10,000. Thus the Makerbot/Thing-O-Matic [TOM] and BFB RP machines were selected for comparison.

Comparison Criteria: When a company or school things about purchasing a RP machine various decision criteria are appropriate. The items include mainly: initial cost, maintenance cost, unit size, machine weight, number of heads, build area/volume, print speed, resolution, build material, material cost, and ease of use. See table 2 for a comparison of the four RP model-makers.

The build volume for the Rapman (320mm*300mm* 200 mm) is over twice that of the TOM (120mm*120mm* 120mm). All use standard 3 mm plastic filament, in various materials. The Thing-o-Matic is able to communicate with the builder with an SD card or a USB cable. Rapman can support three extrusion heads. TOM now only supports two. At this time the Rapman is only able to communicate with a SD card. The TOM has the head only move in the z-direction (the bed moves in the x and y direction). The BFB has the bed only move in the z-direction (the head moves in the x and y direction). Support: TOM has one hour free phone or Skype service support. BFB 3000 says that free phone and email technical support is available (no time limit period was mentioned).

TOM list the z-positioning "theoretical" resolution as 5 microns. The BFB 3000 lists the z-axis resolution as 10 microns. BFB 3000 seems to support a larger variety of thermoplastic filaments.

The TOM has a slightly lower price for the assembled unit: $2500 -assembled], ($1299 – unassembled). The Rapman is about $3500 - assembled], ($1500 – unassembled). However the unassembled units cost are about the same. The numbers quoted are from the most currents prices available from the suppliers from their web pages. Note that to do a real comparison one would have to compare all of the details of the bid unit: number of heads, FDM material included heated plate, etc.

7/5/2011	Makerbot Custom Thing-o-matic (assembled) (www.makerbot.com) (Oriented towards general public)	Makerbot Thing-o-matic (unassembled) (www.makerbot.com) (Oriented towards general public)
Price	$2,500.00	$1,299.00
Shipping	Ships up to 4 weeks after payment, USPS Priority: $54.15, UPS Ground: $30.26; Plus shipping insurance of $22.25	Ships up to 4 weeks after payment, USPS Priority: $48.75, UPS Ground: $26.40
Size	300mm W x 300mm D x 410mm H	300mm W x 300mm D x 410mm H
Weight	not found	not found
Service Contract	None, resources available online	None, resources available online
Number of Heads	1	1
Build Area	Single Head	Single Head
	120mm x 120mm x 120mm	96mm x 108mm x 115mm
Print Speed	not found	not found
Print	Print from SD memory card or computer	Print from SD memory card or computer
Resolution	Theoretical: X and Y axis: 0.02mm Z axis: 0.005mm	Theoretical: X and Y axis: 0.02mm Z axis: 0.005mm
Assembly	Pre-Assembled	Not Assembled
Machine Main Body	Metal and Wood	Metal and Wood
Part Material	3mm Circular ABS, PLA	3mm Circular ABS, PLA
Material Distributers	Makerbot	Makerbot
Material Cost	(www.makerbot.com) $48.00 (1 kg)	(www.makerbot.com) $48.00 (1 kg)
Operation	Head moves along Z axis, Bed moves along X and Y axis.	Head moves along Z axis, Bed moves along X and Y axis.

Software	Any 3D Modeling SW that can save as a STL file, Skeinforge (free) slices the layers and maps print path, ReplicatorG controls the machine.	Any 3D Modeling SW that can save as a STL file, Skeinforge (free) slices the layers and maps print path, ReplicatorG controls the machine.
Resources	Online: Parts, Updates, Material, Forums, Blogs	Online: Parts, Updates, Material, Forums, Blogs
Manufacturer	Makerbot Industries	Makerbot Industries

Table 2. Thing-O-Matic and BFB Comparison- Part 1.

7/5/2011	BFB 3000 (www.rapmanusa.com) (Oriented towards schools)			BFB RapMan V3.1 (www.rapmanusa.com) (Oriented towards schools)	
Price	$3495.00 Single Head, $3895 Double Head			$1,495.00	
Shipping					
Size	580mm H x 520mm W x 520mm D			820mm x 650mm x 570mm	
Weight	31 kg			18 kg (packaged)	
Service Contract					
Number of Heads	Ready to support up to 3.			Can support up to 3, still in development.	
Build Area	Single	Double	Triple	Single	Double
	X axis: 320mm Y axis: 300mm Z axis: 200mm	X axis: 285mm Y axis: 300mm Z axis: 200mm	X axis: 193mm Y axis: 300mm Z axis: 200mm	X axis: 275mm Y axis: 205mm Z axis: 210mm	X axis: 190mm Y axis: 205mm Z axis: 210mm
Print Speed	$15mm^3$/sec max (volumetric flowrate)			$15mm^3$/sec max (volumetric flowrate)	
Print	Print from SD memory card			Print from SD memory card or computer	
Resolution	X and Y axis: 0.05mm Z axis: 0.01mm			X and Y axis: 0.1mm Z axis: 0.125mm	
Assembly	Preassembled			Not Assembled	
Machine Main Body	Metal and Acrylic			Metal and Acrylic	
Part Material	3mm Circular: ABS, HDPE, LDPE, PP, uPVC. Almost any 3mm thermoplastic filament.			3mm Circular: ABS, HDPE, LDPE, PP, uPVC. Almost any 3mm thermoplastic filament.	
Material Distributers	BFB, Makerbot, New Image Plastics			BFB, Makerbot, New Image Plastics	
Material Cost	(www.rapmanusa.com) $85.00/kg reel, $75.00 each if 5 or more purchased			(www.rapmanusa.com) $85.00/kg reel, $75.00 each if 5 or more purchased	
Operation	Head moves along X and Y axis, Bed moves along Z axis.			Head moves along X and Y axis, Bed moves along Z axis.	

Software	Any 3D Modeling SW that can save as a STL file, BFB Axon (free) or Netfabb Engine ($142.00) converts STL files to G-code files and is used to setup the print.	Any 3D Modeling SW that can save as a STL file, BFB Axon (free) or Netfabb Engine ($142.00) converts STL files to G-code files and is used to setup the print.
Resources	Online: Parts, Updates, Materials, Forums, Blogs, Test Parts	Online: Parts, Updates, Material, Forums, Blogs, Test Parts
Manufacturer	Bits from Bytes	Bits from Bytes

Table 2. Thing-O-Matic and BFB Comparison- Part 2.

Our BFB 3000 Experience.

Prior to making a decision to purchase an RP unit we emailed various BFB users and visited two schools in Oklahoma that had purchased the Rapman 3.1 –which is the assemble-it-yourself BFB RP unit. Their experience with the unit varied, but most instructors had acceptable to good performance from their Rapman 3.1 systems and most suggested that people should buy the assembled BFB 3000 if money is available.

Arkansas Tech University purchased an assembled BFB 3000 in January of 2011 for $4195 (not including shipping and taxes). Included in the price was a two-head printer, three rolls of ABS filament build material and one roll of PLA build material – each roll was 1 kg. Setup and startup problems and time were reasonable. CDs with the equipment include an Operators manual, software manual, parts files, firmware and unpacking manual. Setup time took about 5 hours. (The user manual was out of date - but that was easily to downloaded from the website: http://www.bitsfrombytes.com/. No telephone or email support was required during setup-up. All questions or problems were corrected by information on the Forums or the BFB website in general. New firmware is easily downloaded from this website.

An example of one of our first models produced by our unit is shown in Figures 13-15. This is a model of a remote-controlled blimp to be used for a senior project. The model will be used in our wind tunnel to determine the drag characteristics of this blimp for a full-scale build. The model was build in two parts and in "draft" mode to decease the build time. The build time for both parts was approximately 7 hours total. Figure 16 shows the texture of the model surface which is adequate for our wind tunnel testing. The strength of the model also seems to be adequate for our wind tunnel tests. We noticed that one of the fins started to peel up during the build. This will not cause any model problems but it is worthy to note. This "problem" could most likely be solved by obtaining a heated bed for the parts [~ $100 option]. As a result of these initial builds we believe that the BFB 3000 will provide our students with quality educational parts in a reasonable time.

Figure 13. BFB 3000 model – part 1.

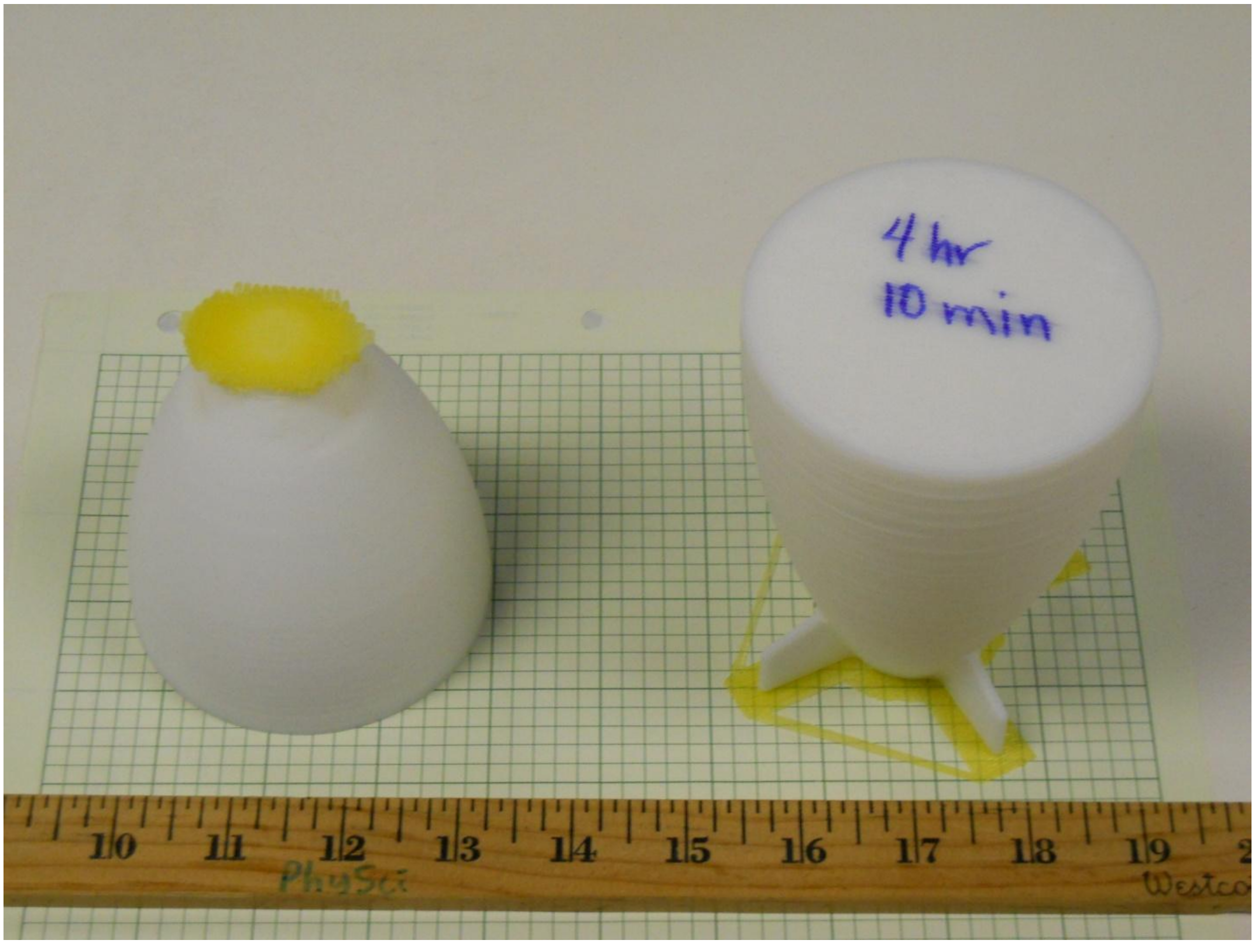

Figure 14. BFB 3000 model – part 2.

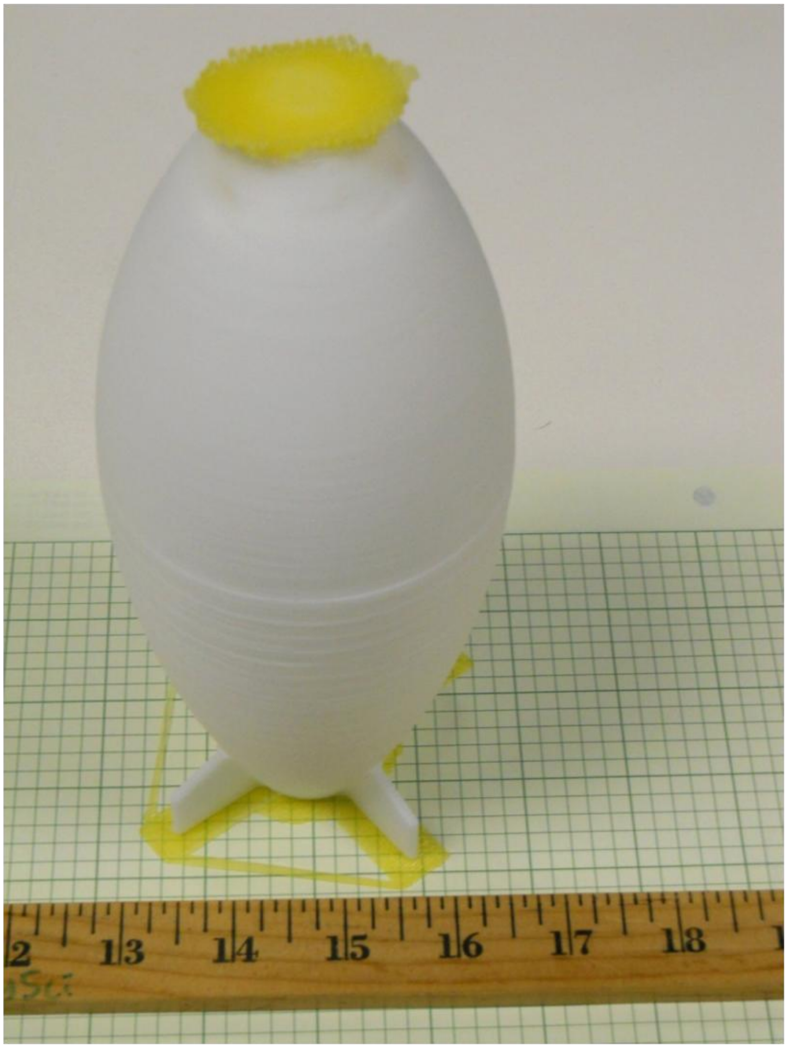

Figure 15. BFB 3000 model – part 3

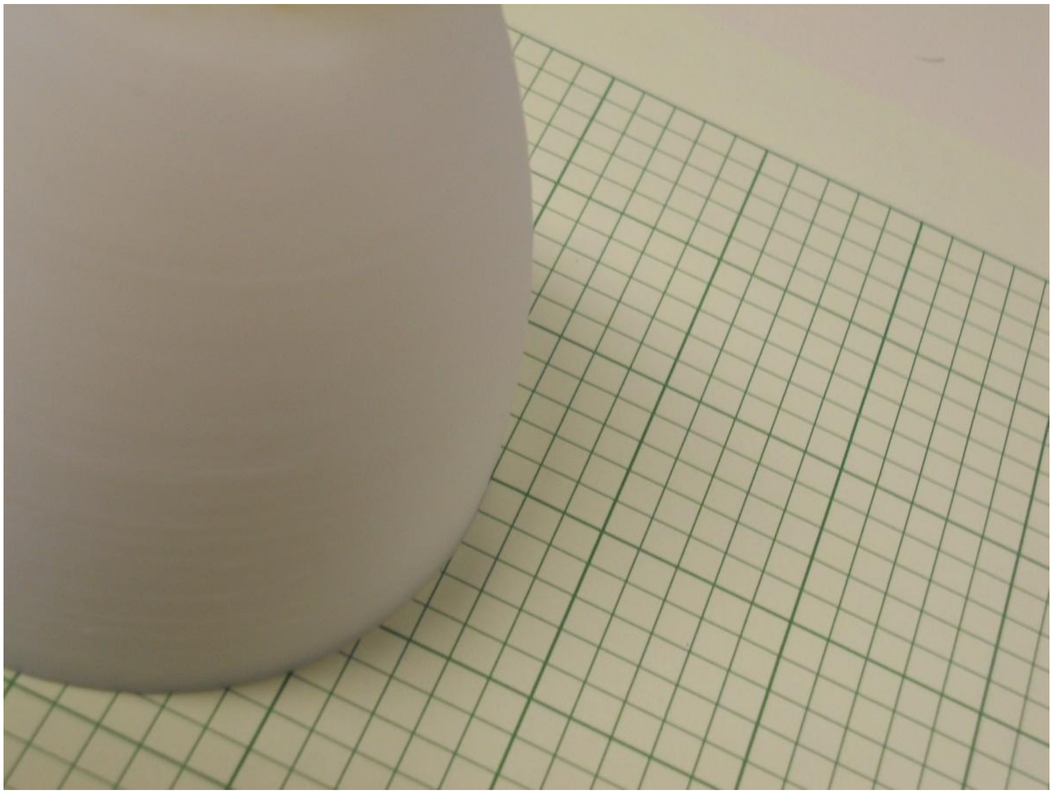

Figure 16. BFB 3000 model texture.

Recommendations for Schools

Based on the information obtained for this study the following suggestions can be made.

1. Buy the highest quality, plug-and-play RP unit that is affordable. Make sure to purchase a service contract to handle unforeseen problems and yearly maintenance.
2. If money is an issue then the BFB 3000 is a quality unit with acceptable performance at a reasonable price.
3. Build-it-yourself systems are acceptable if trained individuals are available for assembly and maintenance. These units can be very good for education and demonstration.

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10. www.uprint.dimensionprinting.com/
11. www.reprap.org/
12. www.boxford.co.uk/boxford/docs/products/rapid_content.htm
13. http://www.makerbot.com/
14. http://www.bitsfrombytes.com/content/bfb-3000-0

Biographical Information

Wayne Helmer, professor. Mechanical Engineering. Arkansas Tech University. He has taught engineering students for over 35 years and has worked at the Rapid Prototyping Center at NASA-Marshal.

Damon Mobbs, student. Mechanical Engineering Arkansas Tech University