

# **Rapid Prototyping Technologies in the Loughborough Design School**

A Guide for Final Year Students

Dr. Richard Bibb



# Selecting RP for Student Projects

RP can be an excellent way of creating complex and detailed prototype parts for student projects. However, RP should not be seen as the default option when prototyping. Students are frequently under the misapprehension that RP is the 'easy way' of prototyping and that little or no effort is required. This is not true and careful consideration needs to be given to whether RP is capable of meeting the physical demands of the prototype, whether RP is appropriate for the form and whether the cost is reasonable.

***Marks will be deducted from project work where RP has been used excessively, unnecessarily or inappropriately.*** You should only proceed with RP when you have the agreement of your project tutor. You should also discuss your prototyping requirements with the technical staff before requesting models.

## ***Shape and Size***

RP is not appropriate for the production of simple forms that may well be better bought in, machined, turned, fabricated or formed. RP should not be used for cylinders, blocks, gears, axles, pulleys, bushes fasteners and other simple components that can easily be bought in. RP costs are directly proportional to size. RP should not be used for large, bulky, thick sectioned or heavy parts. Large parts take up a disproportionate amount of the available build envelope and lead to excessive costs for students.

## ***Cost***

RP is very expensive for students and it should only be used where its benefits far outweigh those of alternative methods. It should also be used sparingly. Preferably, the design should be developed and refined as much as possible in CAD, and RP should be only used when the design is ready for detailed physical evaluation. Cost is calculated by volume (i.e. per cubic centimetre). You can predict the cost by getting the volume from the CAD model but make sure you read it correctly and get the decimal point in the right place!

## ***Physical Properties***

RP methods do not replicate the physical properties of manufactured parts. Strength, stiffness, wear resistance and creep are all typically poor when using RP. Think carefully about the physical demands of your prototype before selecting RP. Seek advice from staff if in doubt.

## ***Availability***

Although the Design School is fortunate to have access to the very best RP facilities, they have to be shared amongst a very large number of students and staff who all deserve equal access. Students must plan well in advance and recognise that RP parts will be built on a 'first come first served' basis and you will have to wait your turn. Also, remember that in final year, you will all be prototyping at the same time and therefore access will be increasingly congested.

We are fortunate to be able to access a wide variety of RP technologies in other Schools of the University but remember that in these circumstances you will not be their highest priority and that you will be relying on their good will to get your parts made. External suppliers can be used for RP but full commercial rates will be very expensive. External suppliers should only be used with the agreement of your project tutor.

***If in doubt about whether RP is appropriate contact Richard Bibb, [r.j.bibb@lboro.ac.uk](mailto:r.j.bibb@lboro.ac.uk)***

# Introduction to RP

'Rapid Prototyping' or **RP** is a phrase that was coined in the 1980s to describe new technologies that produce physical models directly from a 3D CAD. Many other phrases have been used over the years including solid freeform fabrication; layer additive manufacturing, 3D printing and advanced digital manufacturing. More recently, the umbrella term of 'Additive Manufacturing' or **AM** has been adopted to cover all of the technologies and applications. **RP** therefore is a sub-set of AM. Since the 1980s, RP has become an integral and effective tool in new product development and it is now considered standard practice in many industries.

This document describes the RP technologies available within the Design School or available to the Design School through collaboration with other Schools in the University.

Please always remember that not all of the facilities will be available all of the time and that costs will be incurred for materials and services in all cases. Students will also be expected to undertake all of the cleaning and finishing of RP parts.

## The Basics

All RP systems work in essentially the same manner. They take a 3D CAD model and physically reproduce it from a large number of discrete layers of material.

In order to go from 3D CAD to RP and intermediate file format is required. All RP technologies are able to accept a solid three-dimensional CAD model exported as an **STL file**, which has become standard in the RP industry. The RP software associated with each RP machine then slices the STL file into a large number of very thin cross-sections. The software then uses these cross-sections to generate the machine code instructions that enable the RP machine to physically create each cross section as a layer of the object. Usually the machine's build envelope, usually called the 'platform', will be filled with as many objects as possible before commencing with a build session. The instruction data for the whole build session is then loaded onto the RP machine and the machine will be prepared for a new build. The layers are constructed by the machine in sequence until the whole model is complete. Although the objects may take several hours to build, the machines operate unattended. Typically, a build will be started last thing in the working day and the machine will operate overnight. Often the build will be complete by the next morning.

The differences between the various types of RP machine depend on the material and method of producing the layers. All RP systems have some method of supporting the object during the build process, which will need to be removed when the part is complete. This may be using the same material as for the parts but is often a different material. All RP parts will require some form of manual post-process cleaning and finishing.

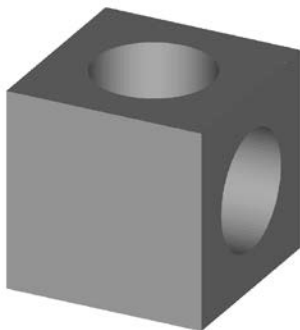
# Layer Manufacturing Description

RP systems work by creating models as a series of contours or slices built in sequence, often referred to as layer manufacturing. The different RP systems vary in how they create the layers and in what material.

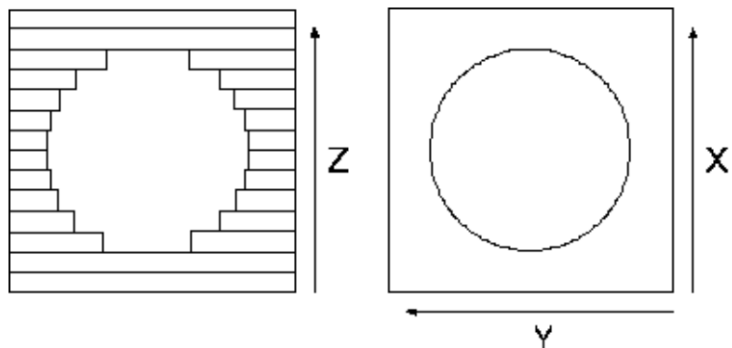
By convention, the axes X and Y represent the plane in which the layers are formed and the Z-axis is the build direction (usually referred to as height). Consequently, the number of layers required for a given object is a function of the layer thickness and height of the part. The layers are deposited or created in the X-Y plane by some form of precision controlled plotting or scanning mechanism. The accuracy and resolution in the X-Y plane is therefore dependent on this mechanism. Most RP systems are accurate to fractions of a millimetre so geometry in the X-Y plane should be faithfully reproduced.

The layer thickness is fixed by the process that adds the layers and may depend on the material being used. The layer thickness is usually in the order of 0.05 to 0.3 mm. This will lead to a stepped effect in geometry perpendicular to the XY plane.

As an example, consider a cube with two perpendicular holes through it, as shown in Figure 1. The hole in the top of the cube as viewed from above formed by the scanning mechanism in the X-Y plane will be formed perfectly (within the capability of the mechanism). However, the hole as seen from the side of the cube will be defined by the addition of layers and so it will show a stepped effect, as shown in Figure 2.



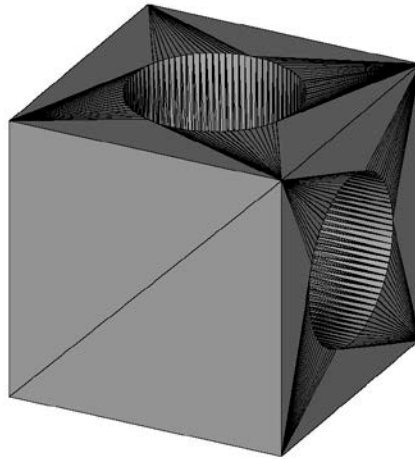
**Figure 1: Cube with circular holes**



**Figure 2: The stepped effect of layer manufacturing**

# STL Files

The STL file is a simple file format that describes an object's surface as a mesh of triangular facets. For example, if we view the object from figure 1 as an STL file we can see the triangles. It can be seen that large flat areas require few facets, but where the surface curves, more facets are required to closely approximate the original surface.



**Figure 3: Cube with circular holes showing the triangular facets**

The STL file is simply a list of each of the triangular facets, which make up the surface of a three dimensional model. Figure 4 shows the beginning and end of an STL file in text format (ASCII format). The first line describes the direction of the facet normal. This indicates which surface is the outside of the facet. The next three lines give the X-Y-Z co-ordinates of the three corners, or vertices, of the facet.

```
solid FILENAME
  facet normal 1.000000e+00 0.000000e+00 0.000000e+00
    outer loop
      vertex 0.000000e+00 -1.204845e+00 -1.658504e+00
      vertex 0.000000e+00 -1.235913e+00 -3.804270e+00
      vertex 0.000000e+00 -4.000000e+00
    endloop
  endfacet

and so on...

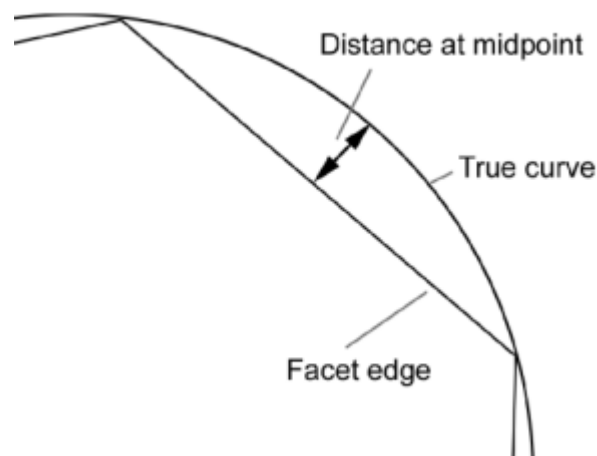
  facet normal 1.000000e+00 0.000000e+00 0.000000e+00
    outer loop
      vertex 1.000000e+00 4.000881e+00 1.221143e-04
      vertex 1.000000e+00 3.535500e+00 3.535500e+00
      vertex 1.000000e+00 3.999953e+00 0.000000e+00
    endloop
  endfacet
endsolid FILENAME
```

**Figure 4: The beginning and end of an STL file in text format**

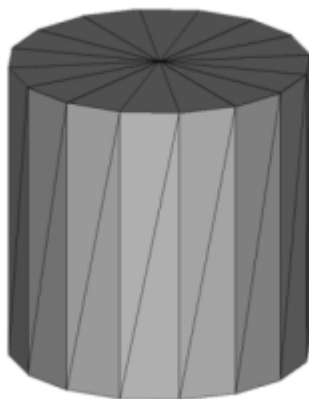
The simplicity of the STL file makes scaling and translation of STL files very straightforward. An STL file can be scaled up or down, rotated or mirrored using RP software during the build preparation stage. STL files can be generated from virtually all 3D CAD packages. Solid modelling CAD packages such as Creo and SolidWorks rarely have problems creating valid STL

files. However, much more care is needed when using surfacing features or when using surface modelling software such as Rhino. The surfaces must all be properly stitched and trimmed. To be valid there must be no holes or gaps in the mesh.

As the STL file is only a faceted approximation of the CAD model, the software that generates the STL file will apply a resolution or tolerance to the file. This is normally done by specifying a maximum deviation. The deviation will be the perpendicular distance between a facet and the original CAD data where the facet forms a chord at a curved surface, as shown in Figure 5. In essence, a smaller deviation will give a more accurate representation of the CAD model, but this will result in an STL file with a greater number of smaller facets. The file size depends only upon the number of facets and so a smaller deviation will give rise to a larger file. In practice a compromise will be needed between a high quality surface and file size as illustrated in figure 6. Most CAD packages allow you to inspect the faceted model before exporting the STL file. Typically, files should not need to be more than a few MB.



**Figure 5: Facet deviation**



Large deviation = small file



Small deviation = large file

**Figure 6: The affect of deviation settings**

Although STL files can be in binary or text (ASCII) format, binary format files are much smaller and should always be used. Highly complex parts may result in STL files too large to email. In which case USB memory can be used or compression software is freely available that can compress an STL file to a small fraction of its normal size.

# STL File Export

## Creo

To export an STL file from Creo select **Save a copy...**, and then under file type select **STL [\* .stl]**

If you are dealing with multiple parts and you want the STL files to retain their positional relationship to each other then remember to generate the STL files from the **Assembly** and make sure you select **All Parts** or **Include** to select the parts required. When outputting from an assembly in Creo, you also need to pick the coordinate system (from the history tree); otherwise, it exports the parts as one shell, which cannot then be disassembled at the Objet machine for multiple materials.

Always select “Binary” and click on **Apply**, you can then see a preview of the faceting that will result. This could be too large as shown in figure 7 below.

Then reduce the **Chord Height** to a very small number (something like 0.0001) then click **Apply**. The number will change to the lowest value possible. Click on **Apply** again to see the result as shown in figure 8 below. Click **OK** to export the STL file. If your STL file turns out to be very large, then try again with a larger Chord Height number until you reach a sensible compromise between file size and faceting.

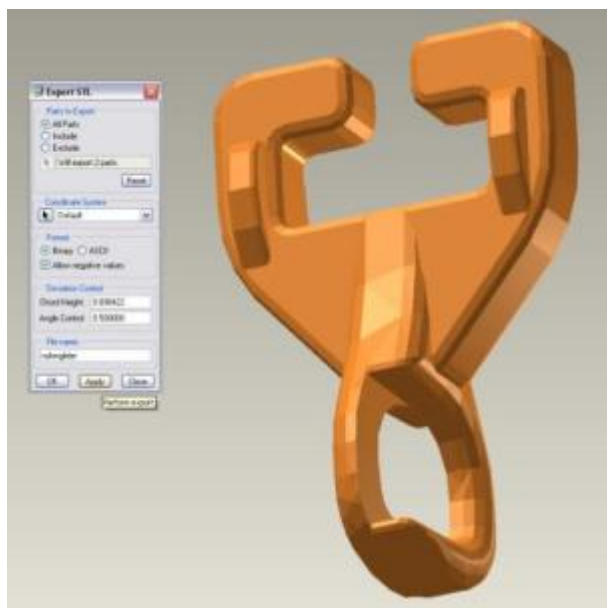


Figure 7: Highly faceted STL file preview

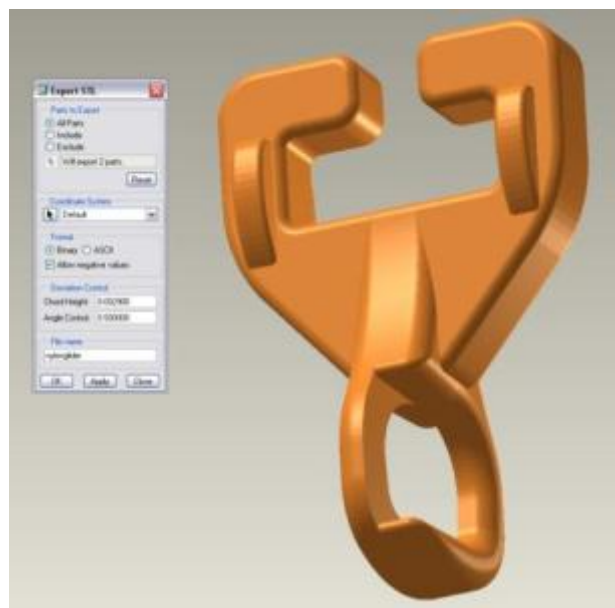
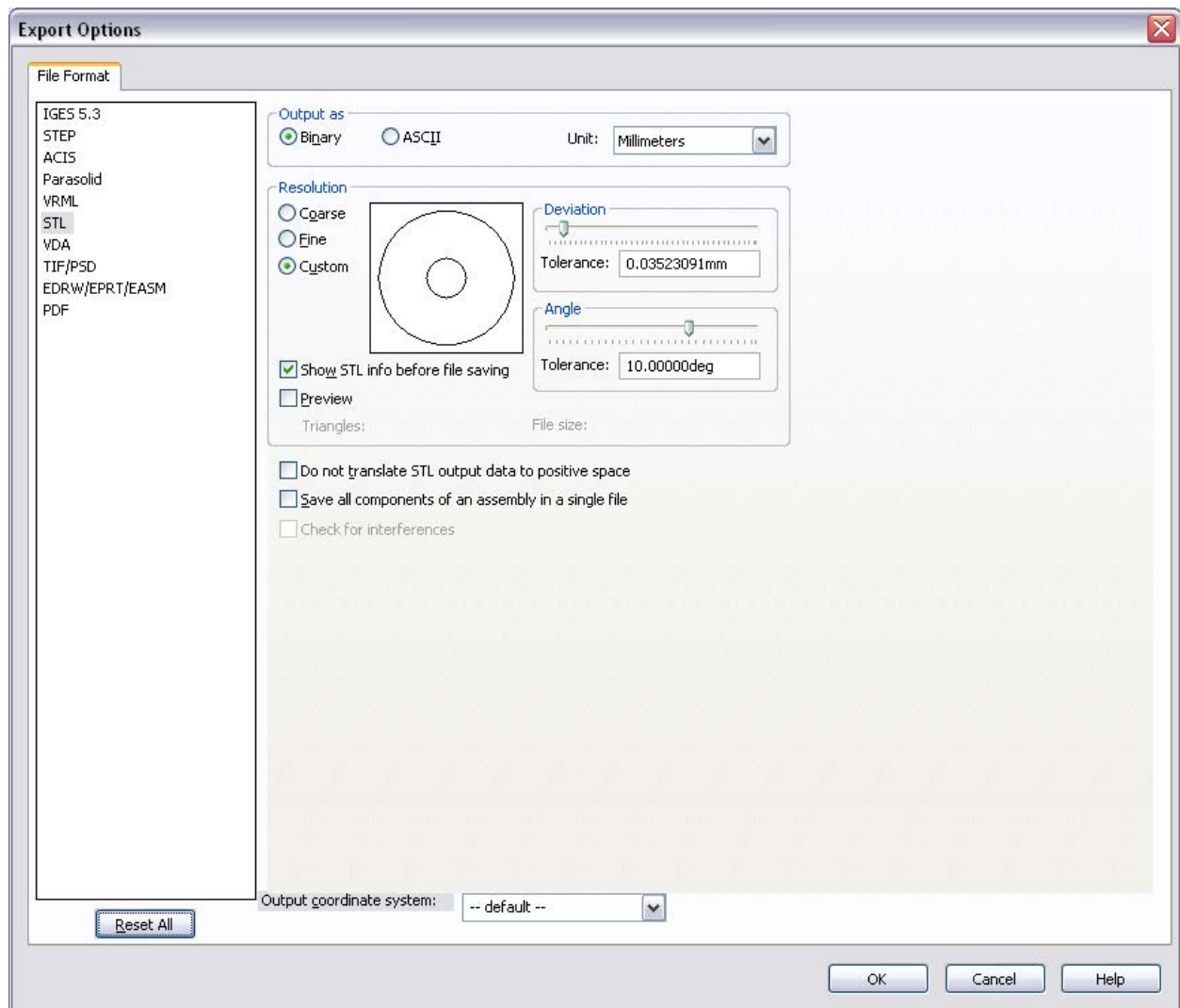


Figure 8: Smoother STL file preview

## SolidWorks

To export an STL file choose **Save As** and set save as type to **STL**; click the **Options** button to change the default settings.



Solidworks allows default **Fine**, **Coarse** and **Custom** settings. Deviation is the same as in Pro-Engineer **Deviation** (same as Chord Height) with **Angle** control being the same.

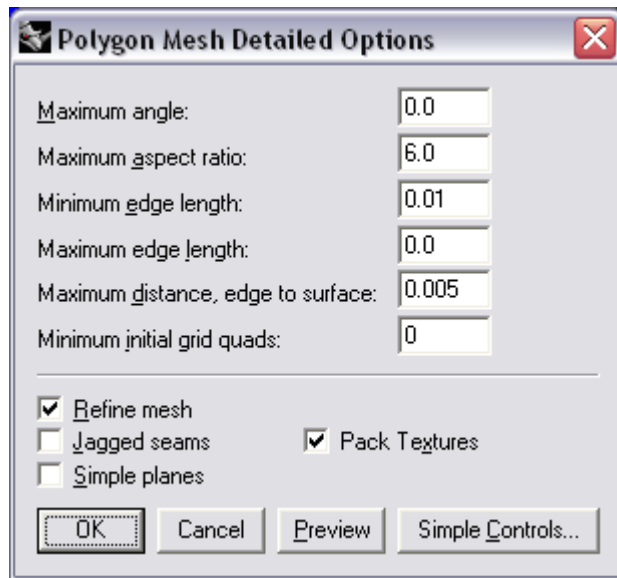
If you are outputting an assembly, you can check “**Save all components of an assembly in a single file**”. This will output all of the parts (unless they are suppressed) with the same origin point – this is necessary for multiple material parts to be made on the Objet Connex 500 machine.

Click on **OK** to give a preview of the file before saving.



## Rhino

To export an STL file choose **Save As** and set save as type to STL



Rhino shows a dialog box to allow you to fine-tune the output file. The only values that may need changing are **Maximum angle** (same as angle control in Pro-Engineer) and **Maximum distance, edge to surface** (same as Chord Height in Pro-Engineer). It is recommended that you just accept the defaults. Select preview to show the outputted file.

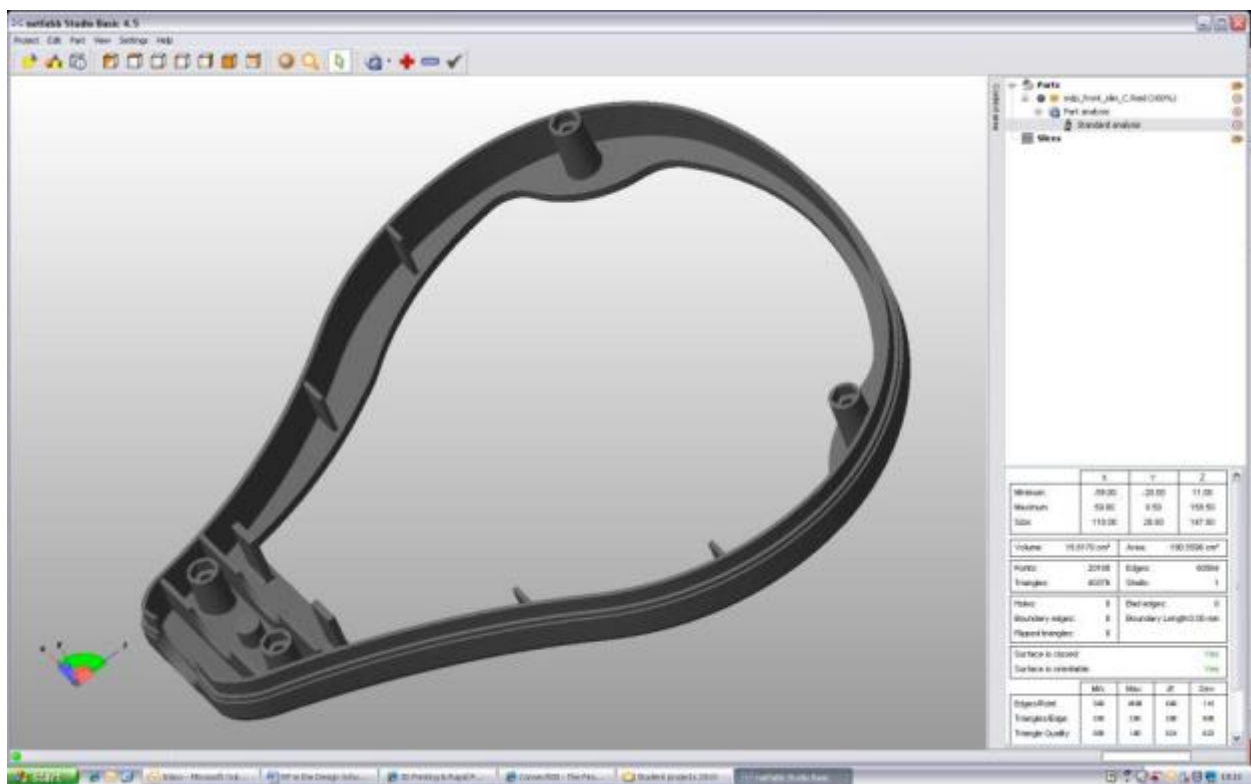
If you need to output as an assembly (for multiple material parts on the Objet Connex 500 machine), you need to make sure that the separate meshes are not joined. Click on each mesh to make sure only that one highlights, if it does not then use the explode command.

It is a good idea to check STL files from Rhino before submitting the files for building (see next section).

# STL File checking

Free, downloadable software is available that will enable STL files to be checked, reoriented, scaled or even fix minor defects. This kind of software is useful for checking the volume of part; which will help you calculate the material costs. MiniMagics enables you to check an STL file and compress it. Netfabb for example will enable you to check the validity of your STL files. It will enable you to reorient them, for example to rotate long thin parts so that they lie flat on the machine platform. It will also enable you to scale parts very accurately. This can be very useful if you are using your RP part as a master pattern for casting or moulding for example by scaling up the RP pattern to compensate for the typical shrinkage expected of the casting. The software also enables you to cut an STL file into parts. This may be required to cut a long part into pieces that fit on the machine platform or to cut off parts of a model that can be made more quickly using other means.

Whilst software like Netfabb cannot make a good STL file from a bad one it can fix minor problems such as very small gaps in the mesh or disoriented facets. It can also be used to check you have the correct number of shells when using multiple materials on the Objet Connex 500 machine (see below for more details).



Links <http://www.netfabb.com/>  
<http://www.materialise.com/MiniMagics>

## Dimension 1200 SST



### Principle

Thermoplastic material is fed in filament form to a heated extrusion head. The layers are made by molten material deposited as a fine bead. The build table lowers an exact amount and the next layer is deposited on to the previous layer bonding due to partial melting. The part is supported by a second thermoplastic material that is soluble enabling easy removal.

### Detail

Parts are made by extruding ABS through a heated nozzle. The nozzle moves in the X and Y-axes to draw layers. Thick sections can be made hollow with a scaffold like supporting structure inside to reduce material consumption and speed up the build process. Once a layer is complete, the build table lowers by a layer thickness and the next layer is produced.

The layer thickness is 0.33 mm and the build envelope is approximately 250 mm x 250 mm by 250 mm. Parts are built onto a removable plastic platform (see image above). Supports for overhangs are built concurrently with the part and are removed when the part is complete. The build material ivory ABS+, fed in the form of a filament from a spool. The support material is a black, soluble plastic. The supports can be clearly seen on the parts in the image above. Supports are removed by placing the parts in a tank of water mixed with a special detergent. It may take several hours to dissolve all supports completely. Once the supports have completely dissolved, the parts can be dried and used.

The parts produced can be handled directly and require no special cleaning or curing. The physical properties are reasonable and thick sections (2 mm and above) will prove quite tough and flexible. Thin walls however will be very weak and tend to split along the layers. When prototyping injection moulded parts, a thicker wall is required.

The parts can be finished to a good standard with abrasive papers but may benefit from a thin coat of filler-primer to be sanded back to a good finish before painting.

<b>Advantages</b>	Reliable Clean and safe process Strong, durable plastic parts Soluble supports Comparatively reasonable costs
<b>Disadvantages</b>	Weak thin walls Surface finish less good than some RP processes Small features difficult
<b>Cost</b>	£1.00 per cubic centimetre
<b>Location</b>	LDS012 Design School
<b>Contact</b>	Phil Dixon <a href="mailto:P.R.G.Dixon@lboro.ac.uk">P.R.G.Dixon@lboro.ac.uk</a>
<b>Links</b>	<a href="http://www.dimensionprinting.com/default.aspx">http://www.dimensionprinting.com/default.aspx</a>

# Objet Connex 500



## Principle

Multiple build materials are deposited discretely by jetting heads. The material is ejected as a liquid, which is subsequently cured to solid using UV lamps. The jetting head moves in X and Y-axes to build the layers. The build platform lowers by a layer thickness and material is deposited on to the previous layer.

## Detail

This very advanced RP machine is one of the most sophisticated RP machines available. The jetting heads can deposit three different materials, two different build materials and a support material. The build materials are acrylate based resins that cure under UV light to form plastics. One of the build materials is usually a rigid transparent plastic material. The second build material is a soft, flexible plastic with rubber like properties, which is transparent. The unique capability of this RP machine is the ability to deposit mixtures of the two build materials to produce a variety of physical properties ranging from very soft and flexible through to completely rigid. Objet refer to the intermediate mixtures as 'Digital Materials' and there may be as many as 11 different options available. Typically, this is seen when mixing the rigid and soft materials. This enables not only a variety of physical properties but different parts of the same model can be in different materials, for example to replicate an over-moulded product. The support material remains in a gel form that can be easily scraped or brushed away but for the best results the supports should be removed by pressure washing with water (available in the workshops). Bear in mind narrow channels or small holes may need extra care to clear of support material. Small parts should be washed by hand.

The platform is large at 500 x 400 x 200 mm. The layer thickness of the machine is very thin, typically 0.03 mm, which provides an excellent surface finish (although finishing and painting will still be required). Soft, flexible parts cannot be painted.

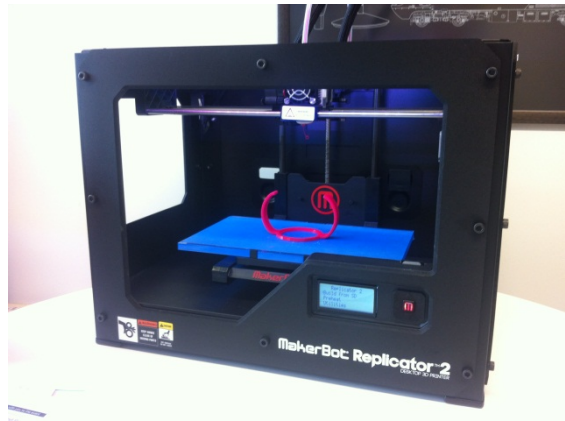
If you wish to have multiple materials in one RP model then the STL file export requires additional steps. You either need a single STL file that includes multiple shells; one shell for each material, or multiple STL files, one of each material component. In order to achieve this, each separate material region must be modelled as a separate CAD part in an assembly. You must remember to export the STL files at the same time; otherwise, they will lose their

positional relationship with each other. The parts must all be touching otherwise there will be gaps between the materials and they may come apart.

Due to the increased complexity and CAD requirements, you should discuss your requirements with Phil Dixon before submitting your STL files.

<b>Advantages</b>	Very accurate, very good surface finish A range of physical properties Multiple materials in one part
<b>Disadvantages</b>	Very expensive Added CAD complexity for multiple material parts
<b>Cost</b>	£1.50 per cubic centimetre
<b>Location</b>	LDS012 Design School
<b>Contact</b>	Phil Dixon <a href="mailto:P.R.G.Dixon@lboro.ac.uk">P.R.G.Dixon@lboro.ac.uk</a>
<b>Links</b>	<a href="http://www.objet.com/3D-Printer/Connex500/">http://www.objet.com/3D-Printer/Connex500/</a>

# Low costs 3D Printing



The Design School has a number of low cost FDM-style 3D Printers. These are Makerbot Replicator 2 machines and extrude plastic in a similar manner to the Dimension machine. However, the machines are basic and the parts produced are not of the same quality. Supports are made from the build material and have to be removed by hand. Finishing is also more difficult. However, materials are very tough and costs are very low and the process is ideal for early models and basic mechanical and functional prototypes.

It is hoped that these machines will be available to students to use themselves but at the moment access is via staff. If you want to use one of these machines please contact Guy Bingham or Richard Bibb (do not ask Phil Dixon for access to these machines).

## Advantages

- Fast
- Tough parts
- Very cheap
- Several colours

## Disadvantages

- Comparatively low resolution
- Comparatively low accuracy
- Difficult to finish to a high standard

## Cost

about 30 pence per cc – or buy your own spool (~£40 per Kg)

## Location

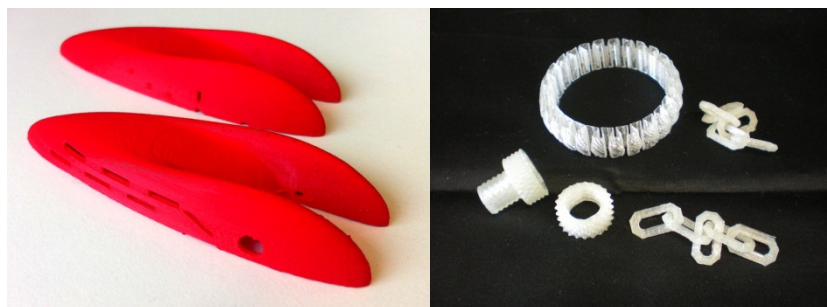
Design School

## Contact

Richard Bibb [r.j.bibb@lboro.ac.uk](mailto:r.j.bibb@lboro.ac.uk)  
Guy Bingham [g.a.bingham@lboro.ac.uk](mailto:g.a.bingham@lboro.ac.uk)

## Links

<http://store.makerbot.com/replicator2.html>

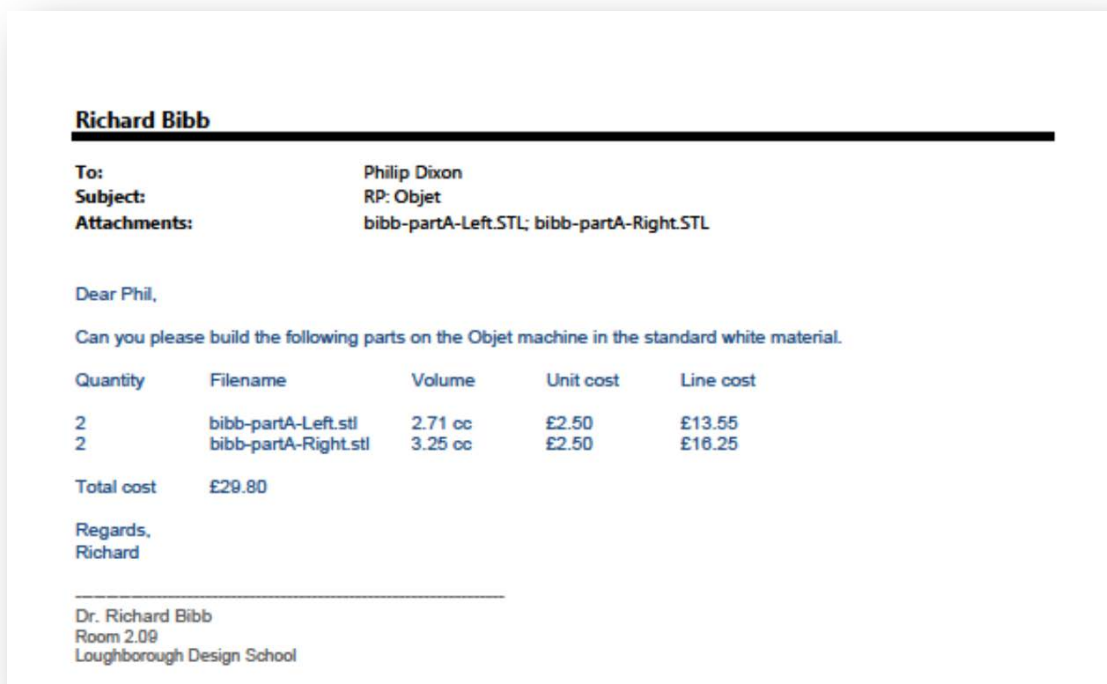


# Process for Ordering RP Parts in the Design School

Before requesting RP parts in the Design School, you must make sure that your supervisor has approved it and that you have sought advice from Phil Dixon, Richard Bibb, Ian Campbell or Guy Bingham if necessary. Remember, making unnecessary RP parts costs you money but also wastes staff time and monopolises the machine capacity preventing use by other students. Plan your prototyping carefully and make best use of the facilities. Check your CAD thoroughly before committing the files to RP.

Remember there will be a queue and builds will be scheduled according to machine and material so you must allow plenty of time for RP parts to be made. The RP machines will become extremely busy so plan ahead. To ensure smooth operation you must adhere to the procedure below. Your email requesting parts forms your order. All orders must be paid for at the point of order.

1. STL files to be submitted by attachment to an email to Phil Dixon [P.R.G.Dixon@lboro.ac.uk](mailto:P.R.G.Dixon@lboro.ac.uk)
2. Files must be email attachments – do not use Dropbox or similar links; files should typically be less than 10MB, larger files may prove impossible to build; do not compress or zip STL files
3. Use separate emails for each machine; do not add parts for both the Connex and the Dimension on the same email; use separate emails for transparent Objet parts
4. List parts by quantity, filename, volume and cost – see the example below
5. State the total price
6. Parts must be paid for at Stores to Alan Hopewell
7. Completed parts are to be collected from Phil Dixon's office (LDS.0.08) upon proof of payment
8. Transparent parts will be done in batches and will require more notice.





# RP Processes Available in Loughborough University

Before approaching any other School for RP parts, you must check that your parts are appropriate for the process with your project tutor, Richard Bibb, Guy Bingham or Ian Campbell.

## Stereolithography (SLA)

SLA machines are precise and expensive and produce accurate parts in plastic-like materials. Parts are made by curing a photopolymer liquid resin to solid using a UV laser. The unused material remains liquid so there is little waste. Parts are built onto a platform that lowers by a layer thickness after each layer is drawn by the laser and then a recoater blade will pass over the liquid levelling the resin but also removing any bubbles or debris from the resin surface. This method also means that there are problems with building objects with trapped volumes as the liquid in these areas is not in communication with the resin in the vat and does not level out. Overhanging or unconnected areas have to be supported. Scaffold style supports are generated by the build software and built concurrently with the part. When a part is complete, the excess liquid resin is washed off using a solvent and the supports removed. It is then post-cured in a special UV oven to ensure it is completely solidified. Dimensional accuracy should be very good and the layer thickness used is typically 0.15 mm. SLA machines come in a range of sizes but the machine in the AMRG has a build envelope of 250 mm x 250 mm by 250 mm.

<b>Advantages</b>	Well established technology in widespread use Very accurate, good surface finish A range of materials available Transparent parts possible
<b>Disadvantages</b>	Expensive Trapped volumes cause problems
<b>Location</b>	Additive Manufacturing Research Group Wolfson School of Mechanical & Manufacturing Engineering
<b>Cost</b>	£1.85 per cc (paid by credit card)
<b>Contact</b>	David Thompson <a href="mailto:D.A.Thompson@lboro.ac.uk">D.A.Thompson@lboro.ac.uk</a>
<b>Links</b>	<a href="http://www.lboro.ac.uk/research/amrg/about/facilities.html">http://www.lboro.ac.uk/research/amrg/about/facilities.html</a> <a href="http://www.3dsystems.com">www.3dsystems.com</a>



## Selective Laser Sintering (SLS)

SLS machines are very expensive and require a great deal of infrastructure. SLS Parts are made by selectively sintering thermoplastic powder material to solid using a hot laser. The material is heated to near its melting point and the laser locally heats the powder fusing the particles together to form a solid layer. The build platform lowers each layer and fresh powder is spread across the build area by a roller. When the next layer is formed, it is also fused to the previous layer. The inherent dangers of handling powders are controlled by purging the build volume with nitrogen gas. Models are supported by the unused powder. Build times are comparatively slow to allow for the machine to heat up to operating temperature and then cool down after the build session is complete. SLS machines typically use white nylon or glass-filled nylon, resulting in relatively strong, robust parts. Surface finish is reasonable but slightly rough and porous as might be expected from a powder and dimensional accuracy good as SLA. The AMRG have two SLS machines with a relatively large capacity. SLS machines are typically only operated when there is enough parts to fill the build volume.

Our masters students have had a good service from 3D Print UK and their pricing structure makes estimating costs and sharing costs with fellow students possible

<http://www.3dprint-uk.co.uk/>

### Advantages

- Tough, rigid parts
- Reasonably accurate
- No supports to remove

### Disadvantages

- Expensive
- Long set up and cool down times
- Porous surface needs sealing and filling to take paint

### Location

Additive Manufacturing Research Group  
Wolfson School of Mechanical & Manufacturing Engineering

### Cost

£1.85 per cc (paid by credit card)

### Contact

David Thompson [D.A.Thompson@lboro.ac.uk](mailto:D.A.Thompson@lboro.ac.uk)

### Links

<http://www.lboro.ac.uk/research/amrg/about/facilities.html>  
[www.3dsystems.com/](http://www.3dsystems.com/)  
[www.eos-gmbh.de/](http://www.eos-gmbh.de/)



## Z Corp – Powder bed 3D Printing

Z-Corp 3D Printing machines work by using ink jet printers to print adhesives into layers of powder to produce solid models. The machines are now made by 3D Systems. The machines are comparatively inexpensive and the material costs are cheap. The accuracy and surface finish are not as good as most other RP processes but the advantage is that the process is extremely fast and the parts are cheap. The finished models are delicate but can be strengthened by painting or infiltrating them with adhesive or resin based hardeners. The parts are supported during building by the unused powder. As the machines typically use white powders and standard inkjet print heads, it is possible to use coloured binders. This enables fully coloured models to be built. Using coloured binders is slower and more expensive but can produce interesting advantages. For example, multiple components in assemblies can be identified by colour and the results of finite element analyses can be indicted on physical models. 3D printing should be seen more as a block modelling process and the parts do not exhibit sufficient strength or accuracy for functional prototyping. They could be suitable for concept evaluation, block models, handles or other ergonomic models. There are 3D printers available in several Loughborough Schools but the easiest to access is in the School of the Arts.

<b>Advantages</b>	Very fast build times Cheap parts Full colour capability
<b>Disadvantages</b>	Poor accuracy and surface finish Poor physical properties Limited application
<b>Cost</b>	£0.30 per cubic centimetre
<b>Location</b>	School of the Arts
<b>Contact</b>	Ben Dolman <a href="mailto:B.Dolman@lboro.ac.uk">B.Dolman@lboro.ac.uk</a>
<b>Links</b>	<a href="http://www.3dsystems.com">www.3dsystems.com</a>

