# DESIGN DATA ISSUES FOR THE CONTROL OF MEGA-SCALE RAPID MANUFACTURING

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## *Abstract*

Construction has traditionally relied on specifications and 2D drawings to convey material properties, performance details and location information. The use of advanced 3D solid modelling and digital fabrication methods are enabling the construction of Iconic buildings with an emphasis on the visual design of form. The integration of function with structure, however, has not yet been realised. Rapid manufacturing technologies are able to create physical objects directly from 3D solid modelling data by computer controlled additive processes. Components can be produced with any geometric form and can add further value through integrating function. Large scale versions of these processes are now being investigated for construction applications and an important aspect of these machines are the build instructions. These are created in a series of discrete steps from the design concept, encapsulated in the digital model, through to the machine code instructions. The use of the language used to describe precision, accuracy, tolerance, resolution and minimum feature size are blurred by the use of manufacturing based processes applied to create a new type of construction. This paper explores these issues and offers definitions of these terms in relation to mega-scale freeform fabrication processes for construction.

***Keywords:*** Freeform Construction, Rapid Manufacturing, Digital Fabrication, Resolution, CAD, 3D modelling

# 1. Introduction

In the manufacturing sector, automation using industrial robots and machines that used direct numerical control took hold in the 1960s. The development of microprocessors delivered computer numerical control in the 1970s and the computer revolution in the 1980s brought computer aided design software. In the 1990s with the advancement of CAD and the increasing power of low-end computer systems, Virtual Reality software products became viable. At the same time, advanced parametric modelling was introduced and the industry has enjoyed the development of the integration of design and analysis tools and machine control. Computer Aided Manufacturing (CAM) is being used today to create components for buildings (Howe 2000, Kolarevic 2003, Schodek et al. 2005, Whyte 2002).

Rapid Manufacturing machines are sub set of the CNC family and they can also utilise digital model information. These processes build components by selectively adding material rather than the traditional subtractive or formative processes. The most recent developments in the technology relate to scaling up these Rapid Manufacturing processes so that whole building components or structures can be built using a mega scale, additive machines. The Building Information Model could be used to drive these processes. The mega-scale concept has been coined 'Freeform Construction,' but it is a new concept who's definition has not yet been fully established. Loosely, it can be described as the application of layer based processes for creating large components for construction applications.

Freeform Construction as a concept has (at most) been evident since 1997, with Pegna's paper on the selective masking of layered sand and cement to produce a 3D form (Pegna 1997). The work was not continued. In the early part of 2000, Berokh Khoshnevis contributed the next informative step developing a process called Contour Crafting; a layer based process that improved the surface finish of objects constructed using extrusion. A key realisation was that extrusion is scalable and can be used with many materials. This work generated radical concepts for house building and the possibility of building on Mars (Khoshnevis et al. 2006). Continuing the development, the UK government has funded a four year project at Loughborough University to develop a new Freeform construction process based on material deposition by printing (Buswell et al. 2007). The work is highlighting issues relating to the description of the quality measures used in the manufacturing and construction environments for this application. This paper explores these issues and defines terms where necessary.

## 2. Selectivity and Deposition

A great many layer based manufacturing processes rely on some way of selecting material to be solid or not at any particular location on each layer of the build. This 'selectivity' can be generated by controlling the location of the deposition of the build material; or, given a 'sheet-like layer' of material, control the activation of material phase change at any given location. When the material is delivered via bed of powder or a vat of liquid, the selectivity is derived from the process of initiating phase change to a solid. When extrusion or printing is employed, the selectivity comes from the actual placement of the material. In both cases the actual solidification process is secondary, usually by chemical curing or by thermal cooling. Mega scale processes are unlikely to employ vat/bed techniques and so this paper focuses on extrusion and printing using pastes that chemically cure.

## 3. Design Information to Build Instructions

Figure 1 depicts the process for the creation of objects through Rapid Manufacturing techniques. The design concept is entered into the CAD environment, which for successful builds must be a 3D solid modeller, either CSG or B-rep. The modeller must be a manifold modeller (Chang, Wysk & Wang H-P 2006). This criteria ensures that the model can be unambiguously sliced. Standard functions can be used to generate and STL file which is a faceted surface representation of the model. The generation of this file is not consistently flawless. The conversion is sensitive to the way in which CAD model has been generated (even if a manifold modeller has been used).

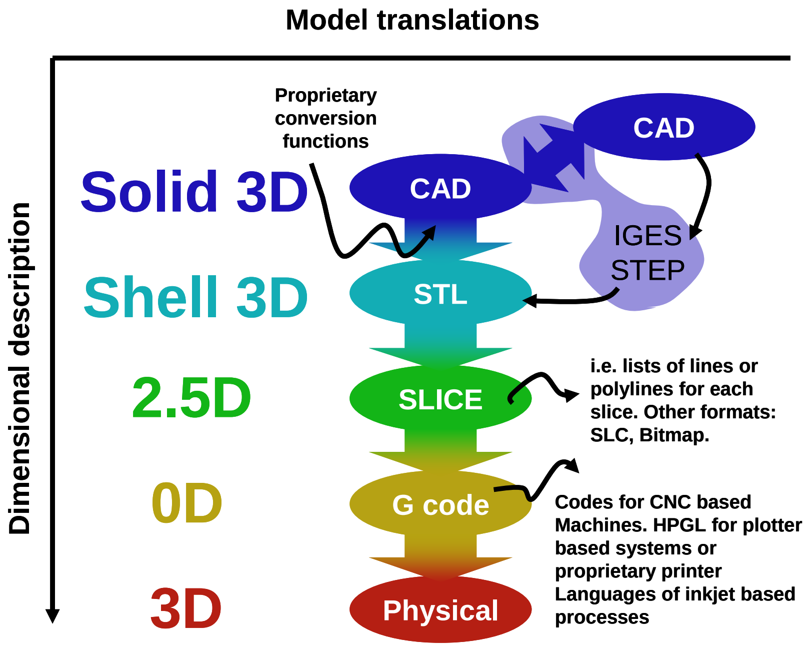


**Figure 1: Steps in producing an artefact using RM processes.**

Depending on the Rapid Manufacturing process employed, the STL file is then processed by RM machine dependant software (although there are alternatives (Jacob, G. G. K., Fai & Mai 1999)). This software adds temporary support structures to aid the build process (support overhanging parts of the build). The whole structure is then sliced into thickness' according to the specific process parameters (Fadel, Kirschman 1996). Each slice is then considered to be 2D a layer and the machine code that controls the process is calculated from contours that are created on each layer. The codes then are converted to machine operations. There is usually some post processing required such as removing the temporary support structures. The artefact is then complete.

The tessellation and slicing operation introduce approximations and errors. These are issues are discussed in a number of publications (Chang, Wysk & Wang H-P 2006, Fadel, Kirschman 1996, Jacob, G. G. K., Fai & Mai 1999, Jamieson, Hacker 1995, Shi et al. 2004, Tata et al. 1998). A number of articles have focussed on issues on the inherent problem that building models in slices has in limiting surface quality (Koc 2004, Kumar, Choudhury 2005, Lee, Sachs & Cima 1995, Pandey, Reddy & Dhande 2003, Sabourin, Houser & Bohn 1996).

Ultimately the slice data must be converted into a sequential set of commands that instruct a machine to carry out certain operations. This is commonly achieved through standard NC commands called 'G-code,' derived from the encoding of manual operations in order to machine a component using cutting, milling and drilling techniques (Benhabib 2003). These define the speed, trajectory of motion, the *tool path*, and the selection of the specific tool to be used. Ancillary operations such as turning coolant on and off are supported. These commands are executed in series and so the support of multiple simultaneous operations is prohibited. The generation of the codes is now automated through CAM software.

To generate the G-code the STL B-Rep model is sliced in to planes and sequential lists of vectors are produced that defined by the intersection of the plane and the boundaries described by the B-Rep. When these are listed counter-clockwise, everything on the inside is solid and vise-versa. The tool path is generated specific to the process and is often optimised to reduce machine time. The processes generally trace the surface of the plane in a sequential order to identify where the solid/non-solid boundaries are. There are many publications of the generation of these paths of which, (Qiu et al. 2001, Qu 2006), are a two.

The CNC/G-code approach lends itself to the SLS and SLA type processes. Extrusion based processes such as FDM and Contour Crafting can be run on g-code or using plotter codes such as HP-GL. The movement commands in *x* and *y*, are issues in a sequential way, similar to G-code. The ‘pen up/pen down’ commands initial and terminate material deposition. The *z* command is incremented once the plotter paths for a given layer is complete.

Some RM processes utilise inkjet printer technology; the Z-corporation and Thermojet processes are two. Standard printer heads are purged of ink and filled with either a binder or wax for the named cases. This utilisation of the ‘drop-on-demand’ (Gregory 1991) technology uses alternatives to the traditional g-code approaches. The translation of the sliced STL to print commands is achieved via an algorithm in the printer controller. solid/non-solid B-Rep is converted into pixelated data that governs when a particular jet in the printer fires in relation to the motion of the head. This slice data is a monochrome bitmap, i.e. there is either ink or not, or, the location on a given layer is either solid or not.

# 4. Build Quality Measures

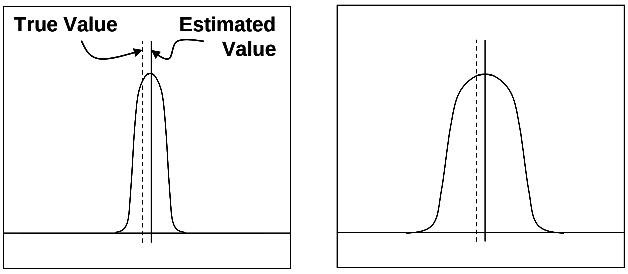
Build quality measures are important so that a desired specification can be stated and the completed work measured against it. The terms Precision, Accuracy, Tolerance, Build Errors Resolution and Minimum Feature Size all have a place as quality measures. These become ambiguous when traditional notions of construction tolerance are used to describe the quality of components produced through layer based manufacturing. These terms are defined here either from the literature, or discussed in terms of their relation to the information translation process and the resultant components made through Mega-Scale freeform construction techniques.

## 4.1 Accuracy, Precision and Tolerance

Accuracy is the closeness of a measurement to the *true value*, whereas the precision is a measure of the uncertainty associated with the measurement itself. These relationships are depicted in Figure 2.

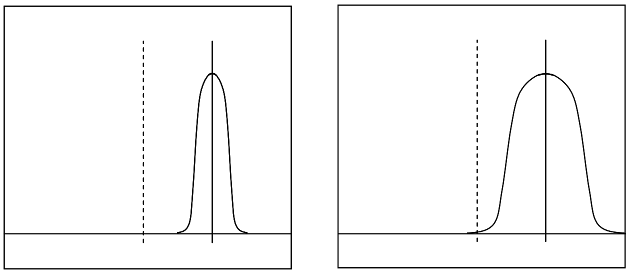
The translation of thought based concept into a digitally represented version will contain some compromise. This study, however, considers the digitally represented design to be a both precise and accurate representation of the geometry of the object to be built. Measurement of the geometry of built object can also be both accurate and precise. The precision of the built part can be evaluated against a level of manufacturing (or build) tolerance. This tolerance is an implicit function of the build process.

The influences of tolerance of various stages of the manufacturing or construction process are typically associated with the machine parameters and the material. An extrusion device use to make bricks of a certain size, which will allow for shrinkage. The bricks are produced with a dimensional tolerance of 2-3mm. These are then used to create a wall that has tolerances for line, plumb and flatness as well as possible aesthetic measures for fair-faced work. A mortar bed is used to account for the 2-3mm variations in the unit dimensions. There is a difference in the manufacturing tolerance of the unit and the build tolerance of the wall.



precise, accurate

imprecise, accurate



precise, inaccurate

imprecise, inaccurate

**Figure 2: Accuracy and Precision in Measurements.**

Layer based manufacturing machines operate within certain parameters, which are maintained so that the build information (the G-code) can be executed to deliver a geometry, manufactured within an acceptable tolerance. Factors affecting the precision of the machine operations are:

- The accuracy and precision of the selectivity process which is influenced by positioning and material handling mechanisms (mechanical systems);
- the selection of the build material phase change/deposition characteristics (layer level operations);
- build process characteristics, i.e. thermal distortion (volume level operations);
- Post process operations, i.e. scaffold removal (component finishing).

The degree to which the end component represents the original digital geometry is the degree to which the geometry has been resolved. This is can be described in terms of the build *resolution*, discussed in the next section.

## 4.2 Resolution

The term ‘resolution’ can be ambiguous because it describes degree to which one thing is represented and hence is not absolute, but referential. CRT displays refer to the number of lines of phosphor dots on the display as the resolution of that display, whereas a LCD display has an array of pixels (picture elements) to display an image. A digitally stored image is described using pixelated data which refers to the number of pieces of image data. Printers use dots per inch (dpi) or pixels per inch (ppi). The higher the dpi, the more accurately the image is reproduced. These terms are not strictly interchangeable; for example, if the image is 200ppi and is printed using a 720dpi printer. These applications are all 2D and given analogue data, the higher the resolution of; a) the quantisation process; and b) the number of cells to redisplay the information; the higher the resolution, or the closer the image represents the original data. 3D images can be described by the voxel (volumetric pixel) and hence a similar definition of resolution applied.

The layer based manufacturing process is an interesting case because: The build instructions are created from data based on sequential planes intersecting a B-Rep model that is a tessellated representation of ‘analogue’ geometry (albeit described digitally); and the layering process introduces two different resolution parameters (one in the dimensions of *x* and *y* and one for *z*). The difference between extrusion and printing based processes also introduce subtle differences in the definition.

Each stage in the production of the machine instructions introduces different levels of resolution when referenced to the original model. The resolution of the tessellated B-Rep model is controlled by algorithm parameters that govern the size and number of the triangular facets and the degree to which the lie on the component surface. Figure 3 demonstrates clearly that the smaller the triangle, the closer the representation to the surface of the sphere.

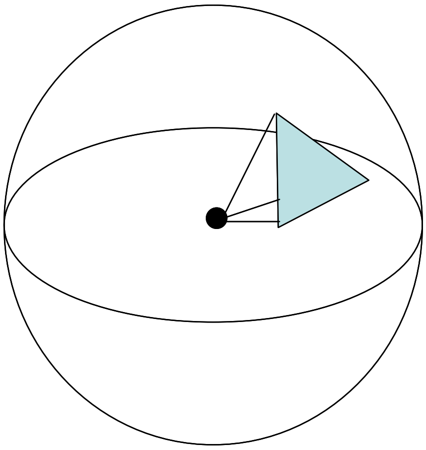


**Figure 3: Depiction of facet size and surface resolution.**

The resolution is also affected by the slicing operations on that STL file. The resolution in terms of the minimum feature size that can be created in the z-direction is dependant on the layer thickness (Δz); Figure 4a. Importantly, although this is technically the minimum feature size that can be created in z, it may not be the minimum feature that can be resolved fully, because the desired feature may not synchronise perfectly with the slice layer. Hence the minimum feature size that a process is capable of producing is in fact dependent on a definition of resolution. The larger the feature size it compared to the minimum (Δz), the higher the build resolution; Figure 4b.

The reproduction of a surface parallel to z can be achieved to a resolution that is only dictated by the material a selectivity parameters. In fact the resolution would probably be more likely to be described in terms of tolerance on the surface finish; Figure 4c. The problem is exacerbated when a non-parallel surface needs to produced; Figure 4d. This means that for any object, especially those with curved surfaces, the orientation in the build chamber will affect the errors and hence the achievable resolution. In addition, this degree of resolution will change over the surface area of the part.

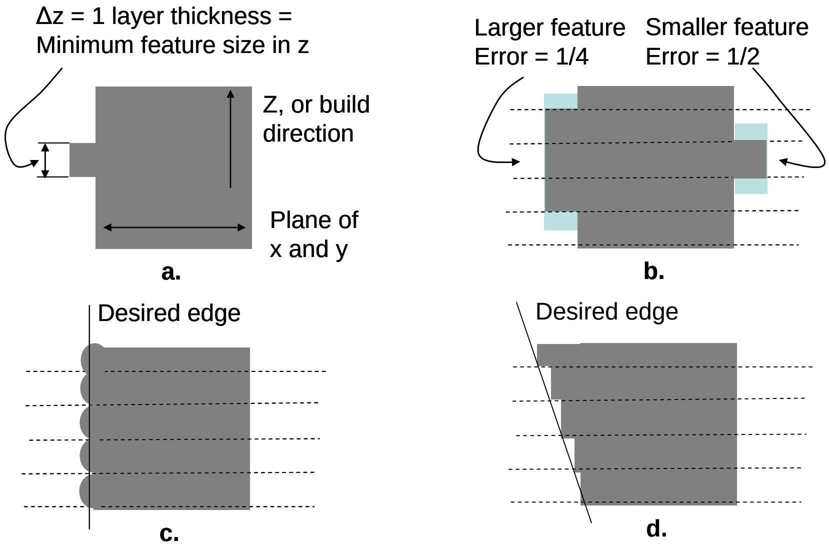


**Figure 4: Resolution issues in *z*.**

The resolution of the detail in *x* and *y* and the minimum feature size is only governed by the precision of the material selectivity or deposition process and the solidification properties of the material. The discretisation of the build operations by plane and the interdependence of the geometry orientation means that a single build resolution cannot be simpley stated for layer manufacturing processes.

## 5. Conclusions

In terms of construction, the description of the quality of a build from a mega-scale rapid manufacturing machine will relate to the exterior reproduction of surface form and the interior reproduction for the desired geometry for function (i.e. maximising thermal resistance and minimising volume of material while satisfying loading requirements). The quality measures could be:

- Surface roughness;
- closeness of net shape to design geometry;
- volume of material deposited.

These are tolerances and because the freeform structure could be a non-homogenous volume, the actual measurement of these relating back to the original design is complicated.

The resolution is dependent on the vehicle used for material deposition. If the build device is based on extrusion, the control of resolution is principally in *z*, unless the width of the extrusion is also variable, in which case there would be two degrees of resolution to define.

If the system is based on discrete volume deposition (printing) the location and volume of a single material ‘droplet’ will dictate the resolution in *x*, *y* and *z* which will also be a function of the geometry and the size of the droplet in relation to the minimum desired feature size dictated by the design.

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