DESIGN AND DATA ISSUES FOR THE CONTROL OF MEGA-SCALE RAPID MANUFACTURING MACHINES FOR CONSTRUCTION

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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. A family of CNC based processes called 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. This paper explores the design and data issues for the control of such mega-scale machines.

Keywords: Freeform Construction, Rapid Manufacturing, Digital Fabrication,

1. Introduction

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 growing in the construction sector. Iconic building design is driving the industry towards a new era of the Building Information Model. Looking to the aerospace and ship building industries, a construction project could be modelled entirely using 3D solid CAD tools. The model then contains all the required information for construction. CNC machinery can utilise this information to manufacture the components for assembly directly. This enables highly bespoke and non-repeating components to be cost competitive. 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 machines. 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 generated a number of papers (of which (Khoshnevis et al. 2006), (Khoshnevis 2004) and (Khoshnevis et al. 2006) are three) that delivered radical concepts for house building and the possibility of building on Mars. 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).

Key to the process are the issues surrounding control of the machine, which requires instructions translated from a digital design model. As with any manufacturing process, that the machine will only build within certain parameters and these need to be recognised in the design. Modelling, layer manufacturing strategies, CAD, data translation for layer based processed, machine control and printing are all discussed in terms of published works in the literature. Literature on the design impact that Rapid Manufacturing has had in the product sector is reviewed and parallels are drawn with construction.

2. Printing buildings

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).

Manufacturing using Computer Numerical Control (CNC) devices have limitations, however. Increasing demands and expectations for the consumer, has pushed the possibility of increasing personalisation in products to give a market edge. Layer based manufacturing methods allow almost unlimited geometrical freedom at no additional cost and so are an attractive proposition fro addressing this market need. Products such as the 'Assassin' football boot from Freedom of Creation or the Invisalign tooth aligner product (Invisalign 2006) are examples. These are examples that have helped push these layer based or *Rapid Prototyping* processes out from model making tools into manufacturing processes in their own right (Rapid Manufacturing) (Hopkinson, Hague & Dickens 2006).

Architecture too is considering more interesting designs, shapes and forms that are becoming increasingly difficult to realise using traditional methods. Digital fabrication is an enabling factor but limitations are being encountered as the boundaries of design possibilities are stretched. Bio-inspired structures could offer new building technology solutions. The increasing integration of engineering building operational functionality and architecture offers the possibility of the reduction in assembly and materials to achieve a given building performance. Mega-scale machines enable the control over material deposition. Integrating the building model with digital analysis tools could generate buildings printed using with the minimum quantities of material and with a greater degree of systems integration and optimised performance.

2.1 Building in layers

Constructing building components in an automated layer by layer fashion, by selectively depositing materials in their final location requires a move away from conventional construction practice. Ten years ago (Pegna 1997) realised that automating construction by employing machines that reproduce human processes is prohibitively difficult. He argued that the key is to build using a process that automated a few simple elemental operations, but the control of these operations allowed structures of sufficient complexity to be useful. Pegna experimented with selective bonding of sand and cement to create freeform structures from traditional building materials. The breaking down of a 3D object into '2D' layers does mean that the possible geometries that can be produced is almost unlimited. In addition to this however, additional data translation issues are also introduced.

Rapid manufacturing machines operate on the same principles. In order to automate the process, however, the build details must be created and stored in a language readable by the machine. This is digital information derived from a 3D model created in CAD software. The problem of designing comes down to incorporating the process parameters of a particular RM process. The CAD tool must unambiguously describe the geometry of the object to be built.

Contour Crafting has been used to produce large (>1m) freeform wall structures that would replace the structural concrete block wall similar to that found in UK house construction. The process extrudes the internal and external 'skin' of the wall to form a permanent shutter that is then backfilled this with a bulk compound similar to concrete. Using materials with rapid curing properties and low shrinkage characteristics, consecutive layers of the wall can be built up rapidly. In order to improve the finish of the visible surfaces, the shutter material is shaped by a secondary manipulator, or trowel, as it is extruded. The combination of processes results in a system that can deposit (relatively) large quantities of material while maintaining a high quality surface finish. The control of the process speed and delivery and hence the cure time of the materials and the bonding between layers will affect what can be achieved given the design of the deposition device.

3. Design and Rapid Manufacturing

The production of all components is limited by scale. At different points, the size of the components produced becomes infeasible, either because of the:

- Physical size of the final assembly, such as limitations in the assembly process such as part weight for lifting;
- limitations in the production process, injection moulding cannot produce a closed box with internal parts;

- limitations in the cost of production, it can be less expensive to produce large, complex and possibly unique systems, out of smaller standard components.

Whether manufacturing or construction is considered, all except the simplest of products are inevitably assemblies. Products that have some active components, are inherently more complicated than passive objects. Buildings, automotive vehicles, ships and aircraft are the most complex products that humans manufacture for terrestrial activities. Vessels that house humans have to deal with some function, have to interact with the environment and have to assist human physiology. The distinction from all other products is simply that we had hold the latter, but the former can contain us.

In order to design these large systems, the design tasks are subdivided and specific function and purpose allocated to distinct elements. Those elements are designed and tested to operate appropriately. Assembling the components then yields interfaces where the systems overlap. It is more difficult when systems and function are not clear cut and delineated, such as in Freeform Construction design or as in active systems that can be found in smart materials.

3.1 Component streamlining/part reduction

Another key area where RM has been seeking to establish a market is in the streamlining of products. The 'unlimited' geometry means that conventionally manufactured parts can be redesigned to produce parts with fewer assembly requirements, or that are aesthetically of functionally optimised in some way. Relevant examples are depicted trough work carried out at Loughborough University and examples here are taken from two publications (Hague et al. 2003, Hopkinson, Hague & Dickens 2006).

Part consolidation offers significant cost savings where numbers of components that would traditionally require assembly to make manufacture possible can be reduced. Two examples were cited in (Hague et al. 2003). An air duct design demonstrates how a complex duct assembly can be reduced from more than 25 parts can be reduced to one, eliminating assembly. In addition, there is the potential for improved performance since the joints in the duct were also eliminated and hence cannot leak.. The second example compared the design and manufacture of an electronics enclosure. The Company produced low volume specialist High Impact Polystyrene or ABS by assembling a number of CNC cut flat sheets. The new design manufactured using stereolithography meant a part reduction from three to one. In addition there was more freedom to custom design. The cost based on Bureau quotations, however, was ten times that of the current manufacturing process.

A further two examples considered the design of a diesel fuel injector system and handbrake lever. Both demonstrated the possibilities of optimising the design to give a better performance. The key being that any design solution established could be manufactured using rapid manufacturing. The traditional manufacture of the diesel pump [picture?] means that ducts internal to the pump housing have to be post drilled and plugged. This means straight cuts and sharp angles round which fluid must flow. In addition, the drilled fluid ducts need plugging which have leakage potential over the life of the product. The RM component avoided all these issues, except that the new component could not be RM manufactured in a material with suitable properties. This is the Achilles heel of the Rapid Manufacture approaches; the study result was in essence a CAD designed concept model. The second example was the design of a hand brake lever for MG rover. This involved design

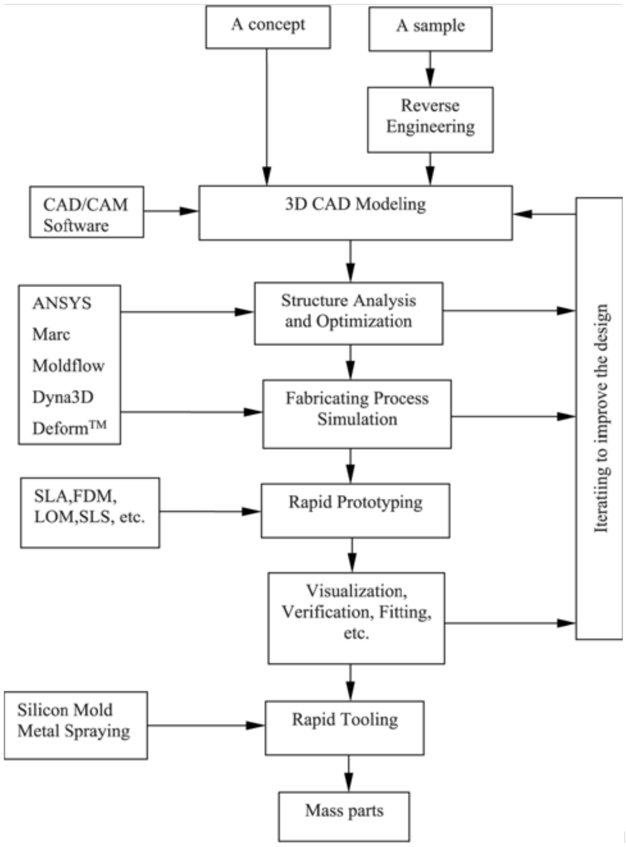

Figure 1: An industrial design process that includes RP.

optimisation that allowed wall thickness to be varied. This cannot be done in conventional injection moulding, but is an advantage in mitigating regions of high stress in the component.

In summary, RM was demonstrated to be able to reproduce the design configurations that can be produced in solid modelling software. Much of the design itself is impacted by the CAD tools used and the skill of the operator. The success of the solution relies on the cost and the material of the RM component. One of the comments made in (Hague et al. 2003) was that CAD was creating a bottleneck in the design solutions possible. This is not a universally shared view. Some experienced CAD users claim that, with the possible exception of texture, any form can be created in CAD modellers. The key, however, is to look outside the 'engineering standard' types of software for tools that are good carrying out certain functions (such as 3D studio Max, Maya, etc.). It is the skill of the user and access to several specialist packages that is arguably the key to digitally creating any geometry.

3.2 Rapid Manufacturing and Rapid Tooling in the design cycle

The traditional role of Rapid Prototyping in is speeding up and reducing cost in the design cycle. An overview of an typical industrial design process is given in Figure 1, taken from (Guanchung et al. 2004). It shows the interaction of CAD, reverse engineering, analysis, RP, RT and production. The key problem of generating the digital from is highlighted, and this can be carried out either by interacting with the Tools in the modelling software package, or by scanning a physical object. Scanning alternatives are CT or MRI (common in the medical field), laser scanning, photogrammetry (optical methods). Of the latter two, laser scanning is probably the most common approach and is good for smooth surfaces. Unfortunately it cannot capture internal geometry, or overhangs (anything out of

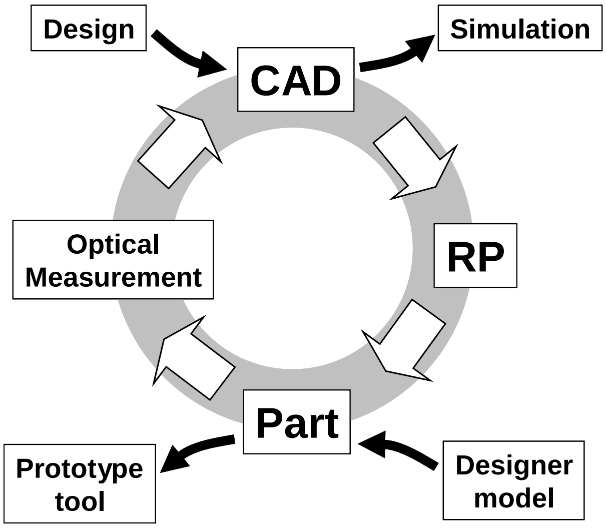

Figure 2: Relationships in the design cycle; reverse engineering and RP.

line-of-site). Destructive slice and scan is commonly used where information on internal geometry it needed. The object is sliced and an image of each layer taken. The slices are then reconstructed in then modelling software: The reverse of RP.

The value of the design model cannot be underestimated. A study by (Evans, Campbell 2003) identified that while there have been advances in viewing digital data directly, viewing and handling physical models remains an essential part of the industrial design process . Figure X has been adapted from (Wiedemann, Jantzen 1999) and depicts the relationships in the design cycle, including reverse engineering and RP as used at Daimler-Benz AG (Automotive). Figure X shows an iterative cycle, once a design has been modelled in CAD an RP model (Part) can be made, this can be evaluated and used for tool design (i.e. tooling for mass production). The iteration cycle is completed by the design modifications being made in CAD. This can be directly, or as in Figure 2 through scanning in the modified part. This is also one of the design process adopted by Ghery (Glymph 2003).

The production of the prototype can generate an appearance model or a functional model (Evans, Campbell 2003). Traditional models are often constructed of material that are not close in characteristics to the production material. These can be useful for appearance evaluation, but the advantage of RP is that the model can be made to be very similar to the production part in form at least. This assist greatly in functional testing and trial assembly procedures (Wiedemann, Jantzen 1999). (Evans, Campbell 2003) describes that design of a hand held tool, where functional product evaluation is expedited by this feature. (Wiedemann, Jantzen 1999) describes the use of the full scale mock up in automotive engine design. Traditional methods relied on constructing the engine block out of wood to investigate the overall assembly process. The key is design iteration. In manufacturing the tool design is critical and RP can be used to verify this. (Wiedemann, Jantzen 1999) reports potential design time savings of up to 60%.

Materials that used in RP machines must have specific characteristics to enable the build process (Bourell 2006, Gornet 2006). The properties of the RP manufactured available materials do not always have the properties of the end product, which can limit functional testing. When functional testing is required one option is to use RT to create a small batch of parts in the final production material for testing. An alternative is to constrain the critical regions in the design of the component and adjust the material placement in the uncritical regions in order that the RP part has the same properties (tensile stress, bending characteristics, weight, etc.) as the production part. This has been called Geometric Tailoring (Rosen et al. 2003, Sambu, Chen & Rosen 2004).

In summary, RM saves time and costs in the manufacturing arena and is integrated with common design practice. RT offers the opportunity for error avoidance and optimisation in the production tooling process and enables functional testing on production like products. The potential savings are again in getting it right first time (Hilton, Jacobs 2000). The use of digital information is still reliant on the creation of physical components to check the design criteria. Modifications made on the physical model have to be returned to the digital environment and that is done in a number of ways. Ghery adopts this approach to verify form and buildability. The impact on the design process is to speed it up, increasing the number of iterations possible and hence reduce the likelihood of error.

3.3 The Impact of Rapid Manufacturing on design

There are a couple of papers that explore the 'design-for-X' (DFX) manufacturing model. Typical 'design-fors' are; environment, assembly, manufacture, reliability, serviceability, recyclability. It is used to implement concurrent engineering. (Hopkinson, Gao & McAfee 2006) carried out a study using design for environment criteria to evaluate the impact of RM on an automobile door handle assembly design. The potential for building the assembly with all moving parts using RM eliminated the need for disassembly and reduced the material count to one. Current environmental evaluation techniques in the automotive sector are based on the requirement for disassembly. Since the RM component required none, the evaluation tool was rendered useless. This raises some significant issues and highlighted the technology as potentially disruptive.

In two papers (Hague, Campbell & Dickens 2003a, Hague, Campbell & Dickens 2003b) explore the comparison of design for manufacture comparing conventional injection moulding with rapid manufacturing. A number of issues were highlighted. Figure 3 shows a product development lifecycle, redrawn from (Hague, Campbell & Dickens 2003a). The work assumes that the shortcomings of material properties of RM products can be over come. It summarises that the key impact that RM would have on this product development lifecycle would be encouragement towards paperless offices and manufacturing facilities because the design is completely driven by digital models. NC programming would be (as it already is) automated and negate the need for separate programming operations. Prototypes would be produced on the same machines as the final product, hence removing the complications in the tooling process that exist with convention methods. In comparison to injection moulding the most liberating aspect of RM is the design freedom, RM can print what can be described in CAD, ie *manufacture-to-design*. Conventional approaches require *design-for-manufacture* where (for injection moulding) issues such as draft angles, non-re-entrant shapes, near constant wall thickness, complexity, split line location and surface finish (injection port location) must be taken into consideration. The complexity of the mould has a direct impact on the cost of the tool and hence of the end product.

Other issues have been explored in (Hague et al. 2003, Hague, Campbell & Dickens 2003b) and (Rosen et al. 2003). Rapid manufacturing relies on a complete digital representation of the build objects geometry. With the development of the internet and service bureaus, there is increasing number of designs being sent to a manufacturing location, being built and then being shipped back to the designer; distributed design and manufacture. Traditionally the design of a component is a composite of the creative thought of an individual, the development of that idea by a team through marketing and engineering constraints and finally

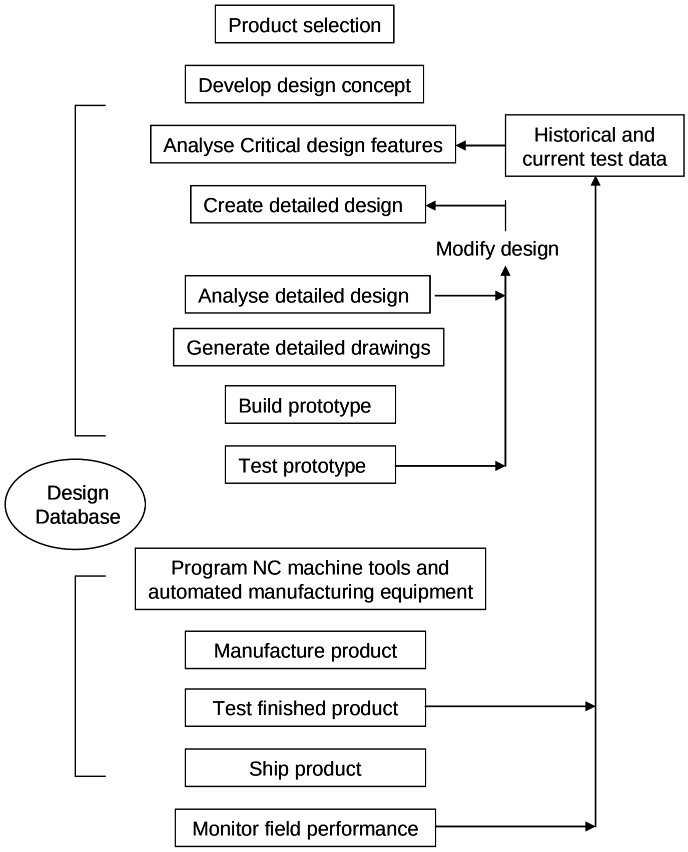

Figure 3: Product development cycle.

through a production team who influence the design in order that it be manufactured cost effectively. All have a stake in the intellectual property belonging to that product. The whole process has until now been inseparable. (Rosen et al. 2003) recognised that RM meant that the design and manufacture process is discrete, because there are 'no' constraints to what can be manufactured with RM. The work investigated if by selecting critical parameters that define the design and acceptable tolerances placed on these, can the design be blindly handed over to manufacture? If so, at what point? An important question arises; who is responsible for DFM? The design and ability to make it are implicitly linked both in practical and business terms. Same thing afflicts construction design. One possibility for FC is that it may be able to separate design and building operations and hence clarify lines of responsibility.

4. Data issues for mega-scale processes

It is worth considering the process that is currently adopted for the creation of objects through Rapid Manufacturing techniques. Figure 4 depicts the process. 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 ahs been used).

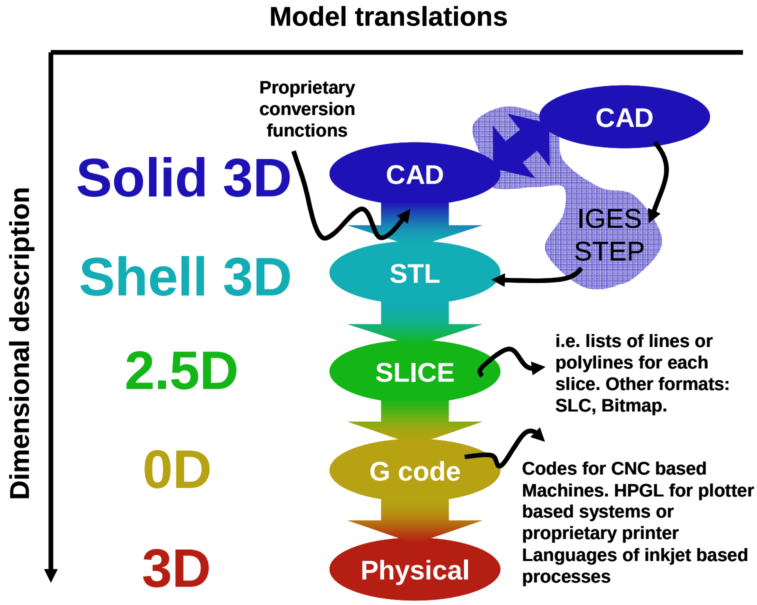

Figure 4: Steps in producing an artefact using RM processes.

Depending on the RM process, the STL file is then processed by RM machine dependant software. 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. 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.

4.1. CAD, STL and Slicing

There are a number of numerical operations that must occur to translate data generated by a CAD modeller into the language understood by a RP machine. The object is first converted in to STL. STL is now the *de facto* standard for interfacing with RP machines. The STL file is passed to software that slices the model. The slicing software is machine dependant, because the build parameters affect the depth of each slice and hence the number of planes to project (Fadel, Kirschman 1996).

Printing control operations can either be based on vectors (as in plotters), or raster i.e. individual dots. Vector operations call for movement in a straight line from x_a, y_a (at height z) to x_b, y_b. Curves are approximated to segments. 'Pen up/pen down' dictates whether material solidification occurs, or whether the device is shifting to the start of a new 'solidification' vector position. For raster controlled operations, each dot on a given layer (resolution determined by the dpi) will either be solid or not. The following figure describes the process and data formats.

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 resolution and finish (Koc 2004, Kumar, Choudhury 2005, Lee, Sachs & Cima 1995, Pandey, Reddy & Dhande 2003, Sabourin, Houser & Bohn 1996).

The whole process filters information in stages so that the original CAD model is turned into a shell, the shell into a series of 2.5D slices which are converted to s sequential set of machine commands that control the building of the physical object. The process relies on everything operating as expected and there being no errors at any point in the instruction derivation. Errors can occur at all stages. Initially, a manifold modeller is required. Even if this is used, the way in which the CAD model is composed can cause errors in the tessellation algorithms used in creating the STL file. This can often result in the production of open loops on a given slice – which the machine code generation algorithms cannot interpret. Specific errors in translation are:

- Due to the facet approximation
  - Distance from true surface to triangle (facet approximation)
  - Chordal (facet approximation)
  - Convex boundary
- Due to STL translation
  - Flipped normals
  - +2 trangles per edge
  - Closure
  - Truncation
  - Coding errors

Other formats to replace STL are CFL, CLI, LMI and LEAF (Jacob, G. G. K., Fai & Mai 1999). Direct slicing of CAD, IGES and STEP formats have been considered, although the problem in adoption becomes the generation of the machine specific G, H and M codes which have to be written for each machine. The problem is the number of interfaces required *N* is given by (Chang, Wysk & Wang H-P 2006):

$$N = \frac{n!}{2!(n-2)!}$$

Where there are *n* systems. So for 2 systems you need 1 interface, for 8 systems you need 28 interfaces. The same will apply to Freeform Construction processes, unless the task the process is not generic, i.e. it is designed for the production of a specific product.

The advantages of tessellation include it being a simple method of representing 3D CAD data; the fact that is a de facto standard; and that for certain shapes, it can provide small and accurate files for data transfer (Jamieson, Hacker 1995). One major problem is file size. It can create files many times larger than the original CAD data file for a given accuracy parameter. This is because the STL file carries a high degree of redundancy since each triangle is individually recorded and shared ordinates are duplicated within a file. The subsequent slicing of large STL files can take many hours and, except for RP processes which can slice while they are building the previous layer. Other problems relate to the inconsistent implementation of STL translators within CAD systems.

There are a number of reasons for using direct slicing, mainly related to the disadvantages of using tessellation:

- reduced file size (over-faceted models);

- greater model accuracy;
- reduced RP machine pre-processing time;
- elimination of repair routines (these are an “unknown” in that they could easily detract from model accuracy and even remove features from the model).

However, there are also potential disadvantages of direct slicing which include the difficulty of adding supports to nested sections and the ability to re-orientate the model is lost, which is often critical to a good build. Other factor such as beam compensation and offsets also still require processing.

4.3. Selectivity and deposition

There are two ways of controlling the selectivity that is required to enable the layer based manufacturing methods:

- through material deposition;
- through phase change activation.

These are tied to the specific selectivity mechanism. When a bed of powder or a vat of liquid is employed, the selectivity is derived from the process of initiating phase change. When extrusion or printing is employed, the selectivity comes from the actual placement of the material. The solidification is via a secondary process either by curing or by thermal.

The key for large scale processes is what is feasible. The vat/bed techniques do not require secondary support scaffold, however, the postprocessing requires the removal of un-solidified material. The material deposit processes require a sacrificial scaffold to be removed, but this will only be where overhanging sections require support. The former process will always have some material to remove unless a solid object the dimensions of the build bed.

4.4. Resolution of the build and model representation

Resolution is an ambiguous term and it is important to define what it is and what it means in different contexts. For CRT displays it can refer to the number of lines of phosphor dots on the display. A LCD display has an array of pixels (picture elements) to display an image. The digitally stored image is described using pixelated data, however, this refers to the number of pieces of image data. Different data formats handle the information differently. The number of colours that can be described on each pixel is dependant on the machine specification (colour depth or bits per pixel). The mapping of the digital image to a screen may not be 1:1, pixel to pixel. That is established by the software that drives the display equipment. A display does not have to display images at it’s native resolution (i.e. the number of pixels it is manufactured with). Images can be interpolated which could be to the detriment of the apparent quality. In addition the pixel does not have to be square and any image that has been described in pixels has been *bitmapped*. The size of the pixel is also critical the perceived quality of an image. 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.

The pixel, dpi and ppi describe 2D data. 3D images can be described by the voxel (volumetric pixel). These do not typically have and x, y, z reference, but are related to each other to form a complete image. Typical 3D CAD modellers represent objects by defining the boundary surface and expecting the ‘material’ between these to be homogeneous and isotropic. For the majority of RM applications this is an adequate description of the information. Then data representing this binary state can be easily translated into a slice information of the same solid

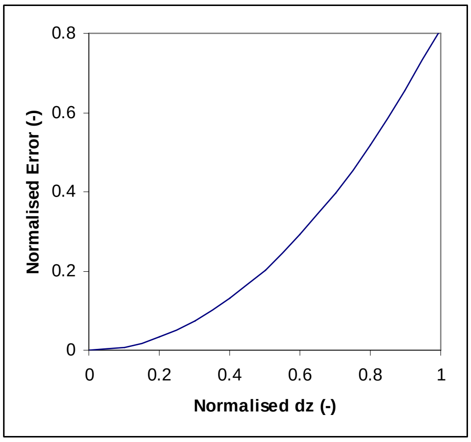

Figure 1: Relationship between ∂z and worst case error.

object. The slice data, however, is 2D, i.e. they are infinitely thin and alone will not form a 3D object if sequentially stacked. A machine and material dependant build parameter is required that established the *thickness* of each layer; $\Delta z = \partial z n$, where Δz is the height of the object, ∂z is the thickness of each layer and n is the number of layers. The 2D data is assigned to that thickness and hence the resulting 3D object can only be an approximation to the digitally created form. In effect, the digital object is quantised by limitations in the analogue process. The approximation becomes better as the layer thickness decreases. Figure 1 shows the worst case relationship between the magnitude of ∂z and the approximation error, e_z. For a simple (2D) case, $\vartheta = 45$ the relationship can be approximated to, $2e_z = \tan \vartheta \partial z^2$, where $\partial z \in \{0,1\}$.

If material grading is required, i.e. the material is non-homogeneous, different fractions of material must be volumetrically identified. This requires volume modelling and subsequently methods of volume representation. (Mercado, Blackledge & Dickens 1999) explore the application of voxel modelling for rapid prototyping. MRI, CT and PET scans all require 3D visualisation and create data that has driven voxel modelling. A voxel is a cubic volume that has a location in space (*x,y,z*) and one or more property values. The number of points is dependant on the resolution of the image. The actual material properties at any location between sample points are approximated to equal the nearest sample point, which is dictated by the limits of the cubic volume.

(Mercado, Blackledge & Dickens 1999) identified that for RM, a useful volume modelling resolution would be about 5μm and so modelling a typical RM machine build chamber of 500mm x 500mm x 500mm and so would require 10^{15} *elements* and there are at least 4, (possibly) 16bit numbers to store for each element. There are only ~2 x 10^{15} bytes of data in all the academic libraries put together (as of 1999). Use of Voxels at this resolution is prohibitive.

For FC we might want to deposit material down for a house volume which has been taken to be 500m^3. If we wanted to describe the *x,y,z* location and the proportions of cement, sand, aggregate, water, plasticiser and accelerator, we might need 9 bytes of data to store this information (as a set of 9, 8bit, floating point numbers). The memory requirements in gigabytes is shown as a function of cubic cell dimensions (volume = dimension^3) in Figure 2.

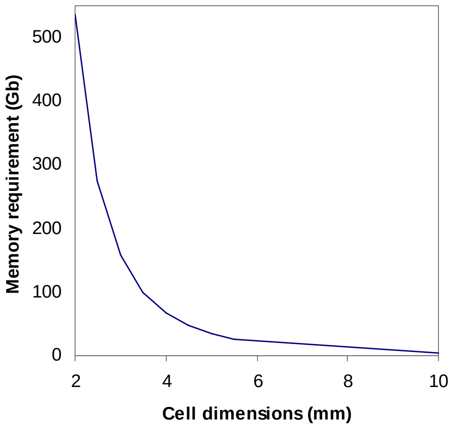

Figure 2: The memory requirements for a 500m^3 volume as a function of overall cell dimensions.

This problem can be circumvented by using 2.5D approach. The bitmap is described as being solid or not, the volume of the voxel is taken to be implicit in the machine parameters. The number of slices is then proportional to the data storage required and the resolution in *z* is a function of the fine-ness of this parameter.

4.5. Machine control

Ultimately the design that has been produced digitally must be converted into a sequential set of commands that instruct a machine to carry out certain operations. It is useful to consider two types of machine control:

- Drop on demand printing
- CNC codes

NC codes are derived from the encoding of manual operations in order to machine a component using cutting, milling and drilling techniques (Benhabib 2003). These are commonly called 'G-codes' and define the speed, trajectory of motion (the tool path) and the selection of the specific tool in relation to the machined. 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. Most RM machines run on g-code. 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 (polylines are used in the SLC format (Chang, Wysk & Wang H-P 2006)). 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 just a few.

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.

There are many RM processes that 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[1] 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. The properties cannot be varied, i.e. a pixel cannot be grey to some extent. Some printer heads can deliver vaying volumes (and hence intencites of ink). The limiting factor is the STL B-Rep model because it is representation of binary states. All the build information is stripped out of the model when it is created.

The problem is two fold. CAD modeller can model different materials. The problem here is how to translate that in to machine control. Using the de-facto standard STL file converts what could be many different components made of different material into a binary description of what is solid and what isn't. Possibilities lie with the new standard that is replacing g-code in order to enable web based *design anywhere – build anywhere* manufacturing; STEP-NC (Albert 2007, Shin, Suh & Stroud 2007). The second part of the problem is dealing with non-homogeneous materials or those properties we might want to change with respect to location in an object. One solution is to quantise the grading of the materials and use voxel modelling as discussed earlier.

4.5 Summary

A number of issues are raised for large scale processes for construction. The material is key. It is likely for some applications of mega scale process there will be a need to utilise mineral based materials. In construction, cost and availability are significant factors. The mode of delivery and solidification is to have a water activated mix that cures. There are three possible delivery/selectivity methods:

- Dry powder bed onto which the activating agent is sprayed selectively (literally, mega-scale 3D printing);
- Extrusion, where the material is placed where required (Contour Crafting);
- Printing, 'drop on demand' material deposition (i.e. a mega-scale version of the Thermojet process)

Certainly for on-site applications in the UK and other regions with a similar climate, a water activated dry powder version for construction could be problematic. Contour Crafting is being developed and is showing some promise. The simplicity of the process does limit the geometries that can be created. If mega-scale 'printer' type process is considered, then the geometrical issues are freed. This leaves the resolution of the smallest deposition volume. For the creation of large components, however, it is anticipated that variable volumes will be required to trade off resolution with print speed to minumise build times. In terms of delivering a volume of material to a location using drop on demand:

- Either constant flow rate and vary time
    - Dithering of machine

[1] More exactly and activating agent; the second part of the two part binder is pre mixed with the matrix material.

- Or constant time and vary flow rate
    - Control pressure at the delivery head
    - Control resistance at the delivery head
    - Control of the area of delivery nozzle

The shape of the deposited volume depends on the shape of the delivery nozzle and the characteristics of the mode of ejection: ie whether falls under gravity or fired and the properties of the material such as viscosity, and whether the material is reopeptic.

The control of the variable volume devices and hoe the function of the geometry and how the mix materials may vary offer some not inconsiderable control, modelling and data storage issues. In addition, the preparation of mineral mix designs builds could potentially build in an element of process control that g-code does not support.

5. Conclusions

This paper has explored the design and data issues that influence the design and application of mega-scale rapid manufacturing process for construction. The use of rapid manufacturing in the manufacturing sector design process has been explored. A number of case studies that highlight the impact of RM on design have been reviewed. The translation of the digital design model into the slice data and then into machine commands have been discussed and limitations on conventional CNC approaches has been highlighted. There are a number of issues over design creation and in the enabling of the machine control, but many of these will be process specific.

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