Rapid Prototyping for Architectural Models

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ABSTRACT: Rapid prototyping (RP) technology has developed as a result of the requirements of manufacturing industry. There are a number of other application areas where RP has been used to good effect and one of these is architectural modelling. However, such application areas often have different requirements from what is offered by the current technology. This paper describes work carried out by the authors to investigate potential applications for architectural modelling, as well as an attempt to explore the limits of the technology. It will go on to discuss how the technology may be developed to better serve the requirements of architects.

1. ARCHITECTURAL NEEDS

Much has been written about the role of drawing in architectural design [Robbins 1994, Schön 1992, Goldschmidt] but the role of the model as a design tool has not been extensively reviewed. Likewise, the demands of architectural design on rapid prototyping have been little explored [Ryder 1999]. An examination of the role of models in design is an appropriate starting point for a discussion of the role of rapid prototyping as a model making technique. This review does not pretend to be an exhaustive review of models in design but presents a survey of the current situation and identifies areas in which developments need to take place.

1.1 Models in architectural design.

Models are used in architectural design for several purposes [Ratensky 1983]. Early in a design cycle, sketch or study models will be created to examine particular aspects of a design idea. Such models are often assembled rapidly and crudely for it is the immediacy of the feedback, which is sought. At later stages in a design cycle, more carefully assembled detailed models may be created to present ideas to colleagues, clients or decision-making bodies. Such presentation models are often highly articulated as they strive for verisimilitude.

In both these conditions, it is common that the models are used to depict form in order to communicate design intent [Eissen 1990]. Often the physical models will be used to supplement drawn images [Ratensky 1983]. It is often noted that models reveal aspects of a design more legibly than drawings to both laymen and those trained to read the media [Koepke 1988]. In this role, models are used at all scales, ranging from town planning to explanation of particular building components [Eissen 1990]. In particular, complex mass-void relationships or spatial sequences are more easily communicated in models. From this we can identify that models play a role as a communication tool.

In addition to representing form, models can be used to examine processes as well. Models can be used to assist in testing constructibility [Burry 2001] or integration of services into complex or tight structural spaces. Models can be disassembled to reveal the components of a building or the spaces within, or they can be abstractions that reveal to the viewer particular properties not hidden when the real object or complete model is viewed [Hohauder 1984].

In a related pedagogical application, models are used to develop spatial thinking [Janke 1968]. Certain geometries can be examined in model form more easily than other means. By assembling and disassembling forms and by representing ideas that are too complex to imagine, models help the
designer to understand the spatial implications of their drawn two-dimensional decisions.

As the science of architecture has evolved, so too models are used to examine particular behavioural aspects of a design, such as its structure, lighting, acoustics or ventilation [Cowan 1968]. It is feasible to test models to failure and learn from these the likely behaviour of the final completed structure. As such, models are a safer and more cost-effective means of examining possible design solutions. From testing models, experimental results can be obtained that validate or extend theoretical understanding of structures.

Finally, models can be appreciated in their own right [Hubert 1981] and as such plays an important role in the process of understanding a design even after a building is completed. Where buildings are not (or cannot be) built, models reveal uniquely worlds to appreciate [Pommer 1981].

1.2 Limitations

Models are always representations of the completed object, for if they are not, the model maker has built the final construction. Architectural models, however, are typically not simply faithful replications of built works; they are always interpretative. Even when full scale, models represent only part of the final design, either by omitting structural properties, finishes or elements. The level of detail, articulation or accuracy in finish is limited by the skill of the model maker and the time available. Sketch models typically sacrifice accuracy for the sake of speed. As these models are used for decision making in the design process, it is incumbent on the design team to recognise the compromises made in the representation of the design idea and to take these into consideration as subsequent design decisions are made.

If models are intended for experimentation and verification, it is essential that relevant properties of the model be considered to ensure similitude in these properties. The model maker must consider the similarity of behaviour with the completed object and the translatability of the results from testing a model [Cowan 1968]. On the other hand, since models are not exactly the same as the finished built object, either by virtue of being smaller, cheaper, lighter or otherwise different, models can allow the designer to try designs that will fail in the real situation.

1.3 Representation

Models are an abstraction in representation. As such, the choice of materials is important, for these will influence the interpretation of the viewer. One of the more important constraints of model making is therefore the difficulty in achieving forms, texture, colour or schedule with the materials and model making techniques chosen.

Some model makers or designers will use real materials in their models, insisting that the model is the real object. There are, of course, obvious problems of literally translating materials from a full-scale object to one at a reduced scale. The choice of materials will often depend upon workability, ability to work at the appropriate size, representational properties or experimental behaviour as well as safety in working. Longevity of the model is also an issue - a model intended for international exhibition and archiving will be made of a different palette than one intended to quickly explore a possible form.

More often, substitutions of materials are made to achieve representational likeness. As has been identified above, we can distinguish three types of model: preliminary, experimental and final. Preliminary are sketch models made quickly to approximate the shape or volume. Such preliminary models may be made from any materials at hand. Preliminary models may be refined into preliminary scale models, which exhibit greater control over the dimensions. Experimental models are made to approximate particular properties of the intended design, the particular property selected depending upon the aspect of the design to be tested or experimented.

Numerous texts present model-making techniques [Hohauser 1984, Ratensky 1983, Pattinson 1982, Koepke 1988 among others]. In these, discussions can be found of the wide variety of tools and techniques to manipulate materials to aid in representing design ideas. Here we find instructions on sheet materials that can be cut, bent, etched, formed or milled. Detailed elements can be made using rubber (latex, synthetic, or
silicon) or plaster casts for cold moulding or using more traditional metal casting techniques. It is noted that finishes are often applied, with such application taking up to one third of the time required to assemble the model [Hohausser 1984]. From this we note that a well-established body of knowledge exists for achieving representational success. All of these note, however, that model making is a time consuming and demanding process which makes it difficult to use as a design aid. The designer often cannot afford the time or have the skill to make any but the most simple preliminary models [Janke 1968]. The compromises made in sketch design models are such that they are of limited use. It is here that RP promises to be of great benefit in design.

1.4 Digital models

With the development of computer-aided design systems, it has become possible to supplement or replace analogue models with digital models. Physical models can be come a by-product of the design process rather than a laborious activity for its own end. A digital representation of an architect’s building design can be turned into a physical model for a final presentation from the same data set as used to produce an animation on screen.

Digital representations offer benefits beyond those of physical models. It has been noted that physical models are most often used as tools to communicate the visual appearance of a design concept. As has been noted, a distinction can be drawn between such visualisation models and a digital building model [Day 1997]. A visualisation model is a representation of what it might look like, a building model is the description of the building, its components and its assembly. As such, data associated with a digital model may be used to direct the model making itself, allowing models to be produced in which, for example, the colour of a component represents its structural state.

RP in model making offers an unusual opportunity as it melds the digital with the analogue. Digital representations can be manipulated in ways that physical models cannot. For example, a designer of an auditorium executing a Boolean operator on two spaces will find it is easier in digital models than in physical. Likewise, digital models have lead to the use of algorithmic design in the generation and exploration of design solutions [Duarte and Simmondetti 1997]. Linked to RP, this offers the opportunity for algorithmic model making.

2. RAPID PROTOTYPING

Rapid Prototyping (RP) is represented by a range of technologies that are capable of taking virtual models created in CAD systems and fabricating them in a physical form. This process is done automatically, generally regardless of the model geometry, and without the need for special tooling or fixtures. Complex, 3-dimensional contours are quantized in the form of stacks of 2-dimensional layers of finite thickness. If these layers are very thin, then the parts made will be close enough to the final desired model to suit a range of applications.

The development of RP follows the increasing use of computers for design. As forms become more complex, so it becomes more likely they will be designed on computers. These complex forms, however, make it more difficult to visualise, test, manufacture, and generally develop products using conventional technology. The aim of RP is therefore to reduce the time and skill required to perform this process and to provide a means for integrating the use of the design data through a variety of stages in the product’s development.

Burns [Burns 1993] categorises RP technology according to basic process used. Extending this classification to include the most recently commercialised RP technologies leads to the following: -

Selective photocuring: Commonly known as Stereolithography (SLA, commercialized by 3D Systems [Hull 1988]), this process has numerous variations. They use a special kind of resin, called a photopolymer, which has the property of turning solid under the influence of light of a certain colour. A scanned laser or a masked lamp delivers light to selected regions on a surface of the liquid to turn it solid in the shape of a single cross
Selective sintering: A laser is scanned across a thin layer of thermoplastic powder to selectively melt and fuse the powder particles to form a single cross section of the object. This is repeated for successive layers to form the whole object. This process is most widely known in the form of Selective Laser Sintering (SLS) from DTM Corporation [DTM 1995].

Deposition: With these processes material is fed through a mechanism to form the object. They can be subdivided into three distinct types:
- **Continuous**: A thermoplastic material is melted and fed through a nozzle, which is moved on a robotic arm to lay down the molten material in desired locations. This is commercialised as the Fused Deposition Modelling (FDM) process from Stratasys [Stratasys 1991].
- **Drop on powder**: An adhesive liquid is deposited in a controlled pattern over a thin layer of powder, selectively joining the powder particles to form a single cross section of the object. The process is repeated to form successive layers of the object. A number of systems have been licensed from the inventors at MIT known as the 3D Printing (3DP) process [Michaels et al. 1993].
- **Drop on drop**: Melted thermoplastic material is deposited in a controlled pattern through a droplet deposition mechanism. A number of systems have been commercialised using this method. Examples include the Sanders Modelmaker [CAD/CAM Publishing 1994] and the Genisys machine from Stratasys [Stratasys 1999].

**Adhesion of cut sheets**: This is a hybrid subtractive/additive process. The contour of each cross section of the desired object is cut, and the cut patterns are stacked and bonded to form the object. Alternatively, the stacking and bonding may take place first, with cutting afterwards. The original and most widely known commercial system using this technique is Laminated Object Manufacturing (LOM from Helisys), but there are a number of other systems now available. It is clear that, with so many different methods available, no single system dominates all others. Choice of system depends on a number of factors related to application and dependent on how the machines are constructed, how they are controlled, and how the final parts appear to the user.

### 2.1 System construction

A number of systems use laser technology. Although the lasers are not particularly powerful, they are expensive and difficult to maintain which restricts them to high-cost, high-end machines. Lasers can take advantage of galvanometric scanning mirrors to effect high speed building of individual layers. Laser mirrors need only move short distances and can therefore scan very quickly. Deposition heads on the other hand, like those used on the FDM machines, have much higher momentum associated with them and therefore require much more energy to move around. Also, in order to get the best results, FDM must extrude material in a continuous filament and therefore fabricates using a complex fill pattern that also slows down the build. However, even droplet deposition methods like 3DP, which can use a raster scanning approach, will still be slower to scan a single line than laser based systems because of the mass of the print head. However, the ZCorp machine [Zcorp 1999], which uses this approach, overcomes this problem by having a multiple nozzle printhead that can deposit many lines in a single pass. The LOM system uses a laser and a travelling mirror (rather than scanning mirror) approach. This is because LOM only requires the laser to separate the part from the waste material at the perimeter. The traverse time of the laser is therefore significantly reduced and is suitable for larger, bulkier models.

Machines are often described as office, laboratory or shop floor environment. This is mainly due to the materials being used and how they are processed within the machine. Some materials require fume extraction that makes them generally unsuitable for placing in an office. Other processes require a carefully controlled environment to ensure the process is not disturbed or the materials do not degrade. Examples of this include SLA, which requires low vibration and humidity and SLS, which requires a continuous nitrogen gas supply.

The more complex systems are, the more expensive they tend to be for low volume
production. This often means they are also more difficult to use, particularly if they require fine-tuning in order to get optimum quality from the models. Training and technical support are therefore important aspects surrounding choice of technology and this is also reflected in the price of the machines.

2.2 System control

System control relates to part accuracy. This not only includes positioning of the scanning mechanism, but also penetration depth and feature width. Some systems can go to very fine layer thickness, which would limit the stair-step effect. Others have very fine deposition heads or beam widths, which results in fine feature in the build plane and wall thickness.

In addition to this, parts can shrink and warp, particularly for processes that invoke a phase change in the material (which is nearly all of them). This can be minimised with precise control of the process parameters associated with the material. With SLA for instance, stresses can be minimised by ensuring even distribution of the laser across the resin surface. SLS and FDM control the material temperatures during build to avoid excessive material shrinkage during cooling.

Whilst control of the mechanism is likely to be just as precise for the powder processes as the liquid processes, the granularity of the material and the random distribution of the particles is always going to limit the final result. Powder particles can only be so fine before they become extremely difficult to handle and so layer thickness and feature definition of liquid based systems like SLA and Sanders are likely to be the better.

2.3 Part appearance

A number of researchers have discussed the development of colour RP technology [Gibson & Ling 1999]. To date, there are only two systems that commercially provide multi-colour capability (although the Sanders Modelmaker has been demonstrated as having 4-colour capability, it has yet to be commercialised). The FDM system has the most versatile capacity to build bi-colour models from a range of coloured ABS plastics. SLA can make bi-colour parts, albeit limited to a red and yellowish/transparent resin developed by Zeneca [Medical Modelling Corp. 1999]. SLA resin has this particular benefit of being transparent, which is unique amongst RP materials.

All parts made using RP technology exhibit a characteristic ‘stair-step’ effect, which results from the quantized, layer based approach. Whilst efforts are being made to reduce this (Sanders and SLA machines can now go better than 0.05mm layer thickness), the foreseeable future shows that parts will generally require manual finishing after processing within the RP machine. The powder-based machines also exhibit a characteristic granular texture.

All RP parts are weaker than if they were made in the same material using a conventional manufacturing process. Some processes result in particularly weak parts, either because the selected material or the bonding method used is weak. The thermal processes (SLS and FDM) result in the stronger parts, suitable for functional applications.

3. EXAMPLE MODELS MADE USING RP

A number of models have been constructed using RP methods. Figure 1 shows parts that formed a space frame construction. These models, whilst geometrically simple, would be quite difficult to construct because of the required accuracy. Originally, the model was attempted using the FDM process. The small diameter of the vertical poles made this a very weak structure. When the supports were removed, the model was unable to stand its own weight and collapsed. After building using the SLS process, the model was strong enough to handle for design analysis.

SLS Duraform nylon was used to create the next model (Rotunda, figure 2). This was also an assembly, specifically made to allow the designer to show the relationship between different room locations. The building consists of load bearing walls, unlike column and strut in Figure 1. The component method also made it more suitable for the SLS process since each part was of manageable dimensions and could fit into the
build envelope easier. Shell structures are best suited to most RP methods since this is their primary application area (injection moulded parts). Had this part been more solid in nature, it would have been appropriate to build it as a hollow component. This would have limited distortion during the build process as well as make it quicker to build.

RP is generally not well suited to building large landscape models. This is because most machines have a comparatively small build envelope of approximately 250mm cubed. Larger machines are available, but the time and cost of building may then become prohibitive. Figure 3 shows a development model for a possible new university campus made using SLS Duraform. This again was a component-based model, specifically divided to allow the parts to fit into the machine. The dividing lines were chosen to minimise the effect on the final model.

4. DISCUSSION

The examples above show that architectural models can be fabricated using RP. However, there are a number of points arising from our experience that illustrate the difficulties faced by architects wishing to make use of RP: -

- **Appearance**: the models are homogeneous in appearance. It is not possible to highlight specific features in the model using changes in material, colour or texture, something commonly achieved in other model making techniques employed, thus limiting significantly the communicative role of RP models alone.

- **Finish**: RP models are typically rough finished and require further treatment to obtain an appearance of crafted work. Even those architectural models not presented as works of art are expected to have a reasonable level of finish.

- **Time to build**: although called 'Rapid' Prototyping, the process takes a number of hours to complete the models (the landscape model took around 5 days to complete all the sections). Applications requiring quick mock-up designs can not make use of RP, although newer ‘concept modellers’ may change this.

- **Skill factor**: while architects use computers extensively in design, there is little experience in controlling RP devices to obtain the subtle differences in emphasis employed in other forms of model making to communicate desired design ideas.

An additional factor is choice of technology. Often more than one RP technology is used to construct different components of a model. Sometimes this is through necessity, due to the required strength or the level of detail. However, choice may also be for aesthetic reasons. Parts made using SLS exhibited good detail and strength, but FDM or SLA parts may be preferable where a less granular finish is required. If the landscape model were placed on a more hilly terrain, LOM would have been preferred to produce the terrain because of its speed of build, with the buildings still made from SLS plastic. The ability to choose different technologies for components presupposes each machine is available, an important economic factor.

As noted in section 1, design models are used to communicate design intent or identify design implications. These models are more than simply faithful scale representations of finished objects. The omission of depiction or simplification of representation has to be made carefully. The homogeneity of RP models force simplification but the designer is, as yet, unable to control this as well is in traditional model making materials. There are many instances in which architects wish to use models with few highlights or which have few surface characteristics in order to emphasise form. For example, early sketch models are often made of white card. Similarly, a building being presented in an urban context may be depicted by a carefully detailed and multi-coloured model while the surrounding masses are monolithically depicted in a homogeneous material. Thus, the homogeneity of RP output may be detrimental or beneficial.

There may be other reasons why RP has yet to make much of a presence in the world of architectural design. Expense is one possible reason; RP systems are still expensive and largely inaccessible to the practitioner. Overall cycle time, after incorporating the computer design time, is another. As has been identified, RP offers greatest
potential in producing sketch models. At this time in the design cycle, physical representations are of use to examine geometrical and other formal properties. As has been demonstrated by some practitioners [Novitski 1994], forms can be examined in digital models that are difficult to achieve in physical models made by traditional techniques. RP can overcome this gap and link the digital and physical once again. This is perhaps the greatest promise for such systems in the realm of architectural design.

4.1. Colour in RP

It has already been mentioned that architectural models are often deliberately made from a range of materials in order to emphasise specific features within the model. Also, as the designs are finalised, more realistic colouring is necessary to allow the design to be fully evaluated within the proper context of its surroundings. This makes it sensible to select a RP system that has a multiple material capability or by selecting more than one RP system for large (and costly) models. It may also be appropriate to use conventional modelling techniques to create large, simple geometry landscapes and combine this with RP for creating the more complex and detailed (e.g. building) components.

It is clear from the models shown that one method for enhancing the models is to create them in colour. FDM in particular would be useful in this sense since it has a range of coloured ABS plastic materials and indeed can make bi-colour models. However, a greater colouring capacity would also be extremely useful. Ling and Gibson describe in their paper [Ling & Gibson 1999] a method for incorporating full colour into the SLS RP process. This is done by placing a colour printer mechanism inside the SLS machine. Initial tests indicate that this is capable of multiple coloured component manufacture but it is uncertain on how detailed the colouring would be. Low resolution colouring would make it possible to create regional colour variations, but if the colouring resolution is sufficiently high it may be possible to create detailed featuring within the part. Parts may eventually be made with the windows and decorative feature incorporated directly into the building models. The technology requires substantially more development, however, since architects are particular about the purity of the colours used and the degree to which the colour can be controlled.

5. CONCLUSIONS

This paper has discussed the different types of RP system that are available commercially in terms of their general advantages and disadvantages. However, when considering architectural applications, it is clear that there are further complications since the requirements are different from the conventional application fields of RP. In particular, speed of build, build envelope, and the general homogeneous appearance of RP models are unacceptable for many architectural models and modellers.

However, it can also be noted that architects are unwilling to use new technologies for the building of models unless benefits can be found over old technologies. Some examples have been shown and it has been discussed that for certain effects, RP modelling can be particularly useful. The most exciting developments appear to lie in exploring construction manufacturing techniques. It is also evident that RP technology can be used more creatively than usual by combining models made with different materials and processes, or in conjunction with conventional techniques to overcome some of the shortcomings of the technology.

It is also clear that the requirements of the more creative designers have been somewhat overlooked, with efforts in applying RP limited to replacing traditional model roles. The development of new CAD interfaces, where designers can interact in a more intuitive manner, and functionally graded RP machines, where models can be created with non-homogeneous characteristics (like coloured parts) go some way to making this technology more accessible to the masses. As we experiment with RP devices in teaching contexts and learn to control the devices, we expect to find opportunities in RP
representational techniques that we can exploit to new design or communicative effect.

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Figure 1. This space frame model was fabricated in 3 parts using SLS Duraform material and finally assembled to form the complete model.

Figure 2. Various views of the rotunda model

Figure 3. Component model of a landscape, consisting of 6 separate sections, jigsawed together