CADCAMing: The Use of Rapid Prototyping for the Conceptualization and Fabrication of Architecture

Thomas Modeen
Department of Architecture & Interiors, Royal College of Art, London, England
Tomi@themarchitects.com

Abstract. The objective of the study is to suggest a methodology for fabricating designs, through the use of Rapid Prototyping, that are innate to this mode of production. It endeavors to do so by involving a more inclusive sensory spectrum as an essential ingredient in the conceptualization and realization of a design.

Keywords. Architecture; Design; Rapid Prototyping; Senses; Avatarial

Introduction

It is difficult to deny the impact CAD has had on the profession and practice of architecture during the past few decades. As the preferred medium for both technical drafting as well as graphical visualization computers seem today to be the norm. However, in architecture, a discipline in which the visual only acts as a part of the total sensorial experience, the computer has had an unduly confining, even hegemonic, influence and impact.

The use of CAM (Computer Aided Design) is still a relatively recent phenomenon in the design related fields. Particularly the additive procedure of Rapid Prototyping (RP) has thus far only been used within certain sections of engineering (Callicott, 2001), medicine (Kwon, 2002), and, within architecture, for the production of complex scale models of buildings (Gibson, I., Kvan, T., Wang Ming, L, 2002; Giannatsis, J., Dedoussis, V., 2002). Similar models can be achieved by other means, but it has proven to be comparatively faster and more accurate to produce them through the use of RP to this level of detail. This practice, whilst certainly an adequate means to an end, still doesn’t seem to reflect or aspire to the fullest potential of this mode of production, it still only manages to 'mimic' designs made by more traditional processes. RP is rarely used for the production of the final, finished article, something the technology today certainly allows for, nor has it really been used as the inceptive catalyst for conceiving a design, something this project aims to amend.

Background

Rapid Prototyping falls primary into two main categories: the subtractive and the additive method. The initial entailing a process in which usually a router ‘subtracts’ material, through the use of a variety of different routing-bits, from a, usually wood or foam, block which is gradually reduced into a physical replica of the original CAD model. Examples of this kind of production are: CNC (Computer Numerical Control) milling, routing centers, and plasma & laser cutting.

In the case of the latter, additive, method, a physical model is sequentially constructed, layer by applied layer (a process referred to as 'stair-stepping'), to finally form an analog facsimile of its digital (CAD) origin. It is this latter additive process this study is exploring.
Of the thirty (Kwon, 2002), or so, additive RP processes (also termed, perhaps more accurately, Solid Freeform Fabrication, or SFF) four seem to have become more prevalent than the rest. These four are: stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), and 3D printing (3DP).

The RP process

In short, the primary steps in the additive process are (http://www.me.psu.edu/lamancusa/rapid-pro/primer/chapter2.htm#rapidmfg):

- The production of a CAD model of a design
- Conversion of the CAD model into a STL format
- Slicing the STL file into sectional layers
- Fabrication of the physical model, layer by singular ascending layer
- Cleaning and finishing the model

Here the use of CAD solid modelers, that tend to represent 3D more accurately than wire-frame modelers, is a safer bet. Due to the variety of different algorithms used to denote such solid objects the STL format has been adopted as the standard by the rapid prototyping industry. This format represents the design as an assemblage of connected planar triangles (like the facets of a cut diamond). Since such planar elements cannot represent curved surfaces exactly, one has to increase the number triangles to improve the approximation of ‘smoothness’, inevitably resulting in a larger file size. The third step involves a pre-processing program that slices and prepares the STL file to be built. Most of these programs allow one to adjust the size, location and orientation of the design (Kwon, 2002). This ability is important since how, and where the design is placed on the build platform influences both the piece’s strength as well as the time required to build the model. The fourth step is the actual construction of the design. This phase is fairly autonomous, needing little human intervention. The final stage is post-processing. This involves removing the design from the machine and the detachment of any support structures. Some of the photosensitive materials need also to be cured before being used. Most objects may also need some additional cleaning and surface treatment.

The cons and pros of RP technologies

Some of the disadvantages of the additive process are:

- In real time the build speed is quite slow. Depending on the required level of accuracy and the size of the design the process can take from a few hours to a number of days.
- Currently there are some limits to the size of objects one is able to produce. Most machines can still only fabricate items within the five-hundred millimeter cubed volume. There are, however, already a number of exceptions to this rule.
- The number of materials available for additive RP is still somewhat limited, particularly in comparison to those appropriate to CNC-milling. Again, however, the number of suitable materials specifically designed for the various RP processes is increasing rapidly.
- The final surface quality usually needs some secondary finishing.
- The completed piece is usually structurally less sound compared to a cast component (Kwon, 2002).

Some of the advantages of this procedure are:

- The ability to produce complex and detailed three-dimensional forms. The additive process allows for deep undercuts as well as features such as building pieces within (even enclosed) other pieces, properties that would be very difficult, if not impossible, to produce directly by any other means.
- Reduce lead times for unique parts (Callicott, 2001). Unlike in many machining operations, no jigs, moulds, or other external support devices are needed to fabricate the object.
- As most RP processes are completely enclosed, thus producing very little noise and waste, a clean
production environment is produced that allows for the installation of the machines into non-industrial environments (Callcott, 2001).

The study

"Our most natural way to assimilate is to combine senses. Multisensory interaction, or at least multiple media, assist our understanding and synthesis. Psychologists generally agree that when more than one sense confirms a perception, the perception becomes deeper, or more credible. Cognitive correspondence between gestures, images, sounds, or symbols help us build an intuition about logical states for which there are no easy words or phases." (McCullough, 1998)

"Conscious attention and skilled action are closely interrelated, and this is one reason why traditional craft has meditative qualities." (McCullough, 1998)

The project was initially catalyzed by some of the seemingly obvious, call them, 'tactile' potentials that the RP mode of digital conception introduced. Here was a means for producing 'real things', that retained all the advantages CAD had as a medium, yet, if formulated in an appropriate fashion, could potentially avoid some of the pitfalls the same medium inevitably possessed due to its 'virtuality', its non-materiality. RP could, if conceived in a suitably crafty manner, manage to reintroduce some of the qualities of the tacit domain into the context that engages both realms of conception, that of the cerebral and conceptual, and that of the inherently tactile and (multi)sensorial.

Although, in the context of the aforementioned, one has to acknowledge that nowadays we often think 'through' the computer. It is the medium that acts simultaneously as ones 'thumbnail-napkin', sketch-book, and tool for executing the various drafts and amendments, including the final rendition of a design. It is the 'pen' (brush, pencil, crayon, etc.) as well as the 'paper' (canvas, film, background, etc.) on which we work. And now, in the context of CAM, it performs as well in the role of a 'hand' (instrument, extension, tool, etc.), that shapes the 'matter' (material, substance, clay, etc.). This presents a fundamental shift in how ideas are introduced, 'induced', and conceived. This commonality or synthesis of the medium, which could easily be formulated as a negative, excessively homogenizing, factor, is here instead conceived as a positive and catalytic device. In this instance a number of degrees or stages separating the inceptive seed of a sketch from the final design are eliminated. By using the computer in the sketch phase as well as the final draft phase the need to 'interpret' the drawing is
removed. Here the sketch is the design, albeit be it still in its initial fetal stage, that will finally result in a built design. In this instance it's a question more of a transition than a translation.

An avaterial
When commingled into an architectural context such interests cumulatively resulted in the notion of an ‘Avatarial’, a neology for avatar-material. An ‘avaterial’ is a notional, made-up, simulated 'material', that exists and is manipulated within the virtual (within the parameters of a CAD software), but is solely based and guided by the properties and traits of a real, physical (RP) material. To clarify the set-up of an avaterial one could claim that within the virtual (in CAD), it is a material; and 'within' the analog world, it is a methodology or process. It is concurrently both and neither, forming a reciprocal, even symbiotic, kinship between the 'real' and 'non-real', the corporeal and conceptual.

An avaterial is not a 'new' material, but an organizational methodology that provides a template, of sorts, for organizing a (RP) material at a very minute level, consequently providing one with the opportunity to adapt and fashion its intrinsic qualities by ‘simply’ readjusting its composition. The aim being to hopefully discover a way of ‘designing’ through the use of additive rapid prototyping technology, a methodology of conception and production that is innate to this form of manufacture, instead of simply being a second-hand reflection or appropriation of a pre-existing one.

Process parameters
At this stage the process is threefold:
- Firstly, it will attempt to establish the ‘vocabulary’ of avaterial properties. This might entail the reproduction of the properties of actual (RP) materials, or the simulation of, call them, material traits (the simulation of qualities such as ‘softness’, ‘slipperiness’, or ‘graininess’ within a CAD program?).
- Secondly, it will endeavor to manipulate and combine such traits by various manual, and potentially procedural (algorithmic), organizational processes.
- And finally, the study will, in conjunction with the initial stages, try to establish an innate link with the RP fabrication techniques. Allow for a symbiotic and reciprocal approach to evolve that, ideally, will result in something that is more than a sum of its parts.

Establishing a vocabulary
For the initial stage a pivotal factor is the fact that through the RP mode of fabrication one can manipulate a (RP) material at a remarkably minute and accurate level. For example, in stereolithography the machine’s accuracy can be focused to produce features as small as a twentieth of a millimeter. This entails that if one was to make a millimeter cube (smaller than a pin-head) it could potentially be consistent of up to eight-thousand variable components (a scale that transcends beyond our physical sensory perception!). These ‘components’, in the context of this study, are referred to as (scale-wise still somewhat mislead-
ingly) ‘nano-naughts’. A nano-naught forms the smallest particle of matter one is able to produce through a particular RP fabrication method. Consequently there is no specific set, universal determinant for the size of a nano-naught, since the size is dependant on which particular RP output procedure is being used. I.e. if, say, stereolithography is used, the size of a (SLA) nano-naught would be approximately 0.05 millimeters, the smallest unit one can produce through this fabrication method; if, alternatively, fused deposition modeling is being employed, the size of a (FDM) nano-naught would be around 0.15 millimeters. How one arranges the nano-naughts determines their ultimate ‘behavior’ (the ‘material’ manners) of the design. The nano-naughts can be organized into a predetermined variety of filamented patterns, trusses, scaffolds or porous solids that, depending on their intrinsic set-up, are designed to fulfill and reflect a melange of different functions and qualities. At this diminutive scale these would be impossible to build by any of the more common manufacturing techniques (such as injection molding, die-casting, or stamping).

The nano-naughts are arranged into molecular groupings called ‘nano-nodes’. These minute clusters are again combined into slightly larger clusters (denominated ‘micro-clusters’), which, in turn, are bunched into slightly more sizable groupings, and so forth. This ascending process of mutable, almost fluid, clustering, bundling and knotting continues until the design finally emerges. By manipulating the redistribution and regrouping of these geodesic patterns at each increment, the final singular massing, the design, can be provided with a variety of different properties. Such, almost ‘biomimetic’, material procession, avoids the usual ‘surfacerness’ or ‘nurbness’ of more generic CAD design. Its materiality forms an innate component of its conception.

A clue for how such interests could be actualized has been provided by, a somewhat unlikely source of research, a study exploring the replication of bone tissue suffering from osteoporosis (Sisias, Phillips, Dobson, Fagan, Langton, 2002). In short, the study explores, through the use of physical modeling using stereolithography, how to simulate the tectonic set-up of cancellous bone. The project has developed a programmatic model of the ‘taberculae’, the cris-crossing lace-work of thin bone fibres imbibed in bone marrow. By adjusting the settings of the guiding algorithm a number of different level and kinds of, call it, ‘porousness’ have been achieved. These, in turn, have been physically modeled into five-centimeter, stereolithographed, cubes, which then can be tested under various strenuous conditions. Such structural tessellation, built at a scale reflective in many ways of the one this study is exploring, provides a number of comparable and useful hints for how to realize some of the above mentioned notions.

For example, by allowing some of the fibers of the (avaterial) matrix to be thicker in one direction and a bit thinner and longer in another (the points between and within the nano-nodes) will result in the physical model having more strength in the one direction and more flex in the another (assuming the innate properties of the (RP) material used allows for this). Or, by adjusting the ‘density’ of the matrix (the size of, and distance between, the nano-nodes), one can control the ‘solidity’ or ‘porousness’ of the avaterial. Also, by, say, connecting and shaping the fibers of this ‘digital-shrubbery’ to follow a weaved, spiraling, spring-like, pattern, one can provide the design with a controllable ‘boucne’ (or a degree of ‘softness’).

Organizational methodologies

If the initial stage provides the ‘alphabet’, the semiotic elements that define an avaterial, this, the second phase, aims to equip it with its ‘gram-
This aspect of the project is being developed in conjunction with Sean Hanna, Siavash Haroun Mahdavi and Jamie O’Brien from the University College of London (UCL), Department of Computer Science, and the Bartlett School of Architecture (http://www.geocities.com/ideolog1/groupwork/index.htm: Apr. 2003). Along with working on the logistic set-up of how such elements could be controlled manually this segment of the study is also exploring how various programmatic procedures could be utilized and contextualized into the RP mode of conception. Here some of the parameters suggested by the cancerous bone simulations are taken as an originating premise, and re-appropriated them in a tailored format to benefit the interests of this project. This involves the production of about one hundred, twenty-millimeter cubes in which a genetic algorithm (GA) is used to evolve the small-scale internal structures of a material that can be manufactured through the use of a rapid prototyping process, in this case a stereolithography machine. The geometry of these cubes is based on a lattice connecting points in three-dimensional space, in effect miniature space frame structures.

In these initial tests the geometry will be optimized for high strength under compression, and low mass. On account of some irregularity in the structural properties of the resin at this scale (bonding between the fused layers the brittleness of thin members over time), the fitness of each generation will initially be tested physically. This involves testing the twenty-millimeter cubes under compression until failure, and weighting their mass. A procedural virtual model will then be derived from these tests. The objective is that after several generations of physical tests, a function algorithm may be found to map the results to a set of virtual models created by standard structural analysis software (such as SolidWorks Cosmos - a finite element analysis program). Subsequent generations of the GA will then use this software technique to calculate the fitness of individuals rather than physical tests. This mapping will then be used to allow for more complex forms to be evolved virtually, potentially even without the need for physical testing (this doesn’t exclude physical modeling for alternate reasons, however). The evolution of these small samples is adopted as proof of concept that may be extended to produce more complex forms, in which the internal space frame varies its geometry across the object. Conceived in this manner the fine scale structure would be optimized at every point for the inherent forces at that specific point, creating an organically evolved and responsive fabrication (http://www.geocities.com/ideolog1/groupwork/index.htm: Apr. 2003).

Physical fabrication

The final phase involves the actual physical fabrication of designs, based upon the sentiments above. This phase shouldn’t be perceived as the conclusive stage, as the process is not necessarily linear, instead it should be considered analogous to a 'bleeding' stratum in an amalgamation that in cohesion forms and defines the project. The process is always going to be mutually and simultaneously reciprocal and interdependent. Aspects of this phase are being explored in affiliation with Professor Brian Derby, from the Manchester Material Science Centre (MMSC), a material scientist with a comprehensive grasp of the material and the accompanying procedural side of the subject. In this instance the approach is to allow the materiality of the process to supply clues and suggest criteria for how the digital realm would need to be adjusted, and vice versa. It is hoped that by looking into how the RP machines themselves, and their accompanying materials, function and
behave one could establish a more naturally assimilated and comprising process for how to conceive designs through this, still somewhat idiosyncratic, medium.

As worthy examples of somewhat similar or related interests and inquests involved in exploring the tangible execution aspect of RP production one could mention the research currently conducted at the University of Southern California, under the guidance of Professor Behrokh Khoshnevis. He has developed a system called 'Contour Crafting' (CC), (a technique somewhat similar to fused deposition modeling), that aims to produce large-scale structures (up to the size of a building), using uncured ceramic materials. (http://www.rfc.usc.edu/~khoshev/RP/ISAPaper.pdf: Jul. 1997). Contour Crafting is an additive fabrication process that uses computer control to exploit the surface-forming capability of a trowel to create smooth, accurate planar and free form surfaces. Complex surface shapes can also be created with the manipulation of various trowel tools. Because of its scalability and its ability to produce smooth surfaces, CC lends itself, as a technique, to the construction of sizable structures. Application of this automated method is envisioned for most building structures, but as entry level applications low income housing, emergency housing and submersible housing may be considered (Kwon, 2002).

The other relevant case comes from 'Materialise', a Belgian company specializing in the production, software and hardware aspect of relevant prototyping. They’ve developed a stereolithography machine, called the ‘Mammoth’, that is able to produce items as big as 2100 X 640 X 490 millimeters in a single build (http://www.materialise.be/PressReleases/MammothStereo_ENG.html: Oct. 2001). What these two samples prove is that it can be done; that in comparison the aspirations of this project aren’t too ambitious. Considered in affinity with the earlier intellecctions, the physical aspect of the study should, with time and patience, be realizable.

The Designs

“The ocular bias and the visual hegemony in the art of architecture have never been more apparent than in the last thirty years, as a particular type of architecture aimed at a striking and memorable visual image has predominated. Instead of an existentially grounded plastic and spatial experience, architecture has adopted the psychological strategy of advertising, of instant persuasion, and buildings have turned into image products detached from existential sincerity.” (Pallasmaa, 1996)

It is through the implementation of the designs that the sensory notions are brought forth. All the designs included are derived from a predominantly non-ocular perspective. They each have a catalytic theme, derived from one of the five generic senses Aristotle defined for us already two and half millennia ago. Three projects spawned from three senses that, from a more customary architectural context, could be deemed the most difficult to interpret.

Even though each design ‘originates’ from what is understood as a single sense, the inherent ‘synaesthetic’ quality (the idea that perceptual senses never ‘perceive’ in the singular, but always involve concurrently a number of ‘overlapping’ senses - smell & taste; aspects of touch, hearing & vision, etc.) of perception plays an essential role in the conception. In all of the following designs the rapid prototyping mode of production plays a fundamental and congenital role.
Design ground [architectura tactilis] (a design induced by the haptic sense)

Is a design that manipulates the ground surface by various means such as differing its consistency at discrete zones, consequently making it 'softer' or 'harder' according to need; having its surface follow a binary pattern, similar to that of fish-scales, that correspondingly can be used to indicate a direction, both by tactile (the scale-pattern is more smooth in one direction than the other), as well as visual means. This surface pattern can also be raised or lowered (making it more or less pronounced), skewed, twisted, or, by inclining a whole surface area, angled or sloping. These various properties can then be given diverse meanings. If, say, used in the context of a sidewalk, the main 'walk-path' can be indicated by applying the fish-scale pattern, its consistency could also be made similar to that of a running track - soft enough not to harm the knees, but firm enough to provide sufficient friction. The street side curb can also be 'felt' due to the subtle inclination downwards towards the spine of the sidewalk (the curb being slightly elevated from the center of the sidewalk), the texture of the surface could also be more pronounced, rougher, as one approaches the curb, allowing one to 'sense' the ledge before actually observing it. Even though the design needs to be produced in segments (tiles) it remains without scale, organic in its conception, entailing that no two segments need to be the same, allowing the design to freely 'flow', potentially infinitely, from one condition to another. The design can be applied both to inside as well as outside surfaces.

Oral architecture [architectura ambrosia] (a gustatory design)

Inspired initially by a text describing how rapid prototyping is used to make time-release pills that would be impossible to be made by any other means (pills with precise and complex time release characteristics, or that dissolve almost instantly).

Here the site is the mouth (the oral cavity, lips, tongue, teeth, thorax, etc), in which an 'architectural-tidbit' (a chewable and digestible item you put in your mouth) interacts with its vernacular. Here the gustatory logistics are analyzed from a more spatial, procedural, mechanical, tactile, olfactory, and culturally semiotic (architectural?) angle. This entails exploring how the various layers of the tidbit dissolve and collapse, and how...
they consequently interact with each other. The project also attempts to consider how things such as saliva, the pace of chewing, the motility of the tongue, and how the disparate flavors commingle and interact.

Olfactory architecture [architectura fragro] (a insinuative fragrant stratagem)
"Olfactory geographies are like haptic geographies, both are quite intimate yet ordinary much neglected as our attention is drawn to the geographical knowledge generated by the eyes and ears." (Rodaway, 1994)

The aim was to make a design as subtle and discrete, yet as expressive and catalytic as a fragrance. A design that is sensed and felt before it is comprehended.

The design forms discrete interventions, interacting with its surroundings through evocation, rather than provocation. Like a benign parasite it conjoins with existing conditions, buildings and beings, stealthily adapting itself to what’s there. The design is a nuance, filling abandoned cracks in walls and pavements, old air-outlets, the space between a wall and the drain pipe, abandoned or broken key holes. Powered, triggered and spread by the wind, the draft from a swinging door, the flapping of pigeons’ wings, a sneeze. The design being 'mechanical' in the sense a termites-nest, a spiders-web or a beavers-dam is mechanical, fulfilling its aims in a comparably congenital manner. The design can be adjusted to acknowledge and respond to diverse conditions, releasing a citrusy scent in the morning to perk up passers by; a more lavender-like smell in the late afternoon, to relax ones stiffened shoulders.

In Conclusion

“Suddenly an experience inverts the virtual and phenomenal. We negotiate space with our legs and arms. A twist and turn of the body opens new perspectives. We feel light with our skin, smell the qualities of space, taste the sweetness of time. The marvelous phenomenal powers of architecture draw us into a space-time cyclone.” (Holl, 1997)

Here the aim was to provide the digital realm with a physical paradigm, to unite the two in a circumstance where they not only co-exist, but merge. The tools for achieving this are the senses, or sensory perception, the component that plays an innate and equal role in both dimensions of conception. Consequently the project ‘feels’ its way forward, embedded with an ‘empirical-naivete’, of sorts, where the desired end result is suggested instead of predicted, attempting not to prove a pre-supposed idea, but trying instead to deduce an appropriate understanding of how the various parties involved might perform in concordance, rather than in hermetic diffidence. The study is currently dealing with the intimate and immediate aspect of how RP can be utilized, both as a catalyst and means, to discover and reveal its tangible or substantive side, analyzed here through designs that can be grasped, and hopefully appreciated, without necessarily involving the eyes (the non-ocular realm). How to expand such ambitions to a more traditional architectural scale, a magnitude beyond the immediate reach of ones
limbs and epidermis, is one of the questions this study is attempting to resolve.

References


