

RAPID PROTOTYPING IN EARLY STAGES OF ARCHITECTURAL DESIGN

by

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RAPID PROTOTYPING IN EARLY STAGES OF ARCHITECTURAL DESIGN

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Abstract This thesis shows how architects can use Rapid Prototyping and what the advantages and disadvantages are in different manipulations of the tool. Chapter two attempts to chart a road map of the rapid prototyping media. The data were drawn from a number of first hand experiments conducted by the author as well as by colleagues in MIT School of Architecture and Harvard Graduate School of Design, and in actual practice.

The whole research lies on the boundary between virtual and real, on physical prototyping from a digital file. Digital prototyping and manual prototyping are mentioned only as references.

The research offers examples of manipulations of the media and conclude that rapid prototyping in preliminary stages of design is most appropriate when used in what is defined as Direct CAD (Computer Aided Design) with Direct CAM (Computer Aided Manufacturing). Furthermore, it identifies Semi-Direct CAD with Direct CAM as the manipulation most commonly used by architects. This manipulation is useful for presentation models but not very useful in early stages where ideas are less definite. This is the reason why rapid prototyping is generally considered inappropriate for early stages of architectural design.

Instead of analyzing Rapid Prototyping technology this work concentrates on the process that involves Rapid Prototyping in new ways in design. It aims to stimulate the designer's imagination when thinking about three-dimensional design, design in motion and design at the interface between people and architecture, for example, chairs and kitchens. In this context Rapid Prototyping becomes merely a vehicle by which the architect explores the design process. Rapid Prototyping is proposed as a media to escape the limitation imposed by flat screen representation in what is defined as true three dimensional digital design.

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This technology was invented in engineering to increase design and manufacturing process performances. Recently with architects using it together with Rule-Based Design, Rapid Prototyping assumes the role of a tool for design thought in the sense that it speeds up the process of unlearning all the bad conventions of the first industrial revolution, the dark machine age, and throws light on both flexible and cellular manufacturing.

The conclusions of my thesis are that change in design is inevitable; that it is difficult to realize the power of change of this technology before one uses it. Socrates skepticism about the value of the book suggests that even wiser people misinterpret the implications of the "new" technology.

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PREFACE

Mitchell writes: "We all know the story of how the Industrial Revolution altered architecture forever, so we need not to rehearse it in detail here. Cities become larger and more complex. Mechanical and electrical systems were introduced into buildings and became increasingly important. New materials (particularly steel, reinforced concrete and glass) and industrially produced construction components opened up unprecedented structural and organizational possibilities. It became necessary to document building more completely and precisely in drawings and specifications and to apply formalized methods for predicting cost and performance. The technical complexity of the architect's task increased, and the architect's role became more sharply differentiated from that of the builder on one hand and from the engineering consultant on the other. A framework of professional licensing, contractual relationships between members of a building team, and assignment of professional responsibility and liability developed and acquired legal status."

Thank you Industrial Revolution! What a list of boring activities for the architect.

Indeed the Industrial Revolution brought many wonderful things, but hidden, or not so hidden, in between the good things there were bad ones too. All these things, both good and bad became conventions over time. The Digital Revolution was particularly fast in embedding all past conventions, especially the bad ones. There is nothing wrong with the technology, rather it is the minds of the people that changes much more slowly. My work aims in the direction of questioning everything in the process of architecture with the hope of eliminating all the bad conventions from the past.

Industrial Revolution has not only brought, but has also taken away both good and bad things that couldn't fit in the machine age. My work aims to retrieve some of the good things that have been lost because they didn't fit in the machine age, the dark satanic mill age, but should not have been lost.

Computer Aided Design has brought designers away from material properties including surface roughness, strength, thermal properties, elasticity etc. and the physical world characteristics including gravity. The CAD office generally looks more like a managerial suite than a builder's workshop. Rapid Prototyping has the potential to bring the material back into the architect's studio and give the designer that "feel" of the artifact that had disappeared.

Mitchell curiously highlights that "The Industrial Revolution of the nineteenth century spread through most of the world in less than two hundred years. Computer revolution has spread throughout the world in just a few decades. It has been an order of magnitude faster than the Agricultural Revolution." Two thousand, two hundred, twenty years are the recorded data for the three revolutions. Is the Digital Revolution over already?

Mitchell predicts "that there will be a de-skilling of designers - a development closely analogous to the de-skilling of craftsman that took place in the Industrial Revolution of the nineteenth century." Has the de-skilling of architects reached its end?

ON DESIGN REPRESENTATIONS

(rapid prototyping in the larger picture)

Imagine two designers at work; they are designing fast, their process happens in a fluid manner.

One's design is marvellous, the other one's is ugly. To an external observer the designers appear as if they are doing the same thing, but obviously they are not: what is the difference?

Marvin Minsky in his course, "The Society of Mind," provides an infinite array of little theories or ideas of how the mind works. His work may also be useful if one wants to build an artificial mind, but it is definitely essential if one wants to use one's own mind better. One of the wonderful characteristics of our mind, Minsky tells us, which makes it so complicated to reproduce artificially is the capacity to switch representations whenever we get stuck, or better, just a nano-second before that happens. It seems that we do this instinctively, but if one is aware that it is happening, one can encourage a faster rate of switches. By switch representations, I mean the capacity to abstract oneself away from the problematic situation and look at it from another perspective.

How does this relate to the design process? Terry Winograd tells us that the most popular motto at Xerox PARC, the highly successful research center in the sun of Palo Alto, California, is: Build what you see, use what you build. If one imagines building in its widest meaning, this motto could be adapted to produce a new representation and use it. This may appear an obvious approach, but we have to remember the great mistake of Artificial Intelligence and as far as I see, of most of design today consists of planning first, executing and then monitoring, just to be able to realize afterwards that the plan had little to do with what really goes on in the process.

What can one do with these switched representations? One can look at, listen to, touch or smell the new representations in search of analogies with some piece of previous knowledge and if an analogy is found, one can think of the next step in the analogy stored in the brain then map the rule found in the next step of the analogy onto the present design problem. In this way one gets unstuck and proceeds to the next step until one gets stuck once more, applies new representations and goes through the loop again.

In looking at the design process from this point of view, we find that the instance of getting stuck is not negative, but on the other hand it is necessary to proceed. If a designer doesn't get stuck she should start to get worried, because that would mean that she is repeating a preset series of rules, much like a dumb machine. Repeating a set of rules can be negative if something has changed in the design problem and by definition something has always changed from one instant to the next. One now should be able to see the difference between the two designers mentioned above. The process of the first designer appears fluid because she is very fast at switching, the one of the second designer, because she is following a predetermined set of rules.

Analogies with previous pieces of knowledge seem influenced by the amount of knowledge stored in someone's brain or in the sum of brains of a design team, but most importantly by the variety of knowledge stored. Also crucial to the retrieval of knowledge is the fluidity in the way the knowledge is stored and the dynamic procedures used to access that knowledge. One's mind does all the above regularly, but increasing one's awareness of the activity improves its performance.

Analogies have to do with accessing knowledge. It seems that people access the knowledge in their brain according to the way in which it was stored: for example it is different to remember from drawing than to remember from hearing.

Imagine one had to design an artifact quickly, for whatever reason. This represents a rather common case for an architect. To imagine more accurately, I rely on a real design exercise I did recently. As soon as one starts designing, one gets stuck. This is also a common experience among architects. Aware of the above and equipped with one's kit of freshly oiled switches and one's list of available representations, one decides to conspicuously run the experimentation.

What does it mean to switch representation in design? Well, it is possible to go from plan to section. From section to axonometric, to isometric and to oblique axonometric and many others. Perspective views are also very different representations. These we can call traditional design representations. Provided that one has access to a workshop, one can build the same first little idea depicted in the plan and other 3D representations in physical models. Also very commonly used are the exercises of switching representations by changing scale and adding colors. Good designers all use these methods of becoming unstuck. We all know them.

Digital design media are an infinite source of different representations and once they have been mastered, it is hard to think that it is possible to ever get stuck for more than a few seconds. The sensation with more and more developed software is that the machine is speaking back to you. Getting stuck in front of a machine for more than a few seconds would be like getting stuck in a conversation for more than a few seconds; it would be very unlikely and unusual. What kind of representations the machine speaks back to you is another matter. More useful conversations occur with certain people, and therefore are very much in the hand of whoever wrote the software. In a CAD software one can find all conventional representations, and this may change in the future when today's traditional design representations become obsolete. It also generally provides rendering algorithms in addition to wireframe and hidden lines. More specific software extensions provide analytical contour maps of light, thermal, finite element, computational fluid dynamic analysis and, in fact, any other analysis that one may think appropriate. For example it is possible to use the representation of an analytical contour map of the degree of continuity of curves in every point on the surface. Software of this kind is highly developed in the world of ocean engineering where the control of the curvature of propellers is of vital importance.



Fig. 1 Saitama Station Plaza Design by Takehiko Nagakura

These analytical contour map representations can lead to very interesting analogies, as for example is very clearly expressed in MIT's Professor Takehiko Nagakura's Design Entry for the Saitama Station Plaza in Japan. (fig. 1). In this design the basic properties of rendering algorithms, such as the reflection and diffraction of light are expressed at public scale.

Rule-Based Design Media provide another set of radically different representations. AutoLisp, Minipascal and Java are some of the different coding languages. Automated Shape Grammars are particularly laborious representations of designs when applied rigorously, but even when applied loosely prove to be amazingly powerful representations for their characteristic of self-generation. Rule-based Media representations of the design do not easily lead to analogies, but this may be partially due to the fact that designers are not generally familiar with designing by numbers.

Geometrical forms can always be approximately represented by mathematical formulas. This particular formulaic representation is simplified by software and for example, it is very often used in the office of the American architect Frank O. Gehry to approximate free-form shapes to meet construction constraints in this period of transition from dumb construction and manufacturing processes to smarter ones.

Design can also be represented by spoken or written words and surely it is this representation that is very often combined with others. How many times by explaining a drawing to someone else during a review, does one clearly discover the next step?

Rapid Prototyping Media form yet another set of representations. They are much newer ones and much more primitive than the Digital Design Media and are of less common interest to architects, therefore the evolution of its use in architecture is slower. They are also mainly confined to a few selected fields, namely manufacturing engineering and industrial design and this does not help the multi representational view necessary for rapid prototyping media representations development. However the potential so well captured by Brick Holtzmann in his poem on Personal Manufacture (page 43) promises a development possibly more astonishing than Personal Computers. Manufacturing in fact accounts for more than 50% of the total income of any industrialized country! As an effect of this, Rapid Prototyping, which could be seen as an intellectual brother of Rapid Ubiquitous Manufacturing will grow very rapidly.

How can Rapid Prototyping assist architects? To put it simply, it provides different representations of the design under development. But closer inspection shows that it provides a full system of unexpected representations. All through the process and not only in the final product, the representations are unusual and different from more conventional Digital Design Representations. Tessellated surfaces, millions of sections, mesh grids and partitioning of the design to fit the limitations of the machine are some examples of this kind of unexpected representation. Different surface tessellation lines can inspire

unconventional and more economical ways of structuring the artifact. The actual prototype is only an additional representation to the intermediate ones, surely sometimes the most telling one, primarily in regard to the materiality of the artifact. In chapter three I will look more carefully at what kind of stories the actual prototype can tell, mainly by providing examples.

The five types of manipulation of the Rapid Prototyping Media, as we will see in chapter two, provide different kinds of representations. It is therefore very important to determine which type of manipulation one is going to use in relation to the kind of representation expected. Manipulations can vary from typing numbers in a text editor to drawing in a parametric solid modeler software or encoding geometry in a programming language. This characteristic gives to the media a particularly wide array of representations, many of which are unexpectedly different and inspiring. One can predict only so much in advance, but prediction is determined by the success of the experience. Far too often people expect something by using rapid prototyping media and they are deluded. I will give 25 examples of what not to do in chapter four.

RAPID PROTOTYPING MEDIA

Introduction

This chapter comprehensively explores the realm of Rapid Prototyping Media from the most direct manipulation to the most indirect or mediated. For each of the five categories I look at the level of CAD and CAM skills required, the computational constraints involved, the advantages and disadvantages, the relative cost involved, the level of accuracy, and provide examples. I also attempt, based on the criteria mentioned above to describe the design activities that each category can support.

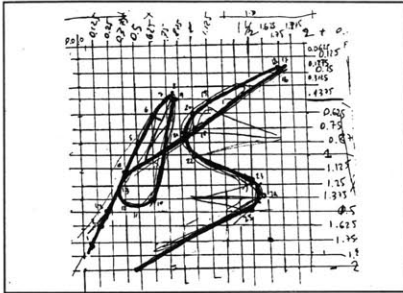


Fig. 2 Sketch on graph paper



Fig. 3 CNC milling of aluminum tile

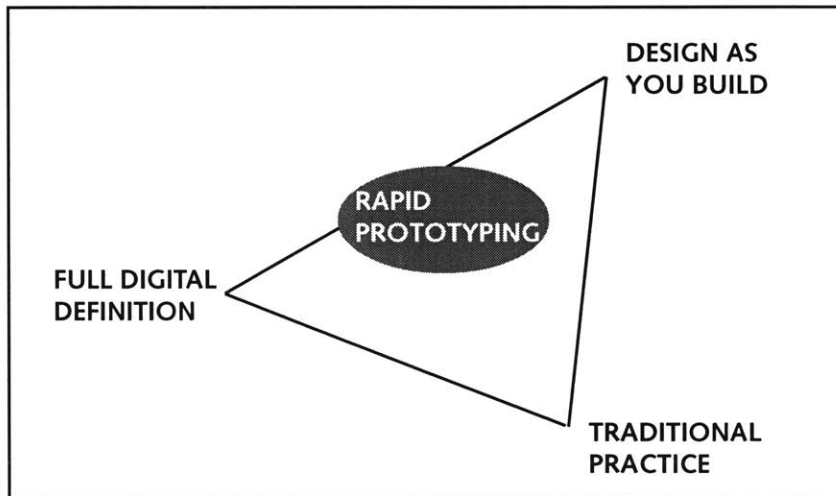


Fig. 5 Rapid Prototyping space

Direct input (no CAD), direct CAM and manual assembly

When automation was first introduced with NC (Numerically Controlled) machines, this level of manipulation was the only one possible. Traditional machines were equipped with servomotors and would accept instructions through a punch card reader. Nowadays it is hard to find these types of machines, at least at MIT, and most shop machines are either Computer Numerically Controlled (CNC) or manual. Having said that, the interaction with, or the manipulation of, the machine at this very low level is still very possible.

The CAD skills required for this process are nil; in fact there is no CAD involved. What one can do, is to write a file in any available text editor in machine readable language, called G-code. One will specify a number of instructions including the type of tool, the speed and then a list of coordinate positions in separate numbered lines. On the other hand, the CAM skills required for this process are very high. One has, for example, to manually position the material to be machined, position the tools at the origin, manually activate the cooling and so of this process are that there is no CAD investment, and no computational constraints by definition, because there is no computation whatsoever. Most of the disadvantages are evident, but perhaps the

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:
N001G70G00G90G40T1M6
N002X.0625Y-1.7500S4000M13
N003G00Z.1
N004G01Z-.0125F5
N005X.1250Y-1.6250Z-.02000
N006X.2300Y-1.5000Z-.02500
N007X.3750Y-1.1250Z.01000
N008X.5000Y-.8570Z-.08500
N009X.6250Y-.6250Z-.08500
N010X.7500Y-.5000Z-.08500
N011X.8000Y-.4375Z-.08500
N012X.8400Y-.5000Z-.08500
N013X.6250Y-1.3750Z-.08500
N014X.5000Y-1.4500Z-.06000
N015X.3650Y-1.4000Z-.04000
N016X.3000Y-1.2750Z-.02500
N017X.3750Y-1.1250Z-.02000
N018X1.0000Y-.7500Z-.06250
N019X1.7500Y-.2500Z-.01000
N020X1.8500Y-.1875Z-.02000
N021X1.7500Y-.1875Z-.03500
N022X1.1250Y-.5000Z-.08500
N023X1.0000Y-.6250Z-.09500
N024X1.0000Y-.8000Z-.1
N025X.9000Y-1.0000Z-.1
N025X1.0000Y-.1.2000Z-.08500
N026X1.5000Y-1.2500Z-.08500
N027X1.5000Y-1.5000Z-.09500
N028X1.6250Y-1.9000Z-.1
N029X1.4000Y-1.9000Z-.07500
N030X.5000Y-1.8750Z.0.0000
N031G00Z.1
N032M02

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Fig. 4 G-codes to run CNC machine

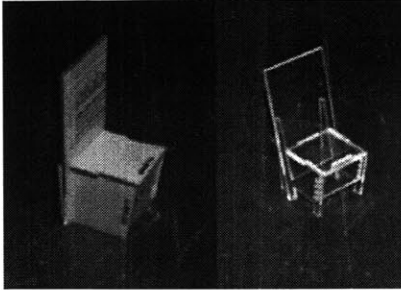


Fig.6 First & second prototype

main theoretical disadvantage is represented by the idiosyncratic quality of the codes. Once you have produced your codes, you can probably run them on that CNC milling machine only, to obtain the desired result. Even though the syntax of the code will be read by almost any CNC machine the grammatical structure of the code would not be understood by another machine and thus the output would be very different.

Figure 4 shows as an example a G-code written for a 3-axis milling machine. Figure 3 shows the design machined by that piece of code on an aluminum tile.

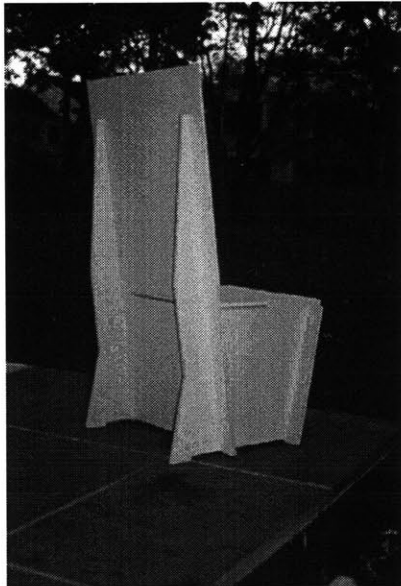


Fig. 7 Third fullscale prototype

It maybe interesting to notice how many operations, can be used to instruct the machine in this very simple way. It was told to me, by shop operators, that they instruct most operation on a CNC machine in this way. Design activities that can be supported are very dependent on the mediation of the machine itself. What is possible however is to easily shape very strong materials like metals.

Direct CAD, direct CAM and manual assembly

With direct manipulation, I refer to the process of drawing in the same CAD software that produces the instruction code to run the automated manufacturing machine. Generally this software has minimum modeling capability, and allows modeling only in two and half dimensions.

The CAD skills required are minimal, only two dimensional digital drafting skills are necessary. The knowledge of CAM required is very high. The user has to know all the variables of the machine and keep them in mind whilst drawing the design. Because so little computation is involved, the constraints of the software are very limited.

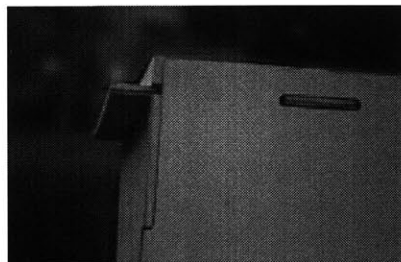


Fig.8 Close fit connection detail

This kind of manipulation, because it is not cumbersome and it is rapid, support at best those design activities at early concept architectural model and study models. Because of the almost nonexistent computational constraints is also the area of maximum potential for the Rapid to influence the design process.

The cost of the equipment is relatively low, and more importantly it is limited to the CAM part, because the CAD capabilities come for free with the CAM software.



Fig. 9 CNC router cutting the chair

Often the user is drawing on the station next to the prototyping machine and the time from idea conception to physical prototype is reduced to the minimum, sometimes only a few minutes. Imagine one is asked to design a chair out of sheet material; one may sketches one side of the chair and then cuts it with a flat template laser cutter. In a couple of minutes the piece is cut. One looks at it and draws the other side, but from the first cut-out template one has already learned that the armrest is too low. So before cutting the second side one modifies the arm rest to a more appropriate shape. In a couple of minutes the second piece is cut. At this point one realizes that the back has to

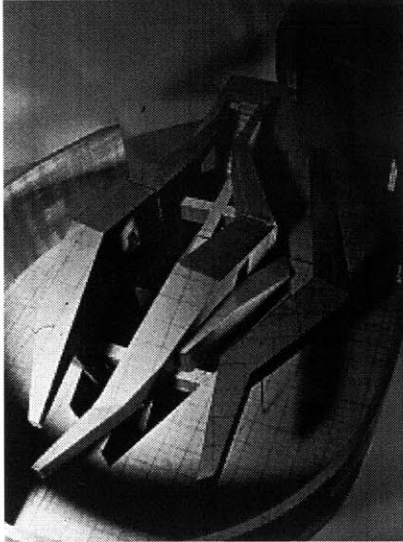


Fig. 10 LOM model of ASE Design Centre

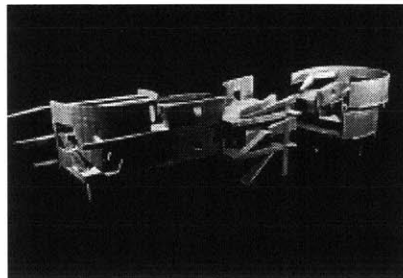


Fig. 11 LOM model of ASE Design Centre

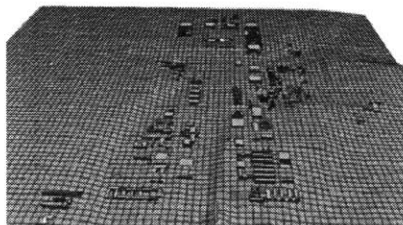


Fig. 12 CAD rendering of the Mall, WA

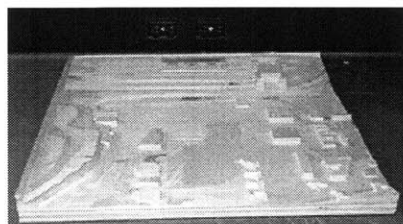


Fig. 13 CNC routed wooden model

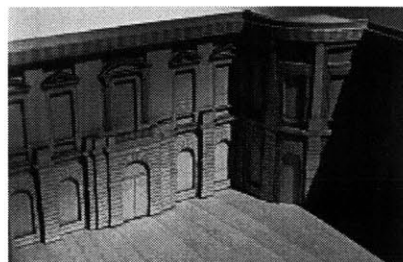


Fig. 14 Laser cut model of existing, Berlin

interlock with the two sides, but the two sides are different to one another, the back piece has to be drawn asymmetrical. In another couple of minutes the back piece is cut. One can now assemble the three pieces. But they don't fit or the prototype of the chair is unstable to lateral forces. One then starts all over again.

The example of the box chair was developed much in the way explained above. The objective chosen by the designer was to design a chair as close as possible to the shape of a box. The first prototype (fig. 6) looks like a box, but the pieces don't lock together, the back is too vertical and because of the long edge in contact with the ground, the chair would stand still only on a perfectly even surface. These issues amongst others are addressed in the transformation of the design shown in the second prototype. The contact surface is maximized in the attempt to achieve a solid lock of the parts. (Fig 8). In the third full scale model in wood the locking of the parts is resolved and the supports for the back are more robust. (fig. 7) From the test of the third model further improvements were suggested to achieve higher level of comfort by improving the flexibility using geometry transformation.

In this kind of manipulation the return of information to the designer proved to be the most significant. This manipulation is very dependent on the limitations of the CAM machine. If the prototyping technology is of the same family, as in 3-axis router or injecting molding, of the final manufacturing process machines, this manipulation is particularly informative for the field of Design for Manufacturing.

Semi-indirect CAD manipulation, direct CAM and manual assembly.

I refer here to the process of preparing a drawing in a software specifically dedicated to CAD, usually a surface modeler, equipped with more or less sophisticated CAD algorithms and then translating to CAM using .dxf translation files. The CAM process is direct in the sense that one directly manipulate the material and the instruction to the machine and manually assembles the parts.

One should have great confidence with the CAD software and know how to use all the sophisticated algorithms that the software provides and be confident with the different representations of complex curves and double curved surfaces, namely splines, B-splines, Bezier and NURBS curves and surfaces, in order to successfully perform this manipulation of the media.

The CAM skills required for direct manipulation are limited to some very intuitive steps that can be learnt very quickly.

Most commonly because sophisticated CAD software does not sit at the station next to the machine, the process is less informative to the designer than the direct CAD, direct CAM. The file translation and the physical translation from a drawing environment to a machine environment usually makes the process more cumbersome. All sort of problems like scale, position of the origin, units, different readings of layers

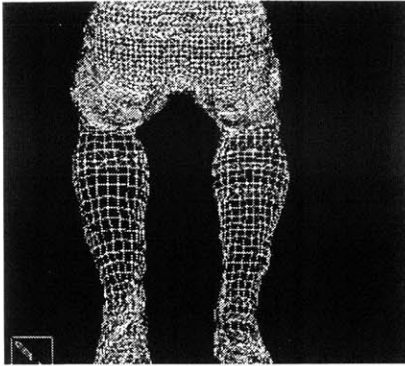


Fig. 15A Custom chair, digitized CAD mesh

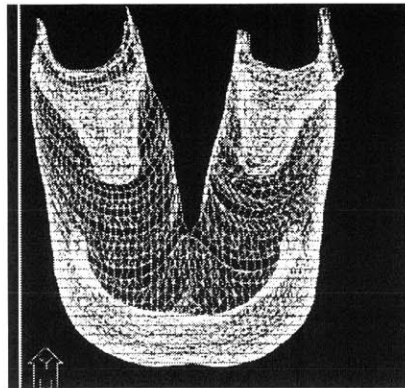


Fig. 15B Custom chair, digitized CAD mesh

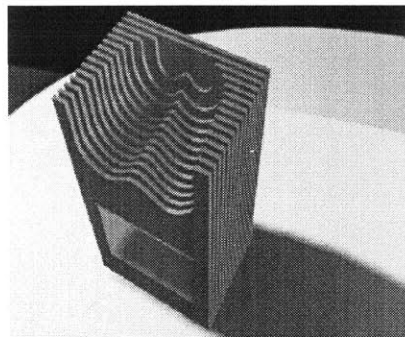


Fig. 16 CAD rendering

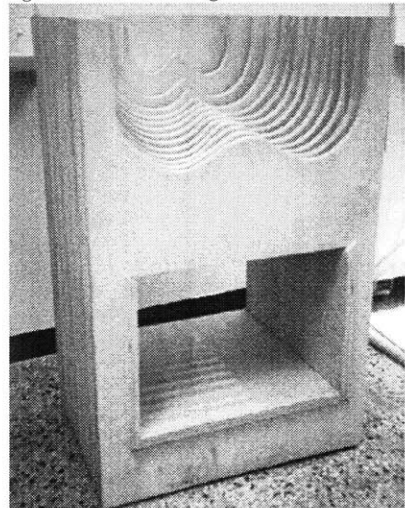


Fig. 17 Full scale wooden prototype

and curve representation, line thickness occur regularly and require substantial editing at the CAM station, which interferes with the continuity of the stream of thought.

The advantages of this kind of manipulation are related to the possibility that one can detach the geometrical constraints of the machine process from the material geometry. One can prototype a three dimensional form into two dimensional template cutter by applying a CAD "slicing" algorithm, then give instruction to the machine to cut all the slices. Once cut, it is possible to assemble all the slices back together. In addition the maximum dimensional constraints can be obviated by breaking the design in parts in the CAD environment and then once cut, reassembling the parts together.

In respect to computational constraints to the designer, CAD software provides more and more powerful algorithms. These algorithms can be as dangerous as a fast car is when driven by a novice. Most of the time is very easy to loose control over what is going on in one's design and this can translate into disastrous mistakes. It is perhaps important here to remember the difference between having a good representation and being able to understand it. They are two very different things and cannot be confused.

Therefore this kind of manipulation best supports activities like site modeling (fig. 10-11) or presentation models for internal review and not so well the process of thinking while modeling. It must be said that this kind of manipulation is the most commonly used in the architectural community in both practice and academic world. Figure 10 and 11 is the model of ASE Design Center, Taipei, Taiwan, by the American architectural practice Morphosis of Santa Monica, California.

An example of this manipulation is the But chair; the cast of the anatomical shape of the back of a person (fig. 15) was digitized using a three-dimensional digitizer. Once the cloud of points was imported in the digital environment a mesh surface was approximated from the points. An oblong shape was created with which the mesh surface was intersected, rotated to the estimated correct position and subtracted from the oblong (fig 16-17). Sections at two inches intervals were abstracted from the resulting subtracted shape and saved in separate files. The files were then submitted to the CAM environment using a translation file and cut out of half inch plywood. One more characteristic of the But chair is that the assembly is made using close fit connections; no bolts or glue were employed.

All throughout the process in this project, I was told by the designers, few informative intermediate representations were found. Once the first idea was defined, the first informative representation came out of testing the prototype. Only at this point did the designers received the kind of feedback that could have led them to a development of the original idea. This represents a case in which a more indirect manipulation, like the one presented in the following section, would have speeded up the process and not taken any feedback away from the

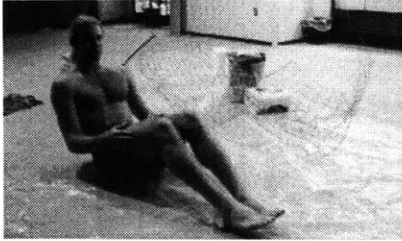


Fig. 18 Setting the body position

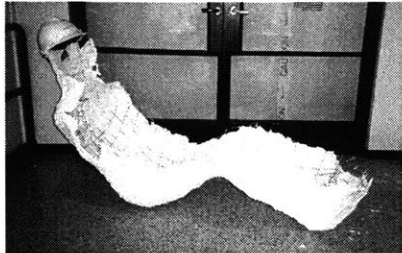


Fig. 19 Cast of the body

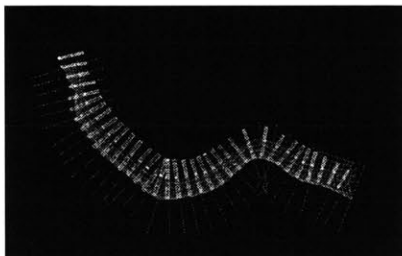


Fig. 20 Slicing the digitized mesh in CAD

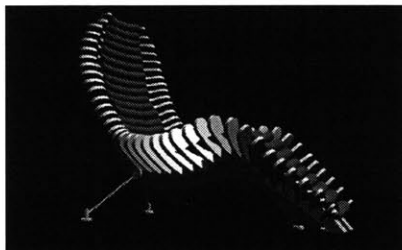


Fig. 21 CAD rendering

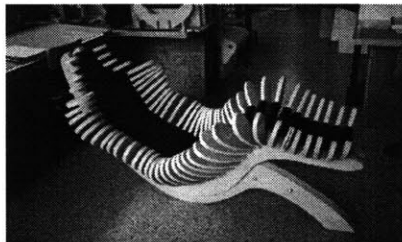


Fig. 22 The Dinosaur, physical prototype



Fig. 23 Testing the prototype

designers. Another similar example of this manipulation is offered by the Dinosaur chair of figure 18-23..

The relative cost involved in this manipulation is the sum of a fairly standard suite of CAD software running on a desktop graphics station and the cost of a CNC prototyping machine. These subtractive systems are found mostly in-house in universities and large architectural practices, but can be out-sourced to specialized workshops. Outsourcing to an external machine shop makes the process more cumbersome and less appropriate to early stages of design.

Semi-indirect CAD, indirect CAM and automated assembly

With semi-indirect CAD I refer to the process of modeling using a fully featured solid modeling software that provides the possibility of creating an appropriate translation file containing information about the characteristics of the solids.

With indirect CAM I refer to the family of additive processes including selective curing (stereo-lithography), selective sintering, selective deposition, selective binding (3DP) and sheet manufacturing (LOM). All these Rapid Prototyping processes share several characteristics relevant to this discussion and I will unify them under the generic name of additive processes. It is important to know that at closer inspection these processes are sometimes fundamentally different from one another.

Fully featured solid modeling developed relatively recently within the specific area of engineering and because of their specialized nature they have imbedded many characteristics specific to that field. Acquiring the skills to master CAD systems of this kind requires long exposure and long training. More importantly, because this software is often parametric, it requires a deep understanding of the geometry before one begins to construct the model. Furthermore, these models automatically provide a series of sets of information valuable to mechanical engineering design that forcefully constrain the modeling freedom and unnecessarily complexify the architect's work.

More recently the possibility to create sound translation files that contains the informations needed for an additive prototyping process is becoming available in CAD software more specifically designed for architects. In the future all CAD software will give one the opportunity to export sound translation files .stl.

The forced completeness of the description, the size of the CAD files and the RAM memory required to execute some of the powerful algorithms increases dramatically the cost of the CAD equipment required. Additive rapid prototyping equipment is also still prohibitively expensive. This is going to change in the near future, but currently no architectural office can justify the purchase and maintenance expenses

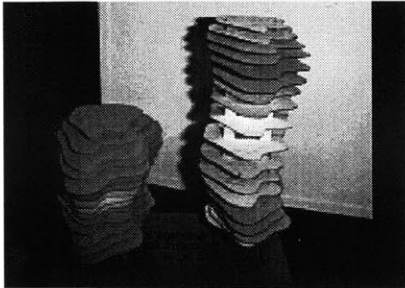


Fig. 24 Laser cut lamp shade

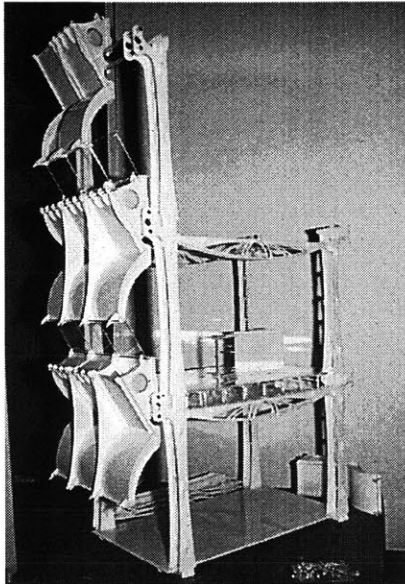


Fig. 25 Laser cut custom components

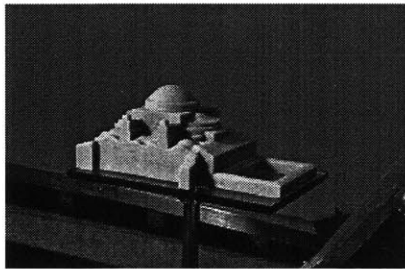


Fig. 26 Hagia Sophia. Laser Sintering model

of such technologies. Therefore the prototyping is always outsourced.

The disadvantage for the designer is that no intermediate representations are available. Every operation is fully automated. The advantage is that once the machine is properly set, to run a prototype is as simple as printing from a laser printer. No particular knowledge is required by the user.

For the world of the designer the great advantage is that no expertise is involved in the use of these three dimensional printers. For this reason a wider group of people, including those not interested in technology, will be and are able to manipulate these prototypes.

For an example of this manipulation please refer to the Hagia Sophia model (fig. 26) , the door handle design and the embassy design described extensively in chapter three.

It is important to point out that within the group of design for manufacturing, resident mainly in the field of engineering, but aggressively creeping into the field of architecture, the additive processes are misleading, at least until the additive processes are not going to take over most manufacturing processes. Rapid Manufacturing, proposed by researchers in the field of Rapid Prototyping, for example the 3D printing group at MIT, means that the outcome of the process is the final artifact. Until this development happens there evidently remains a mismatch between the making of prototypes and the making of final artifacts.

The freedom given by an additive process is much more similar to the freedom given by the digital design environments, as opposed to the constraints of the manufacturing and construction environments, in what is generally called "real world".

The process of Rapid Manufacturing conceptually bonds particles of nearly atomic size together to construct artifacts. The particles can be made of the same material or made of selected different materials. As an example, if two powders are used, steel and concrete, a reinforced concrete beam can be manufactured directly without castings and considerably more precisely. Silicon chip powder could be fed through one of the jets and the beam becomes smart. Optical fiber powder could be fed through the jet and the beam would become communicative. This would happen quickly, with no extra time expenditure; one would just need a richer digital file and different powders.

Today one sees the gap between true virtual world and the real world is being bridged; many of the reasons that designers previously used to motivate their designs are now wiped away. These reasons, when applied today, makes no sense any longer. Designers may have to look at pre-machine age to find the reasons why artifacts are the way they are and not different. Frank Gehry said "there is nothing I can design that we can't build".

```

.....
;; setting variable values
.....

:|
(setq 1stshape
  (getint "select 1st shape: cube, oblong or wedge: "))

(setq 2ndshape
  (getint "select 1st shape: cube, oblong or wedge: "))

(setq cube_side (getint "specify the side of the cube: ")
(setq hei (getint "specify the height of the wedge: ")
(setq leng (getint "specify the length of the wedge: ")
(setq xrot (getint "specify x rotation: ")
(setq yrot (getint "specify y rotation: ")
(setq zrot (getint "specify z rotation: ")
|

;; set the size of the cube
(setq cube_side 1)

;; set the height of the wedge--gable
(setq hei 0.5)
;; set the length of the wedge
(setq leng 1)

;; set xrotation
(setq xrot 0)
;; set yrotation
(setq yrot 30)
;; set zrotation
(setq zrot 30)

;; set the number of double rule application
(setq limit 10)

.....

```

Fig. 28 Extract from AutoLisp codes

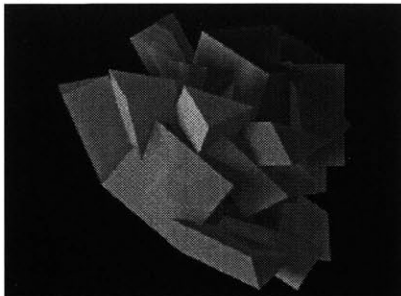


Fig. 29 CAD rendering of 3D design

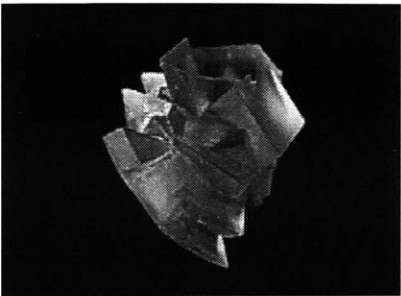


Fig. 30 Stereolithography 3D design model

Indirect CAD and Indirect CAM

By indirect CAD I am referring to the manipulation of CAD environment via scripting in programming languages graphic dialects like Minipascal, AutoLisp and Java. By encoding a sequence of code or instructions (fig. 28) one can generate a design and by tweaking the code one can modify the next steps of design. This manipulation has similarities in this context with the direct coding described in paragraph 2.1 at the beginning of this chapter. The main difference is the freedom provided to the designer by the coding environment and the power given by object oriented programming languages.

Indirect CAD requires programming skills and for this reason it is limited to a small number of architects, but this number is growing very rapidly. Indirect CAM as we already discussed requires very low CAM skills.

The most exciting and interesting part of the discussion in this chapter is regarding the computational constraints involved in indirect CAD manipulation. The curve of computational constraints that reached the peak in respect to semi-indirect CAD inverts the slope to drop down towards zero in Indirect CAD. Non-restricted shape grammars, in other words elegant sets of rules, deals with very low level vocabulary element, points and lines, and therefore would theoretically reduce the computational constraint to nil. Down the slope we find rule based design with high level programming languages that basically encode a series of CAD software commands to be executed by one user. These types of Rule Based design are still very restrictive, even if the fact of coding the computer may give to a naive user the illusion of being less restricted.

The computational power used by Rule Based Design is maximal, so the capital investment in Indirect CAD and Indirect CAM is the highest.

It is hard to summarize what design activities are best supported by Indirect CAD and CAM, because very little experimentation has occurred in the realm of architecture. There are some impressive examples of exploration of forms using this kind of manipulation (fig. 29-30) that someone with a positive approach can imagine as architecture, but none to my knowledge that have the characteristics that we would recognize in the architectural development process.

This I believe is partly due to the power of the tools. Once one has these tools available the design questions that lead from one step of the design development to the next, seem very obscure to many. Also most of the time people involved in this kind of research do not attempt to explain their process of thinking and their reasons of design. Issues of co-planarity, symmetry, parallelism, perpendicularity, axuality and repetitivity that are old questions of architecture become the

relevant questions.

As an example of these types of manipulations, one can refer to the non-orthogonal relation between a cube and a wedge explained in detail in paragraph 3.4.

As we mentioned earlier, we have now gone around the loop and we are ready to draw some possible conclusions on the way Rapid Prototyping in Architecture could evolve in the future. We will see in the scenario outlined under the title of Real Time Prototyping how Rule Based Design could directly prepare information for an indirect CAM system to produce a physical representation of the code.

GALLERY OF EXAMPLES

Introduction

This chapter focuses on four selected design projects where I applied different manipulation of the Rapid Prototyping Media. The projects focussed on non-trivial design problems and were conducted in parallel with the research on the tools used. The design was inspired by questions raised by the research and similarly the research questions were informed by the development of the design.

Learning from the pink chair

This project was produced as part of the Design Studio of the Future and although at this point I and my colleagues that worked on the project had little understanding of Rapid Prototyping Media, I still consider it one of my most interesting experiments.

What interests me in this project is the fact that the process of development itself sparked adventurous experimentation in dynamic/kinematic design. The idea of design in motion was not preconceived. Similar to the popular bean bag chair, the design explored dynamic progressive loading to overcome the fragile nature of the material selected, rigid pink building insulation foam. (Fig. 31)

The interaction with the Rapid prototyping media as defined in chapter two, is semi-indirect CAD, direct CAM and manual assembly. The design went recursively through several iterations. (fig. 32) The first sketches (fig. 33-35) and the first prototype shows the rational application of a formal spring technique with little understanding of the possibilities resulting from dynamic behavior. I want to question here if the evolution of the designer's thinking may not be a direct influence of rapid prototyping technology.

Because of the complex geometries and the uncommon properties of the insulation material, the designer could predict little on the chair's performance, comfort and solidity. It is primarily for these reasons that rational design transformations were difficult to implement using traditional or digital design media. Only prototyping and full scale fabrication could really suggest design improvements.

Little of the original sketch was conventionalized, simplified and abstracted, with all design transformations occurring as a product of rational design decisions taken from testing the full scale prototypes. The final artifact shows clearly the original "feel" of the sketch. This characteristic of the design of the chair created contrasting reactions, and opened interesting questions about the way free form is aesthetically perceived by people. In addition almost everyone thought the design was intentionally sensual. The nature of the curves is in fact perfectly rational, it has no intentional expressionism and was derived

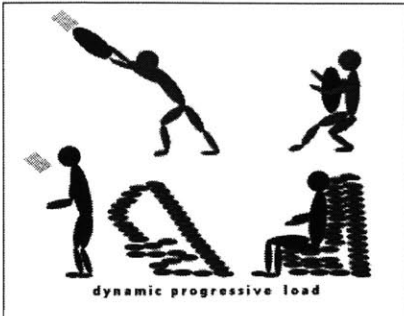


Fig. 31 Sketch design concept

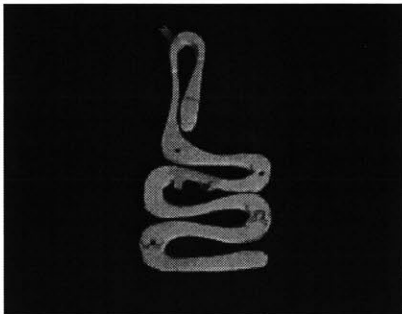


Fig. 32 First hand made prototype

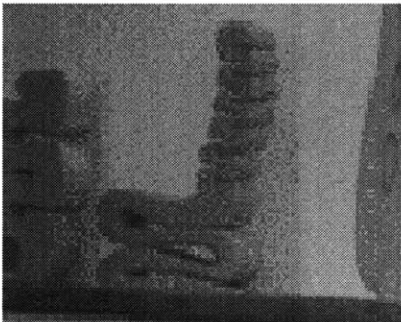


Fig. 33 First water-jet cut prototype



Fig. 34 Second water-jet cut prototype

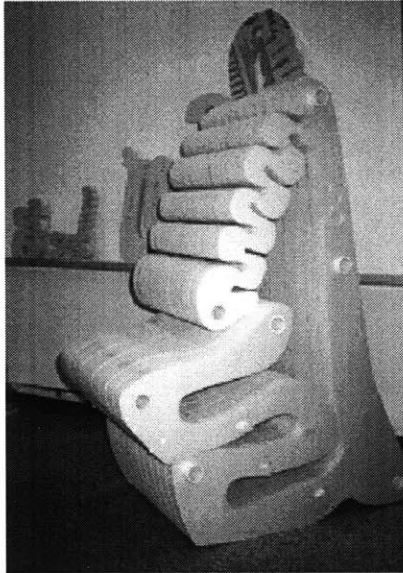


Fig. 32 First hand made prototype

strictly from criteria of formal spring and ergonomics.

In traditional design media, including sketches, hard-lined sections and hand made models it was very hard for the designer to think of an artifact that would perform dynamically. For example, a design like the bean bag chair, although very simple, is difficult to imagine in terms of drawings or CAD models. It is likely that a full scale prototype was made directly from an idea inspired by sitting on a bean bag or something similar. A series of design transformations may have then been developed based on the data gathered by the experience of sitting on full scale prototypes.

Now if one imagines scaling up the problem to the size of a large and complex artifact one first needs to produce a scale model. The model has to be made quickly and particular care must be taken with precise tolerances proportional to the full scale fabrication.

Rapid Prototyping Media may well contribute to these needs. Because of their high control and intrinsic possibility of manipulating tolerances, the medium allows the designer to achieve a clearer understanding of the behavior of the artifact at full scale. A further clear example of this application of rapid prototyping is provided by the images (fig. 36-38).

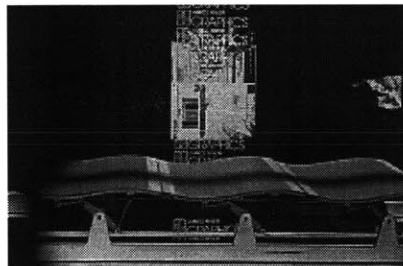


Fig. 36 Wooden model by laser cutter of a moving roof structure, closed

Sophisticated 3D CAD software allow the designer to construct and perform inverse kinematic testing for the interference of components. It is very hard to calculate the related friction between two components and the material stresses involved in the motion.

The luxury given by Rapid Prototyping of running off designs overnight can contribute to opening the mind of the designer to more adventurous explorations of designs in motion, much in the same way, as Seymour Papert points out, computer is helping to make people think more dynamically.

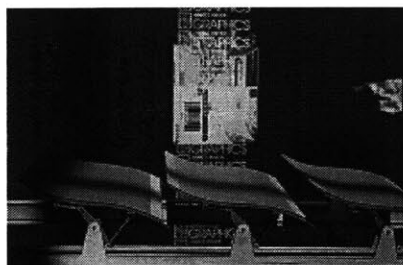


Fig. 37 Intermediate position

Learning from the door handle project

The door handle project was the opportunity to explore three main challenges: experimentation with rapid prototyping technologies, exploration of some research questions that arose during my recent studies and finally learning about the field of design for manufacturing.

First of all the project represented an opportunity to expose ourselves directly to yet another of the numerous technologies available for rapid prototyping. The technology chosen was the very fashionable stereolithography.

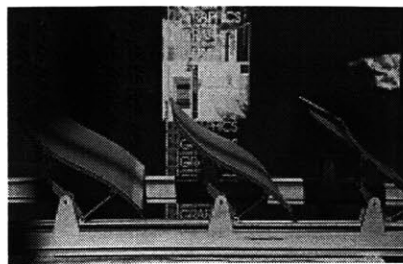


Fig. 32 Open position

Secondly, having concluded a research paper on how rapid prototyping in early stages of architectural design may help the designer to think in a different way, the door handle project began as an excellent opportunity to test some of the hypotheses of the paper. More specifically, the experimentation proves that rapid prototyping is a unique tool to assist

the designer in exploring haptic qualities and complex shapes of the artifact.

Finally the project developed together with Andrea Lamberti within the environment of the CAD/CAM course offered in Fall '96 at Harvard Graduate School of Design by Professor Dan Schodek and Volker Ruhl. Our professor's interest helped us to think, when at all possible, about the implication of the final process of making the real artifact since the early design stages.

In this paragraph I will reflect mainly on the second challenge, the testing of some of the hypotheses of the research paper.

The hypotheses of this experiment were: rapid prototyping is necessary from the early stages of design to control the haptic/tactile qualities and complex double curved shapes of those architectural elements at the interface with the human body: handles, handrails, chairs, light switches and most surfaces within the human reach. From this category of architectural elements, the door handle was chosen as a typical design exercise for architects.

Reflection on CAD modeling

Using Form-Z by auto-des-sys, a double curved complex shape was quickly generated by sweeping, scaling and rotating an ellipse along a path developing in three dimensions. Subsequently, using a bump library texture, a pattern was mapped on the complex shape.

It immediately appeared evident that the simple texture mapping algorithm proposed by the software was not able to deal with double curved complex surfaces.

Despite this limitation some views were created, which proved good enough for discussion. The project was approved by our professor and interesting discussions arose on how to write an algorithm that could pattern the bumps in an acceptable, if not final way. Suggestions by colleagues were directed towards an algorithm that would place the bumps along a spiralling path on the surface. The use of AutoCAD3D and AutoLISP was suggested, but the project was not pursued.

Although Form-Z has built in capabilities for solid modeling and file translation in .stl format, the format that contains the informations needed for the stereolithography machine, our .stl file failed to be read, after being transferred to the remote site, by the stereolithography machine's driving software (3DSystems) as well as by Pro-Engineer, the most common solid modeler software by Parametric Technologies.

Reluctantly, a new model of the double curved complex shape was rebuilt from scratch in Pro-Engineer. As Pro-Engineering is a parametric solid modeler, every entity of the model had to be specified in relation to datum planes or parent entities. Having built the model and having

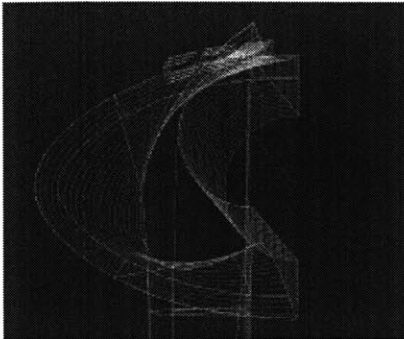


Fig. 39 CAD image of half doorhandle

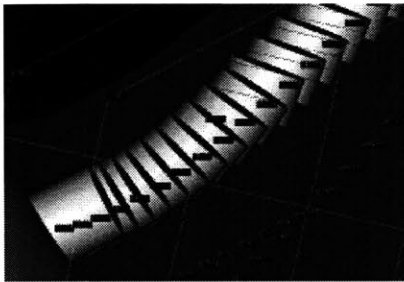


Fig. 40 CAD image of the bumps



Fig. 41 CAD rendering of new design

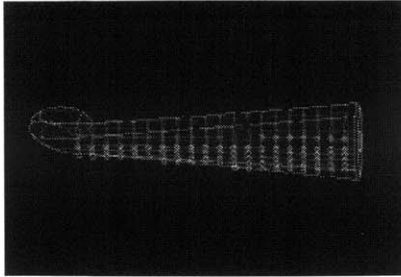


Fig. 42 CAD model, front view

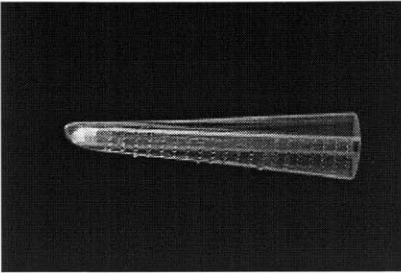


Fig. 43 Stereolithography model, front

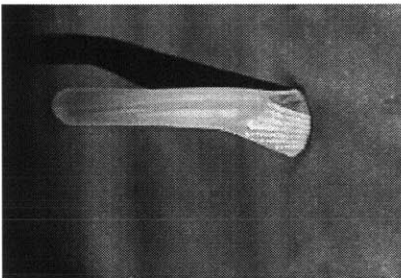


Fig. 44 Stereolithography model, side

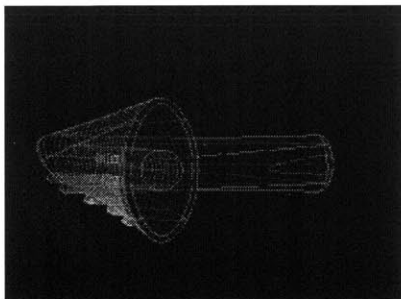


Fig. 45 CAD model, side view

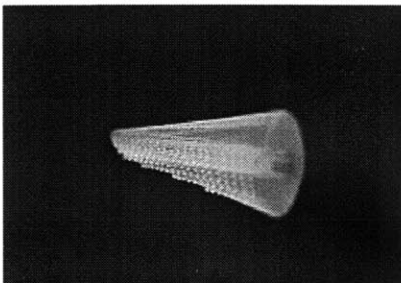


Fig. 46 Stereolithography model, side

placed every knob on the surface “manually” one by one by specifying three parameters per bump, we promised ourselves that deeper understanding of Form-Z’s capabilities in producing readable .stl files will be our next task.

Two personal comments on the Pro-Engineering software are the minimum possible after all the pain we went through by using it. First, the software only allows the building of models in a very different way from the one I, as an architect, think and design them. To think in advance of the definition and specification of six parameters when you are sketching the first generating shape is at the least very frustrating.

Secondly, perhaps due to my limited understanding of the software capabilities, one would imagine that all the specifications of all these parameters may reward the model’s builder when the model is at advanced stages. This was not our experience, simply because the rules underlying a late stage modification are much less linear and more complex than what the software seems to allow one to do.

Having said that, we should acknowledge the robust Pro-Engineering version17 for having given us the possibility of producing a sound .stl translation file and ultimately the physical artifact.

One of the things we learned that is generally unappreciated in academic architectural design environment is that when you deal with the real world of atoms, as opposed to the virtual world of bits, the robustness of the process and tools assumes crucial importance.

Reflections on the use of Rapid Prototyping:

The process of constructing in the solid modeling environment took a long time. During this time many colleagues looked at the attractive images on the computer screen. Several insights arose from those interactions. Most of the people seemed to understand relatively quickly and accurately the shapes, although not all of them. Furthermore, it is important to remember that the colleagues I refer to were almost exclusively from the body of students and professors from the Harvard Graduate School of Design and from MIT School of architecture, an elite of virtual 3D spaces manipulators. It seems plausible to imagine that a different response and accurate understanding, essential in a multi discipline design development team, would have come from a potential client, competition juror or project leader from the traditional school of design, not particularly familiar with 3D virtual environments.

On the other hand, when we presented our physical resin model produced by stereolithography to the final jury, everyone obviously understood immediately and accurately (even too accurately) the

complex double curvature shape.

When I asked Rick Smith, three dimensional CAD consultant for Frank O. Gehry and Associates, why they used extensively rapid prototyped versions of their CAD models, his first reaction was "to verify that the computer has the shape the architect (Frank!) wants".

A controlled experiment, submitting for accurate understanding the same 3D complex shape to a group of various consultants traditionally collaborating with the designer, may give us interesting insight. I can imagine interviews internally in the practice with: junior designer, draftsman and partner (old style) and externally to the practice with, the client, the quantity surveyor and cost consultant, the land surveyor, the structural and services engineer and finally with the contractor and builder.



Fig. 47 Testing of the STL prototype, side

With the project involving the attractive images on the flat computer screen, the best insight came from our own interaction with the 3D virtual model while during its construction. Questions such as: where should we place bumps on the door handle? Would it be better on the inside or on the outside, on the bottom or on the top? We could never agree, not only with each other, but also with ourselves! Should the bumps come out of the surface more or less, and where more, and where less?

After a quick analysis of the form of our hand, we decided that the elliptical section should had been swept and rotated at the same time along the path. But, how much should it be rotated? Would 90 degrees be the best rotation? Or would 45 or 39 degrees be better? And more than anything else, should we start rotating from an ellipse placed with the long axis vertical and end with the same axis horizontal or vice versa? (fig. 39)



Fig. 48 Testing of the STL prototype, front

If we assume that ergonomic form does not mean the mold of the human form, but something more complex that has to do with where the bones are, how load and strength distribute throughout the body and how long the interaction is going to last, as suggested by the Scandinavian design for seating that proposes a kneeling position as the best position for long hours of studying, our three-dimensional virtual model of the door handle was of limited or nil help.

We tried our best anyway, the bumps were placed where the fingers touch the handle, while the palm would interface with the smooth surface.

When we produced via stereolithography an accurate reproduction (precision was in the order of +/- 150 micron) much to our surprise, most of our assumptions, or design beliefs, appeared to have been contradicted within seconds.

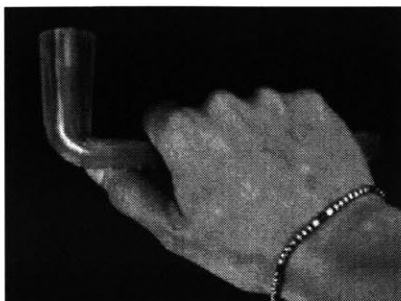


Fig. 49 Testing of the STL prototype, top

First of all, bumps of cylindrical shape of a diameter of 1/16", were too sharp and needed to be smoother. But more than anything else, even

though the rotation proved to be a good intuition, the door handle immediately, as several comments reinforced, proved to feel good as a hammer handle, as it is appropriated by the human hand along the axis of sweeping and rotation. When used by the human hand in the conventional way, as one would do with a door handle, it did not feel good at all.

During the construction of the 3D virtual model, for economic reasons, we decided to carve a hollow core in the handle. To do this operation we swept a circular section, with the diameter shorter than the minor axis of the ellipses along the same path and then we subtracted the solids. The rendering and the wireframe of the resulting solid model appeared correct.(fig. 39)

Much to our surprise, when the door handle was made, a hole in the top surface of the stereolithography model showed (too clearly) that in one portion the distance between internal and external surface was too thin to be manufactured. The mistake looked clear and evident in the rapid prototyped model, where it was almost impossible to spot in the 3D virtual model, without knowing in advance where to look.

Several other comments were addressed to the design of the rapid prototyped model and finally after long time working in the dark, we, as design architects, felt the joy of some real, convincing and helpful answers from our model and the excitement to go back to work and develop our design.



Fig. 50 Testing of the STL prototype, top

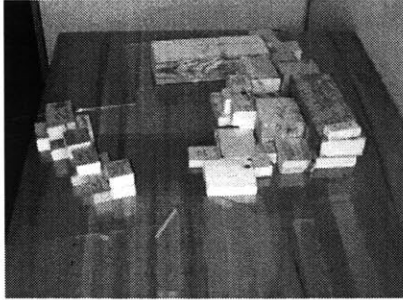


Fig. 51 Handmade wooden massing model south



Fig. 52 Handmade wooden massing model north

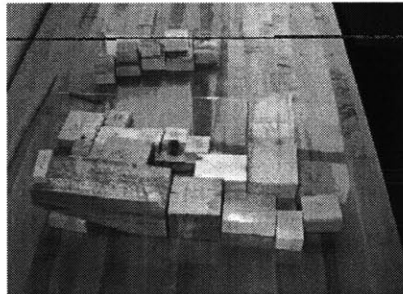


Fig. 53 Handmade wooden massing model east

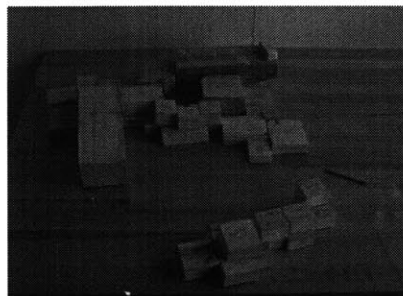


Fig. 54 Handmade wooden massing model west

Learning from embassy project

The US embassy for California project, similar to the door handle project described in paragraph 3.3, has been an opportunity to explore one hypothesis on how rapid prototyping can enhance the design process. The hypothesis was that rapid prototyping media is a unique tool to help the designer develop and understand complex geometries.

The embassy was a competition brief and was chosen for its complex non-trivial nature. The focus of the experimentation was on the early stages of the design process and not on preparing a project to enter the student competition. Below is a detailed description of all the steps of the design development that lasted for three months.

Brainstorming

Step one was a brainstorm session on the design brief with a colleague designer. Several ideas were discussed raised from a series of questions that we asked ourselves. For example, what an embassy reminds you of? Examples such as cities in Southern India, Temples Town, land and air ownership split of international terminals were discussed.

At the end of the brainstorming session we synthesized three main design criteria that were to help me in making decisions throughout the design process. The first was the dichotomy of welcome and security, the second was accessibility, the third was interdependencies, such as views out and across. We also decided that these design criteria should be tackled using primarily geometrical forms and only secondarily using technology.

I looked into nature to see how nature deals with the dichotomy of security and welcome. I found the rose that uses smell to welcome and spines to secure itself. I found the tortoise that uses motion to deal with the dichotomy: it looks cute and welcoming when his head is out and totally secured when his head is retracted. I looked at the moray where the pretty pattern of bright color is welcoming and the bite is used for security and finally I looked at crystal where transparency makes it welcome and toughness of its internal structure makes it secure.

Doubly curved geometric forms were chosen to be used to increase the external walls' impact strength, whilst the orientation of volumes was exploited to deal with the conflict between privacy and functionality issues, and the physical disconnection between structure and slab was used to increase security. Curved geometric forms were also used to give large opaque and secure surfaces a more welcoming look. And finally a curved geometric form was chosen, although unconventional to think about and to make, because it can solve many simple functional basic building problems like economy of structural support, rain

drainage, acoustics performances of large volumes and flow of ventilation and people inside the building to name a few.

Three dimensional modeling.

The second step was the transformation of the areas specified by a detailed written program provided by the competition committee into a three-dimensional scaled (1"=10') physical model hand made in wood. The rules of transformation were very few: the first rule calculates the side of a volume as the square root of the area, second rule calculate the height of the cube as two third of the side. Each one of the twenty five functional spaces in the program, for example the lobby/reception, the ambassador's office, the visa processing area etc, was modeled as a separate volume.

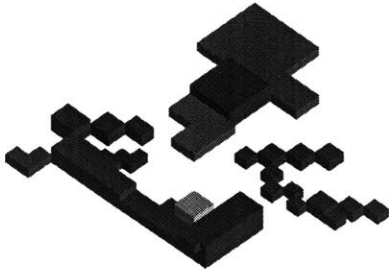


Fig. 55 CAD representation of volumes

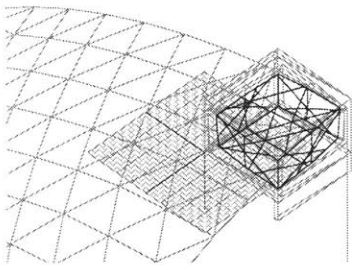


Fig. 56 Subtraction of a sphere sector

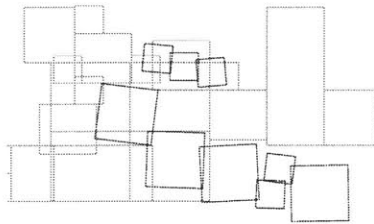


Fig. 57 Example of two spatial relations

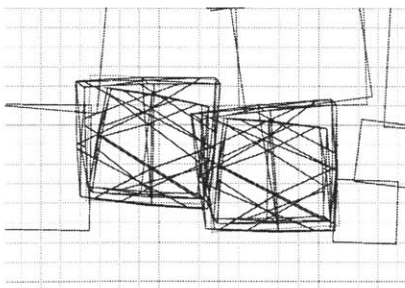


Fig. 58 First rule with curved vocabulary

All of the blocks were then arranged according to a functional relationship derived from common sense and some specific guidelines from the general competition program. A very large number of arrangements are possible (25 to the power of 25 for each spatial relation) and several may fit the functional relationship. There has been a discussion about a small computer program with no built-in intelligence that can produce at a relative fast rate several of these arrangements for the designer to choose from. Due to the shortage of time and my insufficient experience in programming, arrangement's rules were manually implemented.

The next step was the exploration of applying some degree of curvature to the surface of the blocks or vocabulary elements. It turns out that it is hard to decide how to curve flat faces, as there are infinite possibilities. Not all double curved surfaces look good. At this point I looked at how other architects choose to curve surfaces. Many of them, including the spanish architect Santiago Calatrava justify their curved surfaces through structural economy. I found in Frank Gehry, at least the way William Mitchell describes it in *Digital Design Media*, a unique example of an architect that curves plane surfaces for more traditional architectural reasons.

Mitchell writes: "In classical composition, rooms were related concentrically, with coaxial axes of symmetry, or with coplanar planes of symmetry. But Frank Lloyd Wright overlapped interior volumes in ways that (in his later work) carefully avoided these classical relationships. And many of Frank Gehry's compositions juxtapose volumes in ways that conspicuously avoid concentric, coaxial, coplanar, parallel and perpendicular relationships, while still achieving the basic functional connections that are needed."

I decided to apply some of the rules proposed by Mitchell to a vocabulary element. I deformed the cubes as little as possible, but enough to be able to read the intention of avoiding perpendicularity, coplanarity, parallelism etc. First I modeled it by hand using a block of wood, a bench saw and a sander. I quickly realized that the process was not

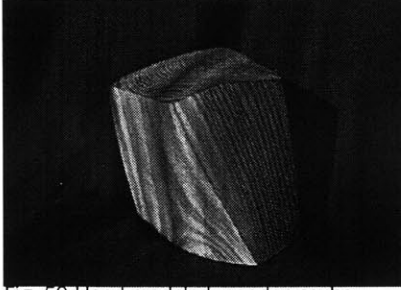


Fig. 59 Hand modeled wooden scube

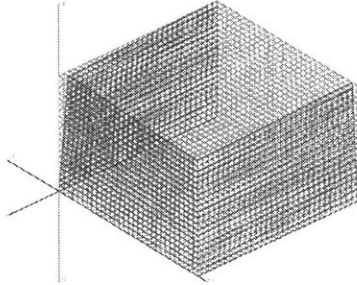


Fig. 60 CAD unreadable representation

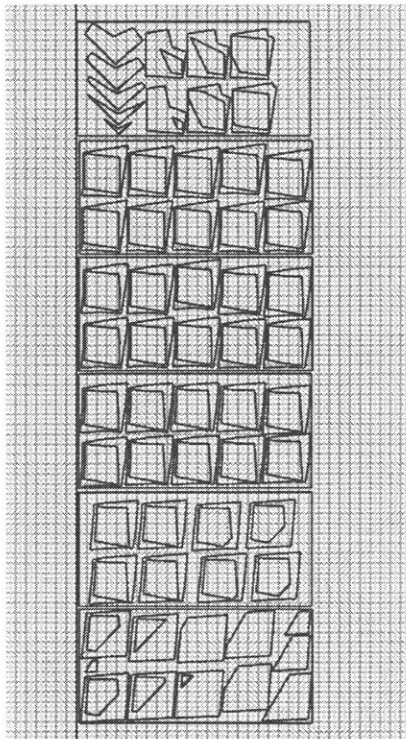


Fig. 61 Section lines laid on a plane

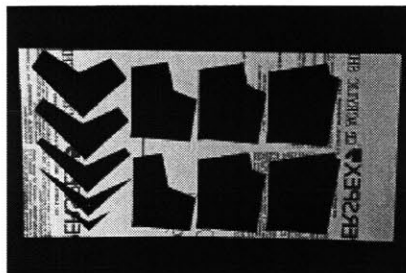


Fig. 62 Laser cut plexiglass from CAD file

accurate and get very time consuming. The notion of as little as possible obviously changes with scale; one degree rotation at full scale is feasible and may move the vertex a couple of feet, but in hand modeling at 1'/'8" (1:100) scale is unreasonable with normal time and skills constraints. Having said that the result of hand modeling proved very informative for discussion. (Fig. 59). In this experiment I have already found the limits of geometrical complexity that can be successfully supported by hand modeling media.

The next step was to import the blocks in a computer environment. I needed a solid modeler and my choice was form-Z. While I had found it very difficult initially to arrange the volumes once they were created and once the big arrangement moves were accomplished, I was allowed me to play around very effectively with small scale rearrangement: for example, rotate on a fixed plane, align with etc. Interestingly no inspiration or change in the arrangement occurred during the manual scanning into the digital environment. Once the main functional relationships were established, I explored the application of the rules to one vocabulary element. Again in this case the rich and accurate representation that the solid modeler environment provides became essential but was only just sufficient.

By moving the oblong's vertices, I eliminated parallel and perpendicular planes. The shape become immediately unreadable (fig. 60) on the stationary two dimensional screen representation. I could not even recognize the deformation on the screen. I therefore decided to cut out a rapid prototyped model of the Scube.

In the Scube, the geometry of a cube with non perpendicular faces was modeled in CAD as a solid, and a second cube with non perpendicular dimensions was placed in the centroid of the larger cube and subtracted from it (fig. 56). Then a slicing algorithm was used to produce the 69 parallel sectional cuts. The section lines were then laid out within rectangular boundaries that reflect the size of the maximum machine dimensions (fig. 61). The file was imported in the CAM environment and edited to instruct a laser cutter to cut it out of thin sheets of Plexiglass (fig. 62). The slices were then manually assembled.

The process of prototyping the Scube was informative from the designer's point of view because it created a series of intermediate process representations that were unexpected. While manually positioning one by one the section to fit the overall rectangular sheet of material, it is possible to learn more about the space in between. (fig. 61). One can by analogy imagine the hollowed Scube as an architectural volume. The representation of figure 61, originally generated to provide cutting instructions to the prototyping machine, gives information of where the internal and external cubes come to contact. One for example can define those points of contact as a starting positions for windows. Furthermore one can think of how to allocate secondary sections. The side of the checkers used for rendering is two feet to

functions like circulation and services in the poche. The animation frames of fig. 63, rendered with a checker grid of two by two feet, gives a good sense of the spatial constraints of the space in between the internal and external envelope of the volume.

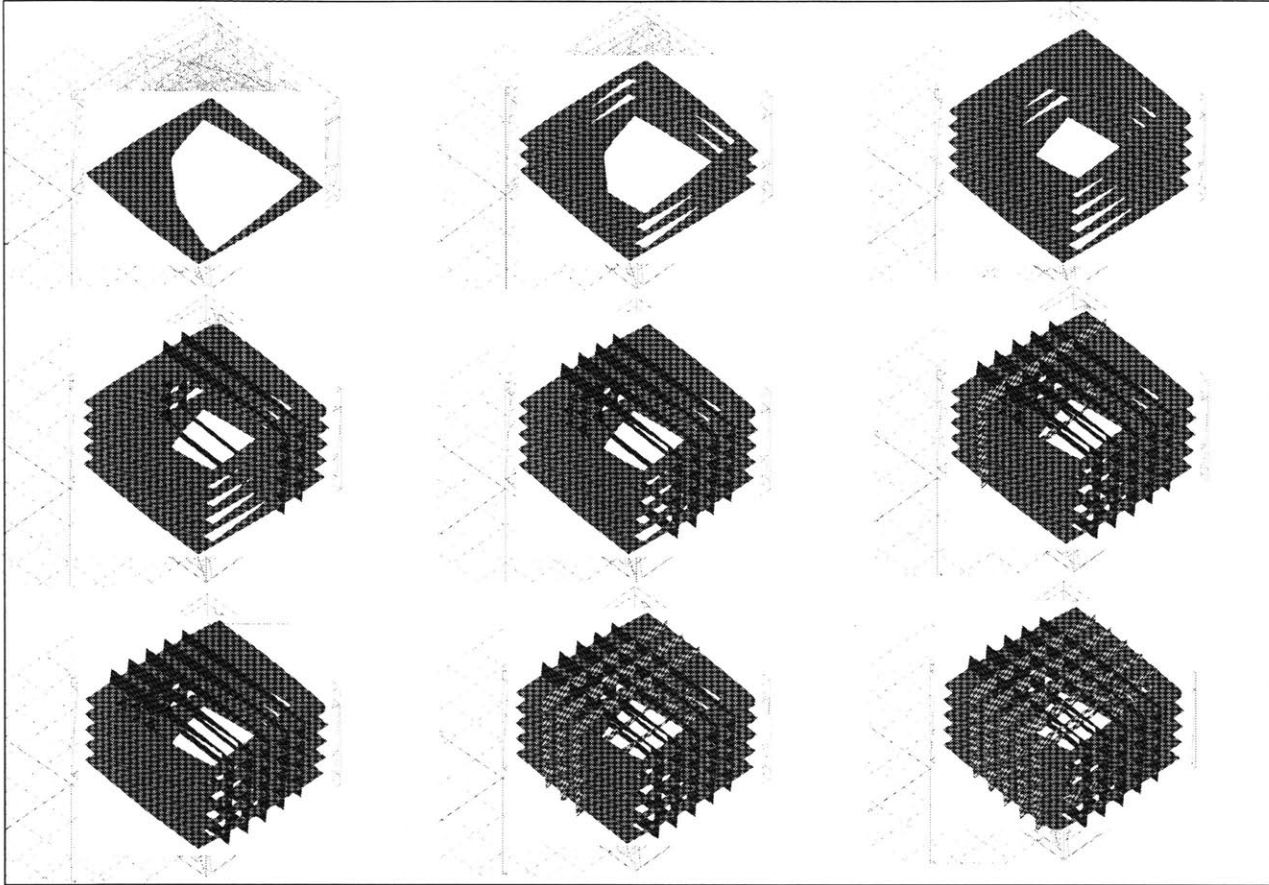


Fig. 63 Animation frames rendered with a checker grid (2'x2')

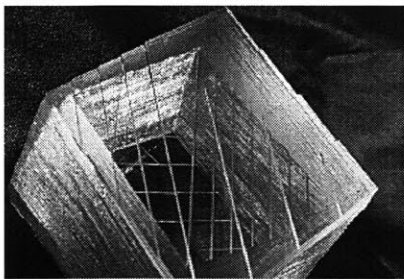


Fig. 64 Laser cut plexiglass prototype view

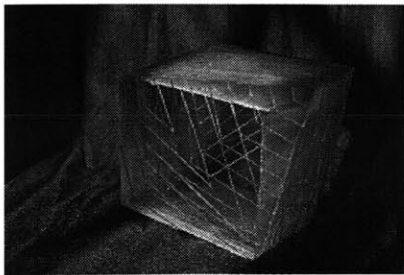


Fig. 65 Laser cut plexiglass prototype view

The physical model showed immediately the incorrect representation of the shape in the computer (fig 64-65). To construct a proper representation in the database, I created a new cube and using Boolean operations I subtracted first a knife shape to eliminate the perpendicularity of the oblong's faces and then a sector of a sphere to avoid parallelity and coplanarity of the oblong's faces. The new representation (fig. 56) of the Scube vocabulary element was now well represented in the computer database and I could replace it in the assembled design of the embassy.

One further boolean subtraction of a copy of the Scube that had been scaled, rotated and mirrored in respect to its centroid allowed me to hollow out the vocabulary element. I was concerned to create an interior shape that would not coincide with the external shape(fig.63). I was interested in creating poche spaces to be used for building services, including structural, mechanical, electrical and computational building services. The poche spaces allow for circulation at the vocabulary elements' intersection, much the way they were used by baroque architects. To understand the space in between I created a sequence of

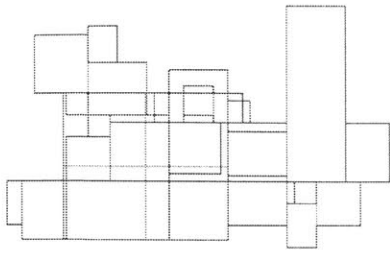


Fig. 66 First functional arrangement

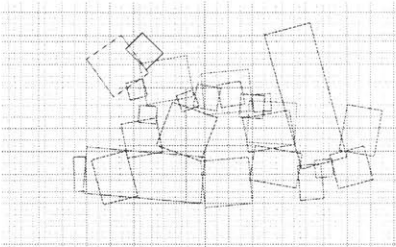


Fig. 67 Non-orthogonal spatial relation

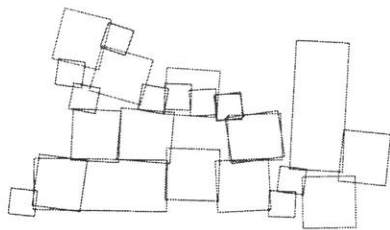


Fig. 68 Loose application of the rules

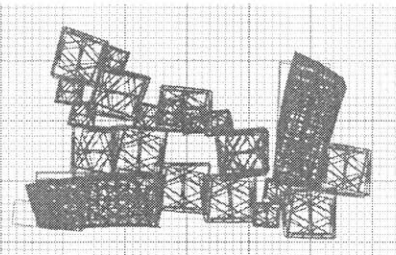


Fig. 69 Non orthogonal vocabulary and spatial relation, plan view

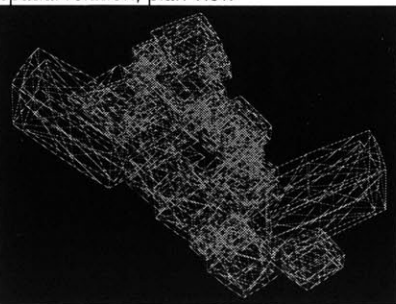


Fig. 70 CAD wireframe, axo view

increase the readability of the space. (fig. 63)

Once I was satisfied in terms of design with the transformation of the vocabulary elements, I substituted them in the previously defined arrangement of blocks. Because of the orthogonal spatial relation between the vocabulary elements, the overall embassy complex maintained underlying symmetry, planarity and axiality.

At this point I went back to the layout of the cubes arranged in accordance to the functional relations and rotated all the elements. (fig. 66) I had achieved a more interesting composition, but I was not convinced by the random application of the rotation rule.

At this point I decided to look at the most recurrent way of intersecting and I defined two spatial relations (fig. 57). One would allow the combining of adjacent elements and the other would deal with elements intersecting at their vertices (fig. 58). I also approximated all the elements in four types as shown in figure 57.

My attempt to apply the rules in a strict shape grammatical way failed several times. Attempt to use subtracting rules and a parametric application of the rules also failed. It is possible that part of the failure was due the cumbersome interface of the tool being used. I therefore decided that as it was a grammar, it could still be a valid composition if it was applied in a loose manner. (fig. 68)

Once all spatial relation were regularized in the plane, any further operation in three dimensional space became very hard to perceive and an overall understanding of the spatial relationship become impossible in the standard digital design environment. I noticed that some volumes seemed to retain axiality in the plan view, despite all transformations, but seemed not to have any in the three dimensional view. Standard set views in CAD programs are valid to understand convex compositions, but become insufficient with concave ones.(fig. 70) Other environments including VRML or immersive environments are aiming to enhance the ability of the designer to manipulate more complex geometries.

However I chose for Rapid Prototyping Media. In light of the discussion of chapter two, I chose an indirect manipulation using a formative process to cross the boundary between digital and physical worlds, in other words to go from bits to atoms.

In preparing the file to be exported, I learned a further lesson, much of the software on the market pretends to support solid modeling, and there is a commercial reason for doing it, but few of this software supports the user in a solid modeling environment from the beginning to the end of the design process in a robust and easy to use fashion. All sorts of problems can happen; for example solid transformations can be

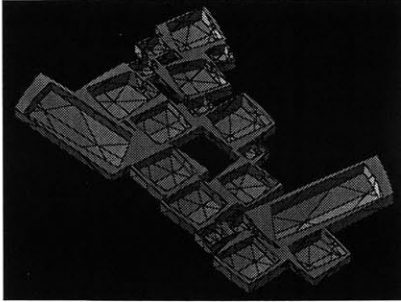


Fig. 71 CAD file for manufacturing, level1

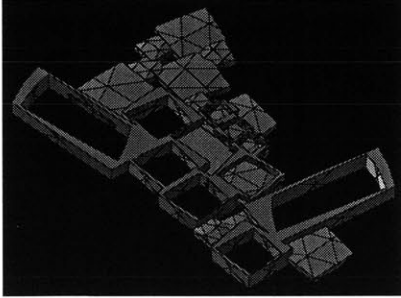


Fig. 72 CAD file for manufacturing, level2

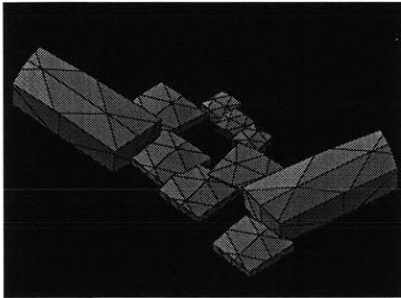


Fig. 73 CAD file for manufacturing, level3

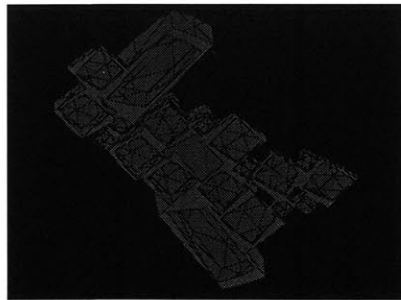


Fig. 74 CAD file, level3, bottom view

applied only once to the objects, and not the second time.

With relative approximations a physical representation was created using Laminated Object Manufacturing (LOM) methods in a service bureau. Once the physical model was created I could as a designer understand what the composition looked like, and how it could be improved. I could also show it to and discuss it with experts in spatial design who were unable to understand the model in the virtual environment.

This experiment ended with the exploration of the design composition of the massing model. Further steps would have been to prototype a larger scale model of two or three exemplary elements to explore the way in which the two shapes interact, and to start thinking of a possible way of construction. A more direct manipulation of the rapid prototyping media would be appropriate to this next stage.

In conclusion, this project overcame its own goal of proving that rapid prototyping is an essential tool for the designer when dealing with complex geometries, by showing the richness of exploration and the great number of discoveries and insights that a non-trivial design problem can afford.

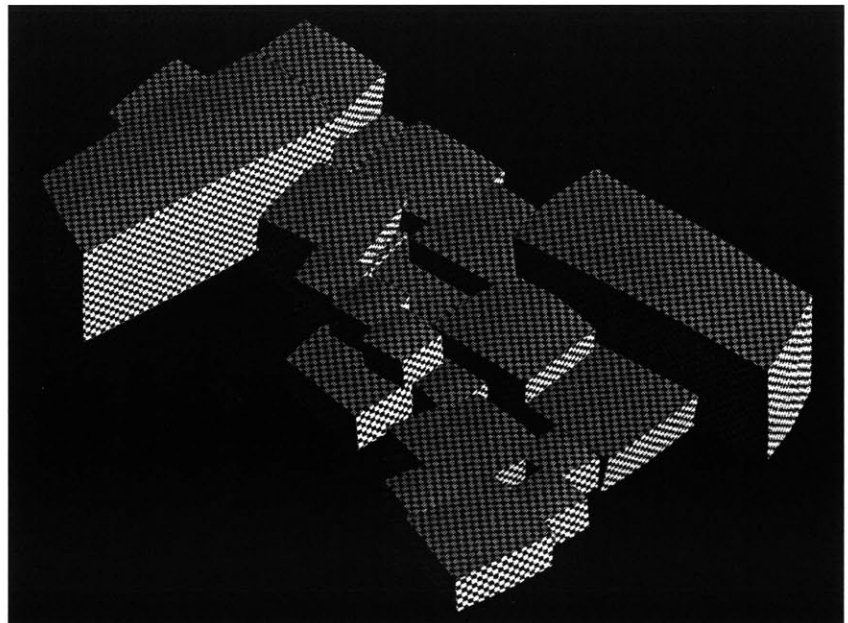


Fig. 75 CAD rendered axonometric view

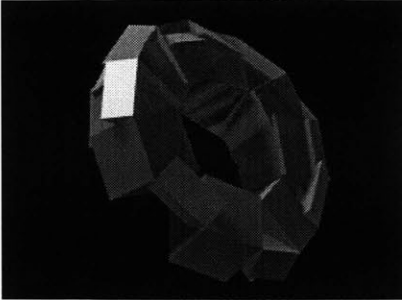


Fig. 76 Design 1, CAD rendering

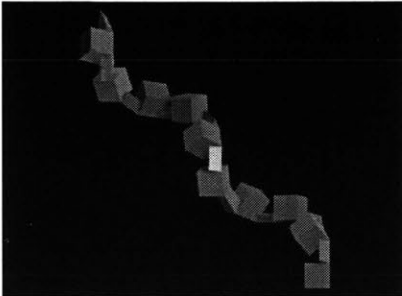


Fig. 77 Design 2, CAD rendering

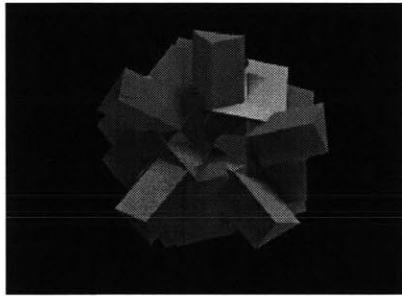


Fig. 78 Design 3, CAD rendering

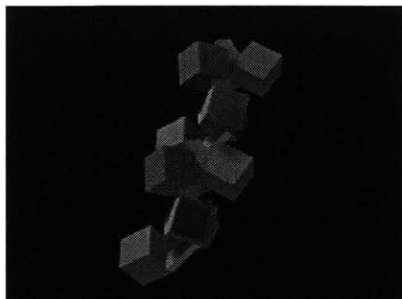


Fig. 79 Design 4, CAD rendering

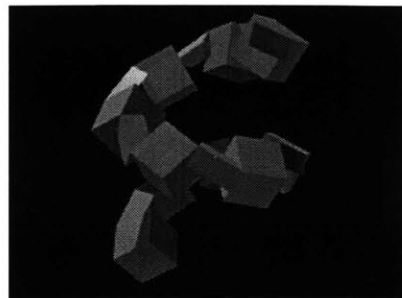


Fig. 80 Design 5, CAD rendering

TRUE THREE-DIMENSIONAL DIGITAL DESIGN (TTDDD)

Introduction

Three-dimensional physical modeling as a less abstract representation for early stages of architectural design, if compared with two-dimensional representations, is becoming standard practice in the most successful schools and ateliers across the world. Architects generally use malleable materials such as laminated foam, clay and light wood to make their first model. Most of the time is dedicated to the choice of glue, a good glue can determine the success of a three-dimensional representation. Glue is the hottest topic of discussion in the designers agenda, in a much higher priority than contemporary design theories.

For example recently at the Harvard Graduate School of Design a student discovered a new glue, named Zap-a-Rap, a bi-component glue made in California, that solidifies in twelve seconds, about ten times and faster and stronger than any other used previously. The student who introduced it rapidly become the star in the studio; pilgrimage to his desk to see a live demo went on for days. Still today the student gets recognition for his discovery with everyone looking at him as the master.

Physical architectural modeling of highly three-dimensional spaces is a difficult and time consuming process, yet it is entirely necessary and has to be precise because in a presentation, it is what everyone will concentrate on, no matter how well drawn the section is, or how flashy the rendered axonometric view. This representation shows the right compromise between abstraction and time consumption in order to understand more about one's own design.

Three-dimensional digital modeling on the other hand is generally considered not appropriate in helping the architect to develop their design in its preliminary stages. It is recognized as being much faster and allowing approximated descriptions of the model. For example, in digital environments, there is no gravity, therefore one can see how a space looks before having to worry about how to support it.

The following experiment highlights the limitation of physical modeling and identifies in its poor representation output the reason why true three-dimensional digital modeling is not perceived as informative in early stages of architectural design and proposes three-dimensional printing as an alternative output.

Furthermore, it proposes an indirect manipulation of the digital design environment (chapter two), or rule-based design input, as the bridge

that helped unexperienced three-dimensional designers, such as myself, to cross from two and half dimensions to three-dimensional design land.

True Three-Dimensional Design (TTDD)

This experiment started as an exploration in highly three-dimensional design. With three-dimensional design I refer to a design that is controlled in every dimension at the same time, including horizontal, longitudinal, transversal sections and all other sections.

One can set a series of properties that the design must respect. In this case the design had to conspicuously avoid perpendicularity, parallelity and coplanarity in the spatial relation between two elements. The two elements selected were a cube and a wedge. Please refer to paragraph 3.3, to see how some of these spatial relation can assume interesting meanings at an architectural scale.

As one can see, a representation using words is very simple and everyone understands it. Finding another, less abstract representation, that is more informative in terms of design turns out to be very difficult. One has to decide what kind of representation one can use to develop, test and rigorously control the design.

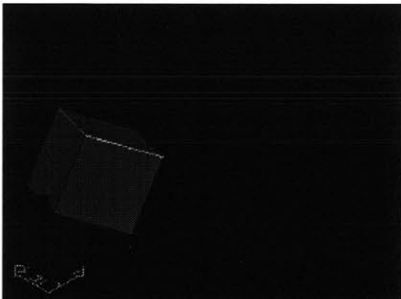


Fig. 81 Cube and prism, spatial relation

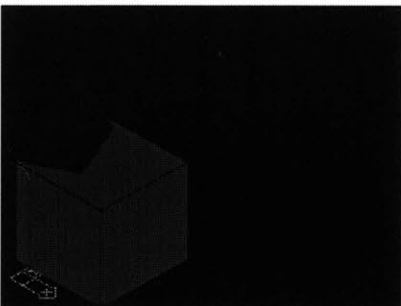


Fig. 82 Cube and prism, spatial relation

These kind of design problems have rarely been explored either rigorously or non-rigorously. Traditionally they are explored using the abstract representations offered by three-dimensional physical modeling. This medium is incredibly powerful in helping people think in three dimensions, but it has its limitations.

First, it is difficult to model a spatial relation where the two vocabulary elements are not adjacent or apart, but instead are intersecting each other. Intersection between elements assumes particularly interesting meaning if one thinks of the objects in terms of architectural elements.

Secondly, once one gets away from the constraints of coplanarity, perpendicularity etc. the choice of which angle the spatial relation should be set at becomes critical. Thirty degrees, sixty degrees are two possibilities, but one degree rotation or one-half degree rotation may be also explored.

Physical modeling media is not appropriate to this manipulation. The human eye is very accurate in evaluating the representation, but the human hand, even when supported by workshop machines, is very inaccurate. Only highly trained hands, such as those of an experienced craftsman, can perform this activity rapidly.

Today one has an alternative, even though it is still at primitive stages of its evolution. One can use a computer programming language to process the data and use a three dimensional printer to output the

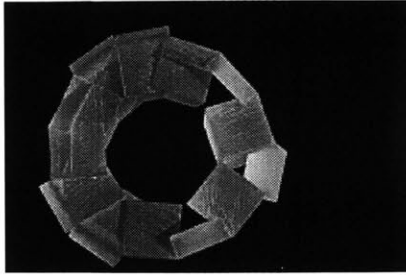


Fig. 83 Design 1, Stereolithography model

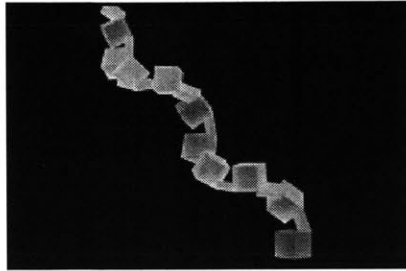


Fig. 84 Design 2, Stereolithography model

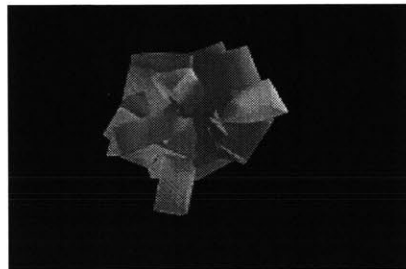


Fig. 85 Design 4, Stereolithography model

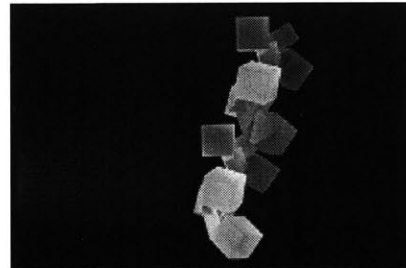


Fig. 86 Design 5, Stereolithography model

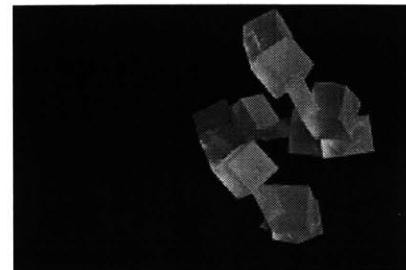


Fig. 87 Design 6, Stereolithography model

physical model.

The programming language is a very similar representation to the word representation we read above. The main differences are that the representation needs to be more accurate in order for the machine to understand it.

The advantage of the three dimensional physical model representation versus screen representation is that one can use the full potential of the human eye perception capacity to solve a recognition problem that is proven to be of great difficulty. (fig. 83-87)

Observing the experiment

With the above set of predictions, I set myself to a real experiment. The results once again offered greater insight than any prediction. In this section I report on some of the expected and unexpected insights.

Sometimes, as in this case, one has the luck of working in a team together with someone that speaks programming languages as well as english. That person was found in my friend Jose Duarte, a doctoral student in design and computation at MIT, who wrote the code for this experiment.

The goal of the project was to automatize the generation of all possible basic grammars given two elements and one spatial relation. Any possible spatial relation should be allowed by the program.

Jose recalled a series of algorithms that he had wrote in the past for similar purposes to generate two-dimensional designs. Jose decided to try and rewrite the code to generate design in three-dimensions.

Once the code were written and the program syntax debugged, together we could make the program do what was supposed to do, in other words, we debugged the grammatical structure of the program. This proved to be the most frustrating part of the experiment, because we could not understand the screen representation.

The two dimensional screen and Autocad Version 13 interface give an abstract representation which we found insufficient to understand the correctness of the design. The screen would offer still representations of the design, which are very hard to understand. The screen interface would be less of a constrain in a CAD software that would provides a programming shell at the same time as real time rendering or better a head mounted display system.

Jose explained that in order to make the machine understanding our design goal, he had produced with a highly parametric program, as in flexible to accept any value for its variables. Because of this, we had all possibilities to modify many parameters, including the size of the two vocabulary elements, the shape of the two elements within a certain

range and the spatial relation between the two. This parametric character of the program was not part of our original goal, but came as a by-product of the translation from english to AutoLisp code.

We acknowledged the potential of the program given by its flexibility, but decided not to use it at the beginning in order to understand whether or not the computer program was doing what we wanted. We decided instead to fix many potential variables with values, including the size of the vocabulary elements in order to concentrate on the most difficult topic of the relation between two objects in space.

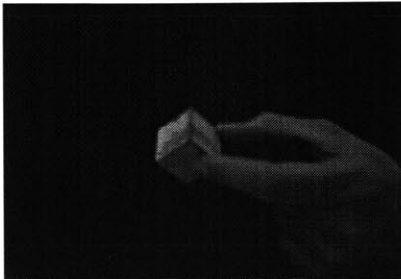


Fig. 88 Wooden hand-made cube

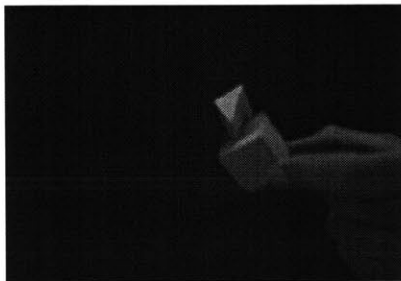


Fig. 89 Wooden hand-made model of the intersecting spatial relation

There are a great deal of different basic designs that one can produce by repetitively applying the same spatial relation when a prism and a cube are positioned in a non-symmetrical relation. To test the computer program, we made in parallel wooden models of the spatial relation (fig. 88-89) and with the help of wooden cubes we defined six different designs.

Our ability to predict what the design would look like, whether the design would be finite or infinite was very limited, so the surprise once the design was generated was extreme. Furthermore there was great satisfaction in having a tool that enabled us to explore more concretely and at a lower level of abstraction the problem we had defined at the beginning of this section, in higher level word representations.

Once we had produced the physical model using the three dimensional printing technology the forms generated by the computer program were obvious to read and easy to understand and finally as designers we could concentrate on issues of parallelity, perpendicularity and coplanarity and not have to struggle with getting the right view in front of a computer screen.

What I learned from the experience.

This experience gave me a deeper understanding of what makes a good three-dimensional design at early stages. Every work of architecture is a three-dimensional object, but this does not mean that every building has been designed in its preliminary stages in true three-dimensions.

Usually if one looks at the massing model of a building in plan view, the spaces look as though they are related in an interesting manner. This is the same response one gets from an axonometric view, but if one checks the elevations or other views they often look flat and boring.

Designing in three-dimensions is not only a question of tools, it is also a mental attitude. In traditional architectural education and traditional practice we are misleadingly taught about method and recipes for good design all the time. These recipes are taught using examples and

somehow stick in our minds in a permanent way.

A good dose of recipes and methods are traditionally considered to be knowledge required to practice good architecture. One can think of recipes and methods as rules for design. In a typically Minskyian fashion, one can think that all the rules of design that one appropriates and applies consciously, or unfortunately also unconsciously, are negative or degenerative.

If one believes in this picture, indirect manipulation using Rule-Based Design and Rapid Prototyping assume the role of a tool for design thought. It speeds up the process of unlearning all the knowledge about conventions derived from the primitive processes of the dark machine age, the first industrial revolution; it prepares the designer for the light of the smart machine age, sometimes defined as the fourth industrial revolution or more generically the digital revolution.

By conventions I refer for example to the fact that we stand at right angles to the ground so all architectural elements tend to stand at right angles to each other. Furthermore because early machines, used in the construction of artifacts, could economically perform only very simple operations and repeat those operation over and over again, simple operations and repetitive operations achieved a high aesthetic value. These are only two examples of conventions that aren't valid design rules today, but once one starts questioning typical design conventions, one notice that not many are valid today.

Why are these conventions bad for architecture? I offer a few examples and then many others can flow by inference. For example, air flows through buildings in a non orthogonal fashion, with corners creating turbines and flat ceilings creating pockets of stagnation. In this manner, people also flows through buildings and hit corners and steps. Water stagnates on flat surfaces, creating ponds.

At a more perceptual level, as suggested by Carlo Scarpa at Castelvechio where he attempts to separate the floor and the vertical wall, one can imagine that a complete separation between the floor and wall could very effectively deal with the problem of keeping visitors away from the art works as well as giving the art works more space to breath.

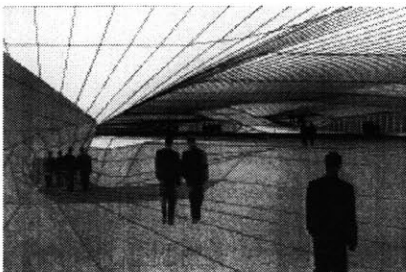


Fig. 90 Yokohama Inter'l Port Terminal '94

A recent architectural project that clearly expresses this point of view is the Winning Entry to the Yokohama Ferry Terminal International Competition by Alejandro Zaera-Polo and Farshid Moussavi of UK. The building is due to be constructed in steel honeycomb sandwich borrowing techniques from naval industry. (fig. 90)

With Rule-Based manipulation as the input in a digital environment and Three-Dimensional Printing as the output the designer has the

tools to effectively control true three-dimensional design.

The problem of representation is crucial in the design of highly three-dimensional forms and spaces. Digital Design Environment in general and indirect CAD, indirect CAM in particular is positioning itself more and more clearly as the bridge to cross from two and half dimensional traditional representations to three-dimensional representations.

25 FREQUENT MISTAKES

The methodology used in this chapter is inspired by Marvin Minsky's theories of the value of increasing negative expertise. Minsky says that it is hard to tell machines what they should do, and it is much simpler to tell the machine all the things it should not do. In this way it is possible for machines to "learn" automatically. This idea is analogous to the way children learn from doing all the things they should not do.

Most of the mistakes listed below are derived from my own experience of manipulating the Rapid Prototyping Media and by looking at others interacting with the Media. I see this as a way to condense all the experience in a way easy for others to appropriate before starting their own manipulations with Rapid Prototyping.

I will attempt to explain why these manipulations are mistakes.

1

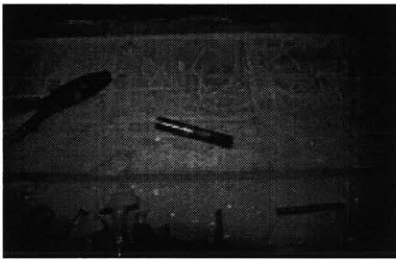


Fig. 91 Burnt router bit

Do not use stereo-lithography, as this makes transparent objects, if you are aiming to understand the formal properties of a solid artifact, as in symmetry, etc...

Do not use rapid prototyping if you are dealing with simple orthogonal geometries, because it will turn out more cumbersome and slower than manual physical modeling.

Do not cut millions of sections of a manual assembly model without a registration pin, because you will not be able to assemble it accurately.

Do not model a design containing elements with dimensions less than a 100 times smaller than the overall dimension of the artifacts, because the Rapid Prototyping will not be able to make it.

Do not model forms that will trap powder or liquid without providing a small hole to empty out the non solidified liquid.

Do not make full solids when not strictly necessary because it will substantially increase the time to build the model.

Do not forget to change the line thickness to the dimension of the laser accuracy selected before cutting on a laser cutter, otherwise the laser will interpret the line as a very long and thin rectangle and raster it.

Do not forget to specify the sequence of lines to be cut, so that the cutting always occurs on parts attached to the main piece of material, as otherwise the cutter will move the floating material whilst cutting it.

Do not forget to orient the part to be prototyped in stereo-lithography in a way that maximizes the coplanarity between the construction plane (the plane of the liquid) and the plane of the smaller geom-

etry elements.

10

Do not make the assembly out of repetitive parts, if it is not necessary for some design reasons, because it does not exploit the potential of part uniqueness intrinsic in the Media

Do not use straight lines, if it is not necessary for the design, because it doesn't exploit the potential of part uniqueness intrinsic of the Media.

Do not use perpendicularity, if it is not necessary for the design, because it does not exploit the potential of part uniqueness intrinsic of the Media.

Do not forget to specify a dimension of the cord height (accuracy) for curved surfaces in the order of magnitude of the machine accuracy in stereo-lithography, because specifying a large dimension will create gross facets on the prototype surface.

Do not forget to check the specific weight of the prototype material and the overall weight of the prototype, otherwise once assembled, you will not be able to move it.

Do not forget to check the material characteristics beforehand, such as durability or thermal qualities, if you do not want them to result in unexpected negative surprises.

Do not forget to maximize the volume to be subtracted by a rough cut, otherwise you will be looking at the router subtracting 1/32" for hours.

Do not forget to take into account the implications of applying substantial forces to the workpiece, because you will end up destroying the artifact during the process.

Do not forget to check the scale of the file imported and the units, because you will end up exceeding the overall dimensions of the machine.

Do not forget to always buy material in excess, because you will end up messing up few times.

20

Do not forget to make several similar copies of the translation files, from different computers, different platforms, (PC, MAC, UNIX) and from different software, because translations files almost never work in predictable ways.

Do not forget to plot some views of the computer model to bring with you at the prototyping shop to be able to compare with what comes out.

Do not forget to think about what you are going to look at in the prototype when you choose one technique over another, because it may lead to complete redundancy of the process.

If you are prototyping in order to learn how the artifact could be economically manufactured, make sure you use a rapid prototyping technique that is of the same type to the one used in the manufacturing process of the final product, because otherwise your prototyping is not going to be very helpful and you will be dealing different problems which are distracting.

WISE RAPID PROTOTYPING FOR ARCHITECTS

Introduction

The purpose of this chapter is to present a view of the future of Rapid Prototyping for architects. It incorporates ideas and discussions with my advisors and colleagues; most of the ideas are theirs and a few are mine.

The discussion starts from the belief that it is frustrating to constrain ourselves, as architects, to a technology developed for other purposes. We started by asking ourselves, what can Rapid Prototyping do for architectural design? Research into the future of Rapid Prototyping for architects was inspired by focussed experimentations concluded in the past year and was conducted in parallel with experiments with the current technology on non-trivial design problems with the belief that the two processes will inform each other.

Stretching our imagination towards how Rapid Prototyping should be reinvented to enhance architectural design led to new and more interesting experiments with the existing technology and obviously the opposite also happened. The large variety of experiments, in different environments from the Department of Engineering to the School of Design and to the School of Architecture has been fundamental for giving a foundation to this vision of the future. On the other hand we believed that experimentation alone would not have been sufficient.

William Mitchell clearly states this iterative mode of research in his vision for the Design Studio of the Future at MIT, the environment where all my adventures with Rapid Prototyping started:

“Use the results of these studies [analysis of the design process] as a starting point for modifying and evolving existing design tools and techniques, and for developing new tools. This strategy can effectively address one of the central weaknesses of much research and product development work in computer-aided design and related fields in that it does not have a firm empirical and experimental foundation, and that there is not rigorous, systematic feedback from experience in use. Experimental or empirical work should focus on intensive, non-trivial design processes.”

Interestingly Mitchell reminds us that although it may sound obvious to some, especially in architecture, this is not a widely accepted methodology of research in well known research institutions across the country.

Research behind the following scenarios was inspired informally by methods used in companies such as the Gillette Corporation. At Gillette designers create focus groups of non-naive users in an area. The coordinator asks the group to list all the things that are wrong with one current product and then to prioritize this list. Then the coordinator asks what the group would love to have from the product. An example of an application of this process in this discussion on Rapid

Prototyping may sound like: "stereo-lithography is mud and extremely expensive and the files are hard to verify." When we completed this process, the result was the grouping of things that Rapid Prototyping should do for people and a list of things it should avoid.

The purpose of this thesis is to simulate a family of machines that do what a new group of users: namely architects, may want. From my point of view the way the machine is made was just the catalyst and represents the "noise" of the system, not the signal. Instead I want to present options and let the user pick the one she likes.

Why Rapid Prototyping?

For those of us who ask ourselves the recurrent question, why should one use Rapid Prototyping, I collected a group of thoughts of well recognized scholars that may attempt to answer a question I feel too much an insider to be able to answer objectively.

Neil Gershenfield, from his promising position as Director of the Things That Think research consortium at the MIT Media Laboratory hints at the importance of the phenomenon of Rapid Prototyping. "[F]or computation to come closer to people's dreams and desires it is necessary to return to the boundary between bits and atoms. Rapid Prototyping and Manufacturing technology intended as a new art of making may play a key role in this transformation."

Donald Norman appropriately reminds us that important invention are best employed when added and amalgamated with existing practice instead of being seen as replacements of the latter. Here specifically I am thinking of the digital revolution, positioning myself as a critic of the 100% digital design definition.

"Socrates, Plato tells us, argued that books would destroy thought... Questioning and examination are the tools of reflection. Hear an idea, ponder it, question it, modify it, explore this limitation... But the author doesn't come along with the book, so how could the book be questioned if it couldn't answer back? ... He thought that reading was experiential, that it would not lead to reflection.... The worst kind of writing for people like Socrates would be novels, story telling. A story engages the mind in an experiential mode, capturing the reader in the flow of events... Susan Noakes, in her analysis of medieval reading, points out that it had been recommended by physicians, since classical times, as a mild exercise, like walking..."

A couple of millennia later I found with surprise the "guru" of the digital revolution, Nicholas Negroponte, emphasizing the importance of having all media, old and new, coexisting in love and harmony.

"Why is Knopf shipping Being Digital as atoms instead of bits ... there are three reasons. The third is a more personal, slightly ascetic reason. Interactive multimedia leave very little to the imagination. Like a Hollywood film, multimedia narrative

includes such specific representations that less and less is left to the mind's eye. By contrast, the written word sparks images and evokes metaphors that get much of their meaning from the reader's imagination and experiences. When you read a novel, much of the color, sound, and motion come from you. I think the same kind of personal extension is needed to feel and understand what being digital might mean to your life."

To conclude the picture of my position in respect of the question, Why Rapid Prototyping?, I will propose a poem which I found on the WEB. Since my discovery I and others have used this poem in every presentation because it masterfully indicates the people's desire to use Rapid Prototyping technology for something more than work. The poem was written by Brock Hinzmann in response to the question: "what you would make on an RP machine?" on the Internet's Rapid Prototyping Mailing List (RP-ML).

"If I had a machine....

Buttons and bows and things that glow
Cups and plates and things that I break
Custom containers and boxes for lovers
Onion-skin packages that peel back to uncover
Hidden gadgets and pageants of glitter and flutter.

Golf club covers and ball mark repair tools
To give away to friends and fools
Who lose such things as a normal rule
Orthotic running shoe inserts, just for my feet
Or maybe new soles that are neater than neat.

Levers and knobs that fall off of the car
Fasteners in the garage that I now keep in a jar
And anything else I can't find when I want it
And can't remember the last place I bought it
But can get on the Internet from someone who's got it.

Just download that file from Tony or Elaine
Of a sailboat or whistle or a puzzle-type game
Listed on their personal Web site for free
Or maybe I might have to pay a small fee
But a lot less trouble and searching for me.

Everyone will be doing this before long
And then mass production of things will be gone
And the computer networks will really be busy
People selling their files as intellectual properties
To the Hallmarks and Time-Warners and even the Disneys."

One further introductory look at the literature will take us to the core of the vision. In the field of Rapid Prototyping there are a great deal of technical engineering papers written, but I found little in terms of critical discussion. Alan Griffiths, a design consultant to the plastics industry, in his papers shows some of the pros and cons that we will be

talking about in the rest of this chapter.

About rapid Alan Griffiths points out that

“ [T]oday marketers, sales managers and managing directors, now aware of the expression “Rapid Prototyping,” are more likely to procrastinate just a little longer before making decisions, hoping to catch up by “Rapid Prototyping”! But if they understood that a “normal” prototype took four weeks to produce, as opposed to a CAD-assisted model taking two weeks, they would be obliged to make their decision to “press the button” just two weeks earlier in order to meet the same eventual target dates.”

This may say something about what one does with the technology. If the only aim is to prototype a traditional design faster, Rapid Prototyping may turn out as a disadvantage, because it will only postpone the decision making process.”

On the other hand Griffiths adds, “The office of the industrial designer Paul Priestman, who has clients in the USA and model makers in the Far East, now has no drawing boards and relies heavily on CAD stations, as well as Rapid Prototyping,” highlighting the fact that when the design process is changed, Rapid Prototyping starts to play a unique role in the design and development process. Later in the chapter I will come back to this point when I talk about WEB Prototyping.

Reading ahead in the paper, I was surprised to see how Griffiths coming from another field and with different reasons comes to similar conclusions as to the future directions of Rapid Prototyping. He says: “it is likely that before the end of this century we will see more user-friendly CAD stations operated by proficient young designers and that, as they draw on their screens, a model will be produced simultaneously.”

Finally, Griffiths briefly indicates what are the likely future directions of research. “The future research area will involve sensor technology, smart sensors and smart materials in Rapid Prototyping applications.” Again his view somewhat coincides with what I think are the future directions.

Relevant Research to this discussion

There are two examples of research that I found relevant to this discussion. One is related to smart materials. I will present here some aspects of the Brain Opera Project at the MIT Media Laboratory. The second example is two projects by Professor John Frazer at the Architectural Association in London.



Fig. 92 Rhythm tree, urethane and piezo-electric strip

Architect Ray Kinoshita explains the approach to the Brain Opera project this way:

“To me, the Brain Opera posed a particular challenge to integrate electronic technology into a spatial, tactile, and artistic environment... We are only beginning to create a physical freedom of interaction with the computer that will someday be completely natural... Raw steel, silicone rubber, and coated meshes provide the appropriately material-yet-immaterial stuff of the Brain Opera forest... In the rhythm tree each drum pad is sculpted out of a urethane material and contains a pressure-sensitive piezo-electric strip.” (fig.92)

As artifacts will begin more and more to have nervous systems we designers will have to integrate them into the early stages of the design, preferably in a more convincing way than our predecessors, who had to integrate mechanical and electrical systems into their artifacts. In order to do this, we need to create effective abstracted representations to introduce them in our models and prototypes. Rapid Prototyping with its level of accuracy and its new capabilities of selective deposition of different materials helps us in prototyping these new artifacts.

When one thinks of Rapid Prototyping, one always thinks of putting the “intelligence” into the machine. It is a laser beam cutting chip board, or a high precision, high strength, steel tool cutting butcher paper. However, it may be interesting to think that “intelligence” can be in the material and the Rapid Prototyping can be a quick, cheap and simple process the way designers want it.

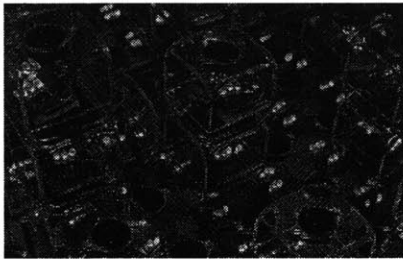


Fig. 93 The Interactivator

This thought leads to my second example where Professor Frazer and his unit in London made the Interactivator, a modular modeling system where “each cell contains an integrated circuit which can communicate to adjacent units. The system knows what each part is and where it is. The whole system is machine-readable. The state of each cell is mapped to a graphics output device where it is represented by color.” (fig. 93) I like to think about this project as a starting point of an interactive modeling kit.

Along the same lines, Professor Frazer, back in 1982 devised “simplified Three-dimensional Input Devices to encourage public participation in design.” This self-builder design kit was a working electronic system for architect Walter Segal. (fig. 94).

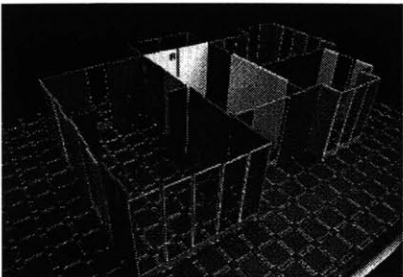


Fig. 94 Machine readable self-builder design kit

Due to the development of the technology at the time, both these interactive modeling environments seem a bit clumsy to work with. But with the miniaturization of computer technologies and the increasing dialogue between physicist and computer scientist, these experiments may become extremely useful precedents.

Analysis of hand architectural modeling

What do designers do when they model that Rapid Prototyping could enhance? And what are they doing today that they do not want to lose tomorrow? And finally how different is what architects do from what engineers and industrial designers do?

When one models, one does both practical things and theoretical things. I will treat the two separately. Figure 95 breaks apart into practical activities the practice of model making in architecture and tentatively pairs the basic activities with current technologies available to automate them.

functions	real-time rapid prototyping	availability
buy material clay-like/sheet	buy powder and liquids variable	available
store material in handy place	robotic arm + selves	available
additive/creative	Z-Corp	50.000\$
subtracting/sculpting	Laser Cutting	30.000\$
choose scale	FormZ	2.000\$
assemble components	Robotic Arm	available?
glue components	3Dprinting	-
cook clay	Oven	available
view overall/detail	Miniature VideoCamera/Monitor	available
touch	Grab with hand	-
throw light	Bulb on CNC Gyroscope	available
move parts	Robotic Arm	-
reassemble parts	Robotic Arm/3Dprinting	available
modify parts	create/ sculpt/ move	-
use library for secondary problems	WEB	free
photograph to record steps	videocamera	-
destroy parts	Laser Cutter//Burning	-
color and patterning	Robotic Arm/spray+3Dprinting	available
measure	3DLaser Digitizing	available?
bread and smell	Extractor	available
protect your eyes	Anti-laser glasses	?
calculate parametric variations	Excel/Matlab	300\$
show to remote others	Video Conferencing	available ?
touch to remote others	Videogames Joystick	?
structurally load and unload	Robotic arm	-
fight against gravity	work in transparent liquid?	?
search for suggestions/solutions	WEB	free
define relational rules	rule based design software	coming....
copy from previous	3DLaser Digitizing	-

Fig. 95: what designers do when they model?

But it is more interesting to understand what is going on while we model in addition to purely practical activities. We discover that there are several activities happening while a designer is modeling and some of them appear enhanced by modeling using the Rapid Prototyping. While others are not. Here below is a list of these examples.

One can learn about the work of a famous architect by modeling her buildings. This method is often used in architectural education. One of the most evident examples of this use of modeling is the study by William Mitchell and George Stiny on the modeling of the Palladian Villas. The two authors abstracted the rules of this great Italian architect and implemented a rule-based system that will generate all known designs of his villas. In this case it seems that Rapid Prototyping would

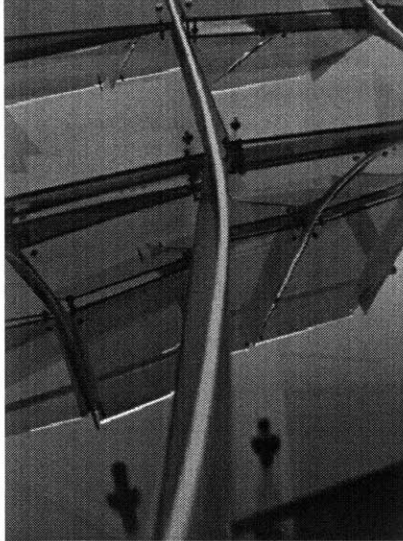


Fig. 96 Full scale mock-up of "ginger"

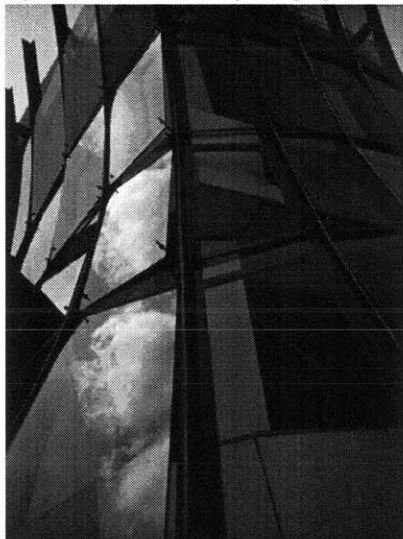


Fig. 97 Full scale mock-up of "ginger"



Fig. 98 Full scale mock-up of "ginger"

not have been of any use in the process of learning.

One can learn about the project site. This is widely practiced by architects. While modeling the site one can gain a greater understanding of it. This seems true if one is referring to the final model of the site, but during the construction of the model, the process used is to cut along contours lines pasted onto sheet material. This is a tedious and laborious process that forces the designer to work with shapes that have nothing to say about the site when they are disassembled and that acquire meaning only when they are properly assembled together. This is a case where the Rapid Prototyping process that involves indirect manipulation (as defined in paragraph 2.5) would be most welcome and would not take away any value from the experience.

While modeling one can learn about building components and industrial processes. As we understood from Jim Glimph, Frank Gehry's partner who is responsible for the raising of many of Gehry's unconventional ideas, much of the architectural design of their artifacts happens while prototyping full scale non-trivial portions of it. Their prototyping is not only in the office, but also at the craftsman site.

For this type of modeling Gehry's office relies on a unique facility, the workshop of Permasteelisa in Italy. Many of the inventions in the project occur in this workshop, in discussion with the craftsman, and not, as one may mistakenly assume, in the designer's office while discussing the project with the client. The Permasteelisa facilities have highly automated manufacturing lines to produce continuous facades, with robotic assembly and on-line testing. Apparently this level of automation in the production of components for large buildings is rarely achieved across the world.

The factory also has highly equipped machine workshop, with manual, NC and CNC machines for large scale work. The blending of technology and skilled craftsmen represents the value of these facilities. The thinking during the manual making of full scale prototypes is always related to the possibility of manufacturing into the final artifact.

Creative design requires tremendous speed. A facility of the kind described above enables the designer to come up with a new idea and get it prototyped within a day or two. Even if at first glance the full scale prototype may look like a part of the final architecture, at a more careful analysis one can notice for example the use of mild steel, rough finishes and approximated construction details, that has the traits of freshness and fragility of a new design (Fig. 96-98)

It is interesting to note that in the case of the Guggenheim Museum in Bilbao, The office of Frank O. Gehry and Associates carried out the early stages of design development at the above mentioned factory in Italy. Once the design was defined and the design problems were solved a group of different contractors, local to Bilbao, were put in

charge of the construction of the building.

While modeling an architect looks at three dimensional symmetries and similar things. Professor Terry Knight in her provocative course on architectural design theory at MIT, teaches some of the basic skills of three dimensional composition that today's architects seem to have lost soon after their childhood. This kind of exercise leads into working with basic design rules, that can be as precisely arranged as shape grammars. With today's common modeling software and today's average CAD skills it is hard to visualize these characteristics on the screen. On the other hand, manual implementation of all the possibilities created by a shape grammar may be tiring for some designers.

Rapid Prototyping plays a crucial role in this area, as showed in the example True Three Dimensional Design. I should note that in more sophisticated, expensive and powerful digital design environments functions such as the auto-spin of a rendered object during its modeling allow an understanding of the object similar to one offered by the physical object.

While modeling one can look at similarities with an object one has in mind. I refer to an example again taken from the practice of Frank Gehry, a seemingly infinite source of exemplary cases. Gehry apparently would ask his designers to design a certain surface in the shape that a velvet cloth would take if laid on that portion of the massing model. The traditional method of modeling didn't work. None of the models convinced Gehry. The reason I assume had to do with the particular level of continuity of velvet, which is hard to maintain in a handmade cardboard model.

The solution was found in Rapid Prototyping. Gehry's idea was taken literary and a piece of velvet cloth was found, cut and solidified in the appropriate position using spray glue. Then the shape was digitized in the computer, where the designer was able to manipulate it in a highly mediated or controlled way. From the CAD file a Rapid Prototype was created using Laminated Object Manufacturing Processes.

This process, which may sound worse in words than in reality, convinced Gehry and the design moved on. I think that all of us have this dream of making the idea that we have in mind without letting it getting infected by overwhelming conventions, and Rapid Prototyping makes this possible.

While modeling one can look at unifying aspects of the design. With unity I refer to a mixture of compactness and regularity. In two dimensional flat screen views, one finds it very hard to see gaps between shapes. Models are very good at informing the designer of where there are gaps between shapes, giving the unity of the design and the relationship between shapes in three dimensions. Fig. 75 shows the project described in paragraph 3.3, which represents one of the examples of the way in which one can use Rapid Prototyping to

enhance the process of modeling in the computer.

It is possible to look at the play of ambient and spot lights on the architectural model. This may be one of the most common ways in which models are used by architects. Especially in those project in which light plays an important role in the design of spaces, a precise rapid prototyped model provides an approximation of raytraced real time images, when one is careful of the treatment of the surfaces of the model.

While modeling one can get feedback on the haptic qualities of a prototype. Rapid prototyping is necessary from the early stages of design to control the haptic/tactile qualities and complex double curved shapes of those architectural elements at the interface with the human body: handles, handrails, chairs, light switches and most surfaces within human reach. The doorhandle project (fig. 39-50) described in chapter 3.2, developed from the above stated hypothesis and the results were extremely encouraging.

One can informally test the relative structural performances. By informally I mean that an architect can apply forces with his finger to the model and see the resulting deformation of a certain geometry. It is not an engineering finite element analysis, but more like a quick check to see if the proposed structure is in the range of credibility. In the pink chair example because of the highly complex geometry this kind of informal test was very informative. The same thing occurred with most of the other experiments I conducted.

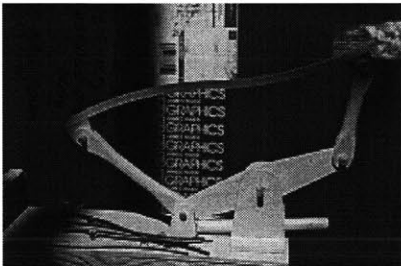


Fig. 99 Hand-made balsa model

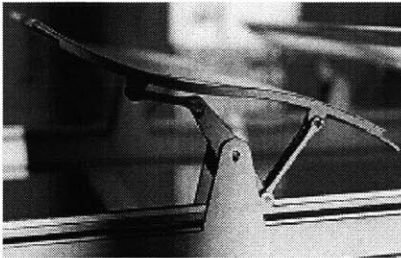


Fig. 100 Laser cut plywood model

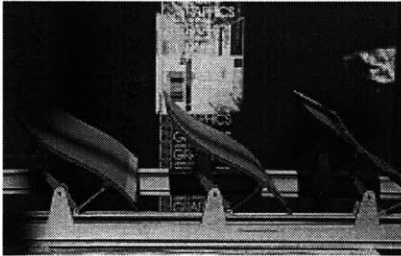


Fig. 101 Multiple copies of the same mechanism

Modeling is the most appropriate media in which one can study artifacts and mechanisms in motion. Sophisticated CAD software that requires high CAD skills allows for kinetic modeling and analysis in virtual environments. Depending on the designer's CAD skills, one can explore more or less properties of an artifact in motion in the digital design environment, but for example for feedback on frictional temperature and frictional noise, one has to rely on a highly accurate physical model.

The roof design in Fig. 99 is an example of a hand carved model. The imprecision of the model compromised the feedback to the designer who opted instead for Rapid Prototyping technology for his second (Fig. 100) and third model (Fig. 101). The accuracy offered by Rapid Prototyping technology and the speed of making and modifying the design were seen as unreplaceable by the designer. Furthermore, the possibility to quickly make extra instances of the same design allowed a certain arrogance in testing to the limits. Once broken it is not a problem to quickly replace it.

These are some of the activities that designers do today when they model. In a similar framework one can find many more. Today Rapid Prototyping allows for higher accuracy, learning about new making processes and the possibility of going back and forth between discrete steps of the modeling process, much like the undo button in a CAD

modeling environment. (This is especially true in direct manipulation CAM, less so in indirect manipulation CAM as explained in chapter two).

In the next paragraph I will present a vision of what Rapid Prototyping may do for designers in the future.

Possible future scenarios

Introduction

Little by little the technology will become more common in the field of architecture and the family of Rapid Prototyping will grow larger and larger and start splitting, as has already happened in the field of engineering, where the meaning of Rapid Prototyping is limited to formative or additive processes, and where the subtractive processes are limited to CNC machining.

At that point in time, when Rapid Prototyping will only include additive or formative processes, if we look back at the classifications made in terms of manipulation in chapter two, we notice that all the direct manipulations of the media will fall out of the family of Rapid Prototyping in architecture. We also notice that we indicated direct manipulation as today's most informative manipulation for early stages of design. What feedback will the designer receive in the future by using the Rapid Prototyping media? What will change in the technology and how will effect designers feedback? How soon we will see this changes happen?

There are two distinct directions in which the technology is developing in parallel. One is towards increasing performances, the other one towards reducing dramatically costs. Both directions will continue to increase the speed of making. This tendency will imply for architects that there will be two options to go about Rapid Prototyping: in-house and out-sourced. This distinction however does not apply to other fields, namely automotive, aerospace or medical where some companies each own today between 10 and 15 extremely expensive Rapid Prototyping machines for different processes.

To predict the speed of change by which this technology will evolve, Brock Hinzmann suggests a comparison with other relevant technologies. He writes, "its rate of installation growth is faster than the early introduction of such industrial equipment as materials-working lasers and water-jet cutting machines."

Several potential scenarios are suggested by the questions above. Three are the main types of scenarios in which Rapid Prototyping may evolve in the future: Real Time Prototyping, WEB Prototyping and Smart Artifact Prototyping. I will portray the scenario and then propose the way forward.

WEB Prototyping and 3Dfax

By WEB Prototyping, I mean the possibility of maneuvering the fabricator over distance using the WEB for communication. I imagine a screen interface much like a conventional network printer that would allow the architect to define parameters. I imagine the equivalent of an identification cover sheet that will define the ownership of the object.

One can think many uses for this capability. One can use it as 3DFAX. I am talking to you on the phone, or videolink, I am struggling to explain some impossible geometry, so I scan a physical representation of the object at the adjacent 3Dfax station and send a 3D representation to your site, where it gets fabricated. This would allow for better group work over long distances.

One can also access files on the WEB that someone has previously created representing uncommon objects that the architect might need for her design. And lastly anyone can manufacture. With a WEB interface an operation that used to be limited to those few that understood the machinery, magically becomes intuitive and not dangerous, a bit like playing with anything else on the WEB. This will allow the more artist and philosopher architect to express and explore their design ideas. Much the same way, as Sherry Turkle clearly explains, Macintosh allows the organic thinker, woman and kids to interface with the digital world.

To portray the implications of 3Dfax in architectural practice we can start looking at current two-dimensional fax technology and how they affected the way architects work. In those areas of the world where digital communication is not very developed, much of communication about design occurs over distance via the fax machine. Because of its characteristics including cheap communication, speed, simple interface and particularly because of its imprecision, faxes are used most at early stages of design to communicate with expert consultants over distances.

Furthermore, because of its characteristic of asynchronous communication fax is often used to communicate across different time zones. On the other hand the fax is rarely used to communicate in more advanced stages of the design process, when precision of representation assumes more importance. Because of the 2D nature of faxes, they are rarely used to communicate design work in those practices, for example Frank O. Gehry and Associates, characterized by highly three-dimensional design.

The change in the practice of architecture caused by the introduction of the fax is sometimes overlooked, but everyone notices when their fax machine breaks down. The fax has contributed to the tendency of architectural practices to out-source services, such as in model making,

consultancy and so on.

3Dfax has the potential first of all to help those architects that work in a more three dimensional fashion using complex geometries that are very hard to represent in two dimensions. It may also greatly increase the communication at later stages of the design between the architect and the craftsman, where issues of precision of information and three dimensionality of the desired artifact is a greater requirement.

Architects will not only be able to work with highly international teams of expert consultants, but they will also be able to pick craftsmen with unique expertise across the world for their innovative work. Once the innovation is settled and the design is defined, the architect will then be able to open a bid for her project, including the specification of the process of construction to whichever contractor will be imposed by the particular context of the project.

This potential is very important in many situations. Imagine one is designing a skyscraper in Malaysia and the structural engineers are in London. Today the engineer will assume that the level of technology used in the building should comply with the possibilities of the local contractors. Therefore in the case of Malaysia, where there is no knowledge of how to build in steel, the building structure will have to be designed in concrete.

Tomorrow with 3D fax, the architect will not only be able to develop the early stages of design with the engineer in London but also the details of construction with the British contractor expert in the specific technology that the design team has chosen. Once the design is developed, and the problems are resolved in a mock up of the relevant portion of the building, then a contractor is chosen according to the local politics of the project and all the knowledge on how to build the building is transferred together with the information on what form to build.

This process will have the enormous advantage of transferring knowledge on innovation to those regions that have less understanding, where the incomplete building may seem impenetrable for most locals to understand. Furthermore, during the transfer, the innovation may get infected by local characteristics, as in a particular type of joint known only in that part of China, and improve the contextual quality of the building.

If this sounds like a idyllic vision of the world, one has to know that this is roughly what happen in the Guggenheim Museum in Bilbao, Spain, by Frank O. Gehry and Associates. In this project all the missing technology was supplemented by the outstanding skills involved, design time and resources allocated to it. The building was designed in Santa Monica, California, scaled models were produces using Rapid Prototyping in Longmeadow, Massachusetts, a full scale mock up was made in Treviso, Italy, the structural engineers were consulted in Chicago, Illinois and once the design was defined the building site was

opened in Bilbao, Spain with local contractors. All the communication occurred via the digital network and via physical people travelling across the world carrying physical models.

All the members of the team despite having struggled with the complexity involved, acknowledged the great transfer of knowledge in innovation that the project carried with itself.

In conclusion one can predict that WEB Prototyping and 3Dfax will increase the degree of innovation in design and stimulate the architect in higher three dimensional control of their design. There is also an other side of the coin, as photocopying machines, once introduced in the architectural practice, increased the amount of repetitivity, in the same fashion a misuse of WEB Prototyping could lead to a similar danger.

Real Time Prototyping

With Real Time Prototyping I define a media that will perform in very similar manner to today's Real Time Rendering CAD Modelers, where the architect draws some geometric object or performs some simple transformation on one and the software automatically produces a shaded navigable image of it. Now one can imagine a very quick machine that instead of rendering an image on the screen, will "render" a three dimensional physical object.

Figure 95, earlier in this chapter could be seen as a preliminary list of specifications, showing that most of the technology is already available to plug together near real time Rapid Prototyping. One can imagine a digital design media where the design interface is not the screen but the actual physical object and the screen acts merely as support to check what the machine is doing, much like some screens attached to servers or plotters. The designer would be able to perform a transformation and pick up the object, view it and touch it and reposition it back for the next transformation. Looking at the existing real time technology, some of the simpler operations are immediate, whilst other more complex algorithms are delayed. For example, a regeneration of a parametric variation of a feature at the top of the tree structure of a solid model in Pro-Engineer can take up to several minutes.

A further analysis based on the designer's needs and not on the limitation of the current technology, would be necessary to show which functions should be real time and which should be delayed, to make sure that no wrong directions are pursued in the development of the machine.

This scenario may become real sooner than we might think, but if it follows the direction of increasing current performances it will move further away from the architect's reach. This sort of machine does not make sense to be used in the out-sourced mode so the price needs to

become comparable with today's high performance workstations.

If one refers to the manipulation described in chapter two as direct CAD, direct CAM, one notices useful similarities to Real Time Prototyping. In the same paragraph, I defined direct CAD, direct CAM as the most appropriate manipulation of the media for early stages of architectural design. In other words this scenario pictures something that is commonly used today with CNC machining, but using additive or formative manufacturing methods.

In respect to the speed of making, today's technology is still very far from real time. To build the doorhandle (paragraph 3.2), at full scale using Stereo-lithography the process took more than seven hours. On the other hand one has to remember that computers once took days to do operations that today happen in real time on a desktop machine. To support this parallel, in a discussion with a person that makes Rapid Prototyping Machine, I learned that in an international competition, their new machine made a part 20 times faster than any other technology. The increase in speed in the near future for architectural use could be even more impressive if one think at levels of rendering accuracy. Much the same way we have quick rendering, flat shaded, levels of raytraced and radiosity, we can implement a machine that provides a different level of accuracy/tolerance for 3D printing.

Real Time Prototyping Media will give the designer the freedom to use the powerful algorithms offered by digital design media, and in addition will eliminate the misrepresentation created by looking at a three-dimensional design through a two dimensional screen.

Smart Artifact Prototyping

With Smart Artifact Prototyping I refer to the ability to mock up components that contain computational matter as well as structural and plain matter. This third scenario provides many powerful and interesting implications for the designer working at the early stages of design.

Today very few artifact have nervous systems but it is likely that tomorrow or in the very near future, computation will be embedded in every architectural component, first in the desktop, and soon after that in walls and elsewhere. This will create enormous design problems. If one thinks of the mechanical and electrical systems, even now almost a century after the first systems were introduced in buildings, we as architects have not devised an abstracted representation that allows us to integrate them in an appropriate way with the architecture since the preliminary stages in design.

Most of the time a building is designed as if there were no such a thing as air conditioning ducts, which are added in the best possible way at a later stage in the design or perhaps when the design is already under construction. Part of the reason why this is the case may be that

architects do not have good tools and representations to allow them to integrate these building services at an early stage of design.

It will therefore be of prime importance to think of a tool that will allow the designer to integrate building computational systems right from the beginning of the design. A unique and scary example is offered by Bill Gates' new house in Seattle, scheduled for completion by the end of the year. From what I can see the disintegration between the design of plain matter, apparently treated to look like a swiss chalet and the design of the computational matter is purposely pursued. This is scary because it violates the property of integration common to good compositions.

Some of the most promising Rapid Prototyping Techniques and I refer here to Three Dimensional Printing, invented at MIT, propose themselves as excellent candidate to help the designer to think about this complex design integration. "Three Dimensional Printing is the most flexible of all Rapid Prototyping technologies. The process can form any material that can be obtained as a powder, which is just about any material. Further, because different materials can be dispensed by different print-heads, Three Dimensional Printing can exercise control over local material composition."

One can imagine the possibility of modeling in digital design media with the definition of different materials and then produce scaled models or full scale mock ups where the composition of the architectural elements is depositing smart, plain and structural matter in a selected fashion, before the design is completely defined.

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