PARAMETRIC CONSTRUCTS

COMPUTATIONAL DESIGNS FOR DIGITAL FABRICATION

BY

SERGIO ARAYA GOLDBERG

ARCHITECT P. UNIVERSIDAD CATOLICA DE CHILE, 1997
MAGISTER IN ARCHITECTURE P. UNIVERSIDAD CATOLICA DE CHILE, 2001

SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ARCHITECTURE STUDIES AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2006

SIGNATURE OF AUTHOR:..
DEPARTMENT OF ARCHITECTURE
MAY 25, 2006

CERTIFIED BY:..
ANN PENDLETON-JULLIAN
ASSOCIATE PROFESSOR OF ARCHITECTURE
THESIS SUPERVISOR

ACCEPTED BY:..
JULIAN BEINART
PROFESSOR OF ARCHITECTURE
CHAIR DEPARTMENT COMITTEE ON GRADUATE STUDENTS
MAY 25, 2006

....

George Stiny
Professor of Computation
Thesis Reader

....

Takehiko Nagakura
Associate Professor of Design and Computation
Thesis Reader

....

Lawrence Sass
Assistant Professor
Thesis Reader

PARAMETRIC CONSTRUCTS

COMPUTATIONAL DESIGNS FOR DIGITAL FABRICATION

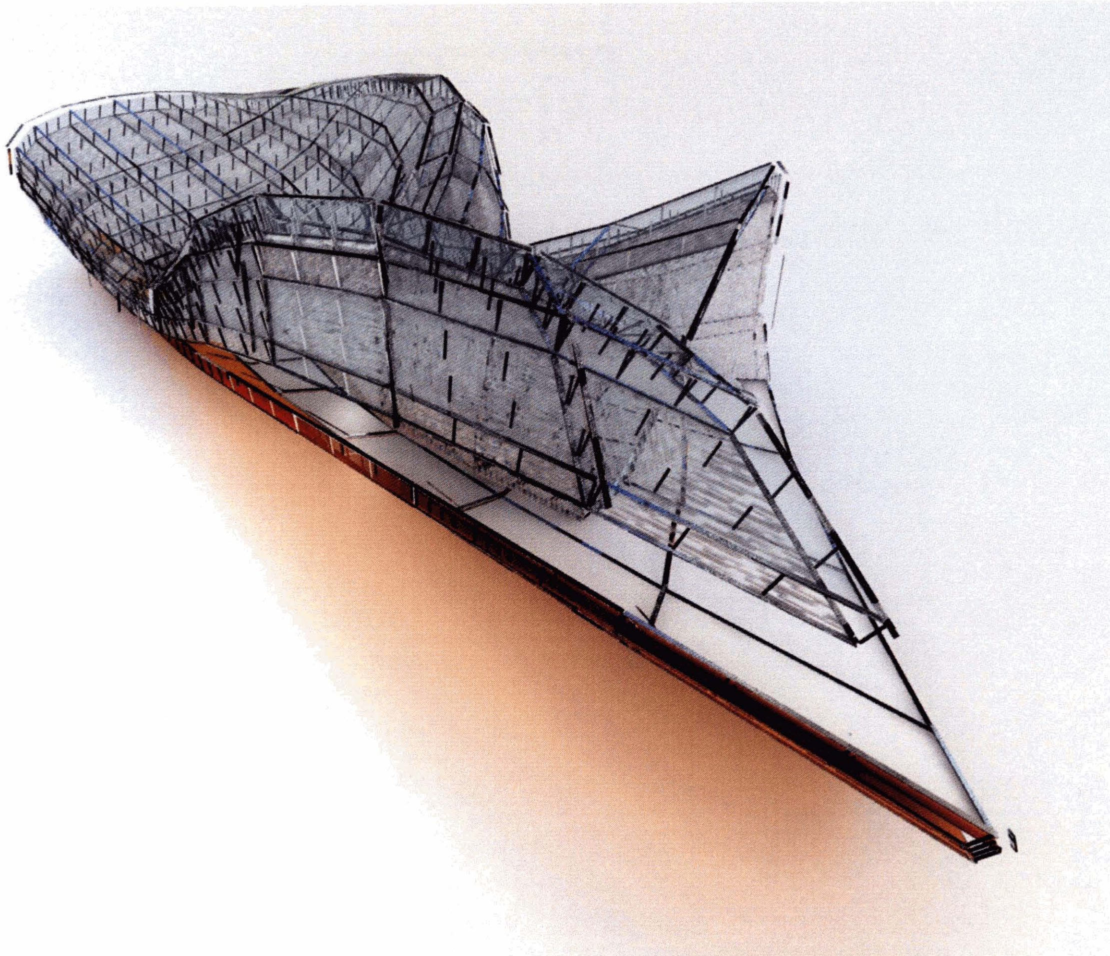
by Sergio Araya Goldberg

SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ARCHITECTURE STUDIES AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

:: ABSTRACT

This thesis explores strategies for building design toolchains in order to design, develop and fabricate architectural forms. The hipothesys of this research is that by embedding ruled based procedures addressing generative, variational, iterative, and fabricational logics, into early phases of form finding or form research process, it is possible to enhance and augment the repertoire of possible design methods yet facilitating the development and fabrication of such designs. Shape computing, parametric modeling, scripting, and digital fabrication are the tools chained in the research presented in this thesis. Complex curved forms were chosen in the different case studies to exemplify the advantages of this method in designing and fabricating this complex shapes which have proven to be particularly difficult to construct by traditional methods, usually requiring a reduction in complexity. The method proposed here allows the designer to maintain certain level of complexity and yet explore better and more appropriate solutions.

THESIS SUPERVISOR : ANN PENDLETON-JULLIAN
TITLE : ASSOCIATE PROFESSOR OF ARCHITECTURE



PARAMETRIC CONSTRUCTS

Computational Designs for Digital Fabrication

SERGIO ARAYA GOLDBERG

Master of Science in Architecture Studies
D E S I G N

Massachusetts Institute of Technology

2006

To Marcela for being the force that gives me life

:: ACKNOWLEDGEMENTS

Sincere thanks to my advisor Ann Pendleton for her constant support and insight during the development of this research, and for all the long enrichening conversations we had about design.

To my readers Takehiko Nagakura, George Stiny, and Lawrence Sass, for their incisive comments and inquisitive critique during this research.

All my gratitude to Robert Aish for inviting me and letting me take part of the GC community and for his continuous support, always stimulating this research and other projects.

To my dearest friends and partners, Onur, Kaustuv, Alex and Ayah, who helped and collaborate with my efforts, who supported me unconditionally. Overall, because they inspire me with their strength and talents and their unyielding commitment in pushing the boundaries.

Thanks to the RPLab and Media Lab at MIT for making this research possible.

To the few people who believed in my work and gave me the opportunity of coming to MIT, especially to the Beca Presidente de la Republica, in Chile, for funding this adventure and realizing this dream.

To my parents, and my parents-in-law for trusting me (again), and for pushing me (us) to come to MIT aloowing us to enrich our experiences.

Most important, to my sons for being the support behind this effort, for their resilicience and unconditional love.

To Marcela, who I dedicate my work and my life.

CONTENTS

1 INTRODUCTION

An architectural design process usually comprises a series of phases of development, going typically from conceptual development and sketching, to programming development and then to design development[1], later in the process, detailing drawing takes place and finally construction planning and documentation occurs. Usually, this implies that some refinement has to be done to the design in order for it to be manufactured using the available construction technologies. The degree of refinement will vary according to the particular design and the fabrication processes involved. In some cases when the refinement has to be more radical, the design has to be simplified, reduced and transformed in order to be fabricated, usually meaning the attributes that made that design valuable in the first place. The objective of this research project is to improve the design process by incorporating manufacturing logics at early stages of the design process.

Parametric Design implies whole new paradigm of non standard design through the propagation of the difference, the repetition of the variation. The ability to control variation and adaptation to local conditions on designs allows more precise yet complex solutions.

1 Sass, L., Rapid Prototyping Techniques for Building Program Study, CAADRIA Conference, 2003

Computer Numerically Controlled Manufacturing (CNC) allows to mass produce non standard elements at almost the same pace as standard industrial processes do with identical repetitive elements.

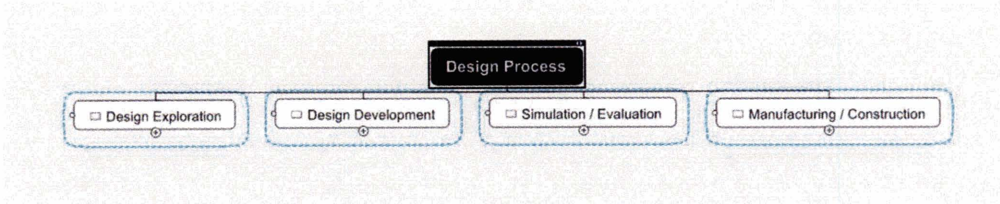
During the last two decades, computers and digital technologies have populated our work environments, including architecture offices. The power of computers relies partially on their ability to calculate very fast complex mathematical formulas. This has allowed that complex geometries, based on increasingly more complicated equations, became possible tools for design, introducing a whole new family of shapes and curved topologies, splines, and spline surfaces. Nevertheless, these tools still offer just a discrete number of choices, and as the relations and dependencies between points and curves and curves and surfaces are usually fixed by default, we cannot fully grasp the latent potency of such geometric constructions. New computational tools however, called parametric design environments, allow programming these dependencies, with variables called parameters, between one point and another, and build the rules to trace a particular curve or geometry, defining the "intelligence" of these points and the relationship between them and therefore the curves derived from them, thus creating controlled curved surfaces. Parametric environments then are usually associated with "smart geometries".

While these digital technologies are now able to manage complex geometries, the transition to actual fabrication has been extremely difficult, and only few designers in fewer projects have succeeded in building such designs, never without yielding part of the complexity of the geometries to the fabrication processes utilized and requiring extremely costly and specialized manufacturing. My project consists in developing a series of tools that can be used to design and fabricate double curved structures. Along the way. And during the different stages of development of this thesis, some of these aspects have been investigated through case studies. Some fragments of this research have been presented publicly in lectures and conferences, and some portions of this thesis have been previously published in conferences and magazines.

1.1 DESIGN TECHNOLOGY REPLACEMENT, FROM CAD TO PARAMETRIC DESIGN

Computer Aided Design CAD has become a regular tool, almost omnipresent at designer's offices from all different fields. Its unquestionable efficiencies make it an irreplaceable tool. One of its many comparative advantages is that of efficiency in performing complex repetitive tasks, much faster than if they were drawn by hand. Nevertheless, most CAD packages available in the market today, operate in a linear way, were the order of the operations is performed and stored in the program chronologically, and thus the data is hierarchically ordered based on this sequence. This implies that every process that modifies something on the design environment, will transform that object or entity into something else, thus acquiring new properties and loosing the preexisting ones. If a mistake is done or just to go back to its previous state, the program will require undoing the operation, loosing the just acquired new properties or characteristics and recovering the old ones. It is very hard or impossible to obtain intermediate results between these two "extreme" results, requiring a lot of "try and error" strategies doing and undoing constantly. This is a very common operation performed regularly during design processes.

Another characteristic of CAD software is that they are based on the assumption that a designer uses the software and its tools as a pallet of functions which are combined differently to produce different designs. Both the tools and the final design are conceived in a static state. The tools can be combined in different ways to produce different effects on the design, but they are always fixed. In this case, different software provides different functions, thus tending to produce a specialization on CADs. While Autocad is universally spread as a 2D drafting platform with powerful yet basic 3D modeling, Rhino is



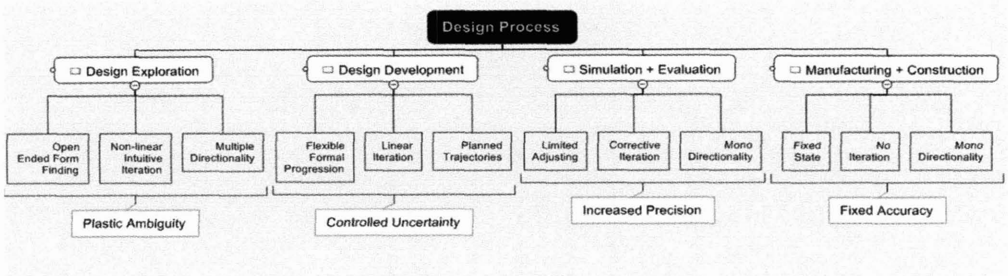
Phases of Design Process

known for its nurbs curves and surfaces, formZ is very good and precise at 3D solid modeling, and 3DMAX is better at performing complex modifications or transformations on geometries and even better at rendering them. This implies that many times, a design undergoes a series of steps in specific software, and then is imported to another one to use different functions to transform its design according to the process, and so on. The result of this is a design that constantly shifts depending on the environment where is being "transformed", but the overall result is always a fixed state that depends on the sequence of the functions applied to it.

A parametric approach provides the opportunity to build a set of relations between operations and or functions, in order to be able to allow the design to be "tuned" or "calibrated" without undoing all the process and restarting from scratch. Also, if the functions are incorporated into the parametric "intelligence" of the model, these could be "adjusted" to test different configurations, or just distributed over time or based on local conditions of the geometry. This methodology allows building a "smarter" model, where the relations and the hierarchy dependencies are coded by the designer. It also permits to change any of these variables or relations, transforming the geometries, but without loosing the previous relations or dependencies. If a parametric approach is combined with scripting capabilities, all the different functions from different software can be accessed from the same parametric platform, eliminating the issue with exporting and translating the geometries, loosing information and "intelligence" of the model in the process.

2 METHODOLOGY

Design processes have been studied and analyzed by numerous authors, and most of them would coincide in describing it as a series of phases which increase in the level of detail and precision as they evolve from concept to construction. Starting at the level of Design Exploration, as decisions are made towards certain design attributes, the process enters a phase of Design Development, where the design is defined. When this definition reaches a level of certainty, the design enters a phase where multiple Evaluations, by the designers and possibly by the clients, are made. In order to perform these evaluations, simulations are built; both virtual simulations and physical



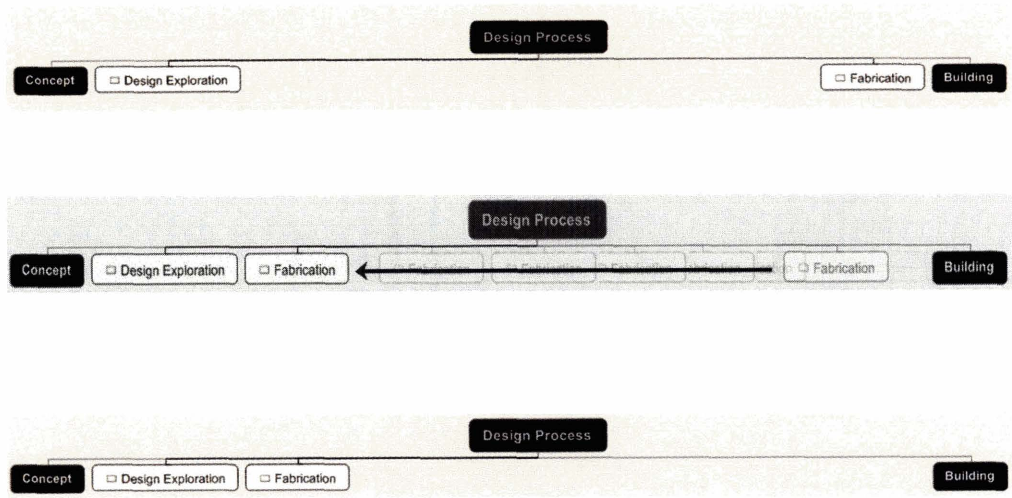
Design Process gradients of flexibility, directionality, definition, accuracy and scale.

prototypes are made. Finally as the process progresses towards the Construction phase, precise detailing and refinement is performed onto the final design. Each of these stages has specific characteristics that identify their functionality during the process, but that also qualify the designed product according to their relevance and influence in the hierarchy of each specific design development. Architects and Architectural Firms that have characteristic signatures, usually relay in their design processes, which are later revealed through the final designs they produce.

Starting with the Design Exploration, a phase which is primarily an open ended stage, where form finding and design research have their highest importance. Usually it follows undefined and ambiguous routes, as the objectives are not completely clear and are evolving with the progress of the procedures these open ended research turns into a still flexible but more defined and formal development. The design gets progressively more fixed and definite, more accurate and precise but limited adjustments are required until it reaches a state of complete rigidity, where the design is finally fixed and construction documents are prepared for construction.

During this process, several iterations are performed in order to test possible avenues of development. At the beginning, in the very early stages of exploration, these tend to follow non linear intuitive iterations, which are custom responses to more or less spontaneous responses. These evolve towards linear and rational iterative process, which allow the designer to investigate different possible outcomes of the procedures applied, when the final procedures are chosen, the iterations tend to be corrections and refinements of the developed schemes, and finally when construction, there should be no more iterations as the design should be completely defined and fixed.

Because of this, a design process at the beginning is usually multidirectional, as it explores several different pathways to try to get the best possible answer to the problem in question. This phase is defined by its flexibility in terms of sustaining a high number of undefined choices, and by the general state of ambiguity, both in terms of the choices made and regarding the interpretation of these choices. Form this multidirectionality, the process evolved to a stage where a few "parallel" or at least "planned" trajectories, are investigated.

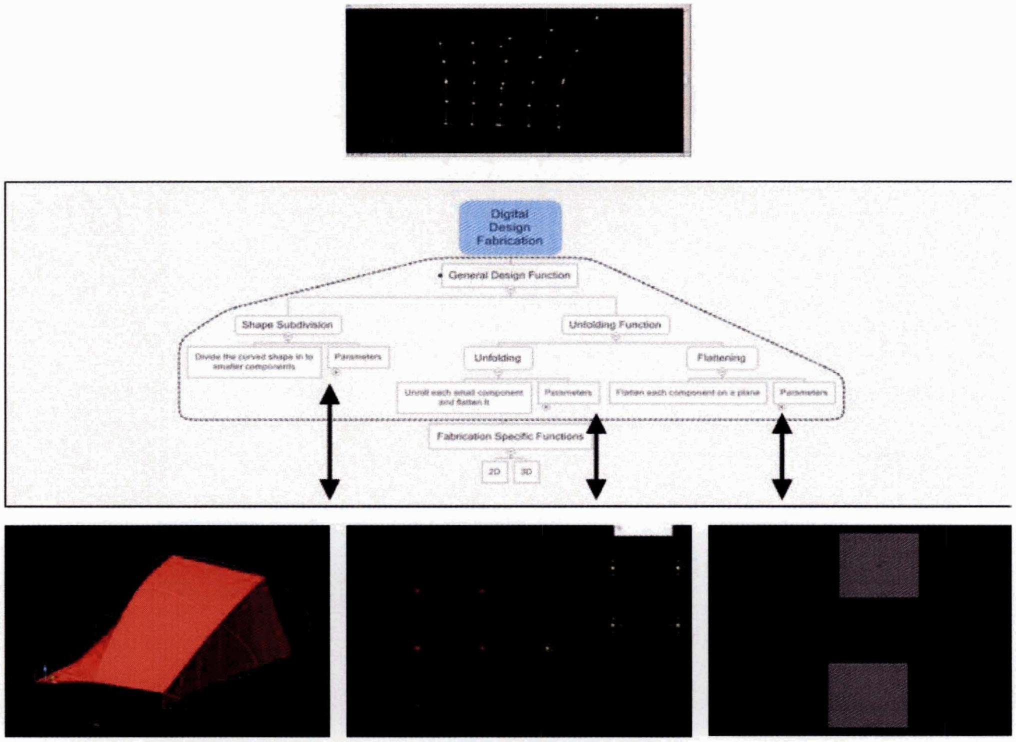


Incorporating final fabrication knowledge at the beggining of the design process

Each of these possible directions represents a possible scenario, and the objective is to be able to test and anticipate possible results. After these explorations, a path is chosen and the development assumes one single direction, the design is the center towards which everything else converges, this mono-directionality is sustained until the construction phase of the design.

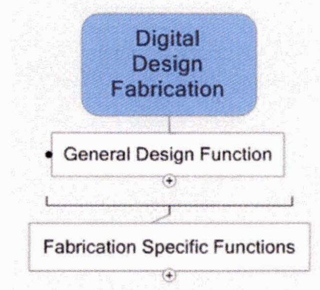
We can represent these process by a gradient of flexibility, accuracy, and definition. Ranging from Plastic Ambiguity to Controlled Uncertainty, evolving into an Increased Precision level to finally become a state of Fixed Accuracy.

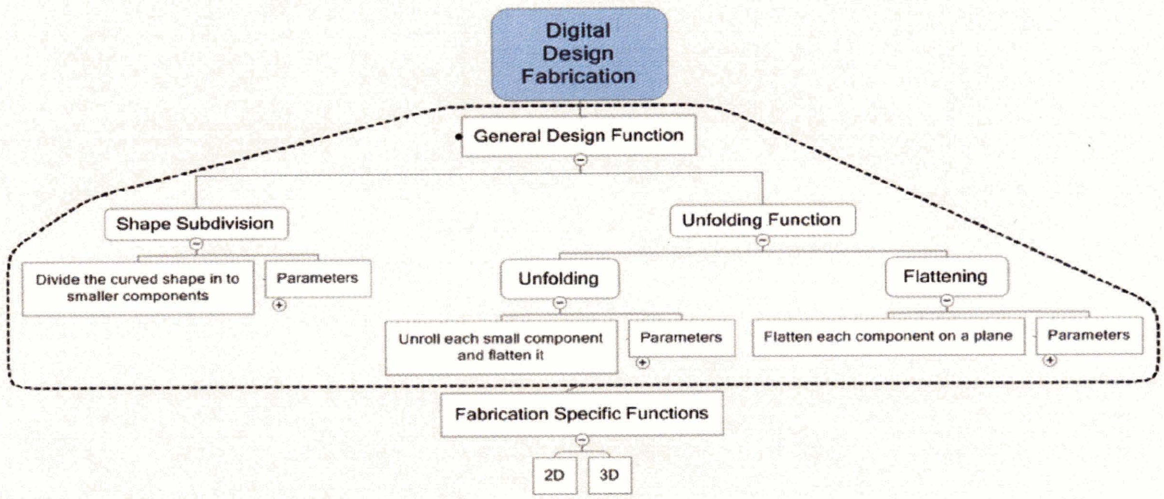
Design processes have to undertake all these stages of development, that is an accepted condition. Nevertheless, the intention of this thesis is to try to connect aspects of this process which are located on opposites ends of this gradient: Design Exploration and fabrication. The methods proposed by this thesis try to bring closer to the first stages of the design process, logics and functionalities that correspond to the later stages of the fabrication processes as we traditionally understand them. The methodology described here consists of a combination of parametric modeling and scripting, to provide the digital tools required. The processes will be evaluated both in their digital environment as through the physical output that they will provide through CNC machining and posterior assembly.



A generic design is channeled through a chain of design functions in order to enable a platform where the design can be conceived both as a whole and as the summ of smaller components

The method proposed, is divided in two parts. The first addresses the challenge of designing a surface considering its later subdivision and re-assembly; this will be a generic method that can be applied to any surface independently of the fabrication process. The second part provides a chance of choosing between different desired output results from the design, therefore choosing a particular fabrication method and materiality. I believe that by doing this at early stages of the design development process it will in same ways constrain the process, but it will also enhance the design solution and material result.





FUNCTIONS AND PARAMETERS

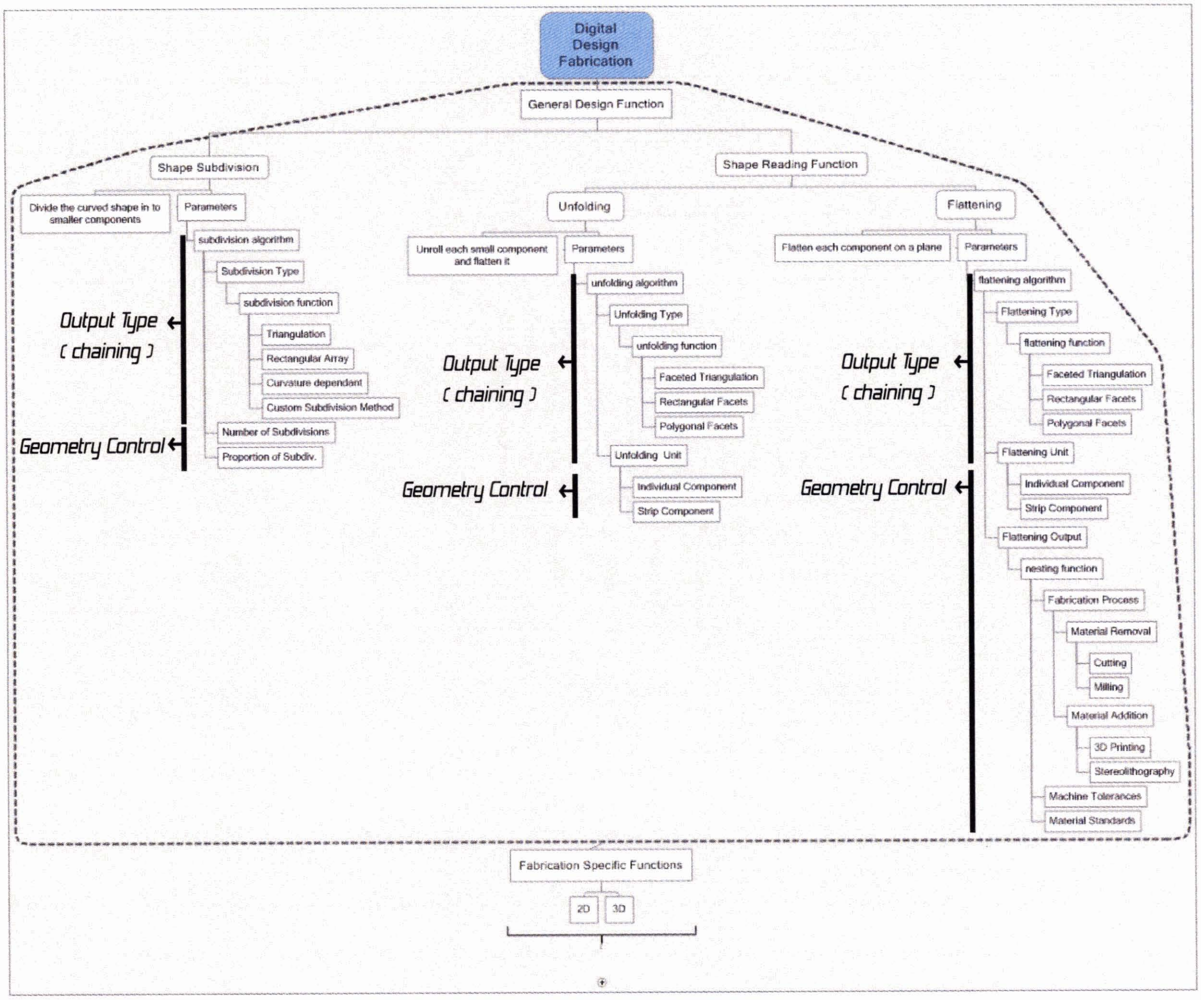
The Design Phase of the algorithm I deviced, consist of three functions:

A subdivision function, which takes care of reading a generic shape decomposing it into smaller components.

An unrolling function, which takes each small curved component and unfolds an approximated triangulated version of it.

A flattening function which nests the pieces onto a flat plane in order to be able to manipulate them and also to work as a fabrication nesting bed.

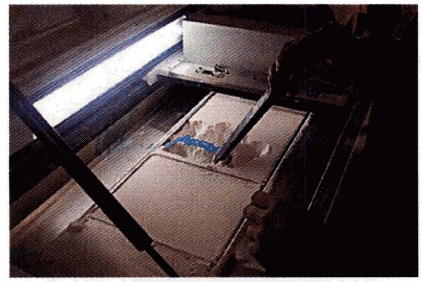
Each function has internal subfunctions, which are controlled via exposing all the parameters necessary to manipulate the geometries.

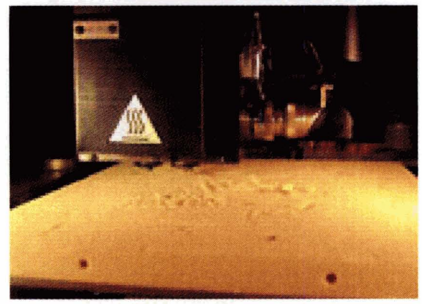


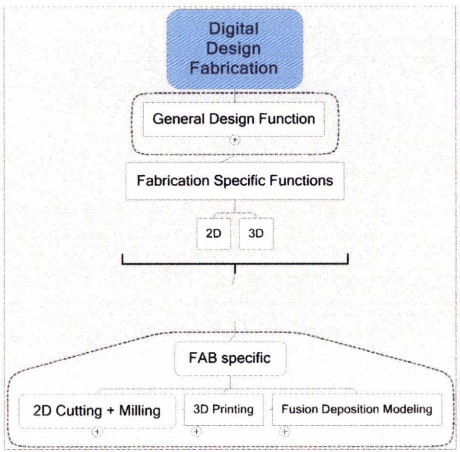
FUNCTION FEATURES

Despite the differences between the functions, they have common characteristics. A part of each function takes care of the the production of a specific kind of geometry, which responds both to the general requirements of the Design Process in general, and to the specific requiremtns of the next linked or chained function. The output of each function becomes the input of the next, thus creating a chain of functions. The requirements in terms of inputs for each functions are then anticipated on the functions that feed them.

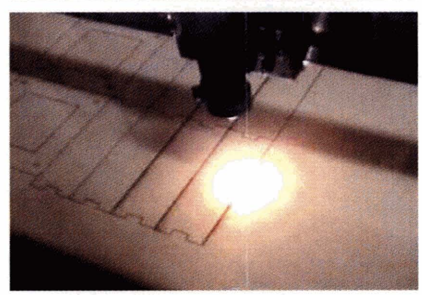
A second function takes care of the parametric control over the generated geometry. These controls are the responsibles for the associativity of the internal geometries created and the hierarchy of depencies built in; but they are also responsible for exposing all the parameters possible outside the function itself, in order to allow exploring variations of the original design through succesive iterations.

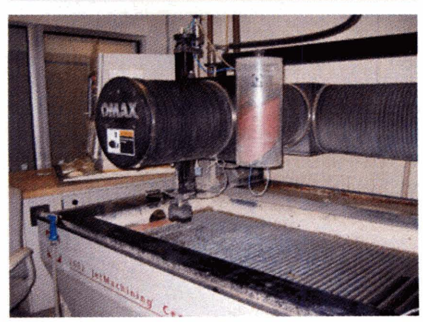






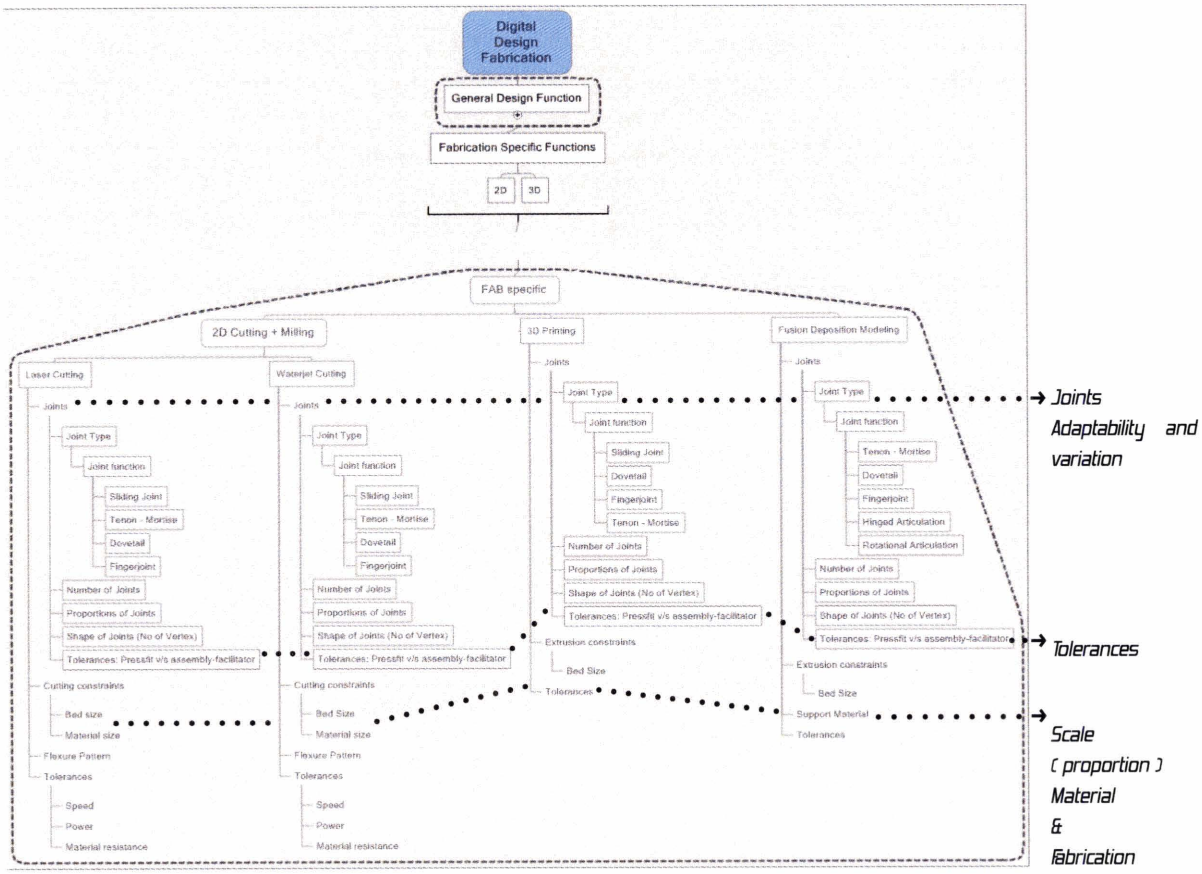
The fabrication Phase of the algorithm I deviced, consist of different functions to respond to the specifity of different manufacturing processes and machining procedures. I have tried to cover a range of fabrication methods and material constraints to demonstrate the application of these techniques into early stages of a design.
All pictures in this page were taken by the author





Left, top to bottom:

1. *3D Printing with a Zcorp machine.*
2. *FDM, solid modelling in ABS plastic.*
3. *Milling in the HAAS Super Mini Milling Machine*
4. *Cutting in the Universal Laser cutter*
5. *The powerfull Omax Waterjet 2652*



Independant of the specific fabrication process requirements and their appropriate procedures, their are certain common conditions which all functions have to deal with.

Because the output of these processes is always going to be parts to be assembled to create bigger structures, there is always the need to put things together, therefore there is a need for JOINTS or connectors.

Because independant of being nailed, bolted, locked or pressfitted, the accuracy of each machine and the necessity of fitting the pieces together, the role of accurate TOLERANCES is crucial.

Because independant of the machine and the material used, there are material standards, and more important, material properties, which necessarily demand for specific SCALES of fabrication, therefore the proportions of each piece is partially determined by the real conditions of both the material and the fabrication process used to materialize it.

Figure 1 Ivan Sutherland's SKETCHPAD, MIT 1963. Image extracted from www.guidebookgallery.org

2.1 PARAMETRIC MODELING

Parametric environments provide a platform for design where the user or designer can work not just with the shapes but also with the functions and the relations between functions and shapes. In a parametric environment, the resulting design is a consequence of setting up a number of conditions regarding geometry of the design, relations between these geometries, functions applied to obtain or derive these geometries, and relations between these functions. There is a higher level of control over the resultant design, and the design process can be streamlined in terms of different iterations on the design, as a change in a variable parameter will affect all the functions that depend on it. This is an advantage over standard CAAD platforms, as in most cases, this update method for a particular design happens in real time, allowing the user or designer, to quickly evaluate different alternatives for a particular solution.

Parametric design has been usually associated to design for fabrication, as some of the relations that can be "programmed" into the design are related to production and manufacturing.

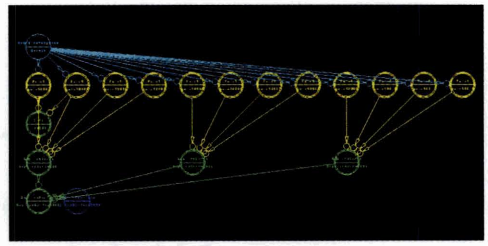
Figure 2 Scripting introduces the paradigm of computational recursion

2. 2 SCRIPTING AND PARAMETRIC DESIGN

Scripting provides a number of advantages when applied as a tool to design. Scripting gives the power of recursion, which allows performing repetitive task in a faster and more efficient way. Recursion provides speed for calculating large number of functions or operations that are of the same kind.

Scripting also gives the power of abstraction, as complicated functions and operations can be compiled to provide a "compressed" function or object that can be then called by its methods of implementation. This provides a chance of programming complex imbricate algorithms which can be compiled into program components.

Scripting also provides the ability to program reasoning, through embedding conditionals which will "read" given information and decide how to proceed according to that information. This allows to program "intelligence" into the design, as it will be able to make decisions according to programmed conditions.



Associativity Graph in Generative Components, geometries and functions depend on each other creating a hierarchy of associations and relations

Digital design tools have been incorporating scripting platforms in their latest versions, as a way of facilitating the ability to extend the programs functionality through scripted custom functions. Some of them provide an internal script editor, some others read and compile scripts created in a regular text editor. The scripts have to be opened in the program and then executed. The disadvantage to this is that in case the scripts is not providing the desire functionality in the design environment, the user has to go back to the script editor or text editor, rewrite the script, save it and reopen it in the design software, and finally re run the script to evaluate the results.

This trial and error method can be extremely time-consuming, especially during a design process as the final objective is being developed during the process itself. And it can be even more disappointing while debugging. Beyond the time issue involved, this method while powerful in terms of extended functionality for the design process lacks the fluent relation between computation and representation expected in digital design environments, which delays the evaluation process of the resulting design and therefore slowing down the design process itself.

3 PARAMETRICS AND CASE STUDIES

For the purpose of this study, I will use a parametric platform called Generative Components, which has been developed by Robert Aish at Bentley Systems, as an extension of their CAAD package Microstation. I will explain the reasons for choosing this particular platform and the methods developed on it for this research.

Generative Components is an associative and parametric design platform that is programmed in C C as an object oriented programming language provides a universal platform for programming. One of its characteristics is that it makes a "blurry" definition of singletons and collections, treating them as similar "objects". This provides the ability of controlling components in a design as singular entities or as series of entities with ease. Another advantage is that the integrated scripting editor allows the user to incorporate the power of scripting into the parametric environment, allowing for real time execution and debugging like all other aspect in a parametric environment. This provides the power of mixing modeling and scripting in the same "level" of the design, enhancing the designer's repertoire of tools to pursue a particular objective.

The approach proposed by this method targets to different issues, how to design for fabrication and assembly, and how to fabricate these designs. The first objective deals with the necessity of designing a complex continuous curved structure, which has to be developed as a whole, but later will be manufactured by assembling fragments or parts of it. For this I provide a method of subdivision of the surface, which gives a surface that is not exactly the original one, but an approximated surface, the degree of approximation can be partially controlled by the resolution of the subdivided output surface. This allows to test, during the design development phase, the most appropriate design in terms of the output for fabrication.

A secondary objective is to provide a number of choices for the design to be fabricated, regarding formal, material, structural and other design criteria. For this purpose I provide a series of methods that address particular fabrication methods, which will constrain but simultaneously facilitate the fabrication process. Three different methods have been targeted for the purpose of this thesis:

2D cutting (Laser cutting)
3D printing in plaster (ZCorp)
3D printing in plastic (Stratasys)

4 BACKGROUND RESEARCH

4.1 CAD AND COMPUTING FOR DESIGN

William Mitchell refers to these technological developments in terms of waves. The first wave was about the emergence of digital technologies that enhanced design environments with new tools and increasing complexities. The second wave was the consequential advance in the field of fabrication technologies and construction procedures, developed in order to build these designs. He foresees a third wave of programmable interfaces-architectures, where both a programmable dimensions and CAD CAM fabrication processes will contribute to produce real programmable structures and architectures. I would later call these systems as Parametric Architectures.

Mitchell wrote two texts with more than 25 years of separation (1975 2001) addressing the relations between computation and design. He explains how computer aided design applications (CAD) became relevant to architects and designers in general. He also demonstrates the importance of understanding computing environments to create better designs.

In 1975, Mitchell argued that if computers were applied to architectural endeavors, the resulting designs would eventually become "characterized by particular stylistic traits."[2]

In the second of these two articles, Mitchell explains how academia and industry, academic classicist pedagogy and industrial mass production later, drove architectural design and construction to a closed system of discrete standardized number of elements which could be recombined to produce large scale assemblies and buildings. Classicist were concerned about the study of types and general schemas, and the definition of parts and elements, to be published and reproduced, an architectonic vocabulary to be used to composed combinatorial design variations. Industry on the other hand, concerned about production and economies of scale, "strengthened this idea of composing a building from discrete standard parts."[3]

As Mitchell points out, "when the first computeraided design (CAD) systems appeared, they reified these well-established design traditions."[4] As these first CAD applications were usually developed to improve the efficiency in the production of construction documents, the next step was usually related to building large collections of standardized vocabulary elements (windows, doors, walls). This further reinforced the implementation of computational tools dealing with standard sets of elements and discrete, definite sets of operations used together to compose in a combinatorial way.

He clearly demonstrates that a design process requires a flexible and undetermined methodology and an open environment, in order to provide design possibilities "on the fly", as opposed to the traditional combinatorial approach. The understanding and involvement of the designer with these computational tools is essential, as "(...)computer systems cannot be regarded as formally neutral tools in the design process"[5] in order to have precise control over the resulting designs. A designer must understand beyond the operational aspects of the application, the formal consequences of the programmed data structures behind the computational process driving the application

"As architects begin increasingly to

2 Mitchell, W. J. (1975). "Vitruvius Computatus," in Models and Systems in Architecture and Building, D. Hawkes, (ed.), The Construction Press, Hornby, Lancaster, pp. 53-59

3 William J. Mitchell (2001). "Vitruvius Redux" in Formal Engineering Design Synthesis, ed. Erik K, Antonsson and Jonathan Cagan. Cambridge /university Press, USA, pp 1-19

4 Mitchell, (2001).

5 Mitchell, W. J. (1975).

work with such systems they will need to devote as much attention to understanding the vocabulary and syntax of form implied by the data structures of those systems as the classical architects of old devoted to the study if orders."[6] Mitchell considers that this degree of flexibility an freedom of choice, inherent to the first stages of a design process, increasingly looses it's ambiguity and flexibility as the design progress from concept to construction. He states that "[...] a design process should begin within the framework of a shape grammar, but it should end up within the framework of a set grammar."[7]

According to Mitchell then, the relevance of computation for design lays on its internal structure and its management of data, as these constrain the operational and then formal results.

Emergent fully parametric platforms allow better control of this conditions as they can be "programmed" by the designer as the design evolves. Furthermore, this is a call for designers to enter into the field of programming, which becomes possible as this has become a common trend in almost every CAD platform, providing ad hoc scripting environments.

Can new parametric software provide a better environment to resolve these issues?

6 Ibid.

7 Mitchell, W. J. (2001).

What role can scripting and programming play in this scenario?

Still, Mitchell leaves open the question about creative design processes, as an undetermined and unpredictable course, "skilled designers do not just simply search for configurations that satisfy predetermined requirements. They watch out for emergent architectural opportunities, they recognize them, and then they take advantage of them to achieve unexpected benefits."

How can digital tools, CAD and parametric software, and digital techniques, scripting and extending these platforms, be used to achieve and exercise these ranges of undetermined freedom? If in existing CAD applications the approach is to "particulate composition,"[8] starting from a library of elements combined with a discrete set of operations, how can programming or scripting in these environments overcome these conditions to provide the desired ambiguity and flexibility?

As Mitchell states, either the classical or

8 Banham, R. (1967). Theory and Design in the First Machine Age. 2nd ed., Praeger, New York.

high modernist tradition of architecture, every architectural element was defined, known and controlled by the designers. Most of the time these parts were even known before the design began, as they were part of an existing vocabulary. But for the emergent CAD/CAM design and construction generations, these parts "are established as the design develops, and they are only fully known when the design development is complete."[9]

If we extend these thoughts to the actual implementation of rapid prototyping manufacturing, can we also extend these definition until the "design is made." If CNC machining allows using the design data as fabrication data, rapid prototyping is doing this in a streamlined way, reducing both the time required and (in some cases) the cost involved. In this scenario, is it possible to change the "threshold of rigidity" proposed by Mitchell, referring the necessary flexibility in design, but the definite determination while fabricating, to a later moment in the process?

Through digital design fabrication, the manufacturing design phase can maintain some flexibility of the conceptual and formal design development. The objective of this research is to demonstrate how fabrication logics can be incorporated into early stages of design, in order to provide conditions for these designs to occur, as physical possibilities and as process related constraints.

9 Mitchell, W. J. (2001).

4.2 CAD, PARAMETRICS AND FABRICATION.

Here I will comment a research Paper published by Sacks, Eastman and Lee, which analyzes the shift from regular CAD to parametric CAD and their relations with manufacturing. The authors describe the advantages and limitations of standard and parametric CAD applications, and how they serve the purposes of fabrication.

The authors affirm that Computer Aided Design and Drafting is a widespread platform in the construction industry. Nevertheless, they argue, it is just accomplishing the functions of an improved drafting platform. They explain that the drawing data produced by these platforms, can "only be read as graphics", proscribing it to be transferred for process driven activities, such as structural analysis, bills of materials, coordination between building systems, quality control, rebar fabrication and piece production, must be done by people."[10]

The cost involved in the translation of

10 Rafael Sacks, Charles M. Eastman and Ghang Lee, (2005) "Parametric 3D Modeling in building construction with examples from precast concrete", Automation in Construction, Volume 14, Issue 2, pp 233-240

graphic information from these platforms into readable information from these other process activities described by the authors, prevent the users (designers) from embracing automated means of design for fabrication.

On the other hand, as this paper demonstrates, the manufacturing and aerospace industries started using CAD software based on 3D Solid Modeling almost at the same time that the rest of the industries started adopting CADD. Today beyond these two, the aeronautical, nautical and automotive industries also largely benefit from such platforms. And even beyond these there are emergent fully parametric solid 3D modeling platforms. But according to the authors survey, and despite "the potential to make modeling of buildings, and their subsystems, such as precast concrete structures, cost effective, thus opening the door to many additional design, production and erection benefits" these parametric solid modeling platforms, "with very few exceptions" (Gehry's work) have not been used in the AEC industry.

In the paper the authors describe the evolution from 3D solid modeling software to parametric 3D solid software. It becomes relevant to my research as it specifically assess the necessity of understanding the design process, in this case as explained in their research, by recording operational steps and functional relations between the design parts defined as "representation of shapes as algebraic formulations of solid primitives", and later referencing parameters that were used to derive such expressions within the sequence of operations. As it is stated by the authors, this allowed designing complex assemblies of pieces, with control over possible variations through subsequent iterations, and providing also the ability to manage non identical variations of the parts that composed the assemblies. This proposes a whole new paradigm of non standardized design while maintaining control over the volume of pieces to be designed and fabricated.

As the authors expressed, after the first CAD revolution of drafting, a new revolution of parametric CAD has begun. The importance and relevance of this computational breakthrough, through its

"(...) significant contribution to design, in that, along with solid modeling, it allows modelers to generate computer representation of physical objects not only as they look, but also to define semantic relationships between the objects' representations, allowing them to easily created and edited."[11]

As the authors explained, parametric systems have many advantages but also have

11 Rafael Sacks, Charles M. Eastman and Ghang Lee, (2005).

some constraints, among which there are "logical limits to the extent to which automated design intent can be imposed using parametric dependencies."[12] Then three applicable methods for embedding parametric variation are described: Parametric adaptation, substitution of a part and topological adaptation.

These are described as rule-based methods, where the first two are, according to the authors of the paper, achievable using existing parametric platforms, but the third required human external intervention. I am interested in exploring the possibilities provided by directly scripting into a parametric environment using ruled based processes, in order to explore these three methods. Rule based processes can be approached through different design approach than the one summarized here, and I intend to explore the application of shape grammars to develop design techniques for these methods.

Research on diverse topics related to digital design and digital fabrication has been done in the last years. Most of this research addresses the potential of combining advanced modeling environments with computer aided fabrication to produce non standard design components. But specifically on the design and production of curved structures or surfaces though, there is less information and it is all more recent.

12 Ibid.

4.3 FABRICATION OF CURVED SURFACES

Axel Killian in 2003 wrote described the fabrication of partially double curved surfaces using a particular joint feature.[13] There, Kilian describes a method that takes into account the particularities of certain computer aided manufacturing methods, for cutting flat sheet materials in order to produced curved surfaces when reassembled. He argues that given the direct relation between the digital design and the input information required by the machine to cut a specific path on the material, there is no need to limit the complexity of the design to traditional hand-crafted type of detailing. Quite the contrary, the machine can process these information and efficiently produce a complex detail which is repeated in a non uniform way, varying scale or even geometry, according to the design requirements, but nevertheless, just a simple tool path for the machine to process.

Kilian explains a process that combines scripting in visual lisp to provide a fast and efficient method to derive the continuous

13 Axel Kilian, (2003). "Fabrication of Partially Double-Curved Surfaces out of Flat Sheet Material Through a 3D Puzzle Approach", ACADIA Conference.

curved detail, by responding to the resolution of the meshed double curved surface sampled. This scripting method succeeds in producing the desired adaptive detail, demands a trial and error approach, by running the script, sending the information to the machine, using the design information to produce the cuts, manually assembling the pieces and then, going back to the script text file to correct any mistakes. In the best scenario, running the script, to see the results in the modeling design interface of the application, and then going back to the text file, changing the code, and re running the script again. There is still a gap between the coding part and the design resulting of that particular script being executed.

Kilian demonstrates that in order to produce these double curved surfaces, a continuous joint detail is required. This approach requires a fine tuning process in relation to the specific machine used for the manufacture and the chosen material. The most critical aspect of this fine tuning is related to the adjustment of the tolerances in order to allow a press fit joint but allowing enough loose joint in order to accommodate in place when assembling the pieces together. The post fabrication analysis shows that the double curvature occurs mainly because of the material deformation that takes place along these continuous joints. A digital simulation and stress analysis shows that the according to the distribution of forces, the higher stress occurs at the nodes, where the displacement due to the pieces resisting the bending is higher.

The results of this exploration result in a surface that curves itself, adapting to the double curved configuration, but which curves in a non homogeneous manner. I intend to explore a different approach, extending the concept of continuous joint detail, but adding a different approach in order to have a continuous

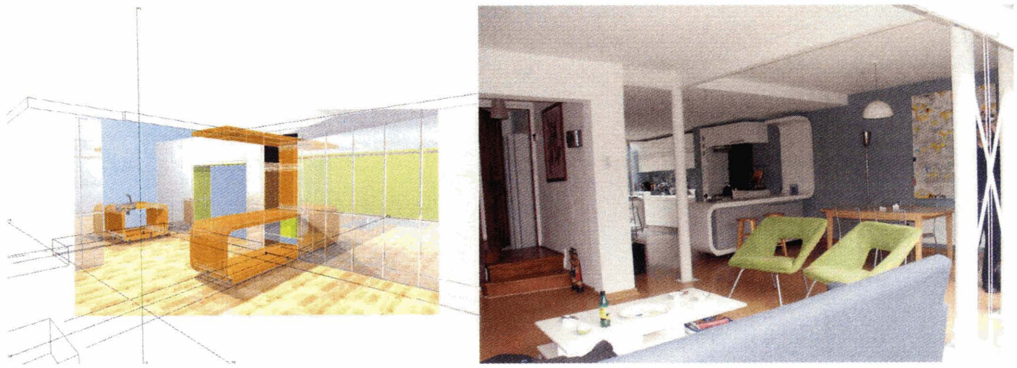
Traditional woodworking fabrication o a curved surface Valenzuela's House, Santiago, Chile 2004 Picture taken by the author, 2004.

distribution of the forces along the surface, and providing a more accurate double curved structure.

4.4 MANUFACTURING TECHNOLOGIES

I have studied construction technologies developed to put things together. There are vast traditions in vernacular architecture in terms of creating designs for assembly. I have been particularly interested in this kind of work for years. I believe that in many ways, traditional manufacturing can still offer real possibilities for architectural fabrication, and that deeply embedded in traditional methods, are huge potentials for future development. I understand then that advanced technological implementations are a complement and not a replacement of knowledge, and many times they can learn a lot from past experiences.

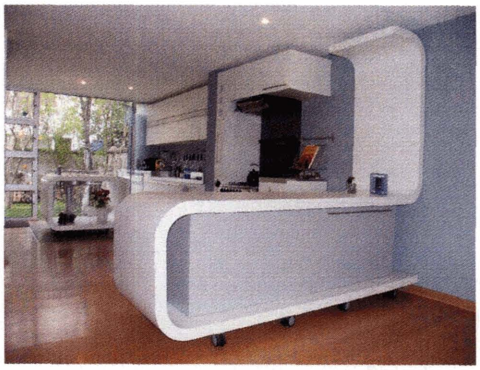
I have encountered these same problems in my professional work, I include here a couple of projects that deal with the fabrication of curved structures, using traditional methods. Later I will briefly summarize manufacturing methods I have investigated in the past and during the present research in order to learn their limitations, how they could be implemented in generative processes or into automated manufacturing.



Schematics of the digital design, and picture of the results. Images by the author.

4.4.1 Furniture_Loft Pereira

I did a house project in 2003, the Valenzuela's House, in Santiago. The interior spatial quality of the interior, proposed a unified fluid space which was programmatically modified only by specific temporal actions. These spatial attributes demanded the creation of a couple of singular elements which could be used for multiple purposes and that would simultaneously create partial temporal division in the space and qualify this same space programmatically. I designed two singular objects-furniture, which became two curvilinear elements in the clean open euclidean space of the house. The curves were designed as developable surfaces, and were constructed using a wood and steel lattice framework with a plywood cover which was itself covered with white porous Formica veneer. The radius of the curves had to be modified after testing the resistance of the plywood cover, which was folded using hot vapor on site. The big bar-counter object has wheels and is usually displaced across the space for events.



The two central pieces, the "o" object (fixed) and the "s" object (on wheels). Wood and steel fram covered in MDF panels and finish in porous white Formica veneer.

The internal ribbed structure was manually cut, and the wood panels were bent and screed to the structure using hot vapour guns to flexibilize the material. The radius of the curves was adjusted during the fabrication to the maximum curvature obtained from the treated wood panels.

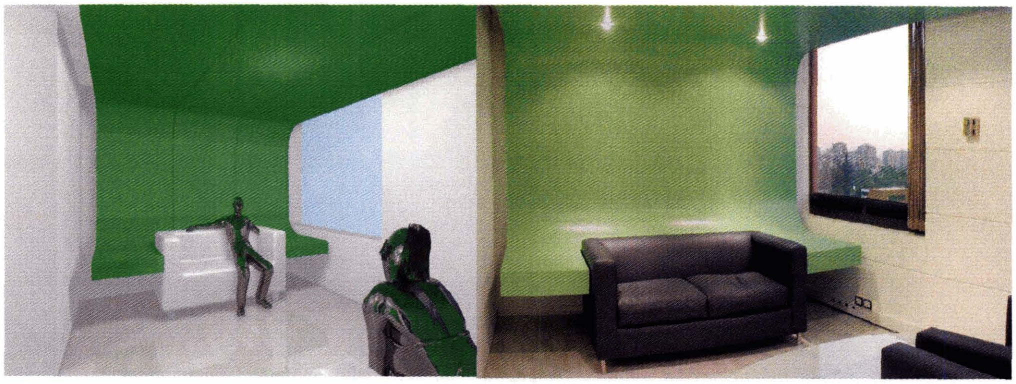
Images by the author.

An underlying structure of parallel ribs supported on pillars 45 cms over the ground, create the base over which the wood deck is assembled. The deck curves twice, once when it meets the perimetral wall, and then again when it surpases the high of this wall.

Images by the author.

4.4.2 Pool Deck

After the completion of the house, the clients requested a pool in the front courtyard, I decided to maintain the maintaining the design line of the interior furniture as this new exterior element was added, the deck is a multifunctional platform that works a the pool deck, but also allows for seating around the courtyard when doing a barbecue or other exterior activity.



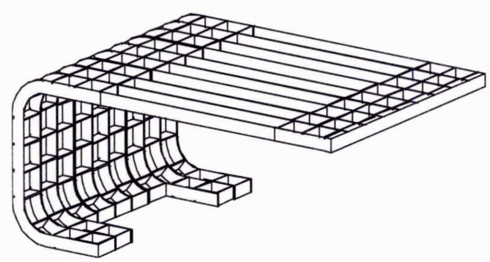
Original Renders of the project and photograph of the result. The structure hungs from the concrete slab using Hilti bolts. The internal ribbed structure
Images by the author.

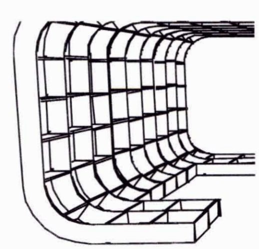
4.4.3 LemonLounge

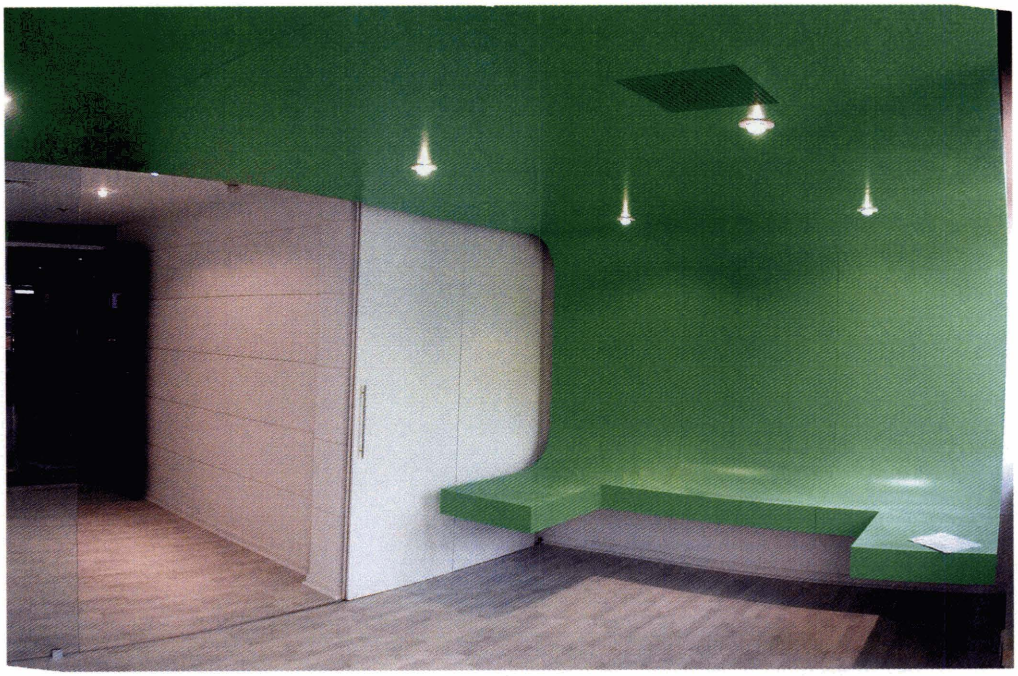
This is part of an office project I did in 2004. The client required a meeting room and I decided to propose a Lounge like meeting space, and I designed a shell like structure that will create a continuous spatial condition unique to the meeting room. The lounge was a very simple gesture of inscribing the space within this curved continuous surface that would wrap around ceiling walls and would levitate over the floor. The color matches the corporate color of the firm, and the furniture was also design especially for the lounge.

The structure was designed and constructed using MDF wood lattice, and covered with 6 mm plywood sheets, bent using hot vapor guns. The structure was hung from the concrete slab using Hilti bolts. The structure ended being so resistant, it could support two person standing on it while hanging 60 cms from the floor. The radius was again adjusted to fit the material properties after being vapor treated.

The ribbed structure was divided in three modules. Each module consisted of two sections, a "bracket" section and a "planar" ceiling section which contains all the electical ducts for lightning, sensors, smoke detectors and AC.
Both sections are bolted together on site and hunged as a single module using heavy duty concrete Hilti bolts, gunned directly on the concrete slab.
Images by the author.







The green lackered finish was done on site after all modules were assembled and hunged.
Images by the author.

4.5 JOINT TYPES FROM TRADITIONAL WOODWORKING OR METAL FITTING[14]

4.5.1 HALVED JOINTS OR LAP JOINTS

In woodworking, or metal fitting, a lap joint describes a technique for joining two pieces of material by overlapping them. A lap may be a full lap or half lap. In a full lap, no material is removed from either of the members to be joined, resulting in a joint which is the combined thickness of the two members. In a half lap joint, material is removed from each of the members so that the resulting joint is the thickness of the thickest member. Most commonly in half lap joints, the members are of the same thickness and half the thickness of each is removed.

4.5.2 Dovetail

A dovetail joint or simply dovetail is a woodworking joinery technique. Noted for its resistance to being pulled apart (tensile strength), the dovetail joint is commonly used to join the sides of a drawer to the front. A series of pins cut to extend from the end of one board interlock with a series of tails cut into the end of another board. The pins and tails have a trapezoidal shape. Once glued, the joint is permanent, and requires no mechanical fasteners.

4.5.3 Mortise and Tenon

Simple and strong, the mortise and tenon joint (also called the mortise and tenon) has been used for millennia by woodworkers around the world to join two pieces of wood, most often at an angle close to 90°. Although there are many variations on the theme, the basic idea is that end of one of the members is inserted into a hole cut in the other member. The end of the first member is called the tenon, and it is usually narrowed with respect to the rest of the piece. The hole in the second member is called the mortise. The joint may be glued, pinned, or wedged to lock it in place.

14 References to different techniques and methods related to traditional woodworking and joint systems were extracted from several online sources.

Keith S. Rucker website

==> http://pages.friendlycity.net/~krucker/index.htm

Frank Campbell website

==> http://www.sawdustmaking.com/index.htm#General%20Information

V. Ryan website

==> http://www.technologystudent.com/

4.5.4 Fingerjoint[15]

A finger joint or box combing or box joint is a woodworking technique used to join two pieces of wood at right angles to each other. It is much like a dovetail joint except that the pins are square and not angled and usually equally spaced. The joint relies on glue for holding together as it does not have the mechanical strength of a dovetail.

4.5.5 Interlocking joints

Vernacular methods provide significant knowledge on systems of assembly, which can be incorporated as design possibilities and extended through the use of digital design fabrication. In a recent visit to Japan, I discovered the numerous solutions used commonly in woodworking and construction. The most notable aspect of it is it almost never depended on friction fit, which was especially important given that wood was one of the main building materials and the changing weather and prolonged rains, which would affect the wood and therefore may have caused structural damages to wood structures.

4.5.6 Patterns

Current fabrication technologies use patterns or templates to what use to be a manual labour of tracing intricate forms on the wood before cutting it. This enhances the efficiency of the production, reducing the time required for planning the operation, which is rapidly executed by electrical; routers. Patters also enable more complex joint details, which could be easily traced by the routers. A limitation though is that patterns are uniform and that they can only perform that type of detail at the scale they were made. Smaller details in smaller pieces will require different patterns and so on. Patterns promote even more the standardization of the designs in order to be efficient.

15 References to traditional woodworking and different types of joint systems were extracted from various online sources.

General information from Wikipedia

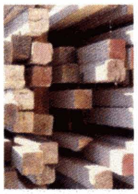
==> http://en.wikipedia.org/wiki/Woodworking

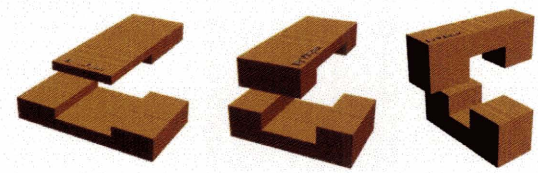
Inside Woodworking website

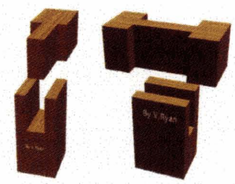
==> http://www.inside-woodworking.com/index.shtml

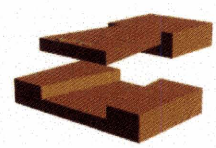
Woodworking Online website

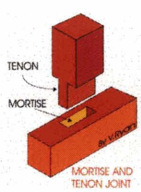
==> http://www.woodworking-online.com/

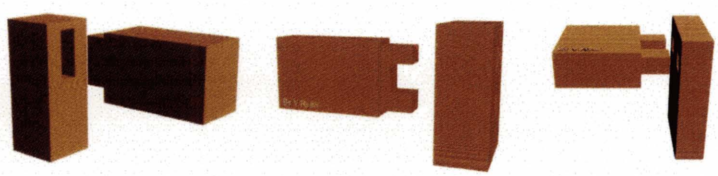


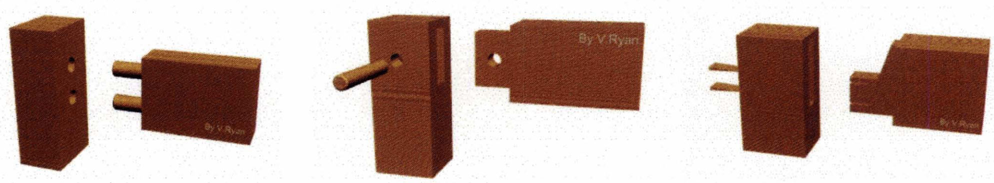


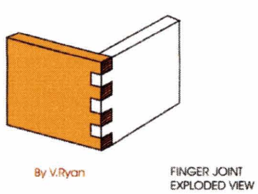


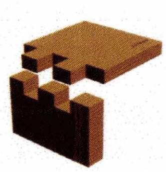




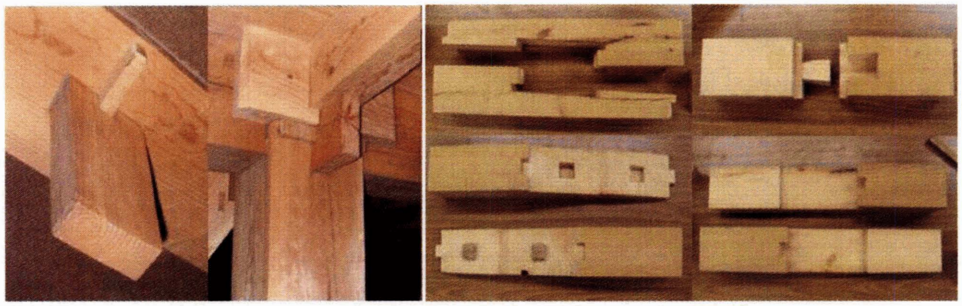








IFigure 3 mages on this page by V. Ryan © 2002-2005
http://www.technologystudent.com/index.htm



Traditional woodworking construction in Japan, pictures of the author.

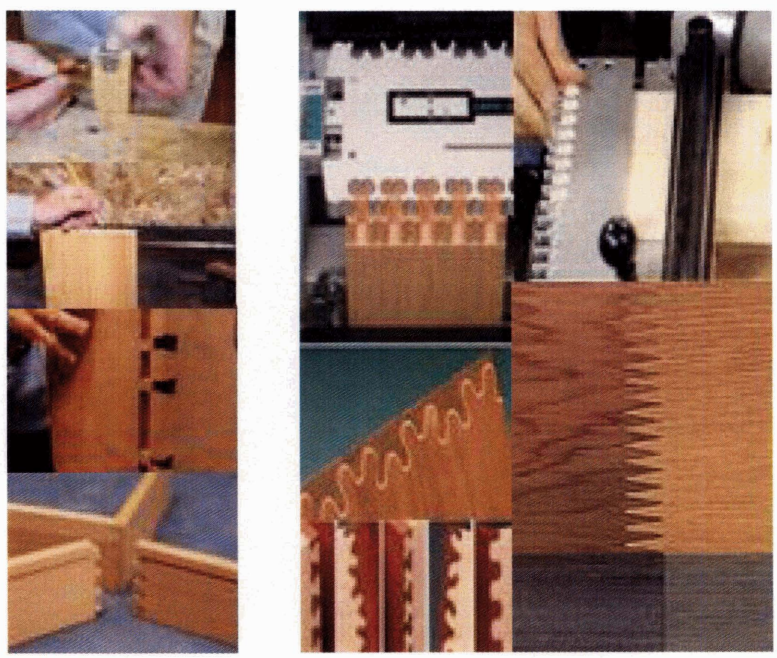


Figure 4 A variety of patterns, templates and gigs for routing are available, to create special dovetail joints and fingerjoints.
Patterns presented here as example, Isoloc Patterns, are produced by Leigh Industries Ltd.

4.6 BRICKS AND BLOCKS

4.6.1 Interlocking concrete blocks

Masonry has provided an enormously rich medium to design and build complex structures. Infinite cases from ancient methods on stone masonry, carved by hand at the beginning, to automated casting methods for the creation of concrete blocks, testify the wide application of such technologies to architecture and construction. Since the methods have been developed towards the mass industrial production of components or blocks, the possibility of having customized blocks for specific functions in a design has vanished.

It is too expensive to create custom pieces with current technology, so custom designs or complex shapes are usually constructed with standard blocks, where the adhesive used to fix the blocks in place is responsible also for absorbing the local deformations or specific conditions of the geometry. Still, the size of the block influences the "resolution" or precision of the detail, which would eventually require smaller and smaller blocks in order to be accurate to the original design. The extreme of this analogy is concrete casting, where the blocks are the concrete particles floating in a dense viscous liquid. This allows obtaining very accurate results in terms of local geometry but, now it requires moldings and scaffolds, which again implies some kind of reduction on the resolution of the detail.

Interlocking concrete blocks[16] have been developed for specific structural purposes, as retaining walls or other structural elements. Self registering geometry is used in concrete blocks to facilitate alignment, as used in paving solution, obtaining different patterns by combining the same block in different arrangements. In structural elements though, it has to do with resistance to forces onto the assembled structure. Interlocking details tend to be rough, and the tolerance levels are high, which is partially covered by the weight and the rough texture of the elements which will add a great friction factor to the joined surfaces.

16 References to Masonry and Concrete Block Construction and different types of joint systems were extracted from various online sources.

Wikipedia website

==> http://en.wikipedia.org/wiki/Masonry

Intralock System website

==> http://www.new-technologies.org/ECT/Civil/psk.htm

National Concrete Masonry Association website

==> http://www.ncma.org/use/masonry.html

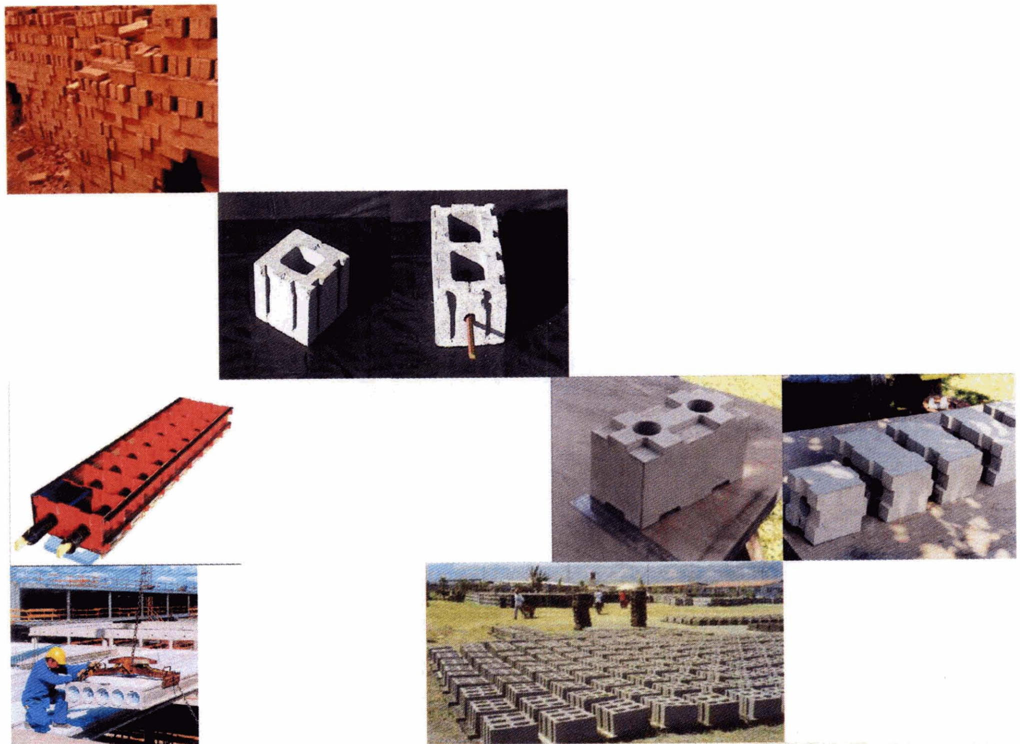
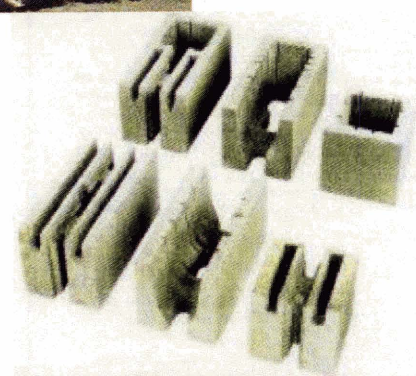


Figure 5 Interlocking building blocks produced by VOBB Verot Oaks Building Blocks (top right) and Intralock System produced by Intralock Corporation (right)



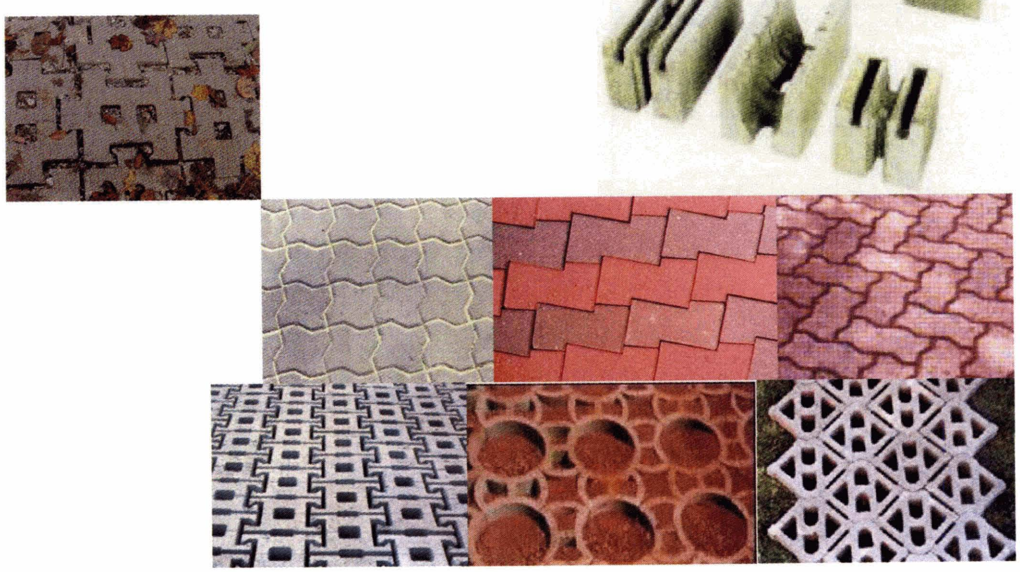


Figure 6 Terrafix and Terracrete, are interlocking blocks sytems developed by Terraforce.

4.7 ARTICULATED JOINTS

Articulated joints can have different levels of degrees of freedom, starting from the revolute joint which has only one degree of freedom, an angular movement, to spherical movement in rotational joints, with 3 degrees of freedoms. Complex assemblies allow extremely complex movement.

Articulated Joints deal with material specific tolerances, especially as they are usually made out of several different pieces that have been assembled together. Tolerance is important in the accurate fit of the different pieces, but it is also essential in the correct performance of the joint itself. An excessively tight joint would not allow an easy articulation, and on the contrary, a loose articulation will be hard to control an maintain in place, it will also tend to be displaced and oscillate inside the "bucket" or concave space of the joint.

The complexity of the pieces made them hard to machine by hand or even by CNC equipment, usually requiring several corrective iterations. Complex joints require more advanced machinery (5 axis or even 7 axis mills). Assembly time increases the cost of these joints.

New fabrication processes, especially those based on additive methods, open up new possibilities for fabrication of such complex components, especially since some of them are starting to incorporate the use of more than one material at the time, allowing for complex pieces made out of different materials, to be made without any post fabrication assembly required, and in less time than what would take to manually machine each piece and then build the final component.

I am particularly interested in these joints[17] as the provide the basic conditions required from low level joints, that is, to put things together, and to secure their junction. But they also allow for further operation of such structures, enabling kinetic behaviors and therefore, variation within the shape.

---

17 References to different types of Articulated Joint systems were extracted from various online sources.

The MathWorks Inc. website

==> http://www.mathworks.com

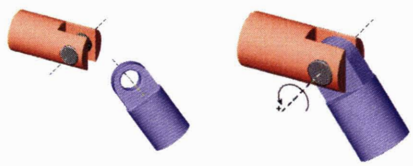
Mark Ho website

==> http://www.zoho.nl/zoho2.html

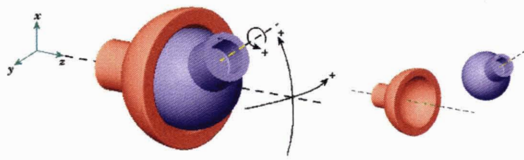
website

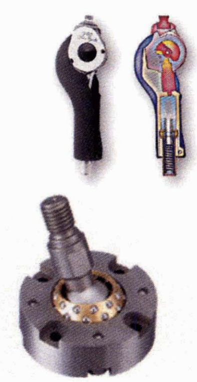
==> Hephaist Seiko Co.,ltd website

http://www.hephaist.co.jp/e/index.html



Revolute Joints samples





Spherical Joints samples

Figure 7 Robotic and prosthetic applications of rotational and spherical joints. The Robot Sculpture on the right has 85 different joints, with 2 or 3 degrees of freedom each.

Figure 8 Universal Laser System

4.8 ABOUT MACHINE PROCESSES

Each fabrication process has its own peculiar methods. These methods are tied to the different machines used. The machines that I had used for this research are but a small sample of the current technologies available. I will briefly describe the processes that each of them implements and later will discuss some other methods, some already available and some under development. It is essential to my understanding of the implications of Digital Design fabrication, to visualize and situate the levels of relations between the physical world of manufacturing and the virtual-abstract world of design. These relations are not fixed to technologies, but have to be embedded into design processes. First it is crucial to understand the processes going on in order to manipulate them to achieve specific results. The development of these methods is not necessarily a linear one. As each technology has many variables and aspects that have to be consider, sometime unexpected results come out of accidents. Many times, this happen when hacking or tweaking existing procedures in order to obtain different results. Different outputs could inspire then new developments for new technologies, and so on and so forth.

4.8.1 Laser Cutting

I have used two machines for the laser cutter exercises. Both are 100 W. Universal Laser Systems Inc. Their bed is 18" by 32", and I used a 2" lens for all cuts. One of the machines was hooked up to run as a plotter from Autocad 2004. The other machine runs from Corel Draw 10. Although the variable settings are the same, the interfaces are different. In Autocad, the cutting file can be opened as a Drawing File (DWG Format), in Corel Draw it has to be imported as a Drawing Exchange File (DXF). This difference makes a bit of a difference as when exporting and re-importing to DXF, some curves can be altered due to the translation. With Autocad this never happens as it opens a native format. In both environments the settings for the speed, the number of pulses per inch (PPI), and the power of the beam, are adjusted as properties of the plotting-printer device within each software, through its specific driver.

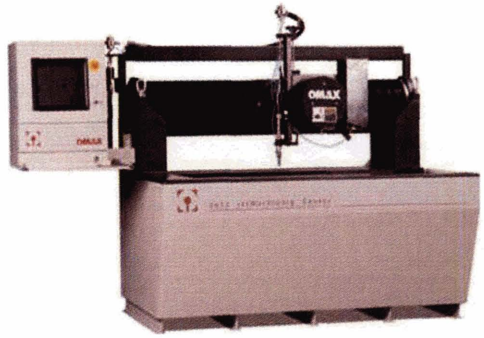


Figure 9 Omax Waterjet 2652

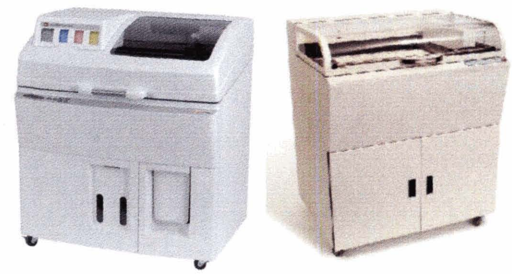


Figure 10 Zcorp Z-406, and Zcorp Z-400

4.8.2 Water Jet Cutting

I used an Omax 2652. The model name stands for the maximum size piece it can work with, which is 26 by 52 inches. The Omax takes DXF files, which means that the drawings have to be translated to this format from the drafting or modeling platform where they were developed. Beyond importing, the waterjet process involves creating the toolpaths from the given file, and setting up the points of "lead in" and "lead out", which correspond to the specific locations where the machine head will start cutting. Due to the pressure of the water, the moment it starts cutting, the cutting column leaves a bigger cut when it first blasts the surface. This is why these "lead in" and "lead out" have to be specified a few mms away from the actual cutting toolpath. This is done at the graphical interface provided by the Omax itself. After the toolpaths are calculated including the leads in and out, the machine needs to be set up in terms of the speed and power.

4.4.3 3D Printing

I have used three Zcorp 3D printers. One is a Zcorp 400, which has a bed of 8" by 10" by 8" (high). This machine is the slower one, with a speed of 2 layers per second and one print head. The second machine I have used is a Zcorp Z 406 model, which had the same bed and speed that the Z 400, but that has a printhead that incorporates color inks in the print, so it can handle up to 16 bit color prints. The third machine is a Zcorp Spectrum Z510, which also has a 2 layer per minute speed, but with a bigger bed of 10" by 14" by 8", which makes it much faster. This machine also has also four print heads, which allows having 24 bit color prints. This machine also heats the composite while is being printed on the bed, which accelerates both the time required for the model to be stable as the digging up process due to the model being more resistant. The slicing of the models was done in the proprietary software ZPrint, which takes care of creating the different layers for the machine to print.

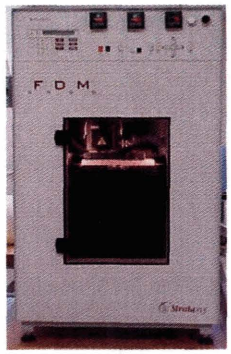


Figure 11 Stratasys FDM 2000

4.4.4 FDM

I have used two machines for Fusion Deposition Modeling manufacturing. Both are from the same make and model, Stratasys 2000. The first machine is set up for ABS plastic and support material. This support material, is strong enough to act as scaffold for the model, but is easy to break apart by hand when the print is done. The second machine is set up to use Waterworks ABS, which basically is a combination of ABS plastic as building material and a water soluble plastic for the support material. This support material has to be drawn into a Waterworks Ultrasonic Tank, where a chemical mix dissolves the support material plastic. Both machines have a resolution of +/- 0127 mm. These machines require running a process to derive the toolpaths and create the support structures. They use Insight which is the proprietary software for this purpose, which has to be run to a PC connected to the machine. The first process slices the model, the second creates the support structures, and then the toolpaths are downloaded to the machine, which calibrates itself according to the data received, and heats up the materials, in order to start printing.

4.4.5 Other Methods

New processes are constantly being developed. And the categories that define the type of fabrication process address by each process are restructured, redefined. This are two cases of different additive manufacturing processes that could be potentially used to obtain different kind of designs exploiting their particular characteristics and methods.

In the realm of the 3D printing process, few other methods have been developed: Stereolithography It consists in building plastic parts layer by layer by tracing a laser beam on the surface of a liquid photopolymer. The photopolymer is solidified by the laser light. Once one layer is completely traced, it is lowered a small distance into the liquid and a subsequent layer is traced, adhering to the previous layer. This process is repeated continuously and after many such layers are traced, the result is that a complete 3D model has been formed. Some specific technologies require further curing of the polymer in an oven. It produces very accurate and precise models, but one of the limitations of this method is the fragility of the final model.

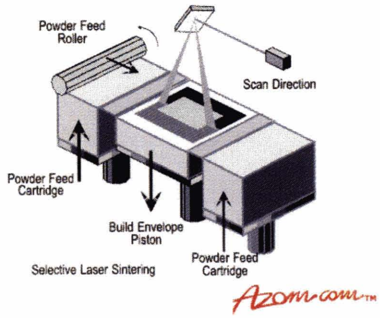


Figure 12 SLS technology, 3D metal printing using powdered metal alloys

Another method being developed is Selective Laser Sintering (SLS) which was developed by 3D Systems Inc. This additive process is a manufacturing technique that uses a high power laser to fuse small particles of plastic, metal, or ceramic powders layer by layer in order to create a solid mass of the desired three-dimensional object. The laser selectively fuses powdered material by tracing cross-sections of the part on the surface of a bed of powder. After each cross-section is traced, the powder bed is lowered by one layer thickness, a new layer of material is applied on top, and the process is repeated until the part is completed. The result is the solid 3D model described by the digital file that was used as input for the process. The melting process can be full or partial, and therefore different outputs depending on the different material and different parameters used in the process, can be the result of such operation. This method allow producing solid metal pieces.

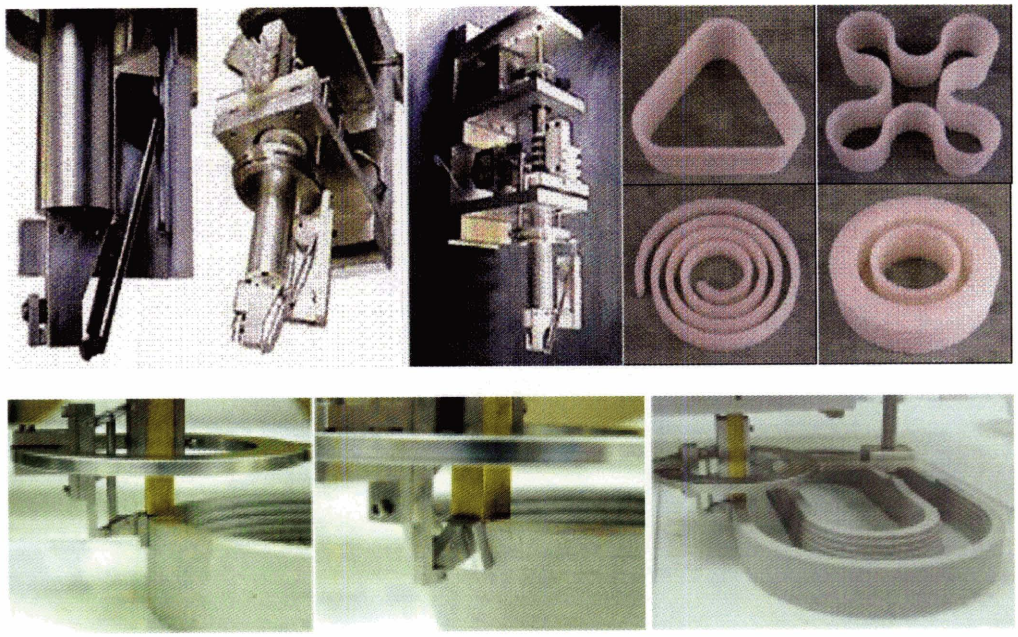


Figure 13 Contour Crafting method, developed by Professor Behrokh Khoshnevis at the University of South California. The materials used in the process to print the solid models can be plaster, concrete, adobe, plastic or even wood particles mixed with epoxy into a paste

3D printing taken into large scale for construction purposes is what Contour Crafting is about.: A research project developed by Professor Behrokh Khoshnevis at the University of South California. It basically emulates in large scale the process of 3D printing using concrete as building material. Due to the different times of curation of concrete, it requires to build a supporting contour on the borders of the wall being printed. Then concrete is poured into the pre defined boundaries. As the process continues and the printing head is raised in the air, as it mounted on a robotic crane, it will finish walls and continue with the concrete slabs. The result is fully automated construction in concrete of modular designs.

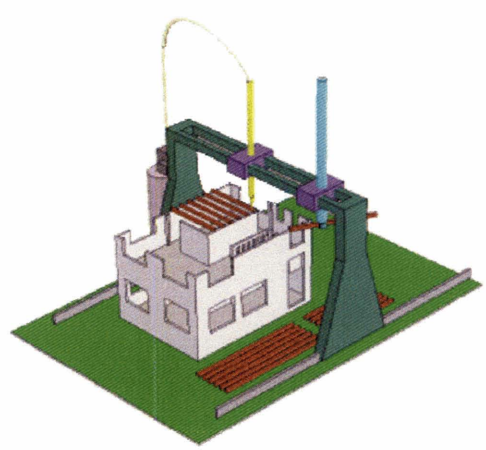
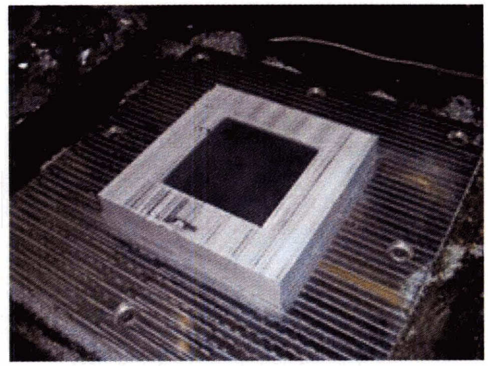
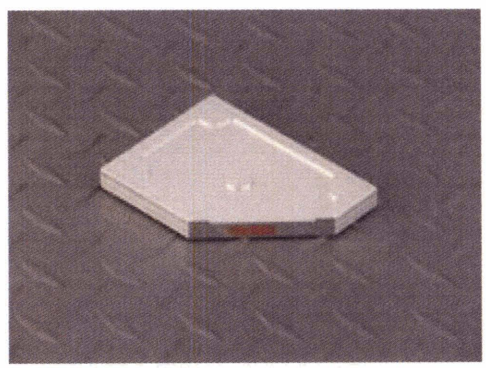


Figure 14 Formation machine which combines both additive and subtractive methods of fabrication

There is a process which blurs the definition between additive and subtractive processes. This method called Ultrasonic Consolidation Formation, has been developed by Solidica Inc, and consists of a mixed process of additive and subractive techniques. It Builds up a model welding solid metal stripes one layer at a time. After each layer a milling head removes the excessive material and creates the cavities required. Then a new layer is welded on top of the first one, and so forth. This process produces highly resistant metal pieces, as they are not composed of powdered metal but of solid metal pieces fused together.. It can weld together different materials and metal alloys, allowing the production of complex pieces made of different materials like embedding electric circuits into solid pieces.

It is to expect further developments in terms of hybrid or mixed fabrication methods in the near future.





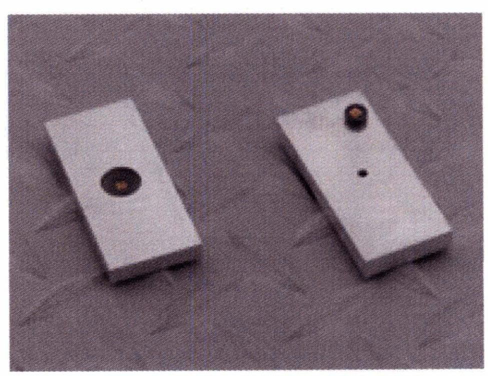


Figure 15 New methods as the patented UCF (Ultrasonic Consolidation Formation), by Solidica Inc, allow to create solid metasl parts made of different metal alloys, by combining both additive and subtractive processes in the fabrication. Models are stronger than SLS models, as they are not made out of dispersed powder, thus avoiding the porous results of this method. On the other hand, the use different material allows embedding subcomponents into the fabricated piece. Here as example, embeded circuits are built within a solid metal piece, eliminating post manufacturing assembly.
http://www.solidica.com/

COMPUTATIONAL DESIGNS

I have been working on this research for two years, gathering experiences from different fronts at MIT. The projects presented below are a brief summary of these experiences. Some of them go deeper in particular subjects and I have not included these investigations for detouring from the main objective of this thesis which is designing computational tools for digital design fabrication, using a toolchaining approach.

Some of these experiences also opened parallel areas of interested which I intend to pursue in later work.

These works have been presented different public instances and have been discussed in an effort of contributing to the current debate about computing design and technology development.

5 DESIGN TOOLCHAINS

A collection of tools used to develop for a particular hardware target, or to work with a particular data format[18]

In computer programming, a toolchain is the set of computer programs (tools) that are used to create a product (typically another computer program or system of programs). The tools may be used in a chain, so that the output of each tool becomes the input for the next, but the term is used widely to refer to any set of linked development tools.[19]

In the context of this thesis, I have used the concept of toolchains in the implementation of a series of digital design techniques using paramedic design tools. The concept of nesting dependencies is native to parametric environments, and I have extended such conceptual understanding of a complex structure, to the actual design of architectural assemblies. This section of the thesis describes and demonstrates the application of design toolchains to digital fabrication. I have undertake this effort through different exercises, tackling this question from different angles, and although none of them pretended to be an exhaustive and comprehensive approach, I have compiled them here in this thesis as a way of describing the problem from different angles and also to propose solutions to these issues. Of course, as in any design context, the minute that the particular design problems where conquered through a particular design, new questions appeared, and therefore this research is still a work in progress. Nevertheless, the implementation of such linked constructions, design toolchains, has proved to be a valuable approached which I would try to extend in future research.

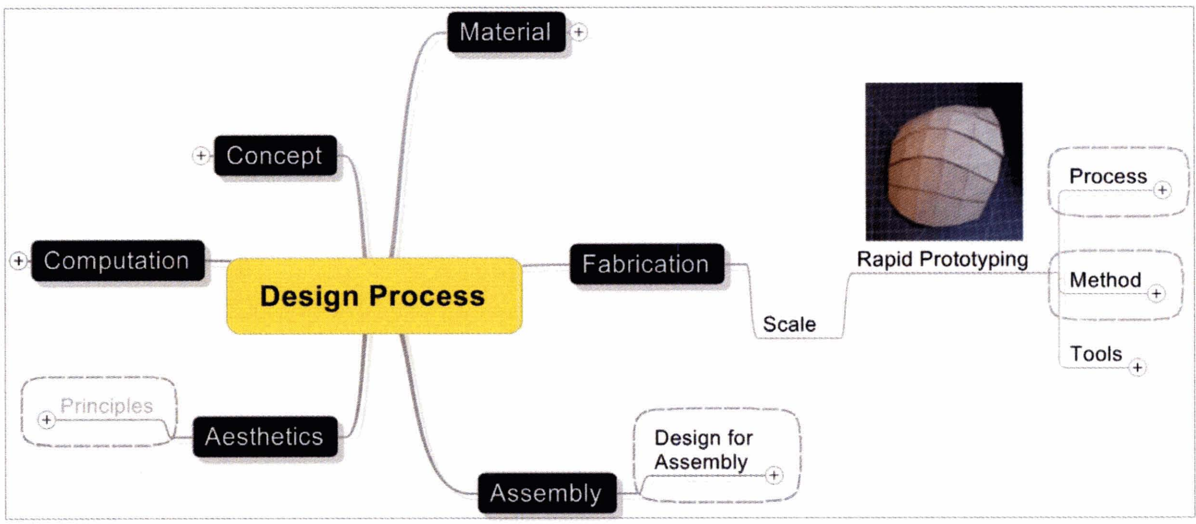
The design toolchains that I have developed for this thesis, developed as design techniques oriented towards the development and customized extension of specific design tools and their application to automated manufacturing, humbly intending by this effort, to understand the limitations and potentials of current design and fabrication technologies available.

5.1 TOOLS, TECHNIQUES AND TECHNOLOGIES

In contemporary architectural discourse, within post digital culture, three concepts are used as synonyms, almost indistinctively, while they have different meaning and refer to different stages of cultural knowledge: tool,

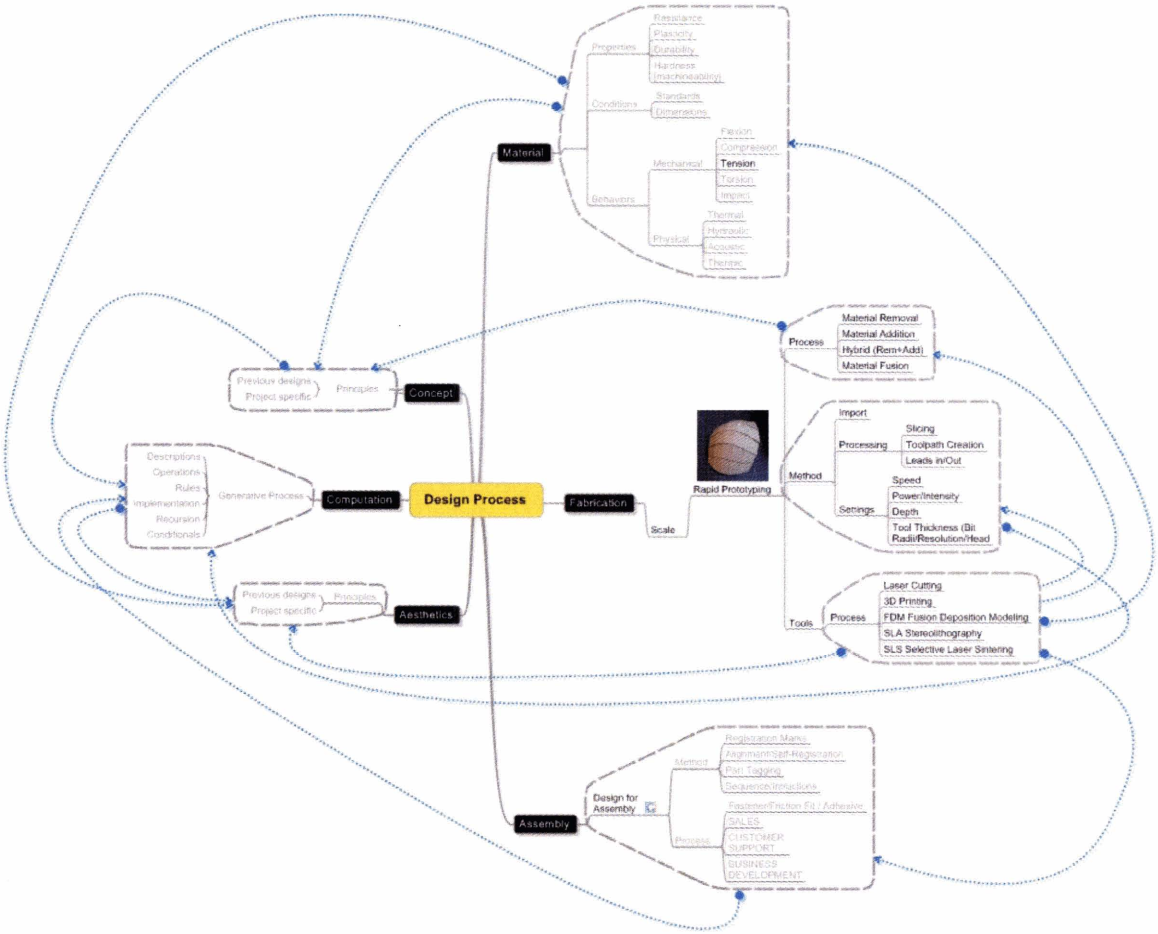
18 http://www.catb.org/jargon/html/T/tool-chain.html

19 http://en.wikipedia.org/wiki/Toolchain



:: DESIGN DRIVERS

Incorporating various levels of development and complexity into early stages of a design process in order to expand both its repertoire of possible solution spaces and to enhance the generative process, improving simultaneously its path towards fabrication and construction.



:: DESIGN TOOLCHAINS

Fabrication used both as a an input for generative and explorative process, incorporating notions of assemblies and material properties, but also as a temporary mode of evaluation of design iterations, which could feed the design toolchain recursively.

technique and technology. Digital tools and digital technologies are often used as equivalents, I will explain the differences. Tool is something that is used to perform an action, it is the instrument. Technique on the other hand, is a method or group of methods for accomplishing a particular task. But technology is the body of knowledge, available to a society, which is of use to achieve specific practical purposes. Then the computer is a tool, as it is the software running on it. They are used to execute specific actions or operations, to achieve certain objectives. The specific methods developed to use computers and software, inventing and perfecting creative processes to achieve better results, are recorded as techniques. But technology is achieved, when a new knowledge is produced from the creation and application of certain techniques, running specific tools, to achieve desired objectives. Although this research is still in progress and the results are partial, I will use them to explain how emergent computational tools, parametric design environments and numerically controlled fabrication processes can be implemented in the development of architectural designs.

The techniques developed to achieve the objective of designing and fabricating complex continuous curved structures, have been divided in two phases:[20]

20 Schema of the algorithm devised for this research. (right)

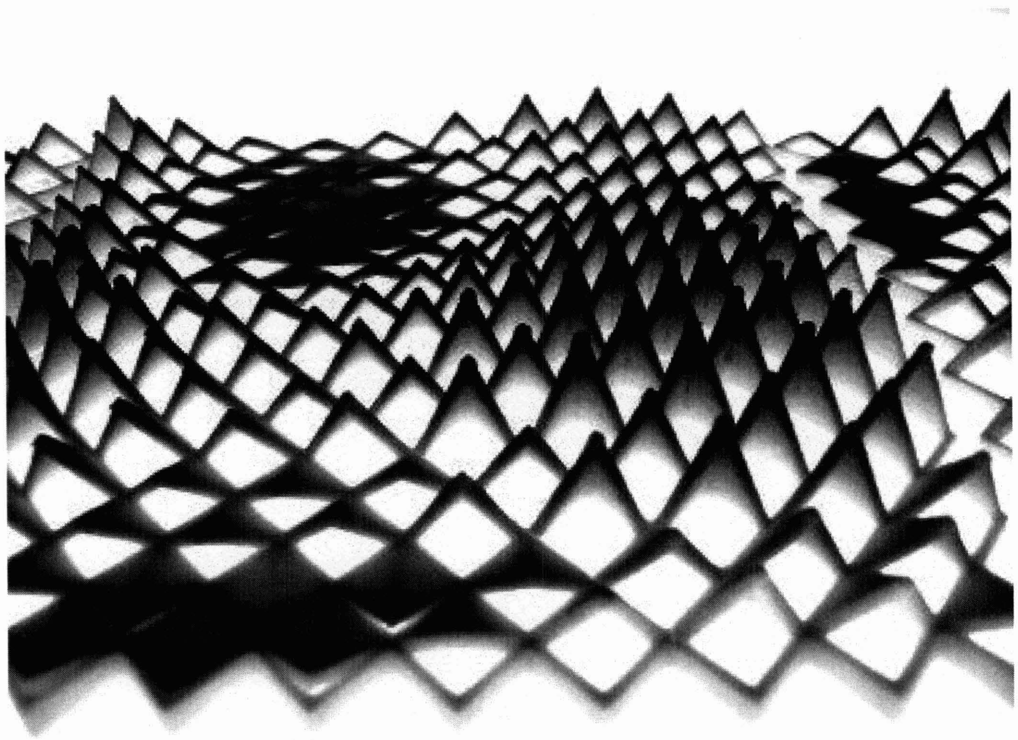
5.2 PHASE ONE _ GENERIC DESIGN FUNCTION

Through a subdivision scripted routine the tool will read a given spline surface and create an approximated facetted version of it. This faceting controls the resolution which is the degree of approximation between the original shape and the derived one. This facetted version is then broke in parts, which for fabrication purposes are flattened down and arranged in a fashion that optimizes them for fabrication. This process will provide a cut sheet or fabrication layout which can be then used by the specific fabrication methods selected to manufacture the design. This phase of dividing and unfolding is common and generic to any surface or structure.

5.3 PHASE TWO _SPECIFIC FABRICATION FUNCTION

Each fabrication method has its own characteristics and its own constraints, some of these particularities will be explored. On the other hand, design for assembly always involves the need of thinking in common issues, independent on the material or fabrication method employed: the necessity of using tolerances and the necessity of developing joint systems. For the purpose of this research I will use a method of self-registering shapes.

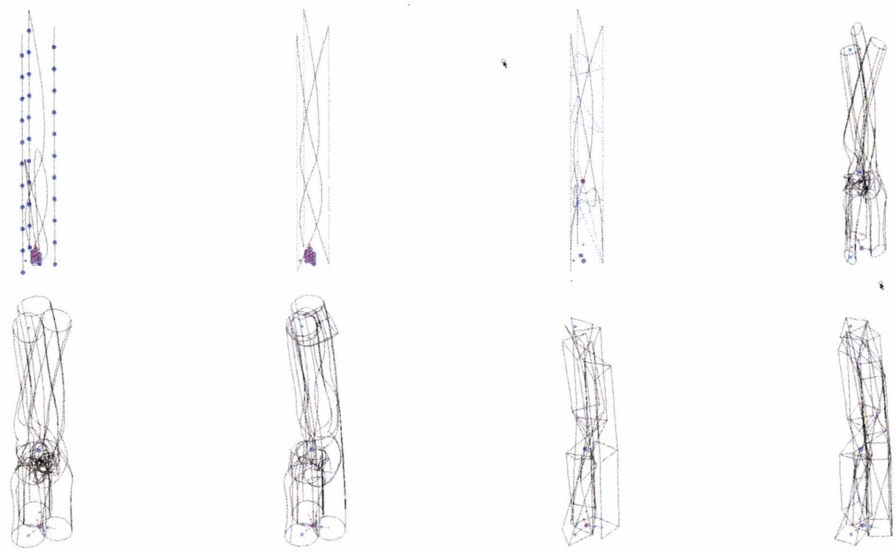
Several exercises were conducted in order to investigate specific methods to design and fabricate. Some are related to modeling conditions, some to designing details, some to fabrication restrictions. Each of these cases proved to be successful in terms of providing a space for investigation using the design process itself both as a research tool and as the subject being examined. This first exercise consisted in designing a structure made out of many different parts, with parametric variations, in order to be fabricated using digital fabrication tools. It was aimed at designing a procedure to use parametric design in order to control variations on complex assemblies through design iterations. This project has been presented at different conferences and lectures and was first published in 2005 at the SIGRADI Conference.



6 ICHTYOMORPH, DESIGN FORASSEMBLY

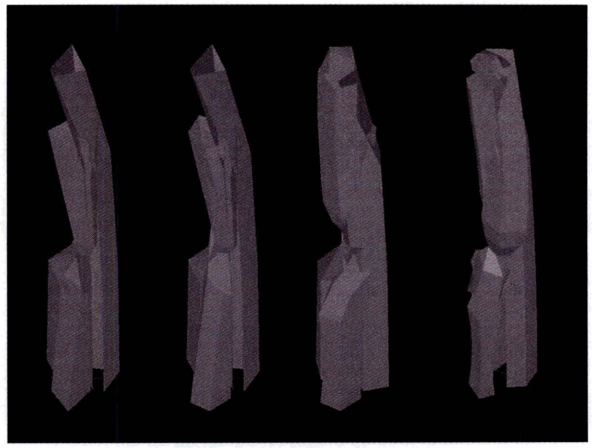
6.1 ICHTYOMORPH-DESIGN AND DEVELOPMENT OF A FISH-SKIN DOUBLE FACADE SYSTEM FOR FREEFORM SUPER TALL BUILDINGS USING PARAMETRIC DESIGN TOOLS

Parametric design implies a whole new paradigm of non standard design through the propagation of the difference, the repetition of variation. The ability to control variation and adaptation to local conditions allows more precise yet complex designs. This work describes a research project designing double skin façade systems for tall buildings using a

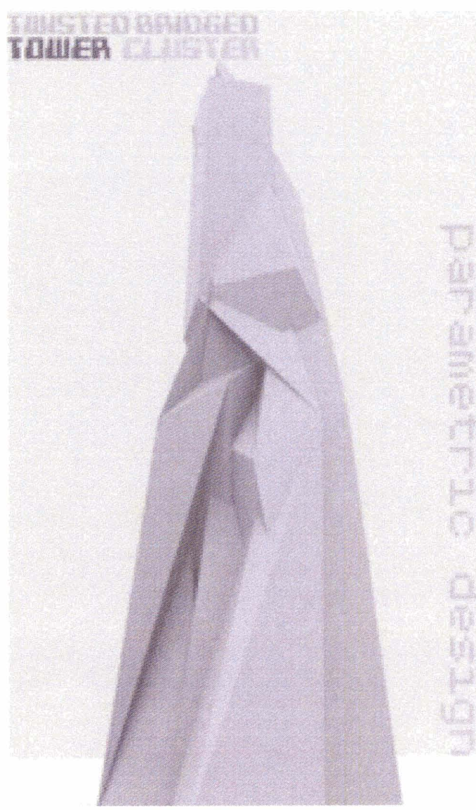


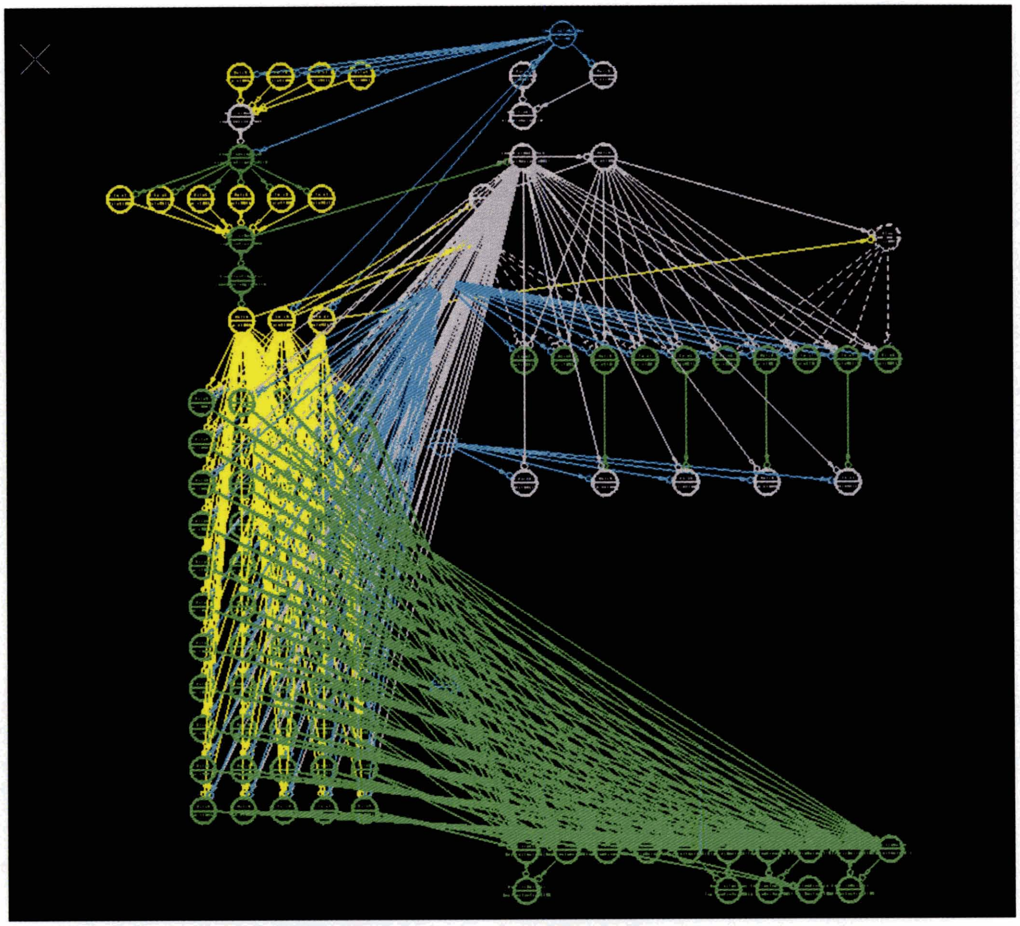
Studies for a tower cluster design weaving three or more towers and connecting them at strategic transfer floors., The designs are taking advantage of structural conditions required for super tall buildings after 80 floors high., where reinforced structural floors are required, and elevators hsafts have to be shifted.
Global parameters control the height of the buildings, the height at which the towers meet, how much they twist or revolve, the number of sides for each tower footprint (from a triangular plan to an ellipsoid plan), and the height of each floor (subdividing the tower).

parametric approach. These designs are tested later through rapid prototyping techniques. This research aims its design towards an adjustable façade structure, articulated according to various complex geometrical conditions on the façade of a building. The skin is conceived as a light, flexible, reconfigurable composition responding to different criteria regarding the design, its environment or the program. It achieves this through different levels of control on different scales of the project, by embedding several layers of parametric features, which are nested one inside the other, in order to produce the overall rainscreen surface of the tower. I will show this technique of nesting parametric components on different scales to build a complex yet controllable double skin facade system.



Few selected parametric iterations developed from the construction in GC.



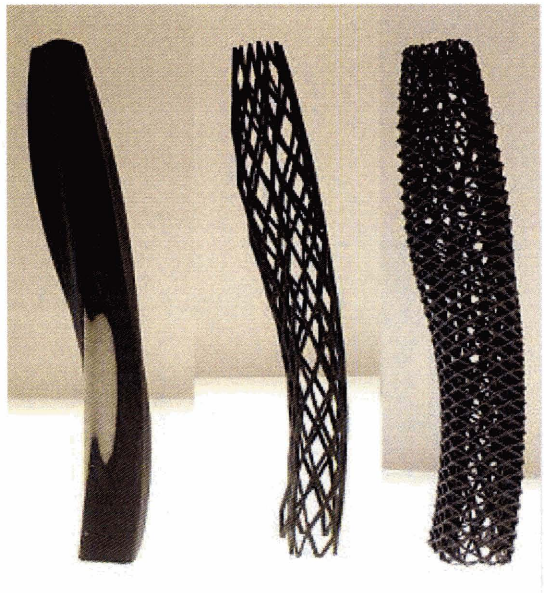


Building dependencies and relations in the model, to create geometry and to control such geometry and its variations

6.2 GLOBAL VARIABLES AND PARAMETRIC FEATURES

Here I will describe parametric techniques that can be implemented to design complex architectural structures. I will point out two particular techniques that use parametric functions present in the last built version of Bentley's Generative Components (GC) software, and their application on a design problem.

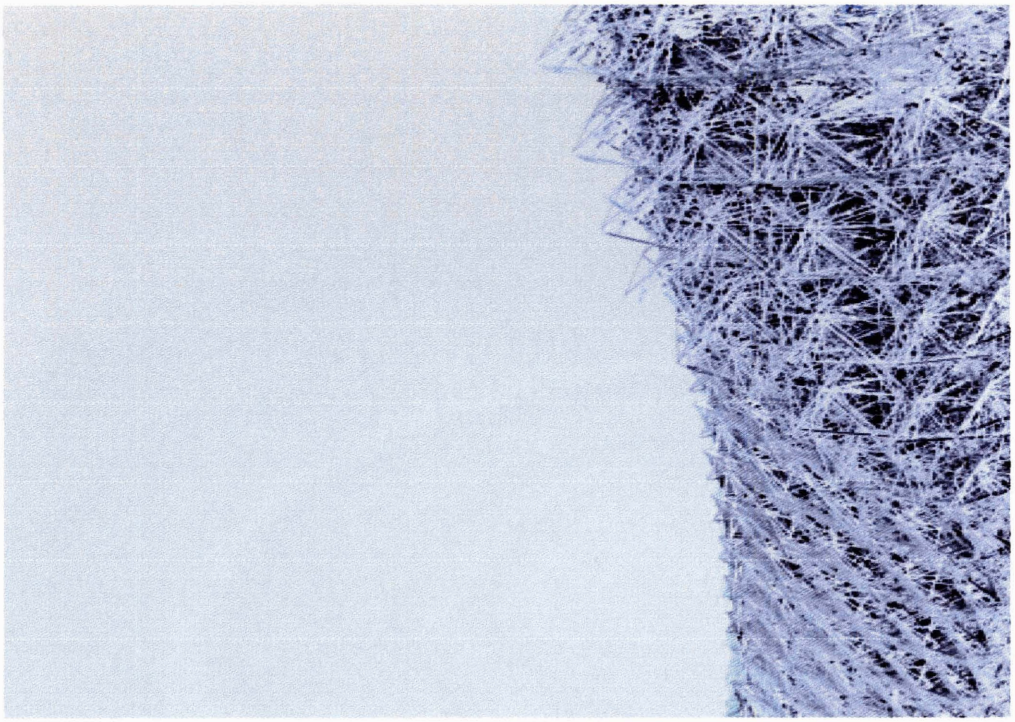
Parametric design introduces the concept of solution space, where designs are not the fixed result of modeling skills from a pre-conceived idea, but the result of a set of relations and conditions built with embedded ranges of variation that allow exploring different possible designs. Two functionalities of the parametric environment implemented in Generative Components were tested for this research: using Global Variables with associative functions during the concept creation and form



Sequential 3D printed models:
Original twuisted double curved shape,
Diagrid structure (supporting exosqueletal structure)
Double Diagrid (supporting diagrid inside, facade diagrid outside)

finding processes, and building associative dependencies and relationships within parametric features or components which will later inform the design. These two strategies influence different scales of the final design, becoming nested conditions linked according to a pre set hierarchy.

A global variable as present in GC is a feature that can be as simple as a numerical value, or as complex as a large mathematical function. The resulting value of this variable can be linked as an input to any other feature, geometry or function, creating a dependency which is external to this second feature. A Parametric Feature is a component which has a particular creation method depending on inputs, a number of functions and internal relations that link the geometries of the feature, and a geometrical output. All this characteristics are programmed by the designer, extending then the basic library of features to create his own library of customized components, depending on particular projects, or on particular methods of work.



Ichtyomorph facade system, parametric scales surface

6.3 FEATUREPOPULATION

Parametric objects have the relations between its constituent geometries and functions encoded as constants or variables of its design; they will adapt to variations of the magnitudes of these values but will always maintain the hierarchy of relations and functions. The result is their ability to adapt while a variable's value is changed.

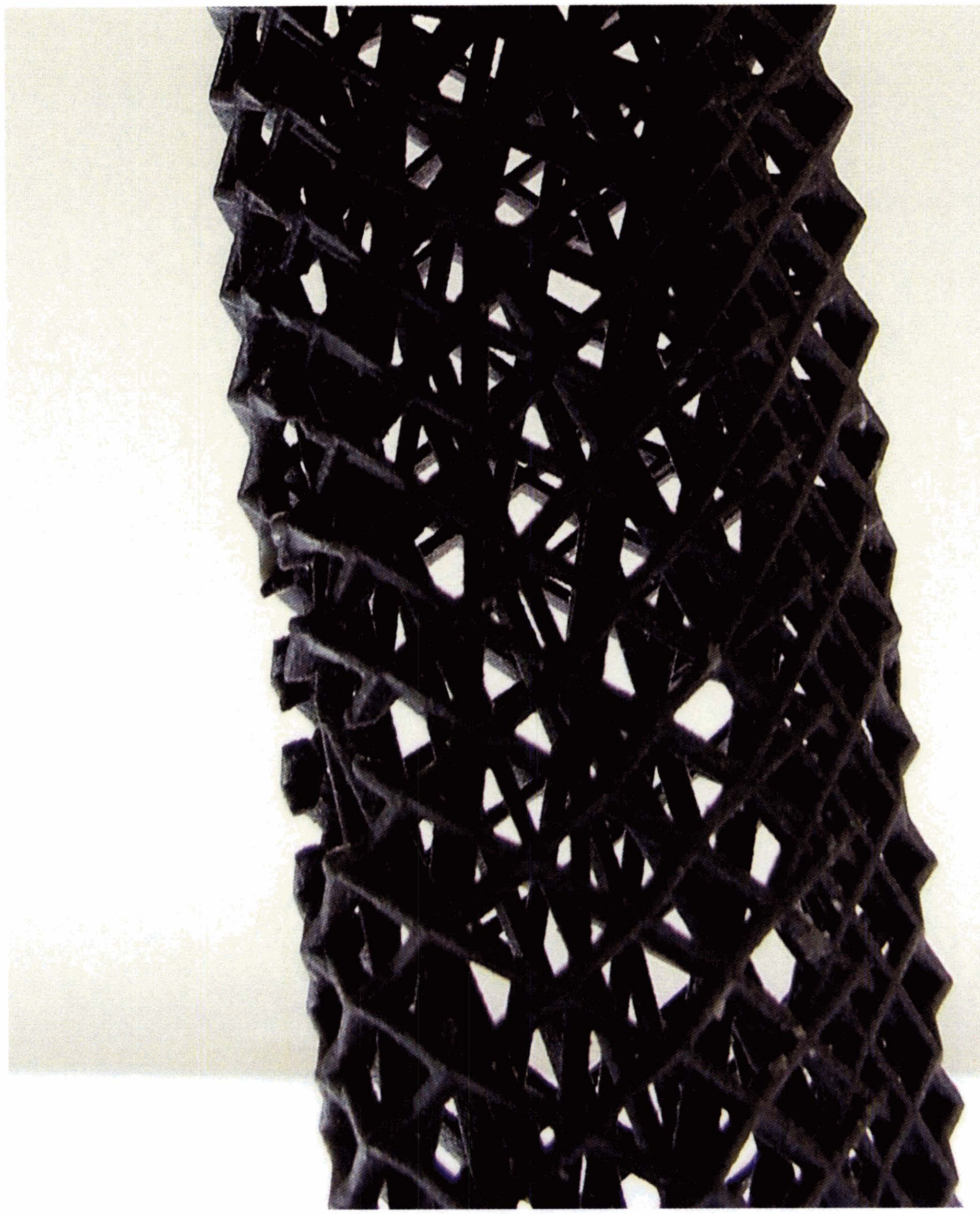
Building parametric features allows the designer to create smart elements with embedded intelligence which adapt to local geometrical conditions. When these objects are replicated numerously on a context field, they adapt to the specific characteristics of the geometry. This method of replication or feature population will result in a collection of different objects, and when the populated field presents heterogeneous and non constant conditions, the result will be a collection of all alike but all different components. It is possible to manage these collections of components created by populating parametric features, by changing the conditions of the context where they were inserted. It is also possible to build into the parametric feature itself, dependencies to global variables, which can be controlled externally. Such strategy allows the designer to set up behaviors and ranges of adaptation inside the features themselves and also allowing external control. In this research paper I explore these functions by embedding both kinds of dependencies on a simple feature, in order to test its adaptation capacity, responding both to internal constraints and to the adjustment of external global variables.

6.4 DIGITAL FABRICATION PROCESSES

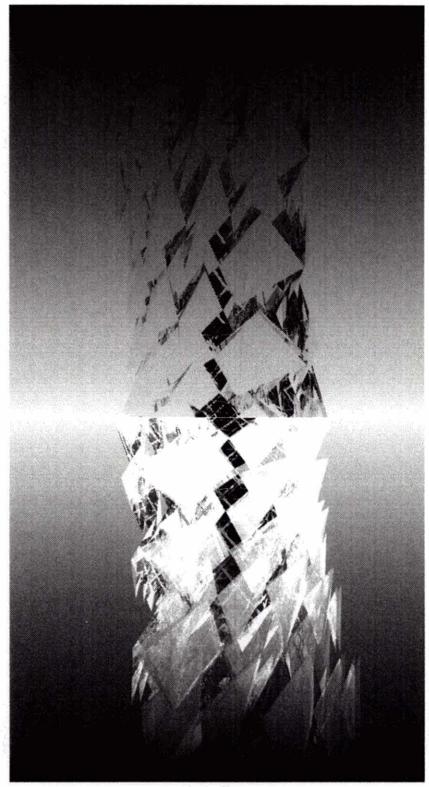
Within digital fabrication every manufacturing process is executed by machines controlled by computers. Each machine has its own particular fabrication method, imposing an ad hoc logic required to manufacture an object. A recurrent struggle on contemporary post-digital architecture, is realizing designs, beyond the electronic environments of digital 3D modeling tools. This is particularly critical when designs are based on incremental variation, as opposed to standard repetition. This case studies precisely the fabrication of complex structures where pieces are all custom variations of a type, each piece being similar but different from al others.

When a parametric model is built, the relationships between primary geometries and functions are set; therefore it allows integrating also fabrication logics, which will later facilitate its manufacture. Learning these fabrication logics implies understanding which processes are best suited for building specific designs. For the purpose of this research, 3D printing methods were used. These are additive fabrication methods, they deploy or add material, using several different processes and materials, requiring specific knowledge of proprietary software, and specific operational skills to operate the machines. Two different processes that employed material deposition building methods were used on this research.

A ZCorp machine was used for testing the results of geometrical dependencies and parametric variations, providing appropriate resolution for scale models and short fabrication times to fabricate several tests. A Stratasys machine, using a soluble support material, was used to build articulated parts that needed movable joints to perform basic movements. I implemented this method in order to build solid pieces with movable parts, and with sufficient material strength to resist the mechanical demands at model scale. The tolerances used, allowed movement between hinged parts but providing enough friction surface to fix the pieces in place after adjusted.



Double Diagrid structure



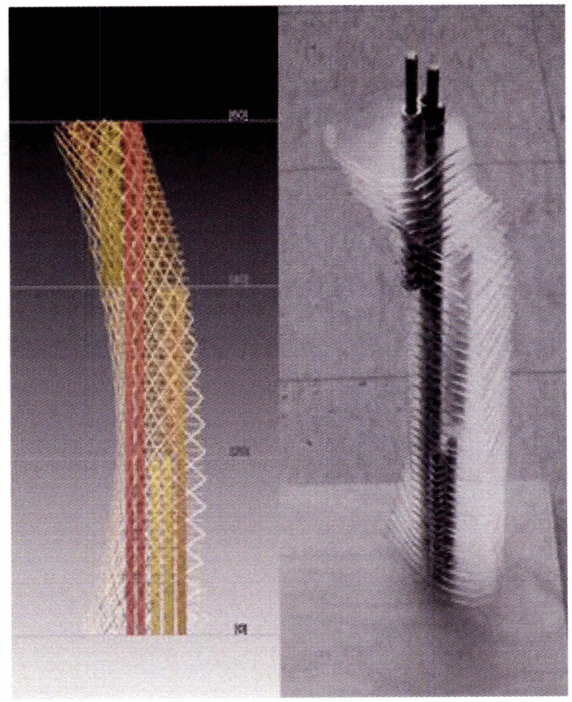
Preliminary visualiazations of the scale - surface

6 . 5 DOUBLE SKIN FACADE SYSTEM FOR TALL BUILDINGS

The case selected for the project is a double skin façade system, specifically focusing on super tall buildings. The name of the research project, Ichtyomorph, responds to being inspired in a fish skin structure. Its ability to turn and dribble while swimming, depend on the skin of the fish, composed of a mesh of layered fibers, which pulsates driving superficial patterns along the skin of the fish. This reorients the hundreds of operable scales which become hundreds of small flaps providing stability and precise control, giving the fish its agility in the water. Ichtyomorph is an adjustable façade structure articulated to respond to varying geometrical conditions. A secondary objective is to design a facade detached from the supporting structure, as a flexible composition that may be reconfigured.

6 . 6 PARAMETRIC SHAPE AND ADJUSTABLE BUILDING SILHOUETTE

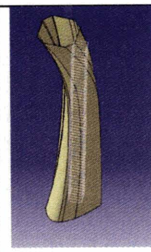
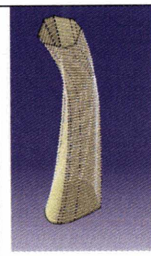
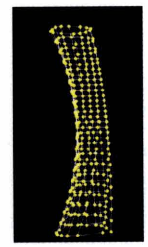
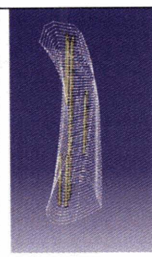
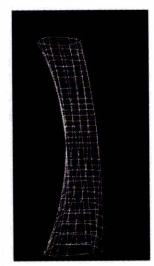
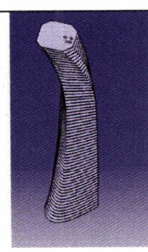
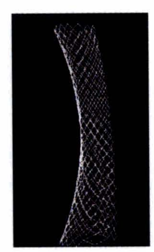
This project was originated as response to an assignment in the Digital Design Fabrication class conducted by Prof. Lawrence Sass, and was later developed as part of this current thesis.

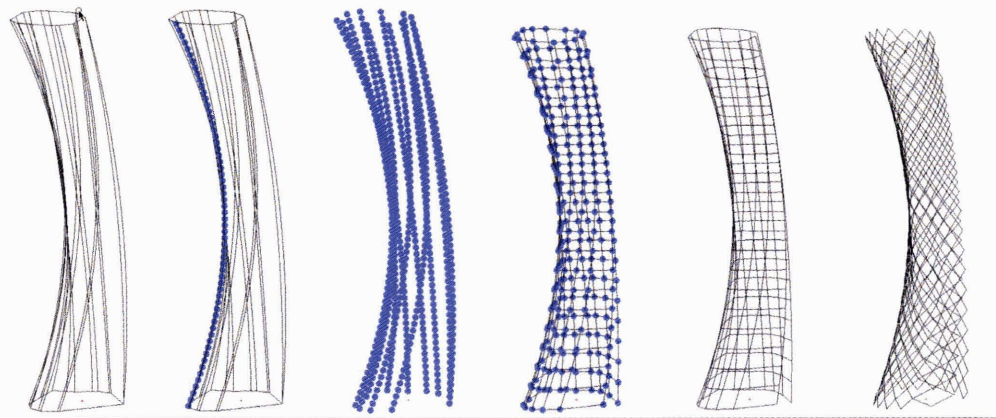


Parametric section of the building with elevator cores and structural diagrids. On the right is a laser cutted model showing the structural support of the elevator cores

Originally the problem required using parametric design tools implemented in CATIA software. Five spline curves placed on a vertical axis control the curvature of a loft surface derived from them. The distance between these control sections is regulated by a function that adjusts this value proportionally according to the desired number of floors. Adjusting the factor of proportionality between the spline control sections, will change the external appearance of the tower. After the shaping process was developed, a rationalization of the building took place adjusting the geometries using the Sketcher in Catia, locating the core structures for the express elevators and deciding the transfer floors. The rationale for the core location included the orientation of the tower on the site, promoting natural sunlight and inclining the tower towards the SW to self shade the west facade reducing heat gain and preventing excessive UV loads.

Table 1: Operational steps applied to rationalize the building design, and populate the diagrid feature over the shape grid surface. Translation from CATIA to Generative Components

Name	General Procedure	Attributes	Image	Name	General Procedure	Attributes	Image
OS 01	Create multiple planes between planes	The lateral position of all floors are determined.		OS 05	Place a series of points on each floor slab	Define a vertical guide to align the structure	
OS 02	Section	The outline of the floor plates obtained		OS 06	Transform each point in a series of points distributed along the perimeter of each slab	Locate the position of nodes for the diagrid The resolution of the grid is adjustable	
OS 03	Sketch + Line + Sweep	Elevator shafts located and generated		OS 07	Create a series of shapes based on the point grid	Define the modulation of the facade	
OS 04	Thickness + Boolean operation	Floor plates with elevator shafts.		OS 08	Insert the diagrid feature and populate the shape array	Converts the lofted surface in a diagrid structure	

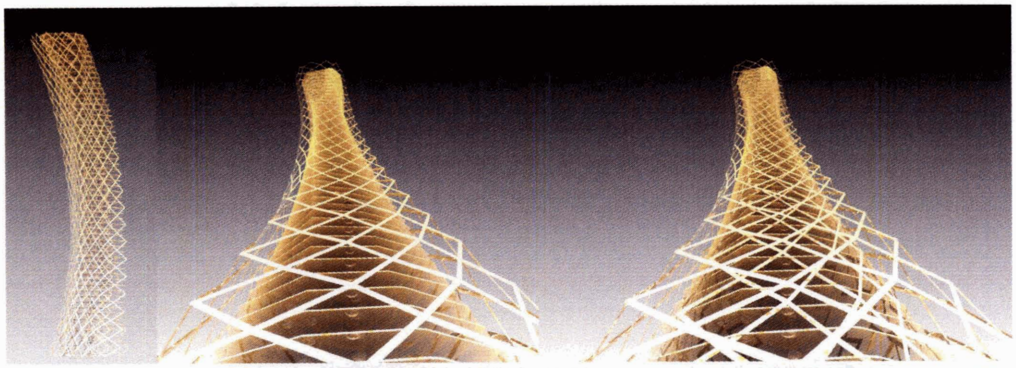


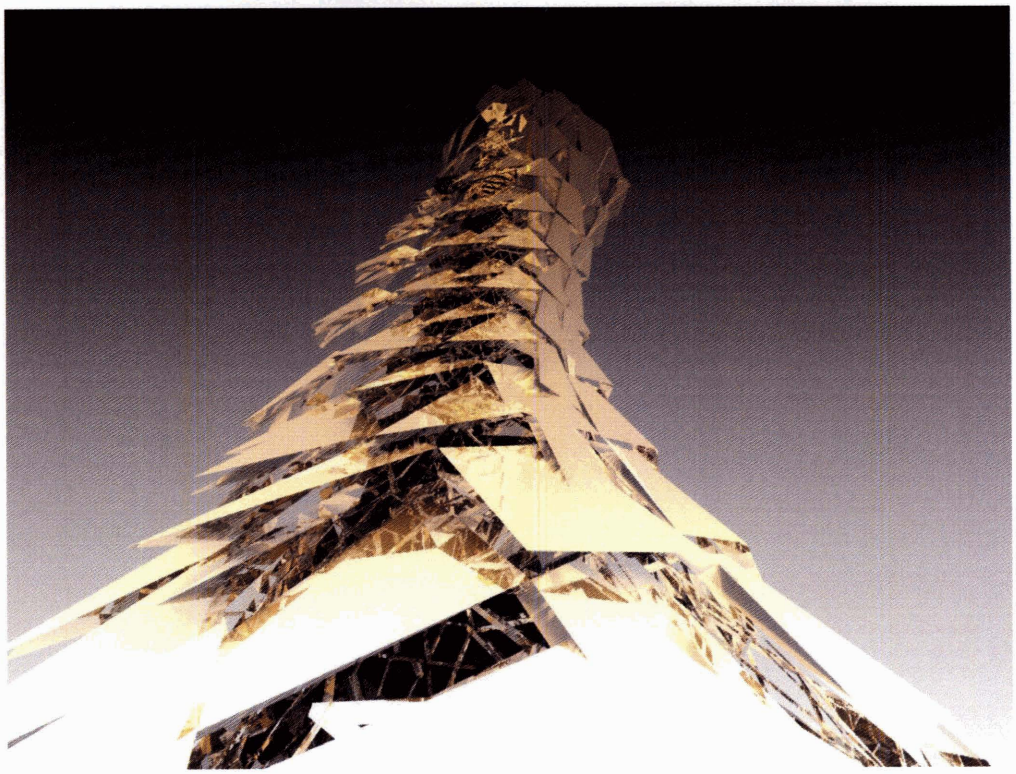
Reading the geometry of the surface sampling points on it to create the point grid to insert the parametric diagrid component. When inserted, the component adapts to specific local geometrical conditions

6 . 7 DOUBLE DIAGRID STRUCTURE

The necessity of controlling custom parametric features after being created and located in the model catalyzed the change of environment, from CATIA to GC. Due to this issue, I later discovered other advantages of this platform which provided a rich environment for this research.

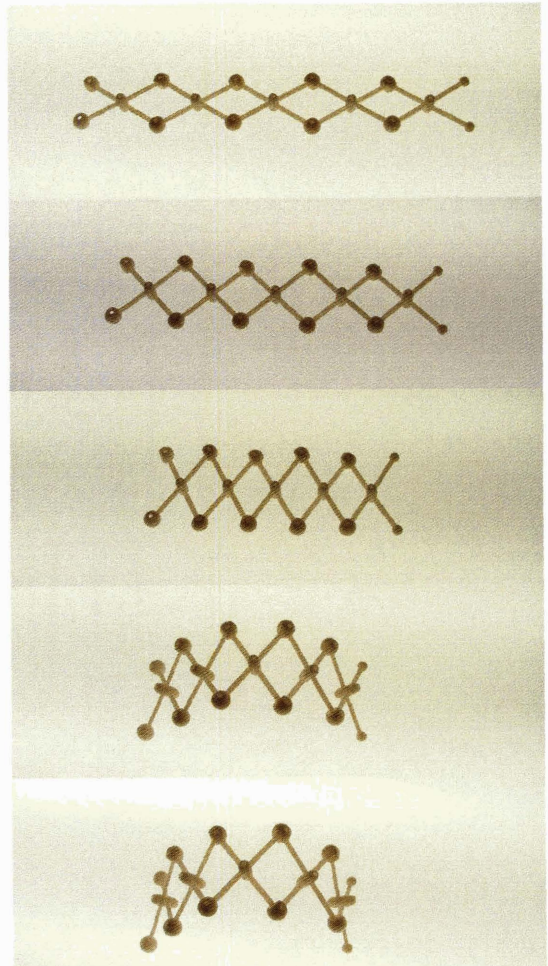
Twisted buildings provide structural advantages as they inherit through this rotation a diagonal relation in the vertical axis, providing a natural diagrid structure. Diagrids are efficient against both vertical and horizontal loads, required given the asymmetry of complex shapes. Given the central spinal core structure, a parametrical diagrid structure completes the support frame of the building. This diagrid was developed as a nested parametric feature based on a subdivision factor on the shape surface.





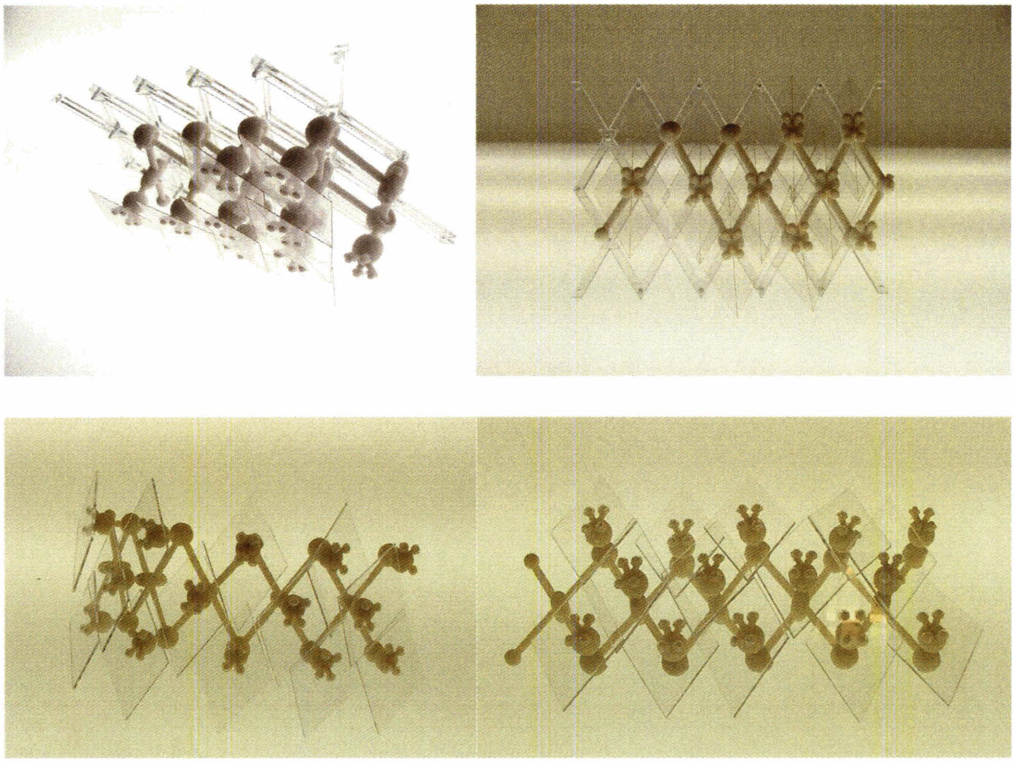
Responsive facade system changing according to variating environmental conditions

A rhomboid feature was created in GC using four points as input reference. The lofted shape of the building was used to place an array of points based on UV values, subdividing it according to a resolution factor, a global variable. This collection of points on the surface is a second order of parametric features, depending on variables that control the surface itself. Using the shape feature as a vehicle, the rhomboid feature is populated creating a controlled diagrid. I set up variables for controlling the magnitudes on the section of the structure independently, responding to varying structural conditions optimizing it accordingly. A second diagrid, offset from the previous one, acts as the support structure for the rainscreen surface.



The spherical articulation provides A hinged joint allowing double curved deformation on diagrid structure. This secondary diagrid can respond dinamically then to actuation controlled by changing environmental conditions or by programmatic requirements in the interior of the building

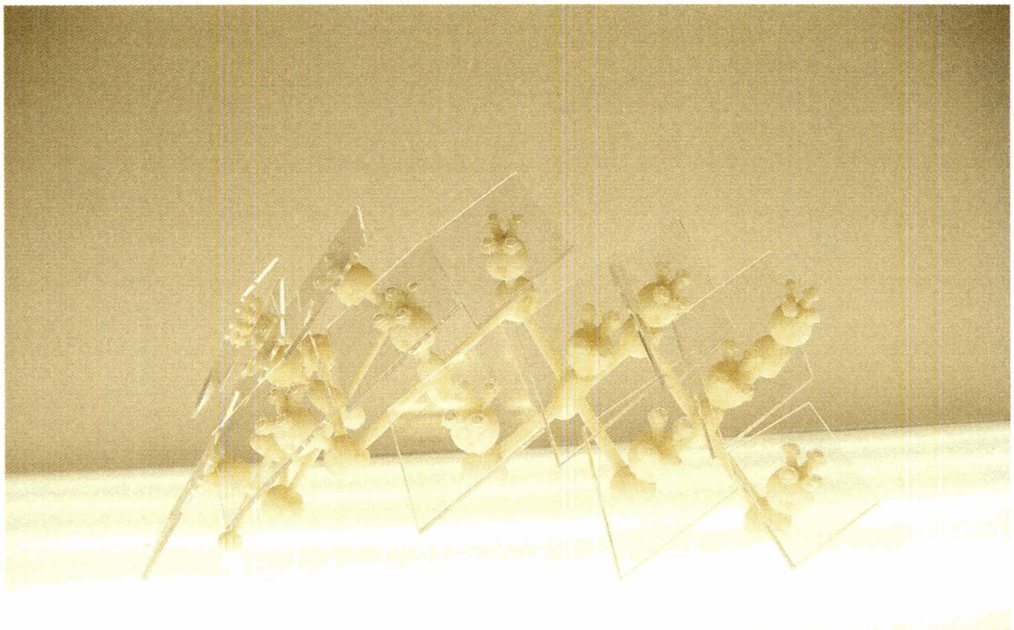
The fabrication technique used aallows to create movable and operable components printed or built as one solid piece, without any post fabrication assembly, by properly adjusting the tolerances in the parametric model



Two prototypes for the skin fish. One on top with rigid structural diagrid but operable spider joints.
The second one below, an articulated diagrid structure supporting operable spider joints provides maximum flexibility to the structure

The same method was used, but the resolution of the subdivision function is four times bigger, as the structural diagrid nodes appear every four floors, but the rainscreen support diagrid based on the floor levels is aligned to each slab. This second diagrid is a flexible structure that can be re-formed (deformed) according to varying external and internal demands, changing slightly the silhouette of the building. A special parallelogram articulation scheme was used, providing proliferation of deformation along the structure, reducing partially the need of distributed actuators, as the articulation system will "transfer" the deformation or kinetic operations throughout the whole structure.

A parallelogram articulation works only on a plane, so I implemented a spherical knee articulation to provide three axis of freedom. This was developed as another parametric feature, with controllable size (radii) and variable tolerance for the articulation. The tolerance was adjusted to the FDM process used. Finally a connection node was also developed for

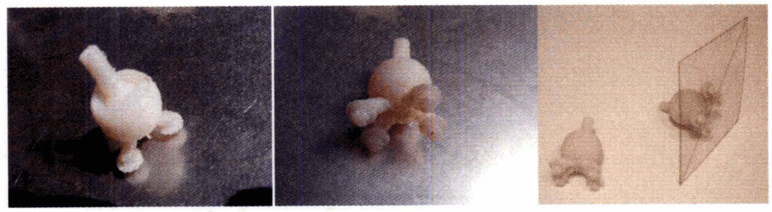


the joints where the rainscreen structure is connected to the supporting diagrid.

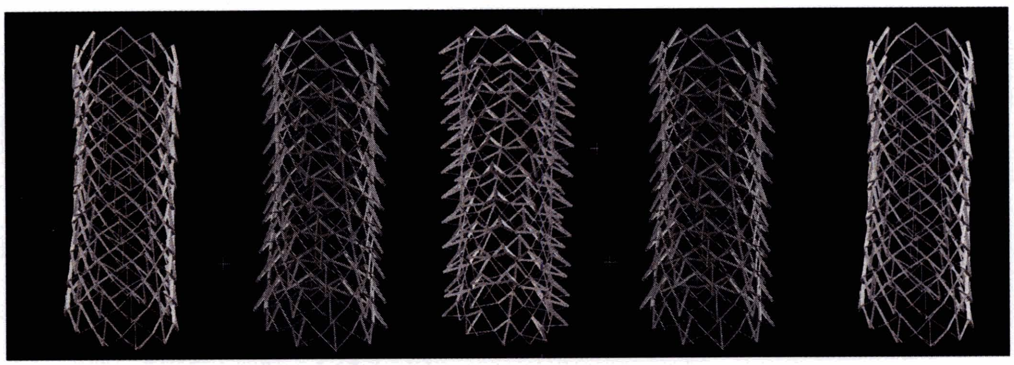
Different stages of results were 3D printed. The shape of the building was built as a reference. Then the supporting structural diagrid was printed to examine its varying section. The double diagrid was printed to study the overlapping diagrids.

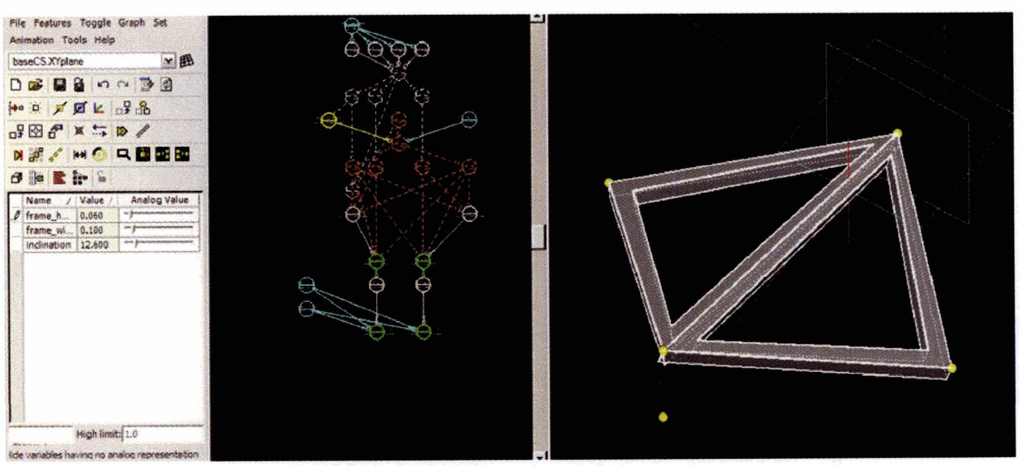
6 . 8 FISHSKIN

The final set of features nested into the design, is the scale feature used for the rainscreen. Given the doubleskin strategy, the external surface does not need to be hermetic, as the internal diagrid structure supports the glazing of the building. Furthermore, it provides an air chamber, allowing natural ventilation as an air refreshening system and as a natural cooling device to reduce energy consumption inside the building. The scale was developed as a frame, supporting two triangular glass

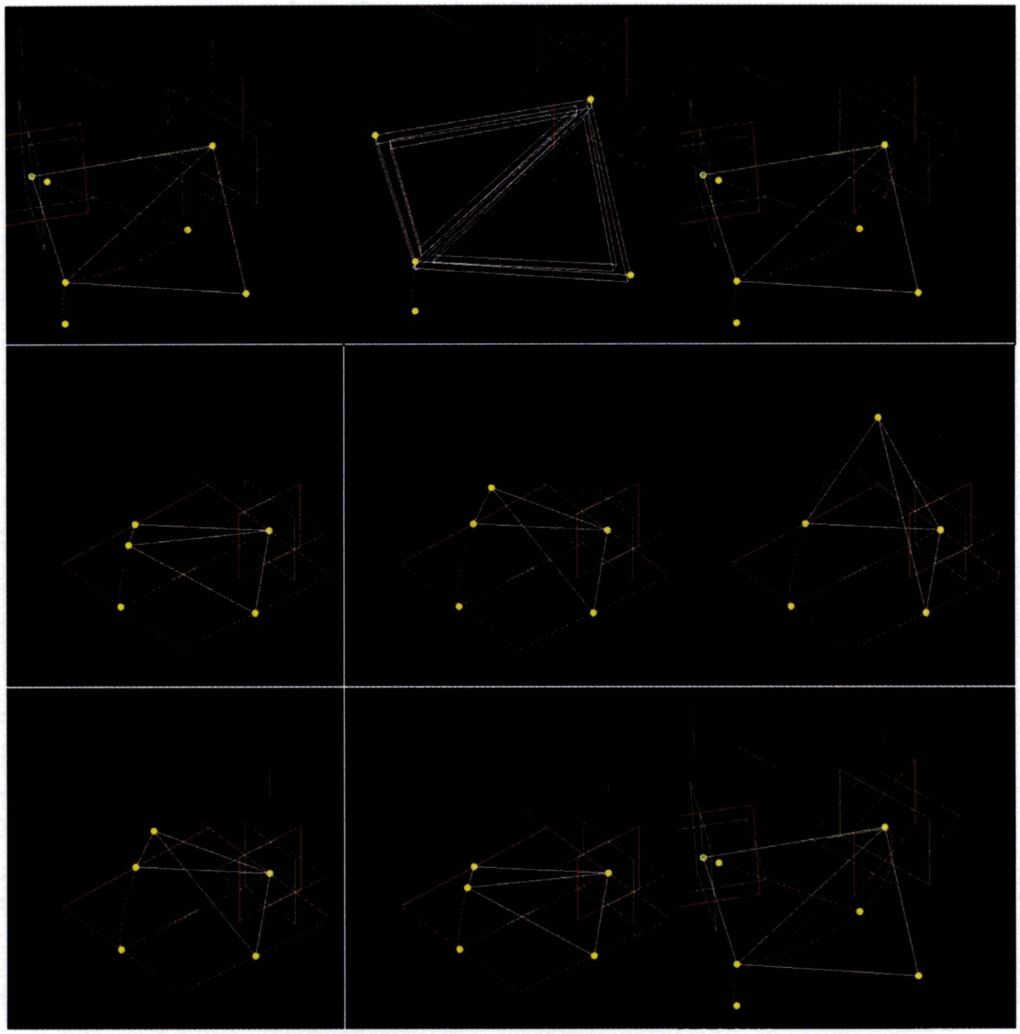


Articulated spider prong joints provide independent operability for each scale feature

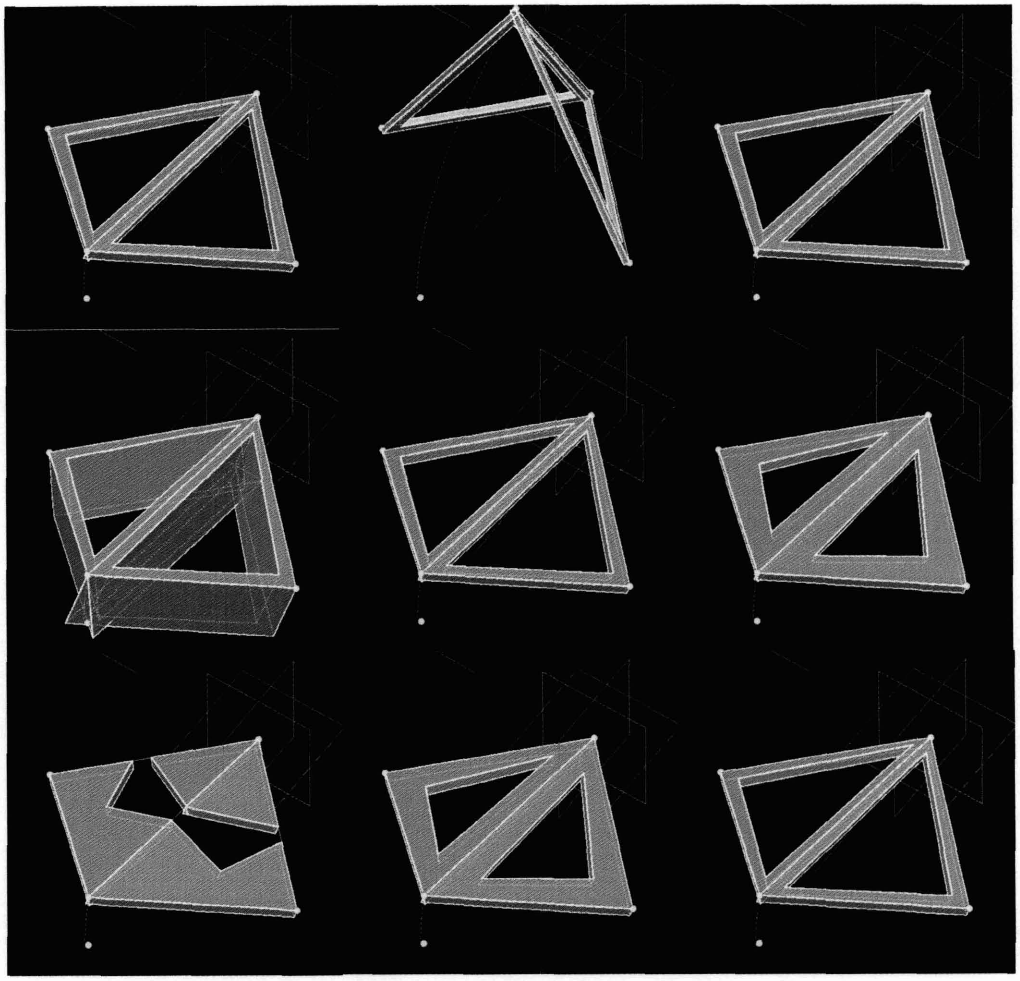




parametric scale with adjustable frame and surface controlled angle of opening for the scale.
The dimensions of the frame were fixed in length and widht considering maximum standard sizes of glass panel. Only the angles of the triangles change.



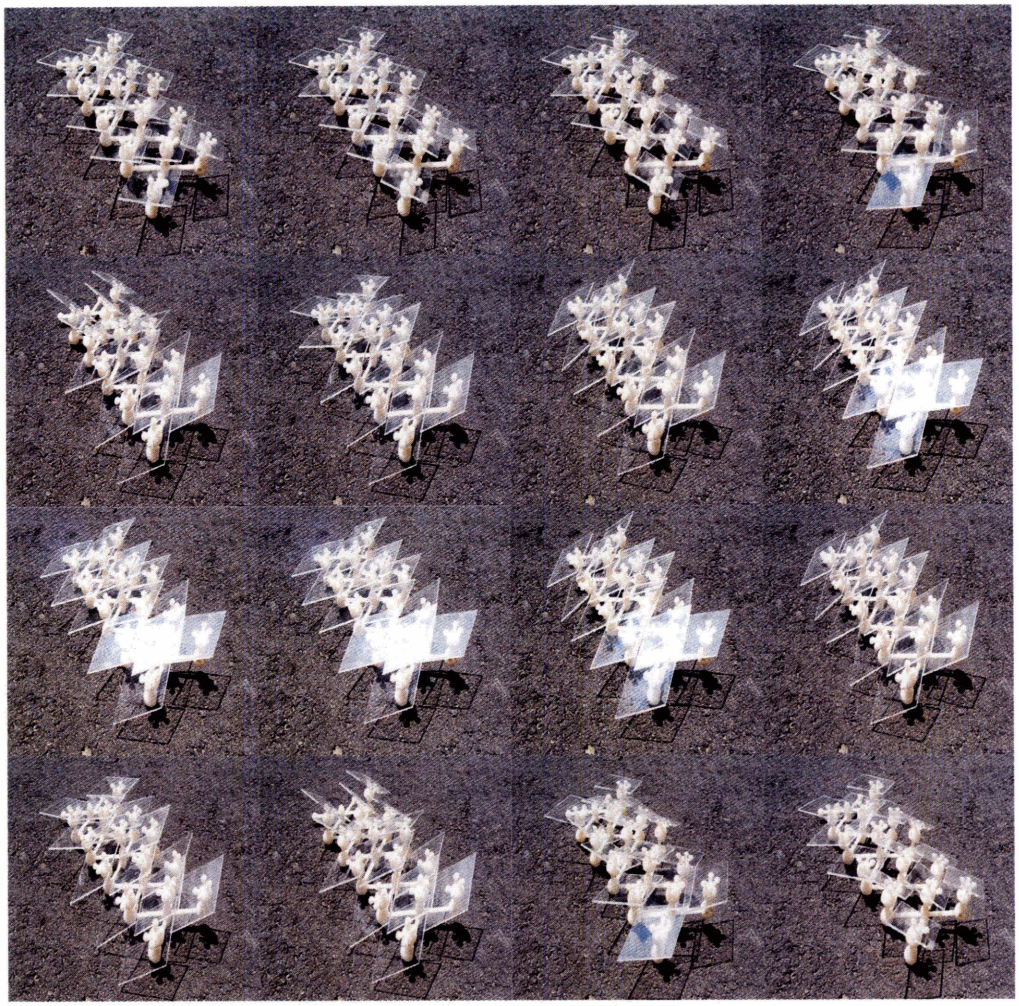
Kinetic behavior of the scale feature simulated by external global variables. Parameters control the angle of movement



External parameters control the type of frame that will support the glass panel on each scale. The geometry, dimensions ratio of transparency / opaqueness is also controlled by this parameters.

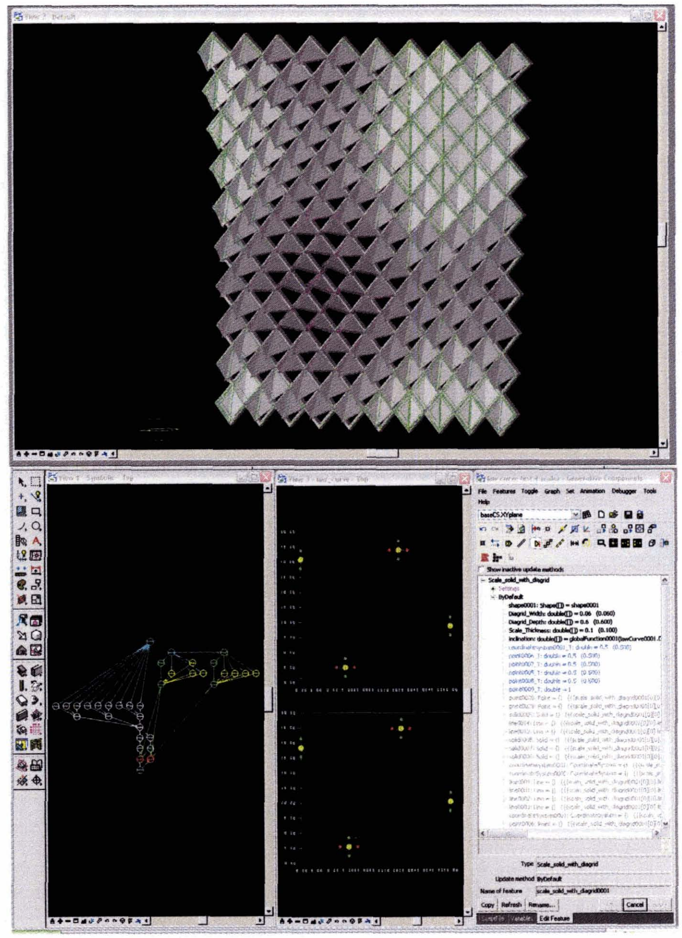
scales in a rhomboid fashion, scaled to match the rainscreen diagrid. The scale feature is controlled by several global variables, in order to reproduce its kinetic behavior. The frame is controlled in size and section, and also in shape, allowing different support/transparency ratios according to the orientation of the scales on the façade.

The crucial function is the variation of the angle of the scale, which is related to the reaction of it due to weather conditions or programmatic requirements. For this purpose I scripted a function where the angle was controlled by two law curves, in order to produce a non linear series of values, achieving a surface effect control over the scale-surface.



Articulated diagrid structure that can extend and bend acquiring flat or curved shape. Articulated spider joints support the glass scales and provide three degrees of freedom to each scale. This sequence illustrates possible variable configurations on an Ichtyomorph skin module

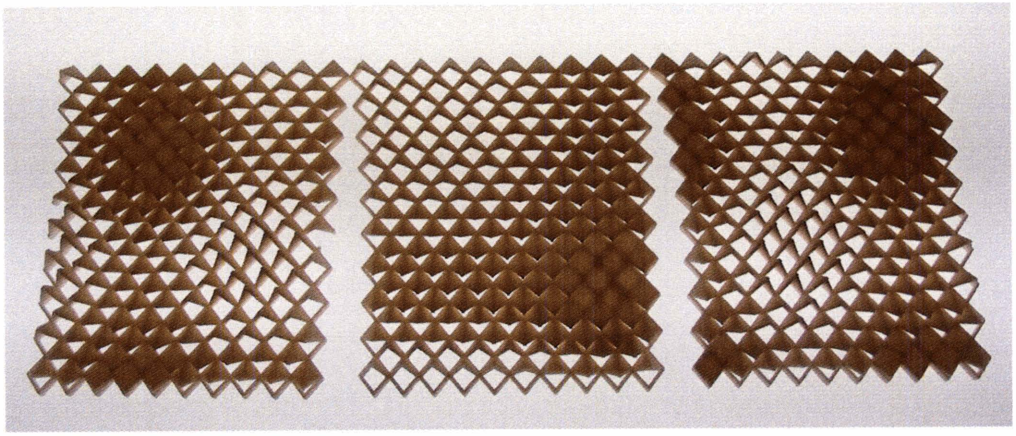
simulated surface effect of the parametric scales, two variations



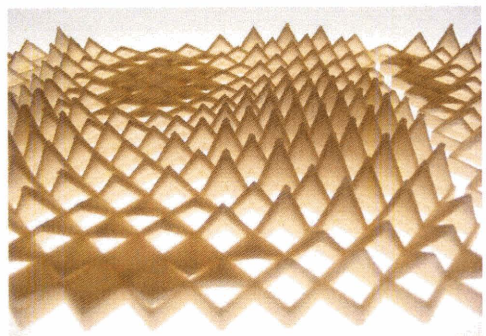
Parametric scale model designed to be controlled by two orthogonal law curves in GC

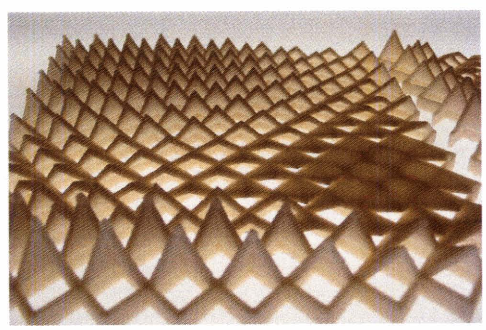
One law curve controls the vertical orientation of the scales, and the other law curve controls the orientation in horizontal, meaning all the scales of the same floor. Several tests were printed to examine the results of these embedded parametrics and possible variations. The tests were printed solid, discarding the transparency of the glass scales, favoring the visualization of the surface patterns obtained and the strength of the scale model, and also allowing light/shadows studies.

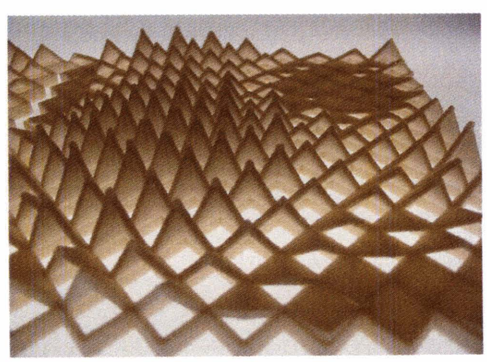
For the purpose of this research, basic solenoid actuators were created, using stepper motors and translating rotational movement into linear motion. The stepper motors are controlled by a microcontroller programmed to run the motor a precise number of turns in one direction or in the other. A node composed of four actuators would provide complex three-dimensional actuation over an articulated surface. For the scale feature developed in this research, only one actuator is required, providing the necessary linear movement. Basic

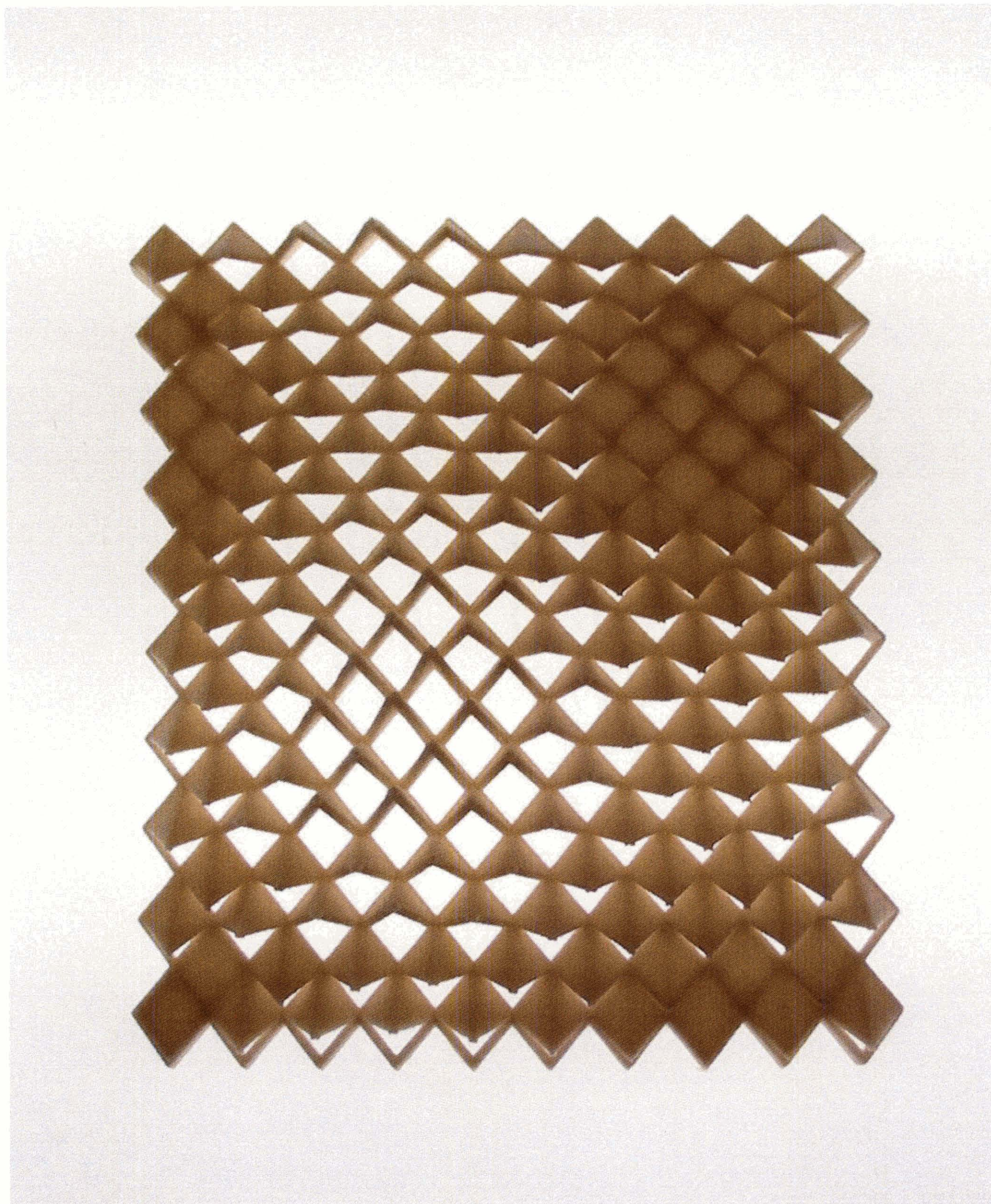


Surface effect pattern printed on ZCorp to test light/ shadow performance. Three variations of the model were printed to evaluate transparency and shading behaviors according to orientation.

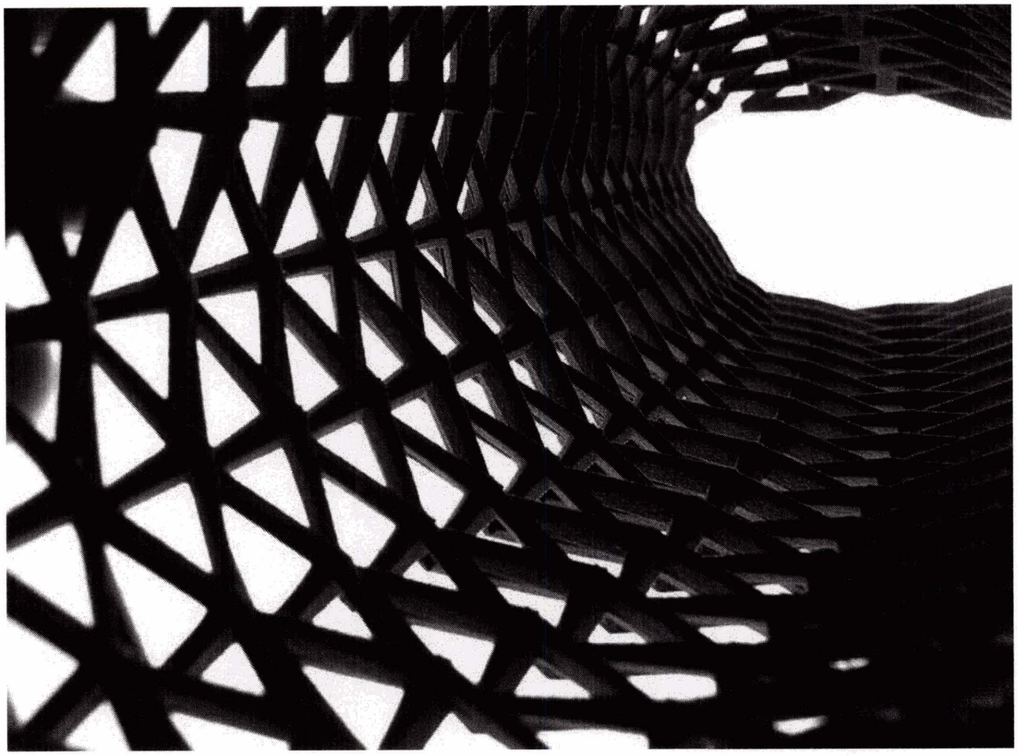


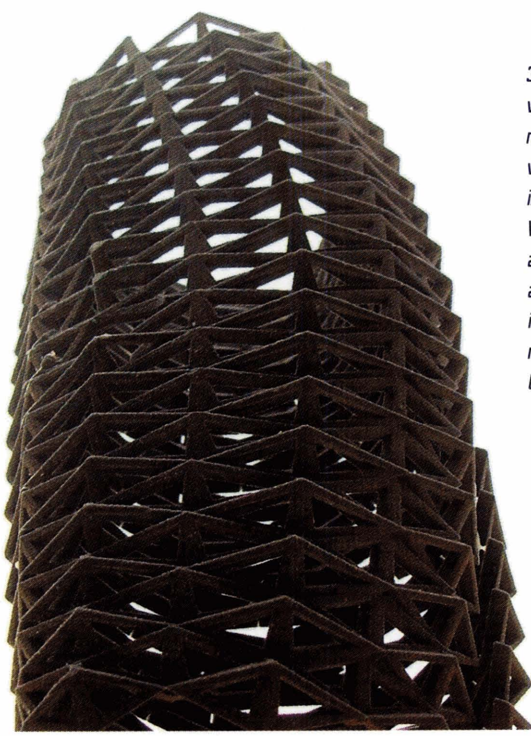




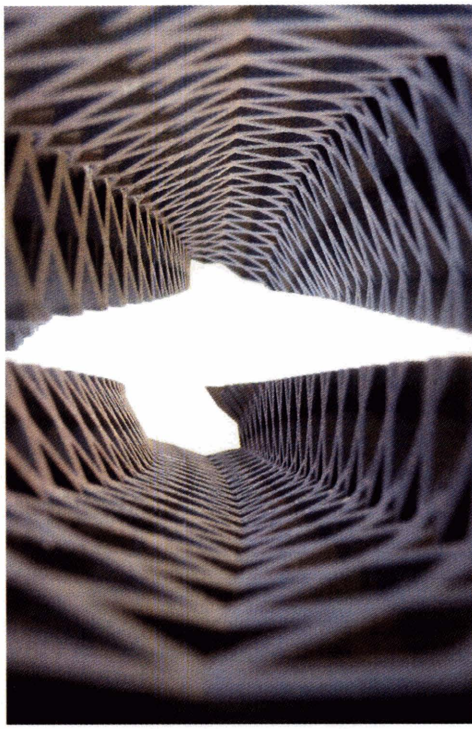


Surface controll effects on a facade test. Surface effect variation could be related to changing environmental conditions, increasing natural ventilation and shading. They would constantly reshaping the silloutte of the building.

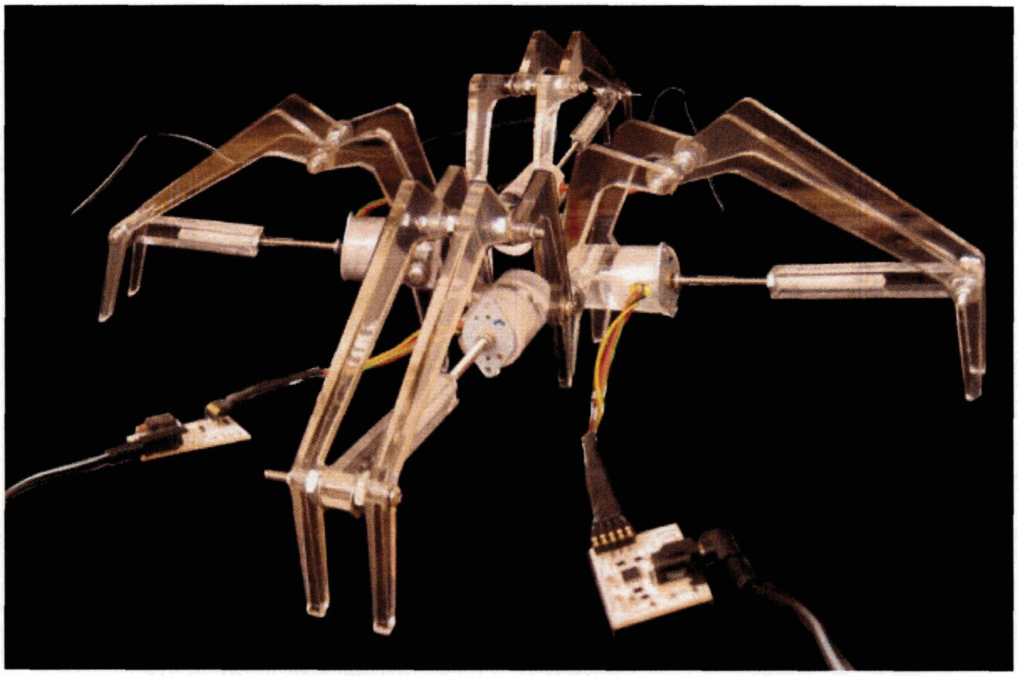




3D printed model of the frames of the scales, testing visibility and transparency results. Due to the material restrictions of the 3D printing process used, the scale was exagerated in order to mantain structural coherence in the model.
Variations in the profile and dimensions of the frame are controlled by external parameters. In this case, all scales are actuated simultaneously, there is no independent surface control effect, only the variation related to adaptation to local geometry on the shape of the building



Section Model of the structure studying the surface effect pattern of scale features. this model contains both a supporting structural diagrid and independantly controlled scales using the double law curve parameterization procedure. On top of the adaptation to local geometries, the scales are controlled by the surface effect of the law curves, having variations in their bahavior across the surface of the building. Again the scale had to be exagerated in order to ensure structural integrity of the model



Microcontroller and actuator node using four solenoids created from stepper motors. Each arm turns rotational movement into linear actuation,

capacitance sensors were developed to test the possibility of turning on and off a device based on proximity of a subject. The sensor now turns on an LED, in the same that it would turn on the microcontroller triggering the actuator.

6.9 CONCLUSIONS

The example used for this exercise shows how different parametric techniques can be used to respond to large complex design projects. It also explains how these parametric strategies can respond to different scales of an architectural problem, during the design process, from form finding stages to layout and programmatic decisions to detailed resolution of a compound assembly.

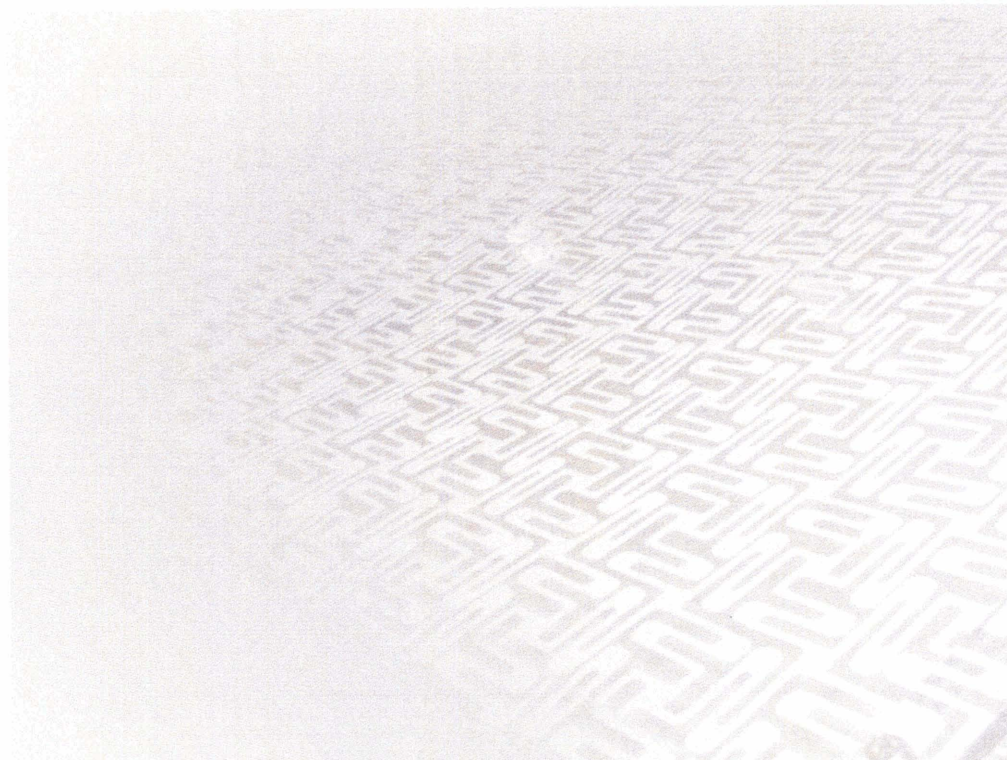
This project illustrates how these tools allow constructing a solution space, beyond providing a dimension of freedom for design exploration and fabrication, which can be used to enhance solutions responding to increasingly complex problems with creative and flexible solutions.

This work shows the scalability of parametric techniques using a nesting strategy, creating dependencies between geometrical elements as well as between mathematical functions and relationships. Furthermore, this scalability is also desired for fabrication purposes, providing the ability to be tested using rapid prototyping techniques but being later implemented through industrial CNC production.

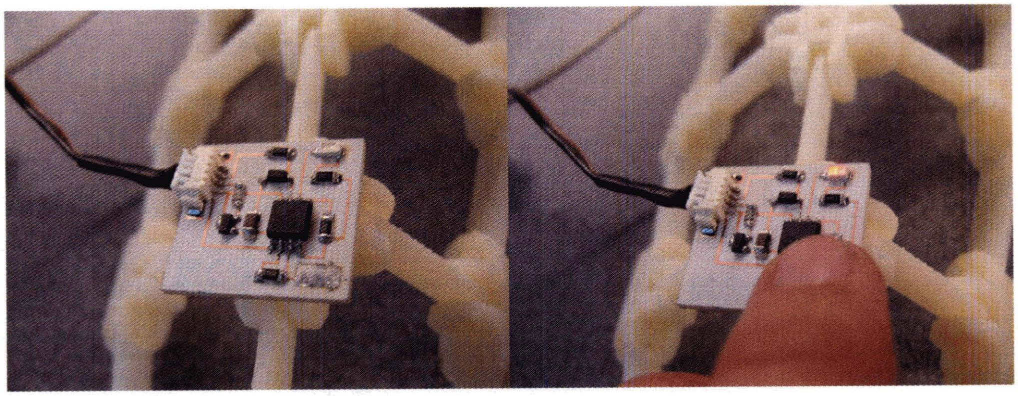
Further development of parametric design techniques and implementation of new techniques using rapid prototyping methods, will progressively change the conceptual approach to the application of computation in design processes. The required comprehension of the relations between precise mathematical constructions and forms, and the application of fabrication logics at initial design stages, will lead to a much richer platform for architectural design. The ability of embedding kinetical behaviors and mechanical properties in designs to match actual fabrication CNC methods, allow us to imagine responsiveness and kinetics as integral dimensions of smarter architectural designs.

6.10 FURTHER RESEARCH

The research presented here is still in progress and the results presented are partial. Some of this have been addressed in other exercises in this thesis, some others are waiting to be reconsidered in further research adventures Although basic, the explorations done so far regarding actuation and sensing systems is promising. Different actuation methods should be developed for different demands, providing robust solutions. Sensing system require more in depth exploration. Distributed actuation has only been tested in this research as hard coded patterns, testing the coordination and communication between distributed actuators is yet to be explored.



7 KINET, ANIMATED FORM

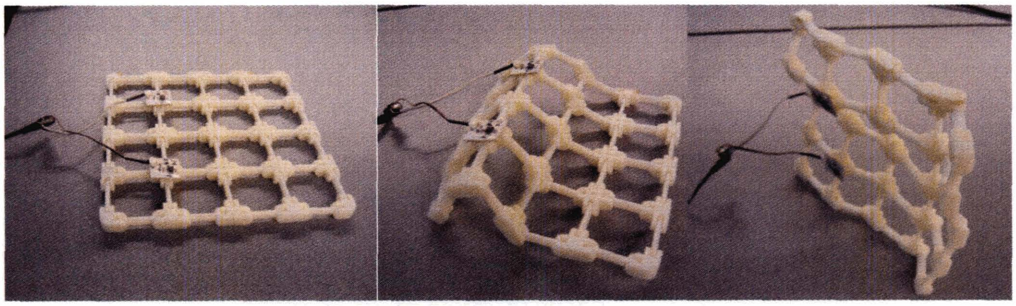


First proximity sensors developed for KINET, the images show how the proximity sensors activitate an LED a a response to proximity of a body .

In many ways this exercise is the beginning and the end of this Thesis research. It touches upon all the different issues than orbit around this thesis, not necessarily answering these issues, but enquiring about their potential. I is about Digital Design and Digital fabrication, but also about Responsive Kinetic Structures and Parametric Design. This project started as response to a class at the Media Lab called, "How to Build Almost Anything", conducted by Professor Neil Gershenfeld, and was developed in collaboration with Ayah Bdeir. It has been further developed later as part of this research and has been presented in different conferences and lectures and published. It was first published at the GameSetMatch Conference in 2006, Delft Netherlands.

7.1 KINET - TOWARDS ANIMATED ARCHITECTURE THROUGH RESPONSIVE MODULAR WALLS

This paper describes the concept and results of kiNET, an ongoing project researching and developing an animated surface. Flat sheets and panels are transformed into flexible surfaces through "flexure" structures developed in parametric environments, rapid prototyping tools and CNC machining. The flexible surfaces are then animated using electromagnetic actuators (solenoids), activated by a microcontroller board that responds to proximity. We describe the different processes involved in setting up the responsive wall: design and fabrication of the actuation system, design and implementation of the microcontroller, and the fabrication of the actual surface that will be animated.



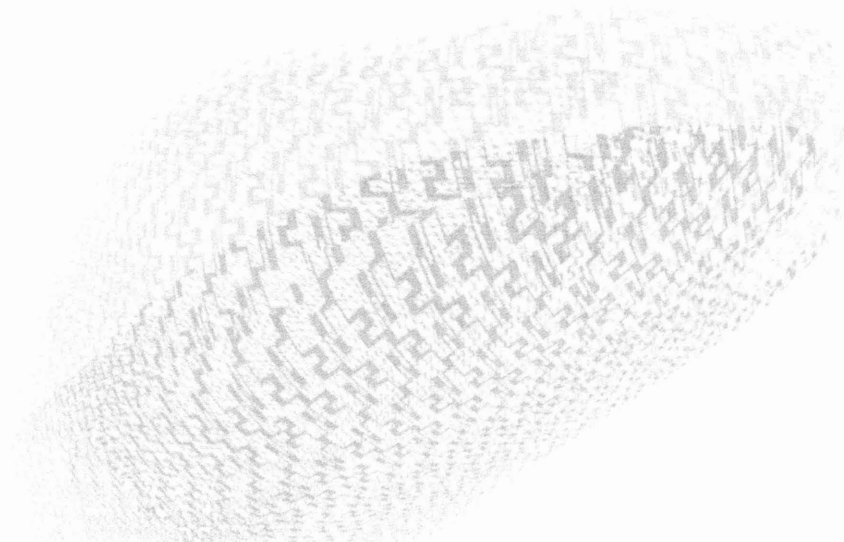
Original Kinet demo models, articulated grid structure. 3D Printed as a solid articulated piece where each joint has 2 levels of freedom.

7.2 STASIS VERSUS KINETICS

Architecture has historically been defined through material stability and permanence; the human mind has always been fascinated and drawn to what is volatile, moving. The research project described below is an attempt to reconcile the sustained and unceasing desire for the creation of the ephemeral, with the architectural vocation towards a material built environment. When the material stability of our built environment, shifts from the perception of stasis to that of motion; from inert to responsive; from flat to curved; from static to kinetic; then the perception of the body inhabiting such environment changes with it.

As Merleau-Ponty sees it, our perception of the world is (partially) determined by our consciousness of our mobile body. According to this theory of phenomenology, the act of perceiving is inseparable from that self awareness of the body as object of this perception. When we see an object, we are only able to perceive visually a part of it. We can recognize that object if we had a previous experience. When we recognize that object, we merged together the different parts perceived, moving around the object to capture as much different visual angles as possible, in order to get what the object is. This is how we gather different fragmented views of the world around us, and by stitching them together; we (constantly) reconstruct the movement of our body moving in space. But what happens when the perceived world is also in motion?

Motion sickness is the result of the conflict in our brain of contradictory perceptions. The equilibrium apparatus in the ears signals to the brain a certain movement whereas the eyes, unable to perceive the motion, indicate an immobile state. How do we overcome this destabilizing sensation, the dizziness of our senses? While the body requires a stable ground, the senses look for a fixed reference. Sea sickness can be overcome when focusing on a distant point, recovering a relative fixed reference to reorient our body, which in turn adapts to the constantly varying movement. Land sickness later is the result of the body

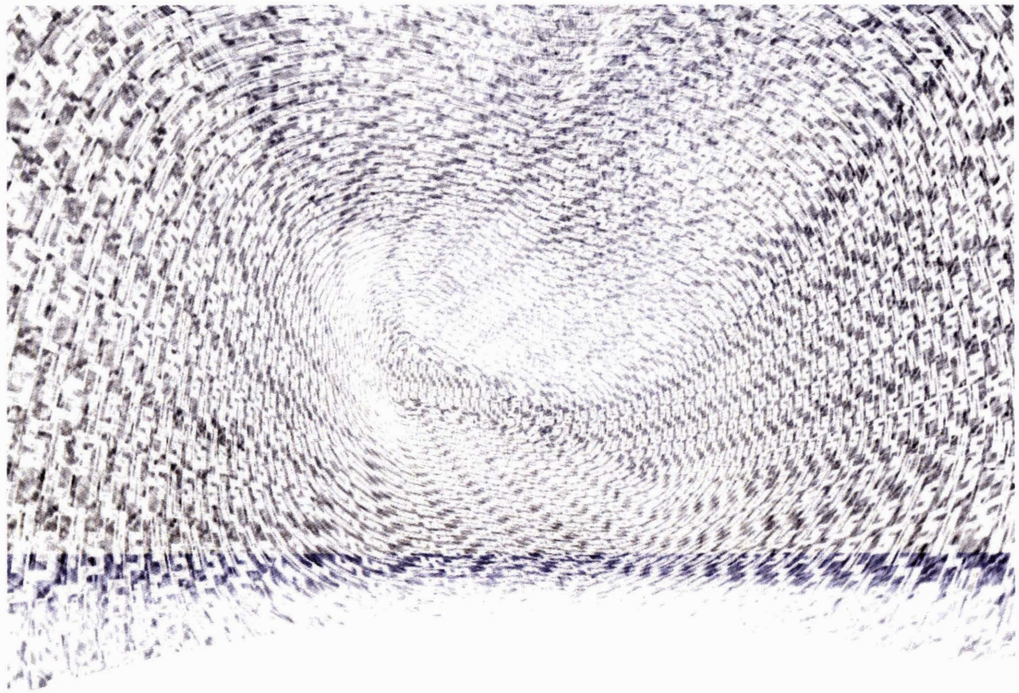


Felxure patterns to achieve double curved structures

reorienting itself to a fixed ground. These symptoms may also occur as the result of other cases of sensorial signal conflict in our brain.

On the other hand, we are all aware of the powerful hypnotic effect of fire flames molding light in unpredictable shapes, or the motion of the waves on the shore, or the reflection of the moon in deep sea. Staring at the ocean while the rippling effect of the wind curls the surface of the water bouncing the reflection of the sun, the body becomes a neutral instrument of perception, almost disappearing and becoming part of the eternal movement.

We chase ephemeral effects, liquid like behaviors, fluid random vibrations of surfaces and objects responding unpredictably to subtle changes in force, direction and material resistance. Maybe this fascination is partially derived from a need of recreating the act of perception. This act, which as Merleau-Ponty points out, is inherent to our conscience coming to existence becoming aware of the self as a perceiving mobile subject. We envision a provocative architecture, sensuous, unpredictable, an architecture that challenges the senses, engaging the body in a phenomenological experience of conscious acknowledgment of the act of perception. This unstoppable condition of change has motivated our desire for embedded kinetic behaviors in typically static structures. Traditionally, architecture was build for (cultural and social) stability; using inert (neutral) material; attempting to achieve permanence (even eternity). It has been address as the art of substantial immobility, timeless constructions build for permanence.



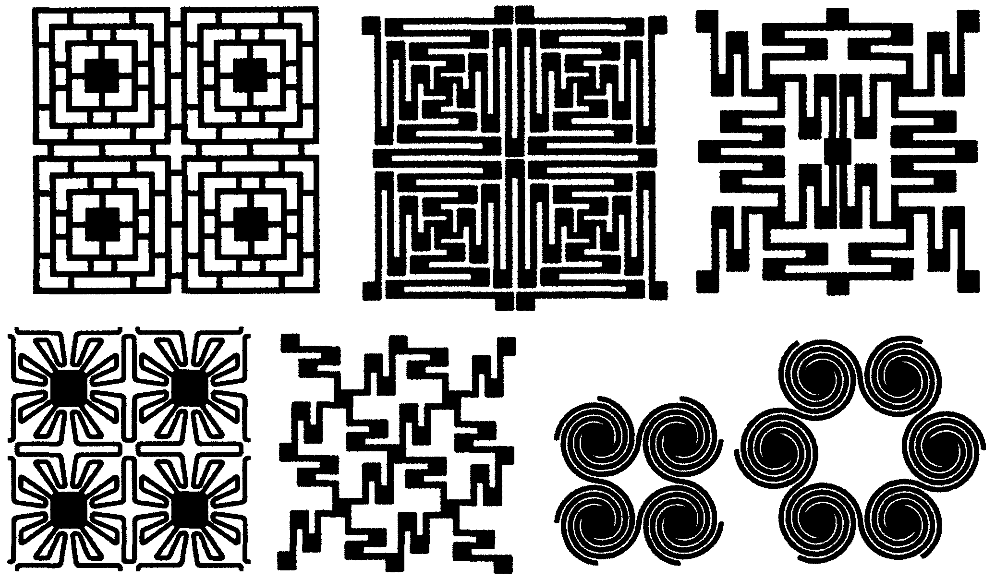
Original renders about the idea of animated flexural structures, that vibrate and respond to human interaction

The paradigm of the digital era introduced among others, the concept of temporality. The ability of high speed calculation derived from computation advances, allowed the proliferation of digital tools that could iterate fast enough to explore real time variation and modification of conditions. In design this lead towards the emergence of complex geometrical modelers first, then the spread of animation tools and recently the appearance of parametric environments. The combination of these new available tools can simulate and embed into the design changing temporal behaviors, thus opening a door for the design of smart environments.

We envision a provocative architecture, sensuous, unpredictable. Test design: Double curved wall system with distributed array of actuators.

7.3 ANIMATEDWALLS

kiNET is an active wall. A wall that performs, changes, shifts, adapts. We want walls to respond to us, walls that can alter themselves, and with them, alter the space they define. By augmenting the concept of animation an animated surface turns the spectator into an actor while figure and background conflict in the same first plane. Provoking human interaction,



Samples of Flexure designs developed for this research

the usually neutral and stable role of matter becomes the bate for a new relation between the human body and the architectural body.

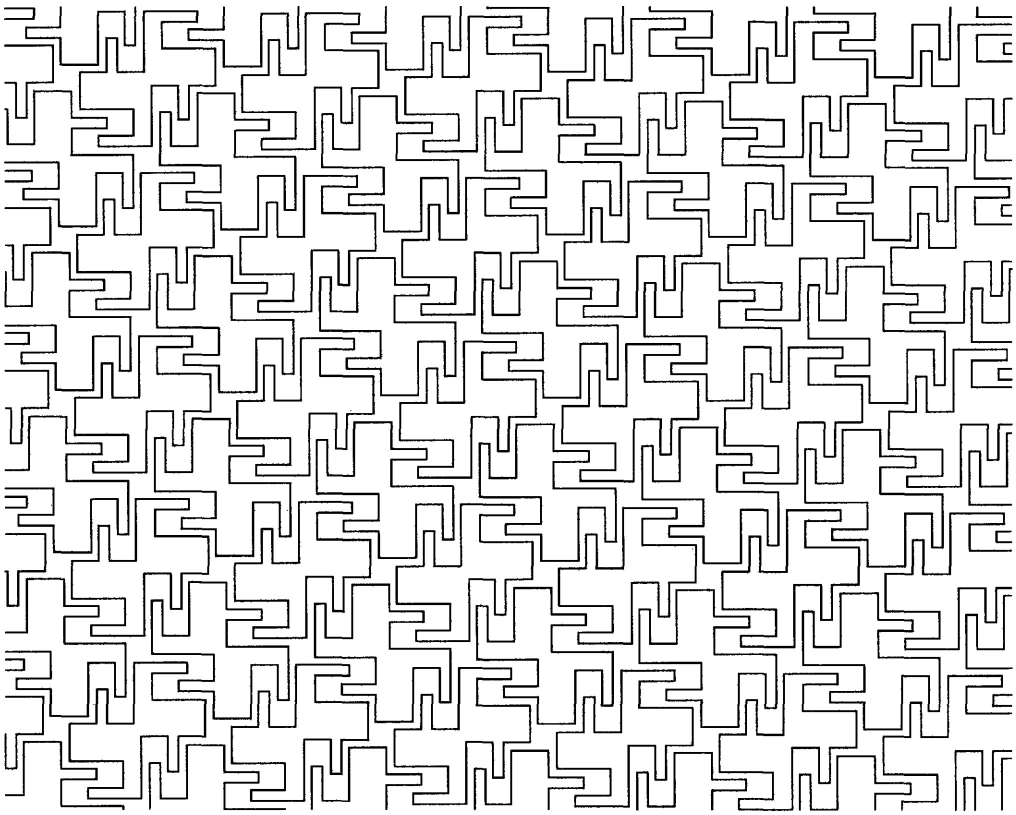
We attempt to blur the boundary between architecture and media art. The wall is no longer the opaque plane that encloses our bodies in space; rather it is an active intervention in space, a window, a painting, a canvas. Only the canvas is not a static surface on which the artist lays his work, it is a body in movement, a mural constantly redrawn for the actor/spectator who performs in the (un) defined space.

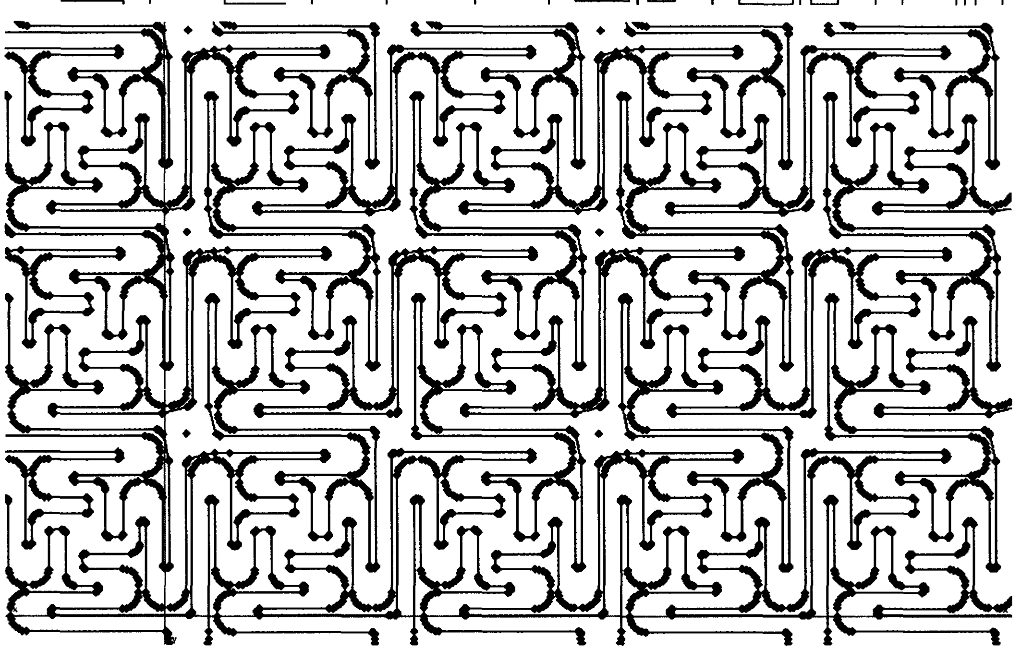
7.4 DESIGN AND IMPLEMENTATION

The undertaken procedures and some of their results are shown here as this is still an ongoing development of kiNET as an animated wall structure module. Describing the different processes involved in setting up a responsive system, we intend to expose the complex material dimensions involved in an attempt to construct an evanescent mirage. Different fabrication methods, from rapid prototyping techniques to the CNC machines were employed to produce the flexible surfaces; and a microcontroller board was responsible for driving the system and creating the patterns and movement.

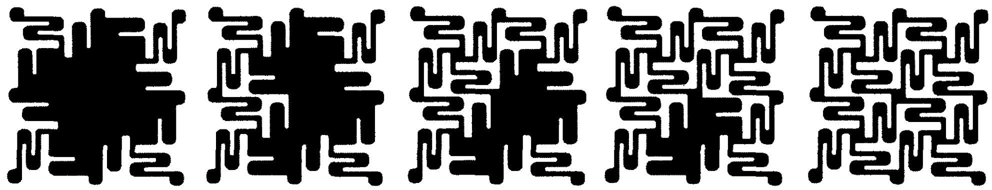
7.4.1 Flexure surfaces

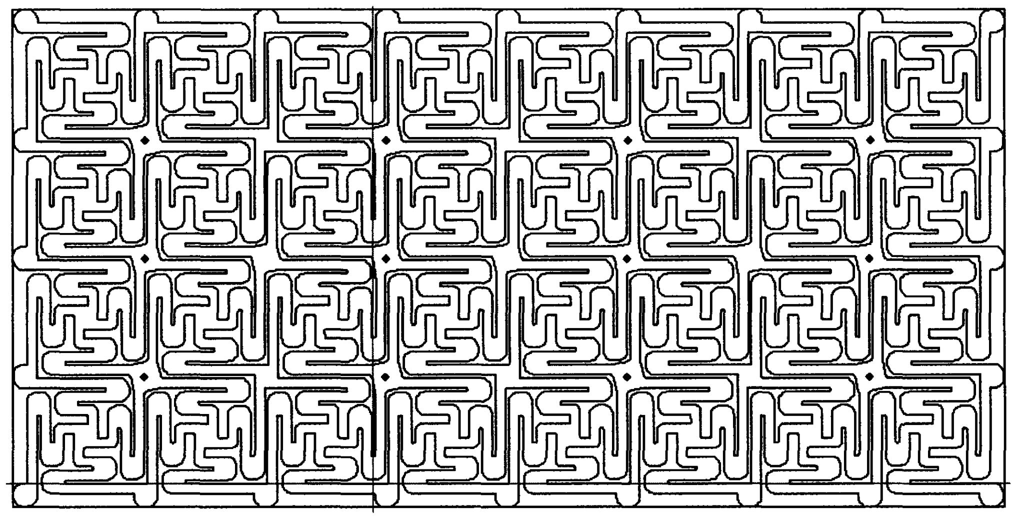
The construction industry is founded on standardization and modularity. Most construction materials come in flat sheets or panels. kiNET uses a procedure using "flexure" structures developed in parametric environments, to embed elastic attributes in structures built from flat. In a larger perspective, this approach could lead to a deeper investigation on the notion of



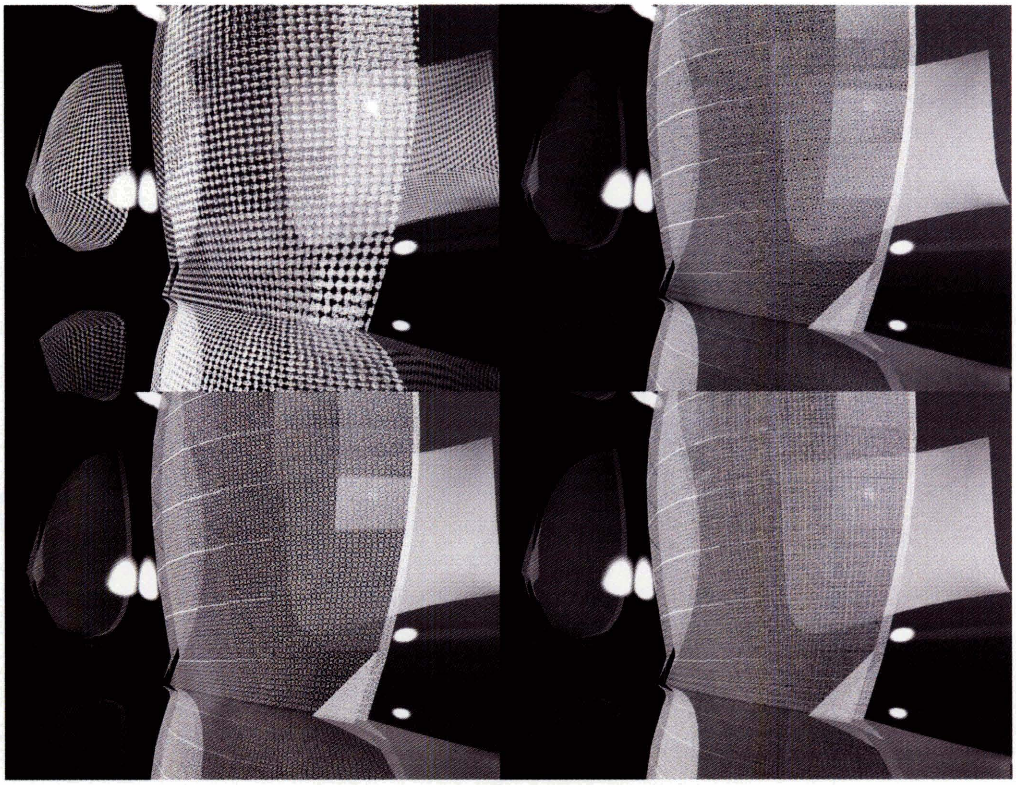


Depending on the material, some patterns require smooth continuous outlines to avoid breaks in the corners when stressed.





Final flexure Pattern designed, with smooth outlines and minimum gaps adjusted exactly to the tolerance of the Omax Waterjet. Alignments of the ends of the pattern provide seamless connections between different cut sheets



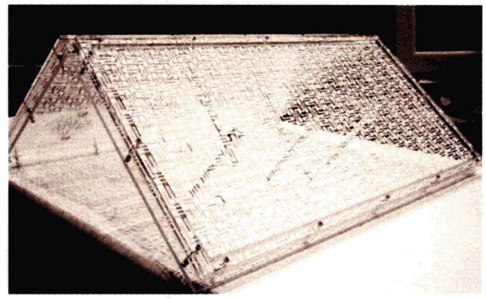
Parametric pattern variation studies achieve different transparency attributes and anisometric flexure behavior.

generative design tools and their ability to use digital design fabrication logics and processes to extend the actual boundaries of constructability in contemporary design.

Compliant structures are those who can change their shape when a force is applied to them, and that will return to their previous state if the force is taken out, for example springs. One type of compliant structures that behaves similarly to springs is called flexure. Flexures can deform elastically depending both on material properties and on their geometry. The approach for this project makes use of these properties to create flexible structures from flat rigid panels through the flexions of these structures.

According to Larry Howell, it is a special kind of mechanism, "a mechanical device used to transfer or transform motion, force, or energy" Typically they are made of "rigid links connected at movable joints." A compliant mechanism or flexure, however, while still performs the same basic functions of transferring or transforming energy or force, gains at least part of its mobility "from the deflection of flexible members rather than from movable joints only"

Flexure structures have several advantages as they reduce the number of components involved, reducing assembly time and effort, and therefore reducing costs. But more important for this investigation, is that



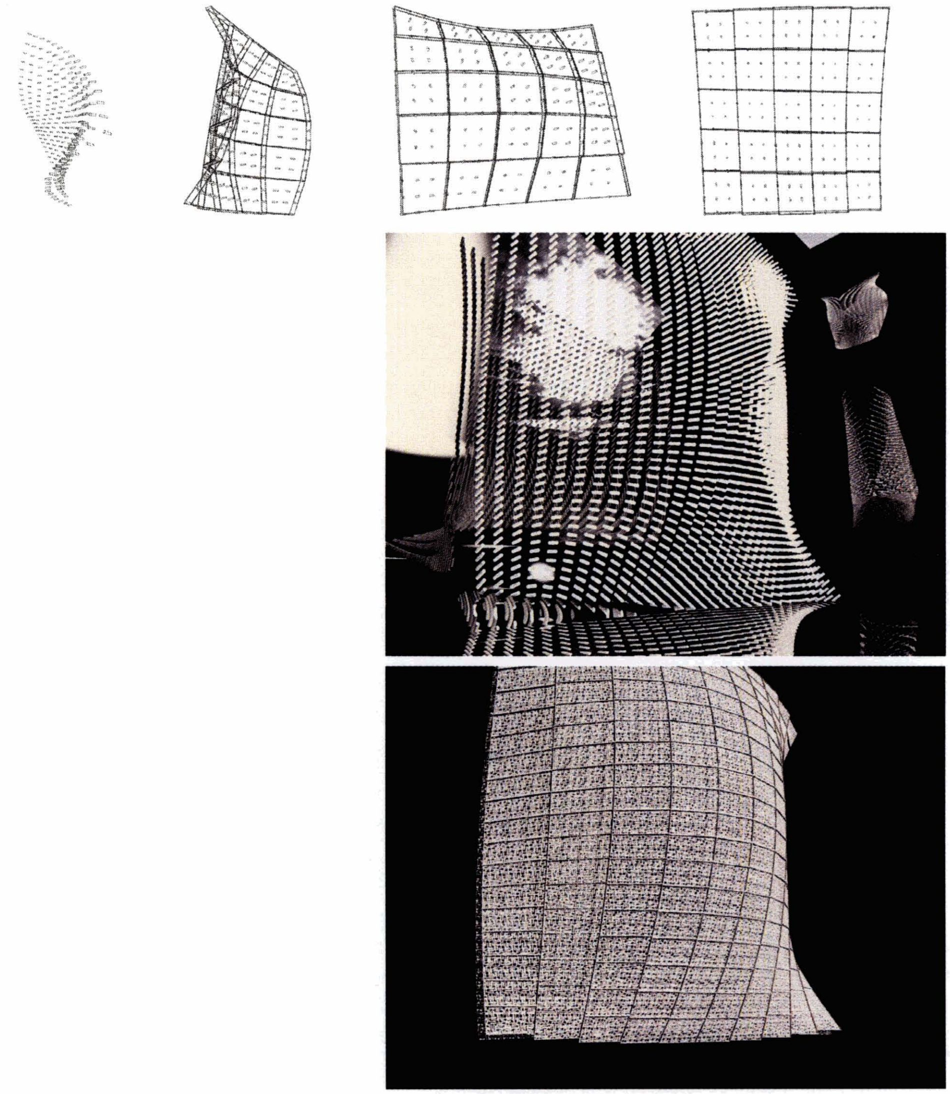
ABS plastic panel transformed into a flexible surface through laser cutting

they can be developed from single pieces. Flexure structures are frequently used in machines that require very precise movements, as they have a reliable displacement precision. They can effectively isolate their movements to the axis where the maximum flexibility has been provided from other lateral movements, "reducing the vibration natural to hinged joints, eliminating the friction between movable parts and the backlash from their rigid body and hinged counterparts". Applying this notion of flexure in this investigation provides a method of material transformation, where solid rigid flat boards can be developed into partially flexible structures. This process was conducted through experimentation on different geometrical patterns and the performance obtained from them when applied to a solid material. The fabrication process chosen was material removal by cutting these designed flexure patterns onto the rigid boards.

7.5 ELECTROMAGNETIC ACTUATION

Once the surface is given an elastic property using the flexures, we animate the dispersed, distributed nodes by electromagnetic actuation, hence no visible mechanics are involved. This creates an impression of magic, eludes the obvious and embodies some mystery. The actuation produces a low metallic tickling sound that propagates through the surface, driving attention beyond the visual, appealing to a wider engagement of the senses and the body.

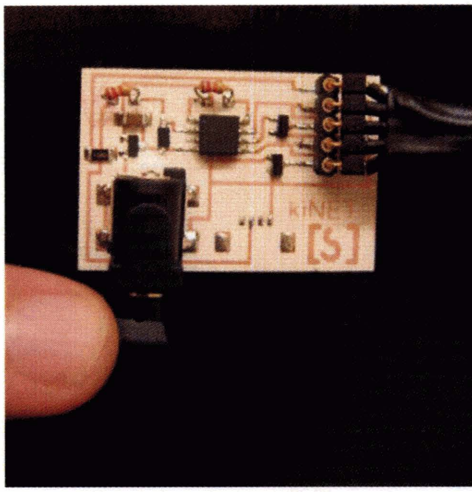
kiNET consists of two layers of surfaces separated by a small gap. The inner layer is like a base. It is fixed. The second layer is the outer surface and it is flexible. On nodes of the outer surface are thin metallic coins. On nodes of the inner surface are some electromagnets. We control the electromagnet with a microcontroller driver board explained below and can animate each node individually. The electromagnets

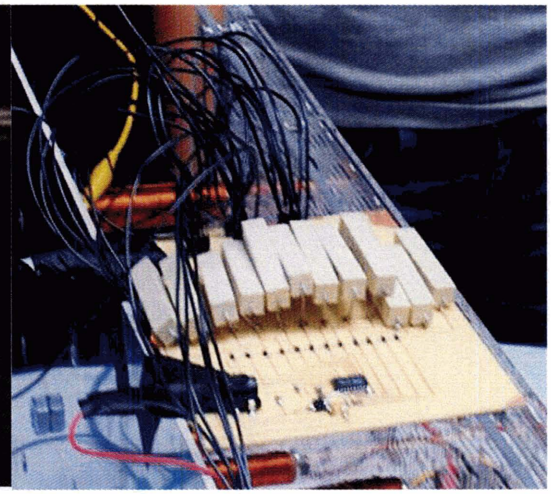


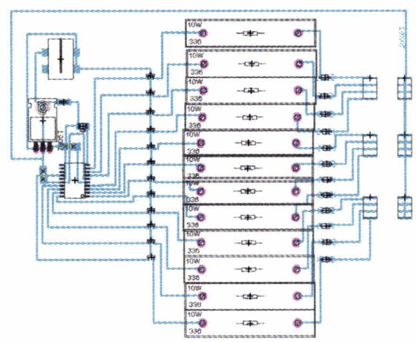
Distribution of actuation nodes in parametrically designed modules. Actuation distribution and alignment with flexural patterned surface

consist of a long continuous piece of thin insulated wire (28 AWG) wound around iron rods (0.5 inch in diameter). When a pulse is sent to the electromagnet, it is energized and transforms into a magnet. When it does, it attracts the metal coin attached to the outer surface, creating an inward movement of that surface at that particular point.

By avoiding the mechanization of the system, stepping out of the repertoire of heavily mechanized robotic systems, not only do we achieve the ephemeral, moving effect but also use the actuation nodes as material structure. The solenoids also provides actuation to both sides of the wall, therefore actuating on both sides of the system, varying the entire section of the wall, not just on one side.





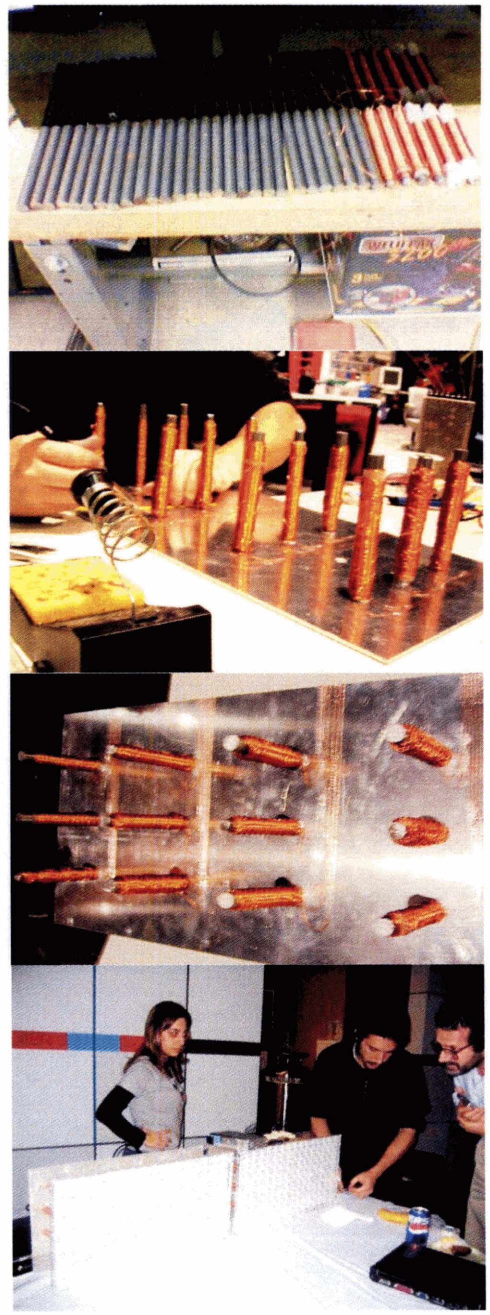


First kiNET microcontroller driver board on the left, the final microcontroller up and on the right

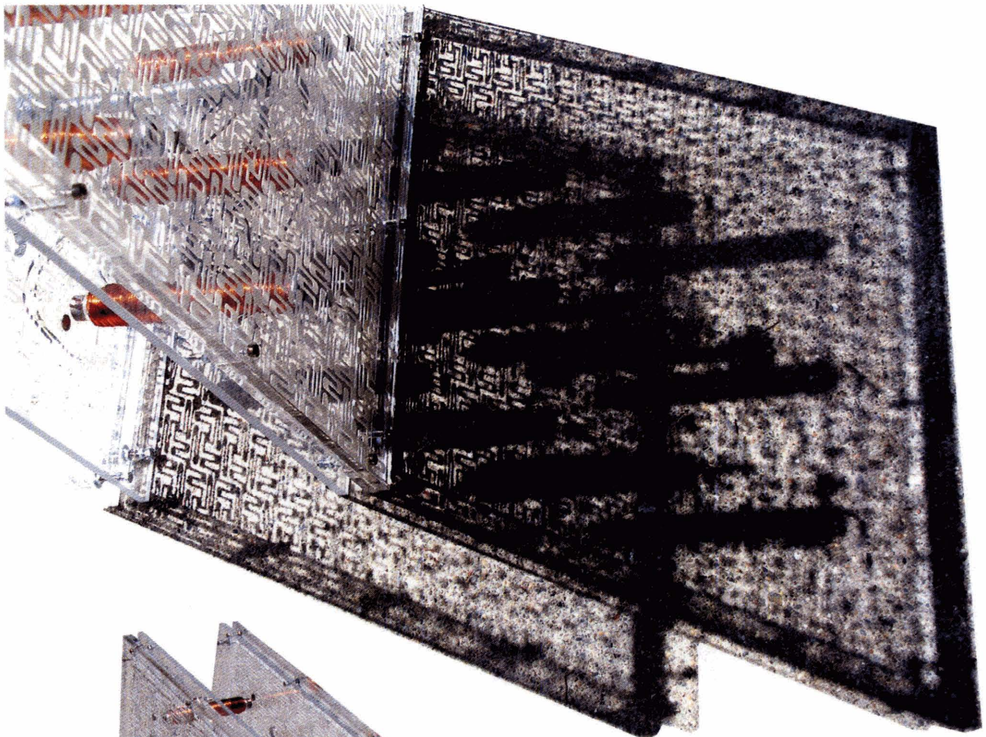
7.6 DRIVING THE TICKLE

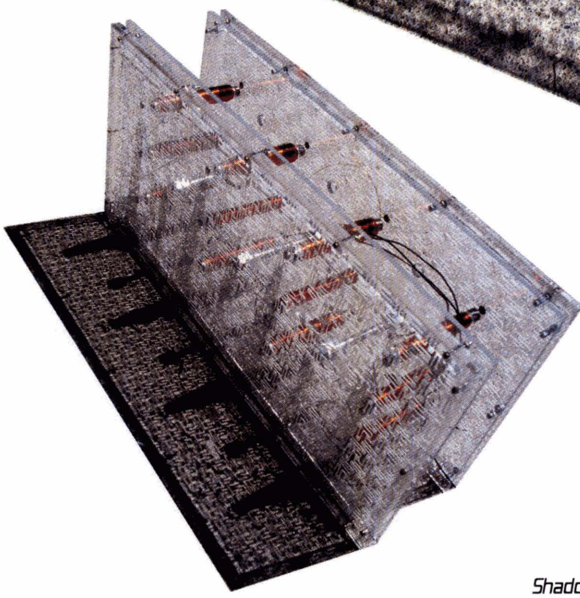
In order to energize the solenoids properly, and to create the desired movement, a microcontroller driver board is made. We use a small microcontroller, the ATTiny26L which controls the electromagnets by a switching mechanism. The switches are electronic ICS called mosfets. In the kiNET prototype, the program loaded on the microcontroller sends a series of repetitive pulses to columns of electromagnets at a time creating a wave pattern on the surface. In upcoming prototypes, the pattern does not need to be specific or hardcoded, and could be controlled by sensors or human input of another form.

Ultimately, we want to make kiNET responsive to human interaction and presence. The surface would for example detect the proximity of a hand and move accordingly. This can be done using capacitive sensing to create a movement following the location of a hand on the surface. Many other potential interactions come to mind. With the main structure and mechanism implemented, input methods are numerous.

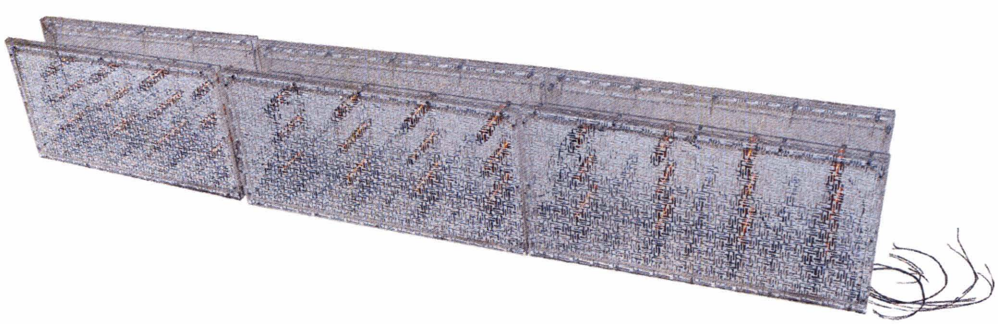


Sequence of fabrication of kinet, from manufacturing of the electromagnet solenoids, soldering the circuits on the board and installing solenoids, soldering electromagnets to microcontroller circuit board and first demo run at Media LAB

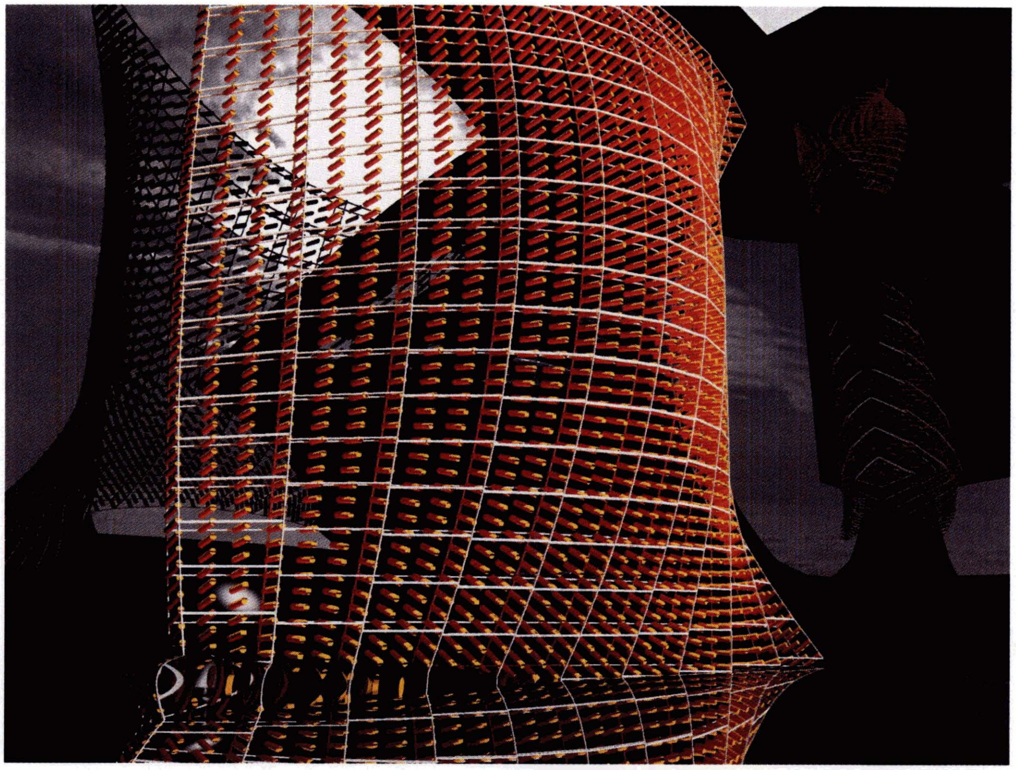


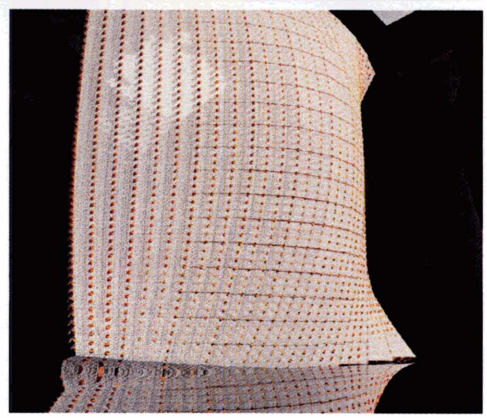


Shadow patterns derived from flexure patterns.
Three kinet modules pre assembly



Transparency of a demo Kinet module

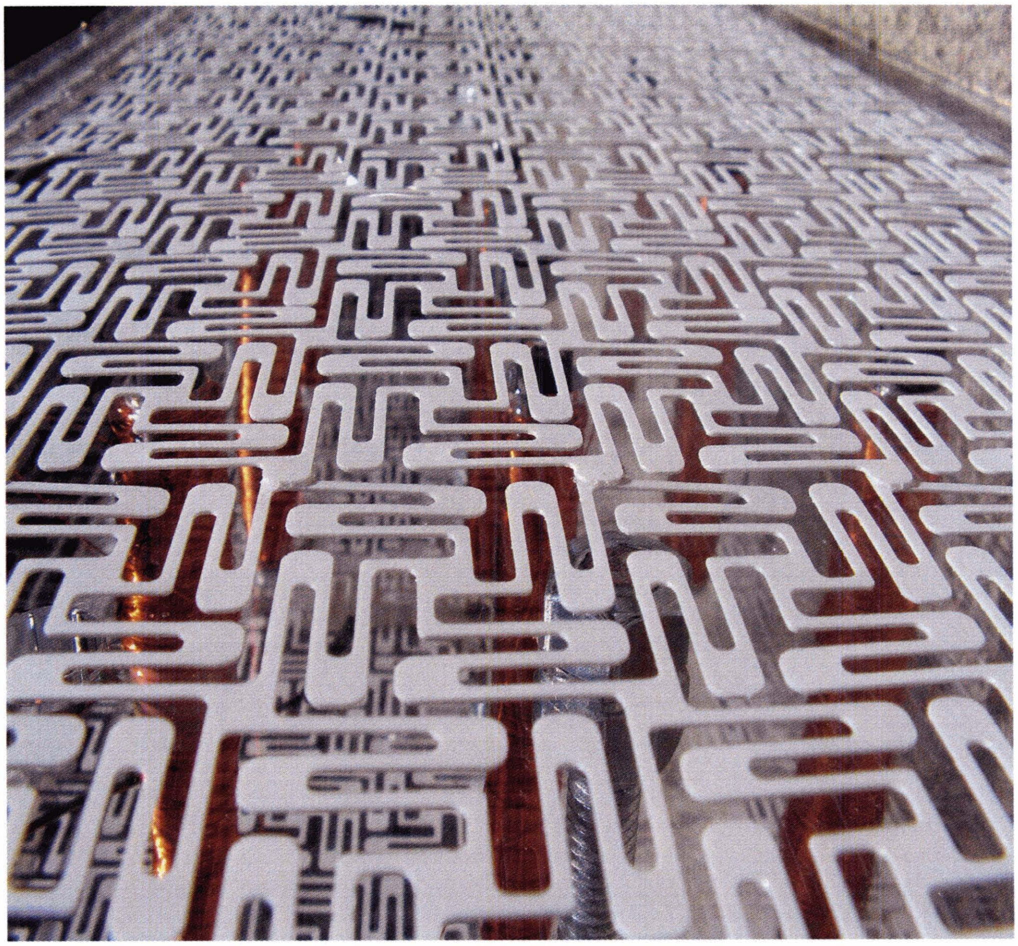




Final design for kinet implementation, Three modules have been fabricated so far

7.7 CONCLUSIONS: FROM DIGITAL ANIMATION TO LIVELY SURFACES

KiNET addresses a critique towards the latest development in the field of design as a consequence of the digital revolution. Digital design technologies enhanced the abstract space of design, both conceptually and instrumentally, extending the limits of what can be thought in relation to what can be drawn. Animation tools have been influencing design through its ability to engage transformation and variability in time. Digital technologies, advanced CAD and animation tools have provided a new way to simulate these issues. But there are still too few attempts of realizing these concepts into material realities. Today, these questions can only be asked in the abstract space of design, and there is still an enormous gap between



digital design and concrete implementation and actual products. Our own obsessions deal with anxieties when faced with of the (im) possibility of transposing the digital into the real, the virtual into the concrete. This is an attempt to break these anxieties, jumping through that gap.

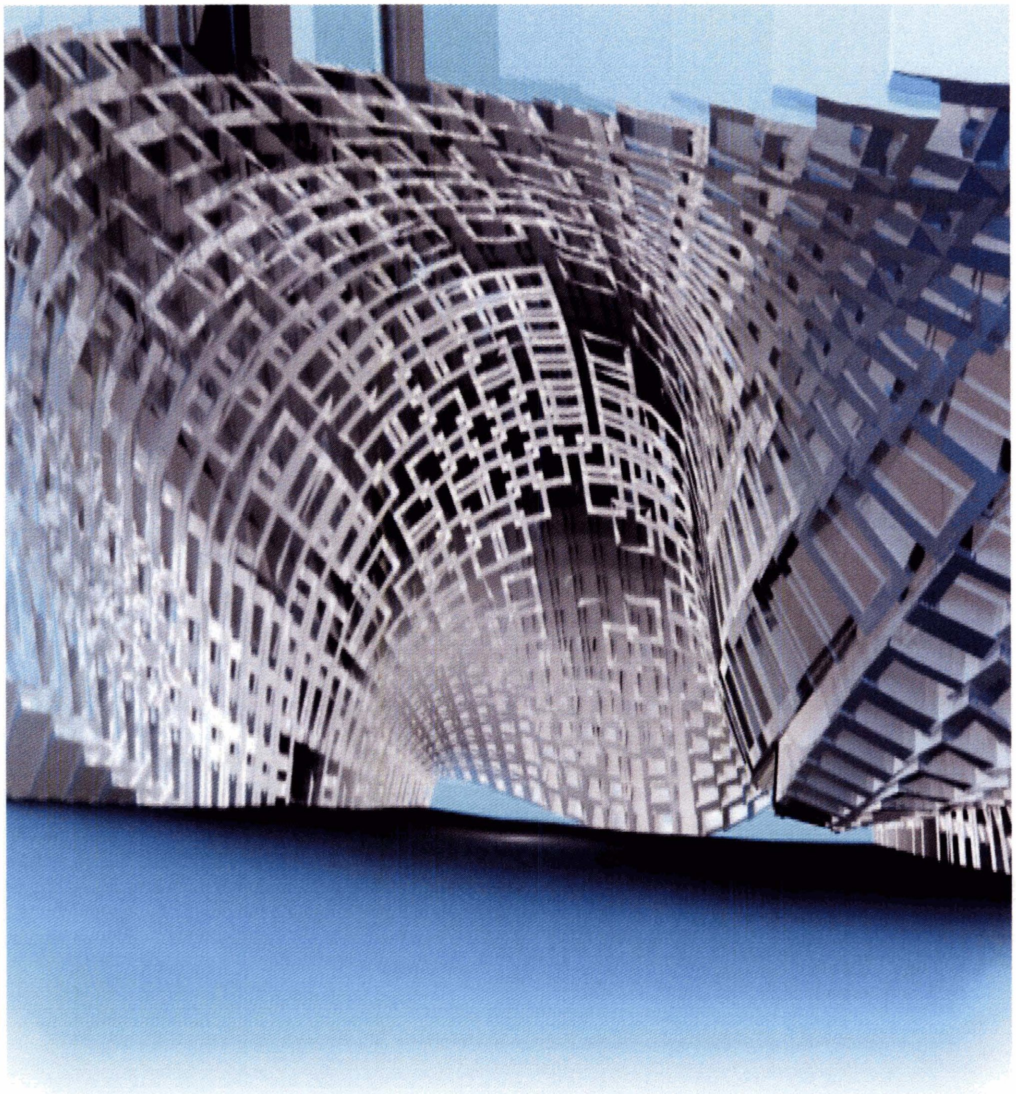
7.8 FURTHER RESEARCH

Although the results of the latest demos, further investigation towards more precise control of the actuation, and more complex patterns of motion should be coded and programmed in the microcontroller.

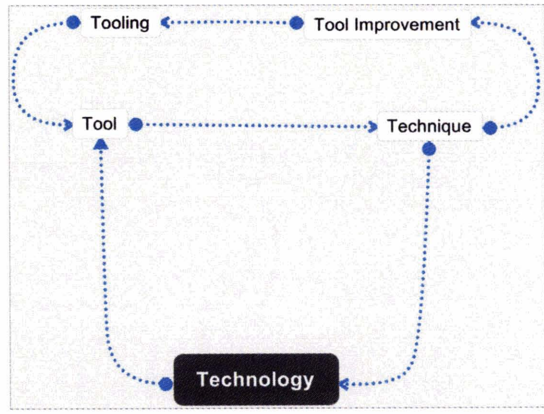
The results from the flexural surface are satisfactory, but it is necessary to extend the current investigation to different materials and machining processes.

The electromagnetic actuation can be used for limited off-plane motion, thus other actuation methods should be investigated.

More research should be done in other to parametrize the design and improve the modeling - prototyping iteration time.



8 CCCS COMPUTING FOR FABRICATION



Technology progresses in cycles. To acchieve certain goals, specific tools are developed. The use of such tools become advanced techniques. When developed techniques start being limited by the current tools, new tools have to be created, restarting the cycle. When tools and techniques make posible the achievement of a substantial body of knowledge, technology advances, and eventually a new technology is defined.

8.1 DESIGNING CONTINUOUS COMPLEX CURVED STRUCTURES TO BE FABRICATED FROM STANDARD FLAT SHEETS

This project explains how complex curved structures can be constructed from flat standard panels. The main objective is to link both design techniques and digital fabrication methods to solve a recurrent problem in contemporary architectural design, building double curved structures. It achieves this by using common fabrication methods and standard construction materials. It describes the processes of programming a set of computational tools to study and develop designs to fabricate continuous complex curved structures. I will describe this through a series of experiments, using parametric design environments and scripted functions implementing certain techniques to fabricate these designs using rapid prototyping machines. I compare different fabrication methods using computer numerically controlled machines to process these flat panels to obtain certain properties, allowing them to bend, twist, fold or stretch in order to achieve these complex forms.

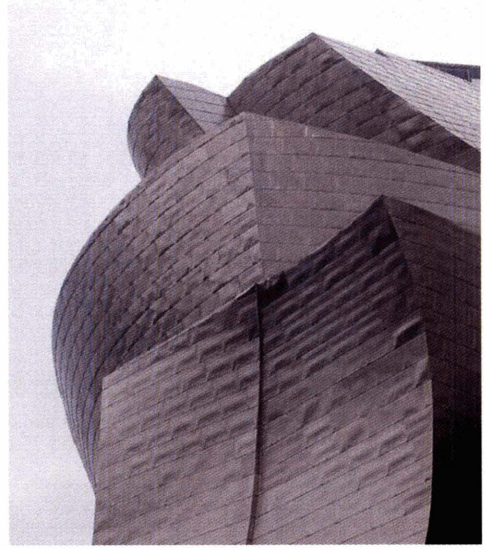
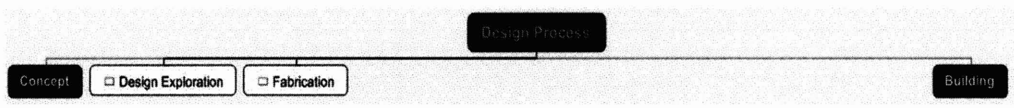


Figure 16 and figure 17 The smooth continuous surface of the Yokohama Port project, built as a faceted set of planar surfaces restricted by the material used. The curved shapes of the Bilbao Guggenheim, show the wrinkles of the titanium shingles, as they were cut from flat panels and cannot bend into double curved pieces.

8.2 INTRODUCTION

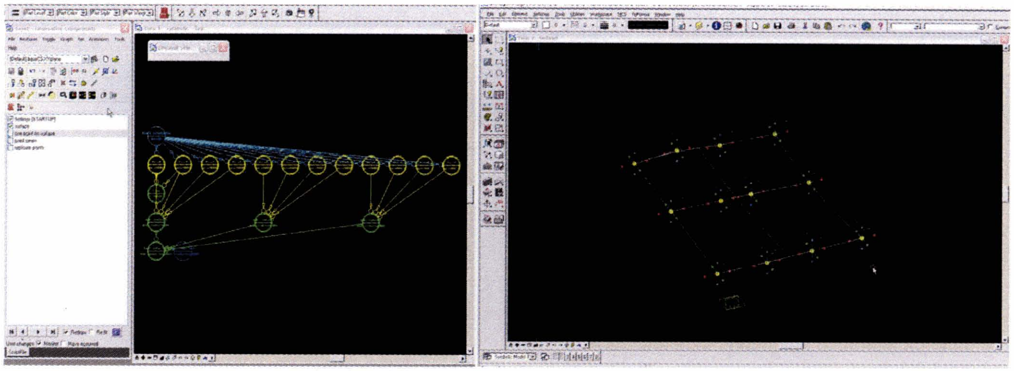
An architectural design has to evolve through a number of stages to be realized these phases of development, go from concept to construction, and the path between all these stages is requires an increment in precision and accuracy, and a progressive development of the descriptions and representation of the design. We know that construction documentation requires precise and detailed drawings for every singular element, part, component or assembly of a design. This has been one of the main reasons why standardization has become the norm. It saves time both from the designer's perspective, which has to deal only with types (stereotypes) of details, from fabrication, as they can program a specific process to produce many of a particular type of part or piece, and to construction, as they have to deal with less "custom" parts, and many equal parts can be assembled and placed in the same way. Due to this fact, complex designs that require higher number of differentiated pieces, are usually reduced or simplified in order to fit them within the standards.

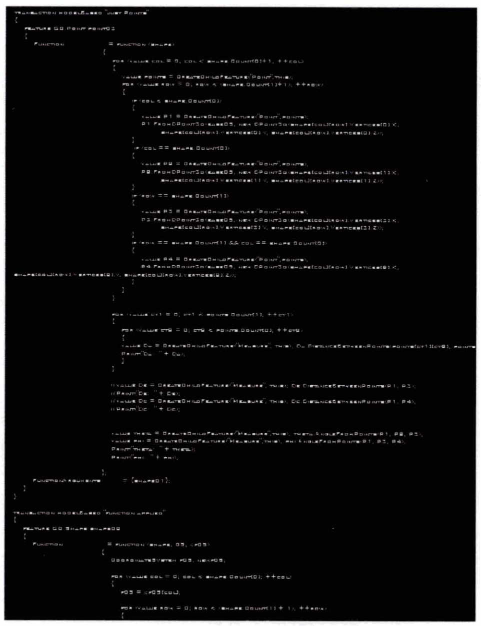


The degree of simplification or "refinement" will vary according to the particular design and the fabrication processes involved. Two types of results can be observed from designers actually trying to extend the constrain of standardization in design and construction. Or they push towards keeping the design as pure to its original attributes and qualities, therefore experimenting and exploring new ways of fabricating with traditional materials, sometimes even exploring the creation of new types of materials, but sacrificing sometimes the quality and finesse of the final built result. The other approach is to apply traditional materials and construction process but reducing the complexity of the design, thus yielding aesthetical and plastic properties of the design in order to realize it.

The objective of this research project is to improve the design process by incorporating manufacturing logics at early stages of the design process to tackle these issues.

As I have argued before, parametric design

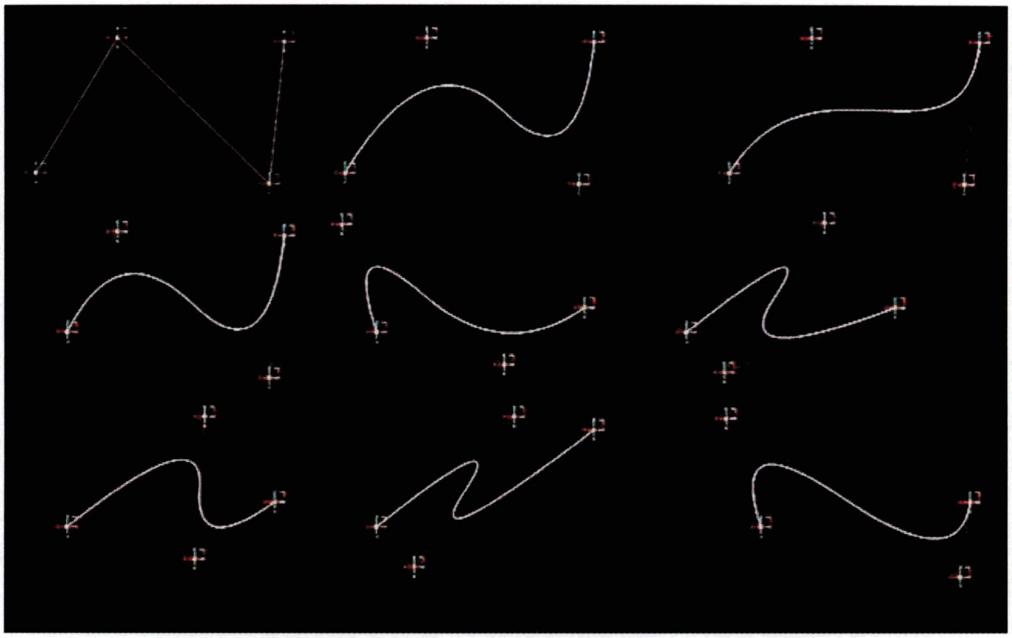




Levels of associativy present in Parametric Design platforms, and the particular implementation in Bentley's Generative Components. Parameters Controlled through a Graph Variables TAB, Symbolic and Hierarchical Graph, Graphical Modelling interface, and Programmatic and Scripting Interfaces.

implies a new paradigm of non standard design through the propagation of the difference, the repetition of the variation. The multiple levels of associativity present in parametric software allow to embed variable parameters driving functions and geometries using different interfaces. Parametric variability can be tested visually by modeling in a graphical interface, can be embedded within the symbolic and hierarchical representation of the design, or can be embedded using programmatic or scripted functions. Each of these interfaces provide specific functionalities and work in parallel allowing variation to be embedded within the design and opening opportunities to perform iterations and evaluations .

"We already had a digital revolution, we



Parametric BSpline Curves constructed by poles, showing the curve and the control polygon, and several variations of the same curve re defined by translating the control points

don't need to keep having it"[21]

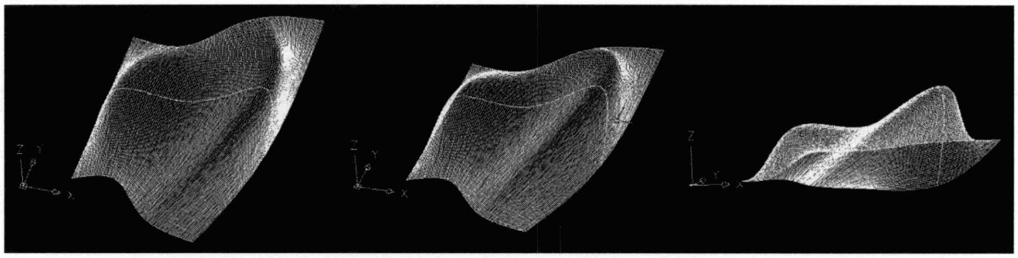
N. Gershenfeld

The Director of the Center for Bits and Atoms, Neil Gershenfeld, points now to the imminent Revolution of Making, the programming and fabrication of the real world, not just the electronic virtual worlds.

The success of CAAD tools since their initial development at MIT when Sketchpad was introduced by Ivan Sutherland, has been rooted on its efficiency in graphically representing and manipulating, complex mathematical descriptions of designs. Originally, CAD was intended primarily as an interface for machine fabrication. It wasn't until later that it became "autonomous" and digital design became an environment for design representation and design development. The efficient performance of computers aiding with these complex representations relies on the fact that computers can calculate complex mathematics extremely fast. This has allowed that complex geometries, based on increasingly more complicated equations, became possible tools for design, introducing a whole new family of shapes and curved topologies, splines, and spline surfaces.

The construction of these family of shapes requires calculating third and forth degree

21 Gershenfeld, Neil, 2005, FAB the coming revolution on your desktop-From personal computers to personal fabrications, New York: Basic Books



Double curved construction, spline surface created by series of spline curves

differential equations, which would take time to solve by hand, but where the computer can really show its power. Nevertheless, the presence of these shapes in standard commercial CAAD available is restrained and the control over them has been limited in order to simplify their descriptions and their manipulation. This ends up in implicitly creating a series of conditions and assertions regarding the design's shape, which can not be controlled by the user, who has to accept and assume these assertions as norms.

The mindset and framework inherited by using any CAAD package available is widely discussed and confronted by Shape Grammars theory, and people like George Stiny have dedicated a lifetime to the search of alternatives ways of engaging design.

Nevertheless, the ability to program new functionalities into a CAD platform, represents a first and basic gesture of flexibilization of the platform itself, and an attempt to stretch the boundaries imposed by these embedded computational assertions. Parametric design represents the latest attempt in incorporating this programmable, flexible and extendable attitude towards design into CAD. While requiring to construct every relation and link between geometries and functions, it also allows embedding fixed or variable parameters, which represent a new and deeper level of control of the tools used to design, therefore on the design produced by using these tools. Parametric environments then are usually associated with "smart geometries"[22]

One of the main applications of parametric design has been in design for manufacturing,

22 Smart Geometry Group, founded in London in 2005, by Lars Hesselgren (KPF), Hugh Whitehead (Foster and Partners), and J. Parrish (Arup), in collaboration with Robert Aish (Bentley Systems). < http://www.smartgeometry.com/>

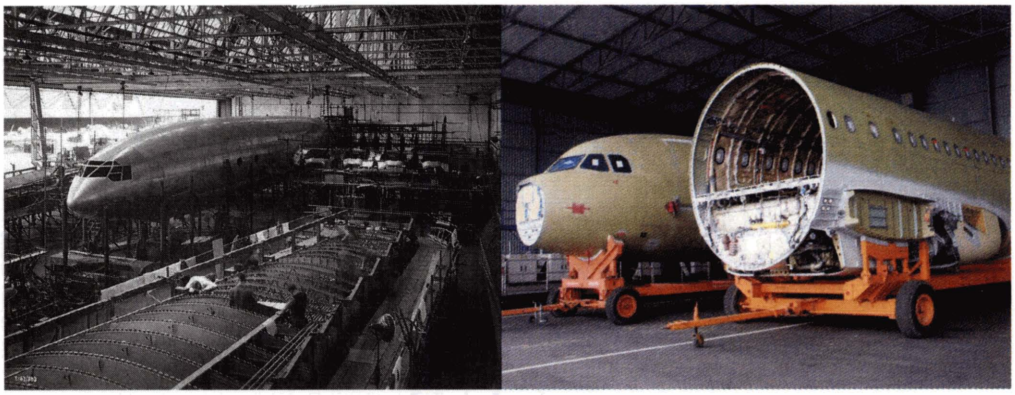


Figure 18 Design for Manufaturing has been primaily developed and applied ti aeronautic and automobile industries. Complex continuous and curved descriptions were originated from aerodynamic models to improve performance. www.airchive.com

precisely because specific geometric conditions regarding fabrication procedures and procedures to obtain proper descriptions for machining processes, can be input in the designs facilitating the manufacturing later. This research project targets both fronts, as it consists in developing a series of tools and techniques that can be used to design and fabricate double curved structures.

8.3 METHODOLOGY

This project was conceived methodologically as a process of chaining different functions developed during previous research and experiments. Some of this functions had to do with understanding how to decompose a complex structure into smaller assembled components, and how to work in parallel in both scales. Other tools and techniques had to do with building progressive levels of geometrical control onto nested components. The goal targeted by this research is to incorporate these techniques and tools to conceive and fabricate complex structures using standard flat materials, proving that complex designs do not necessarily mean complex fabrication methods.

8.3.1 Parameterization of the design intent

Parametric modeling software offer a platform to design where the user or designer cannot work just with the basic given palette of shapes, in fact, there is not such thing as a palette of basic shapes or solids in parametric software; everything starts always, and has to be built bottom up, from points. But it includes also the ability to integrate the functions and relations between shapes, and even between functions themselves. In a parametric environment, the resulting design is the consequence of setting up a number of conditions regarding the geometry of the design, the relations between those geometries, the functions applied to obtain or derive these geometries, and the relations between those functions. This results in a higher level of control over the resultant design, where the design process can be streamlined in terms of different iterations of the design, as a change of a parameter will affect all the functions that depend on it, modifying the end result, the actual resultant shape. This is an advantage over standard CAAD platforms, as in most cases, these update methods for adjusting particularities of a design happen in real time, allowing the user or designer, to quickly evaluate different alternative solutions for a particular problem.

This aspect of parametric design increases considerably the amount of possible answers to specific problems that which can be reviewed and evaluated, this has been referred by some authors as the enhancement of a "solution space" thanks to these parametric design methods. Parametric design has been usually associated to design for fabrication, as some of the relations that can be "programmed" into the design are related to production and manufacturing. Parametric environments were originally developed and have been used for years in the car industry as well as in the aeronautic industry. It has been introduced to the architectural arena in the last years by firms like Gehry and Partners, Foster and Partners and others.

Crucial to this research then is to conceive then the required parameters that have to be exposed and which will provide the control over the functions and the resultant geometry. The process then to provide a flexible and functional set of parameters is a design task.

8.3.2 Tool Programming

Working with particular platforms investigating different ways of achieving specific goals leads toward the development of specific techniques and methods. These techniques start by using the available functionalities in innovative creative and combinatorial ways to do specific tasks. Further development of these techniques involves using and combining available functionalities in unpredicted ways, tweaking or hacking the functions to perform in different ways, sometimes even considering erroneous behaviors as desirables experimental results.

But there is a point where the functionalities provided by a tool would require to adjust, change, enhance that tool. This is where scripting languages enter the scene as Software Development Kits (SDK), present in almost every CAD package available in the market. This scripting languages are always customized to the specific tool where they would be implemented, requiring specific learning training to acquire the knowledge to implement new functionalities in that CAD.

Furthermore, as some scripting languages are not implemented within CAD's native scripting editor, it usually requires to actually code in a regular script or text editor outside the application itself. One of the requirements of this kind of procedure and due to its lack of GUI, is that the user has to be familiarized with all different possible descriptions of an object, especially because he won't be able to rely on its visual representation to address it. As every scripting language is custom, different descriptions of common objects (points, lines, surfaces) have to be internalized to be implemented.

The specific implementation of GCScripting is a language based on C# which is the programming language it was built on. The particular implementation of C# provides a number of advantages, among which the possibility to compile a specific code to make it available for Visual Basic or some of the other languages included within the .NET Framework of Visual Studio, constitutes a great advantage. A second advantage is the integration of a script editor within Bentley's Generative Components platform, which allows for integrated compiling of the scripted code.

While scripting can provided an embedded access to programmatic levels of associativity and object creation, it does not provide a substantial performance enhancement compared to normal modeling techniques. This can become certainly an issue as recursion is one of the main reasons to use scripting in the first place. For that reason, function can also be coded directly in C# in order to improve the performance and speed of the calculations. For the purpose of this research I have not yet tested direct C# coding, and I have conducted all my scripting experiments using the native script editor inside GC.

8.3.3 Parametric constructions using Generative Components

For the purpose of this study, I have done the entire experiment using Generative Components, which has been developed by Robert Aish at Bentley Systems. In some ways it has been an adventure in testing an under development platform, but being involved in its development has provided numerous opportunities for exploration.

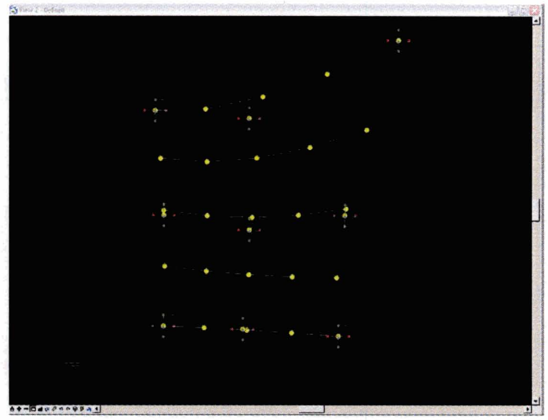
8.4 DESIGN STRATEGIES

The approach proposed by this methodology targets two different issues, how to design for fabrication and assembly, and how to fabricate these designs.

The first method deals with the aim of designing a complex continuous curved structure, which has to be developed as a whole, but which will be later manufactured by assembling fragments or parts of it. This implies that in parallel it has to be thought both as a whole and as a series of related parts. For this I use a method of subdivision of the structure (the original surface), which returns an object that is not an exact copy of the original one, but a fairly approximated one, where the degree of "approximation" or of "likeliness" can be partially controlled by the resolution of the subdivided output object. This allows to test, during the design development phase, the most appropriate design parameterization in terms of the output for fabrication. A secondary method is implemented to provide a number of choices for the design to be fabricated, regarding formal, material, structural and other design criteria. For this purpose I built a series of functions that address particular manufacturing requirements, which will constrain but simultaneously facilitate the fabrication process.

The methodology that I applied consists of a combination of parametric modeling and scripting, to provide the digital tools required. The processes were evaluated both in their digital environment as through the physical output that they provided through CNC machining and posterior assembly.

The method proposed, was divided in

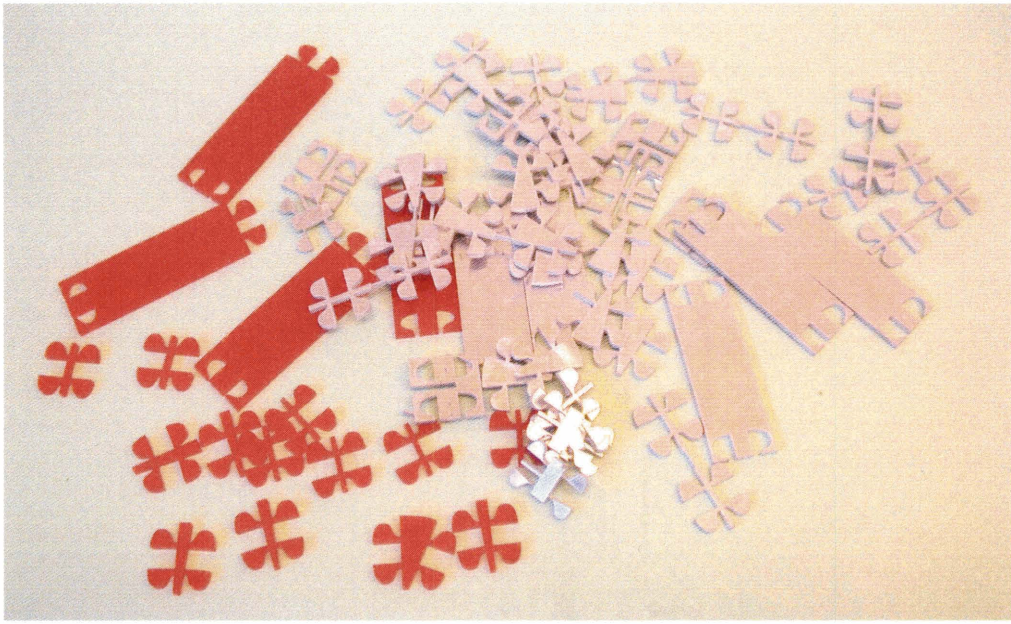


Double curved BSpline surface redefined as a faceted aproximation using series of point placed on the surface by UV values

two parts. The first addresses the challenge of designing a surface considering its later subdivision and re-assembly; this is a generic method that can be applied to any surface independently of the fabrication process. The second part provides a chance of choosing between different desired output results from the design, therefore choosing a particular fabrication method and materiality. I believe that by doing this at early stages of the design development process it will in same ways constrain the process, but it will also enhance the design solution and material result.

8.5 TOOLS, TECHNIQUES AND TECHNOLOGIES

In contemporary architectural discourse, within post digital culture, three concepts are used as synonyms, almost indistinctively, while they have different meaning and refer to different stages of cultural knowledge: tool, technique and technology. Digital tools and digital technologies are often used as equivalents, I will explain the differences. Tool is something that is used to perform an action, it is the instrument. Technique on the other hand, is a method or group of methods for accomplishing a particular task. But technology is the body of knowledge, available to a society, which is of use to achieve specific practical purposes. Then the computer is a tool, as it is the software running on it. They are used to execute specific actions or operations, to achieve certain objectives. The specific methods developed to use computers and software, inventing and perfecting creative processes to achieve better results, are recorded as techniques. But technology is achieved, when a new knowledge is produced from the creation and application of certain techniques, running specific tools, to achieve desired objectives. Although this research is still in progress and the results are partial, I will use them to explain how emergent computational



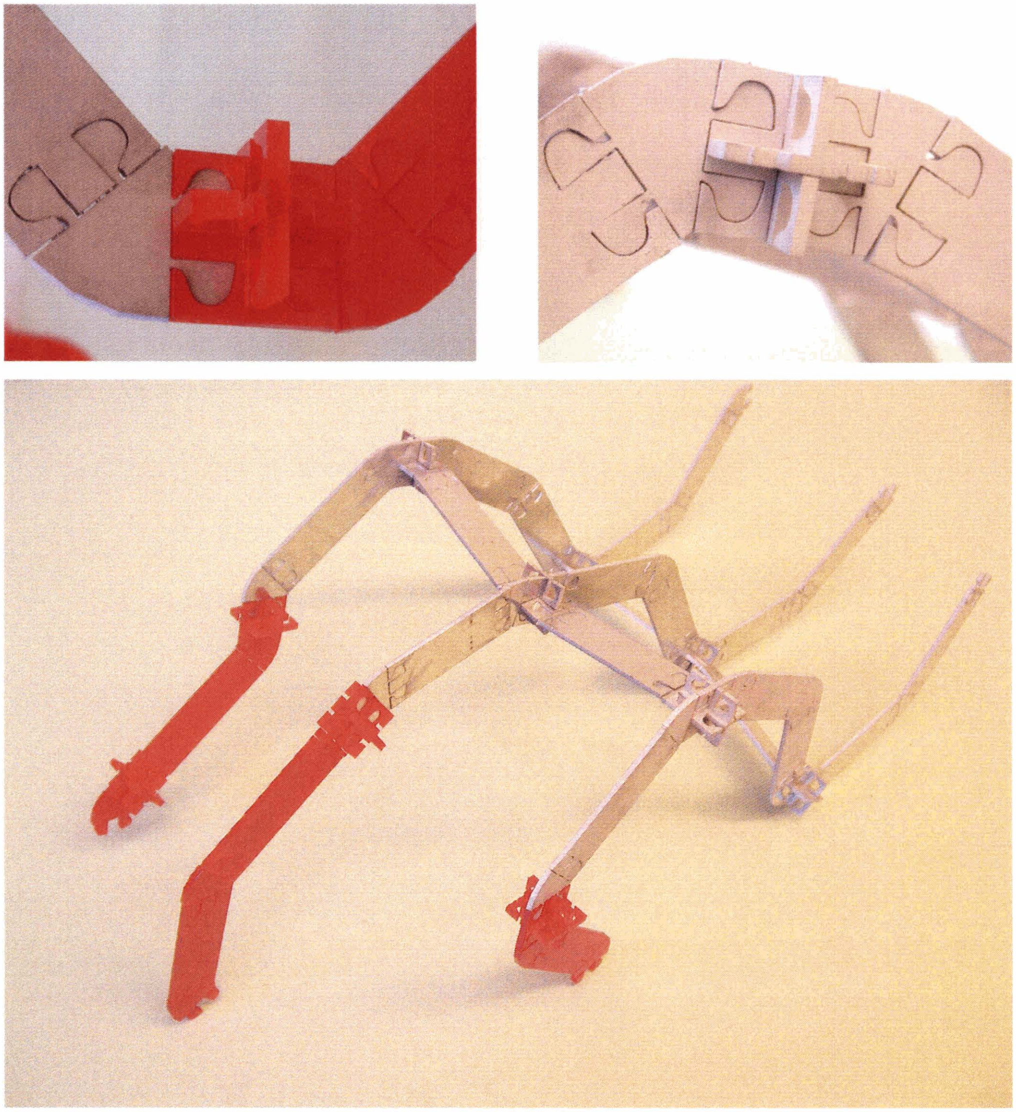
Fabrication of large amount of different pieces, in order to create a larger complex asemled structure

tools, parametric design environments and numerically controlled fabrication processes can be implemented in the development of architectural designs.

8. 6 GEOMETRICAL CONSTRUCTS

Spline curves are traced using the vertices of a control polygon. Modifying the position in space of this poles alter the geometry of the spline. In the same fashion, surfaces can be traced by a grid of poles, resulting in complex curved surface. A spline curve, is always tangent to the first and last poles, but the rest of the poles remain external to the curve. While the continuity of the curvature is one of its main appeals, it is also a big problem. If a spline is cut in two each resulting segment changes, becoming tangent to the new edges and acquiring a new geometry. When this new splines are put together, there is no continuity on the curvature. Usually, when this happens in real construction works, the pieces are stressed to fit, almost always wrinkling and even breaking as a result of these forces, the titanium tiles of the Guggenheim Museum at Bilbao, by Gehry and Partners is an example of this. Another aspect of these continuous complex curved structures is that cutting them in pieces will result in large collections of pieces, almost all equal, but every single one slightly different. In regular CAD this operation is extremely time-consuming.

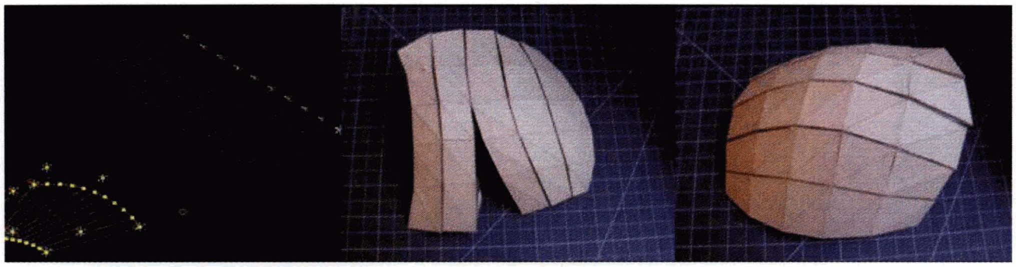
Parametric environments tend to be streamlined towards fabrication, which facilitates



Assembled components ito confrom a courved structure. Variation in the components is limited to arrange and final design variation is limited to a small number of combinatorial variations

building processes like for example, unrolling ruled surfaces. But there is no possible unrolling of double curved surfaces. The technique that I developed for this research uses the unrolling principle to obtain a flat panel from an approximated double curved surface. This paper explains how complex curved structures can be constructed from flat panels, borrowing a concept from mechanical engineering: "flexure structures".

8.7 MANUFACTURING



Controlled geometrical extraction of a facetted strip of the surface and re-assembled to rebuild the double curved structure

CURVED STRUCTURES

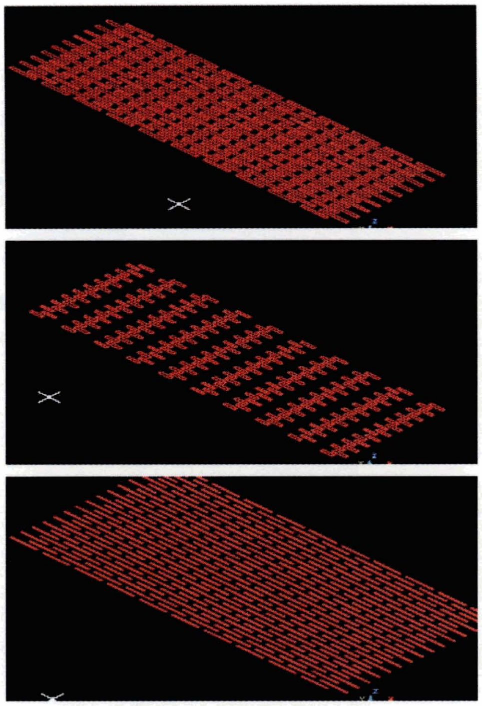
Construction industry is founded on standardization and modularity. Most construction materials come in flat sheets or panels. And casting materials that can acquire free forms also require molds that have to be made from flat panel materials. Therefore, the process of translating these continuous complex curved structures is always painful and usually requires translation to a more rational expression. This paper describes a procedure using "flexure" structures developed in parametric environments, to fabricate partially double curved structures from rigid flat panel using rapid prototyping tools and CNC machining. In the larger perspective, this research approaches the notion of generative design tools and their ability to use digital design fabrication logics and processes to extend the actual boundaries of constructability in contemporary design. Furthermore, this approach engages the reality of construction industry and local economies, providing an affordable response to these complexities.

8.8 FLEXURES

Compliant structures are those who can change its shape when a force is applied to them, and that will return to their previous state if the force is taken out, for example springs. There is a type of compliant structures that behave similarly to springs, called flexures. These structures deform elastically depending both on material properties and on its geometry. This paper describes how to create complex curved structures from flat rigid panels through the flexion of these structures. According to Larry Howell, it is a special kind of mechanism, "a mechanical device used to transfer or transform motion, force, or energy" Typically they are made of "rigid links connected at movable joints."[23]

A compliant mechanism or flexure,

23 Howell, Larry L, 2001, Compliant Mechanisms, New York: John Willey & Sons.



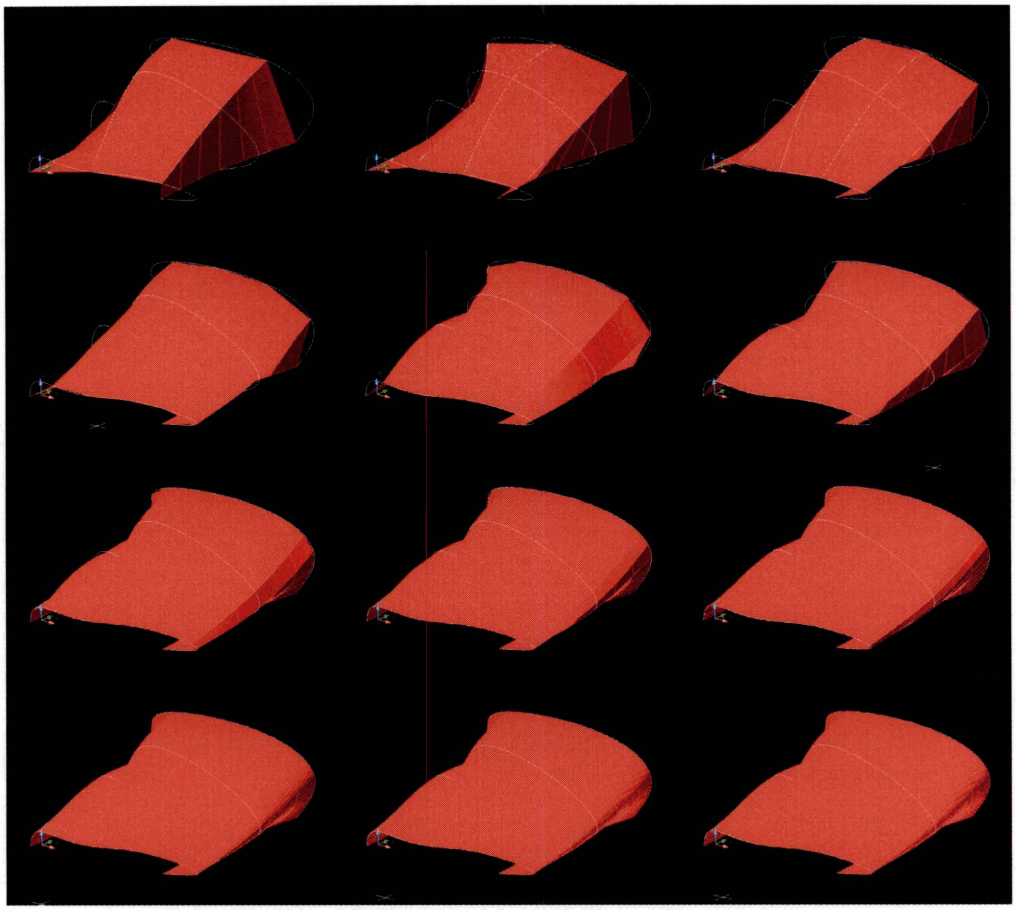
Parametric variations of a single flexure pattern to be cut on wood panels using a Laser Cutter

however, while still performs the same basic functions of transferring or transforming energy or force, gains at least part of its mobility "from the deflection of flexible members rather than from movable joints only"[24]. Flexure structures have several advantages as they reduced the number of pieces involved, reducing the assemblies required, and therefore reducing its costs. But more important for this investigation, is that they can be developed from single pieces. Flexure structures are frequently used in machines that require very precise movements, as they have a reliable displacement precision. They can effectively isolate their movements to the axis where the maximum flexibility has been provided from other lateral movements, "reducing the vibration natural to hinged joints, eliminating the friction between movable parts and the backlash from their rigid body and hinged counterparts"[25] .

Applying this notion of flexure in this investigation provides a method of material transformation, where solid rigid flat boards can be developed into partially flexible structures. This process was conducted through experimentation on different geometrical patterns and the performance obtained from them when applied to a solid material. The fabrication process chosen was material removal by cutting these designed flexure patterns onto the rigid boards.

24 Ibid.

25 Ibid.



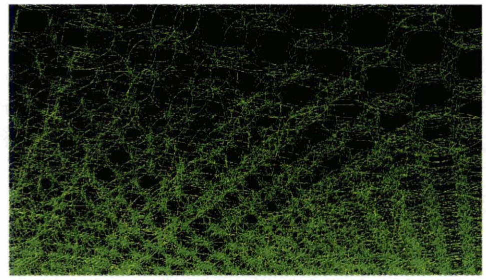
Autolisp Script to subdivide a series of splines and obtain an approximated double curved surface with parametrically controlled smoothness

8.9 DESIGN FOR FABRICATION

The computational algorithm utilized, was to abstract and fragment the complex 3D geometry of the surface in order to process it as smaller flat 2D shapes that could be used as fabrication models. Then specific functions developed according to particular manufacturing procedures and machines are applied.

8.10 PARAMETRIC COMPONENTS.

Two different strategies were explored and compared to model these curved designs: One was writing a script in Visual Lisp to be executed in Autocad, to create a parametric flexure patterned structure, the other approach was by creating several nested parametric features in Generative Components, and then populating an unrolled approximated double curved surface with them.

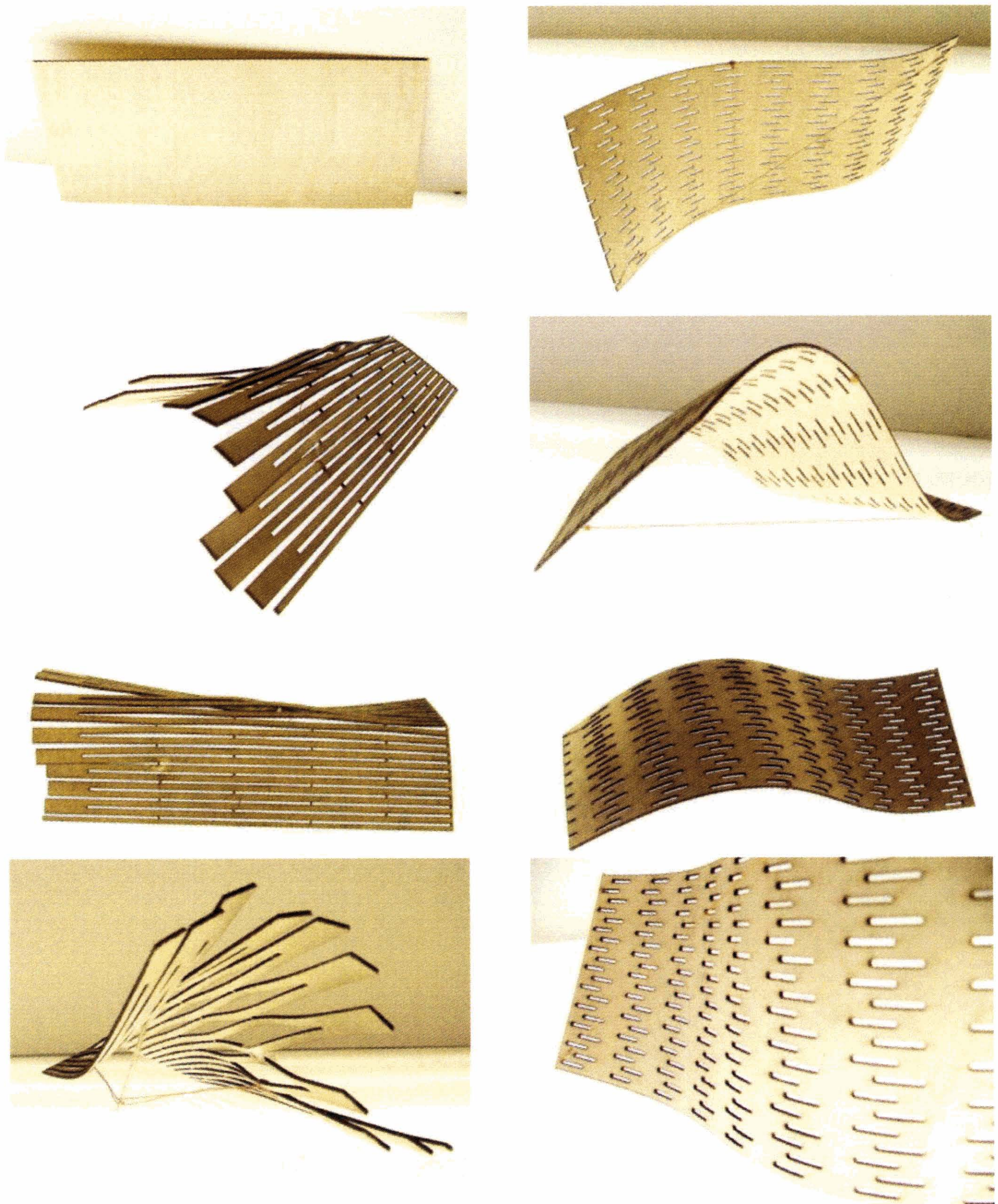


Autolisp script design testing possible patterns and variations

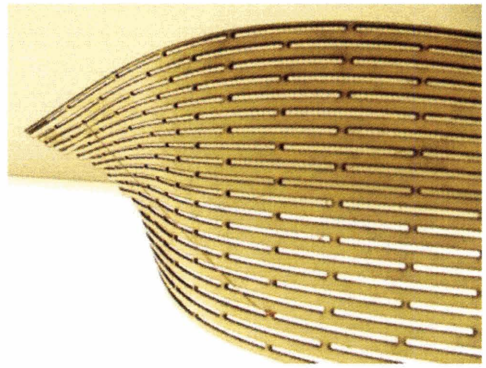
The first strategy developed a Visual Lisp script that draws simple flexure patterns. Two variables control the size of the cut figure, and another two secondary variables control the spacing between them. This first script works only in two dimensions, but allowed me to test different material behaviors, manipulating the variables, studying the tolerances required for a machine, and a specific material. A second script, still in progress, works on three dimensional curved surfaces. The first step was to create an approximated spline surface, because Autocad does not have spline surfaces or nurbs. So I wrote a script that uses splines as inputs. Then I used a spline subdivision function written by Takehiko Nagakura[26], to create lists of points which are used to create another series of splines, going in the opposite direction, connecting the first point on one of the original splines, with the first point on the second original spline, and so on. This second list of splines provides the resolution on U direction on the future spline surface. This list is subdivided again , obtaining the resolution on V direction, creating a dense point grid in 3D space. Based on this script, I wrote a couple of functions that create ruled surfaces between the splines obtained, producing an approximated spline surface, even though, each segment is a developable surface. Based on this properties, each of this segments could be unrolled or developed, and then used as a base for reproducing a two dimensional flexure pattern.

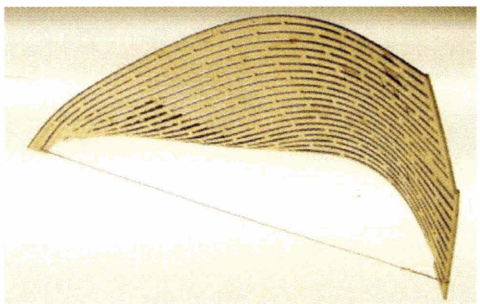
According to different materials and design requirements, this procedure of decomposing the surface into quad-patches could be useful, providing a precise layout for each facet to be fabricated out of a flat panel. In other cases, it might be better to decompose the surface into strips to be cut from larger panels. As the objective of this research is to enable possibilities for design, through the embedding of fabrication logics, these options were kept as parameters in the script. By facilitating the unfolding of the bspline surface points into a flat bidimensional representation, this procedure transforms the design geometry into a fabrication layout, but at the same time, allows to conceive, adjust and perfect such design according to the procedures that would be later involved in its construction.

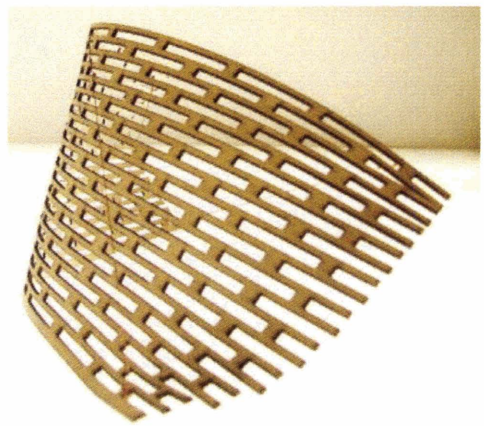
26 Nagakura, Takehiko, 2005, 4.207 Formal Design Knowledge and Programmed Constructs < http://cat2.mit.edu/4.207/ > (08-11-2005)

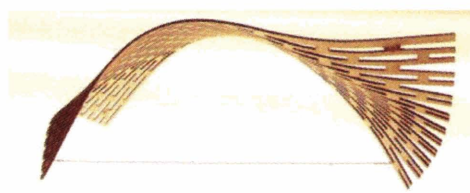


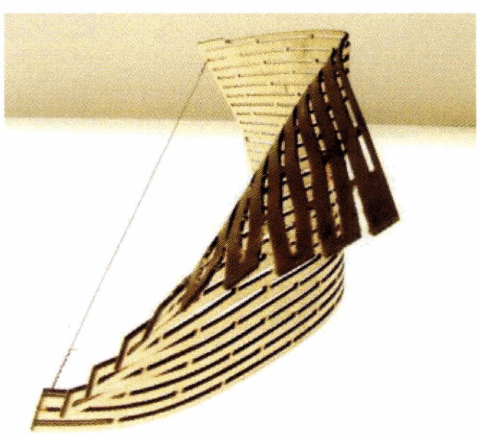
Flexure patterns variations cut on plywood rigid panels and testing elastic properties by applying tensor cables in similar configurations

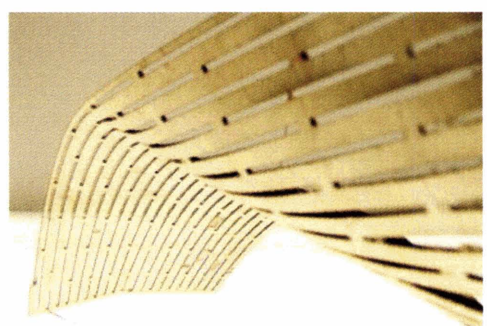




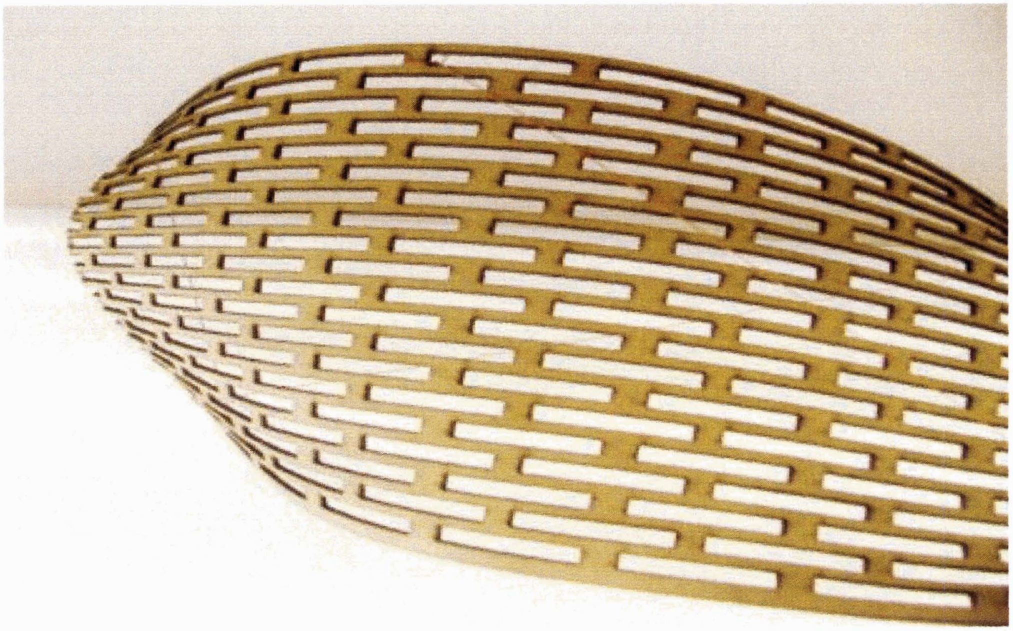


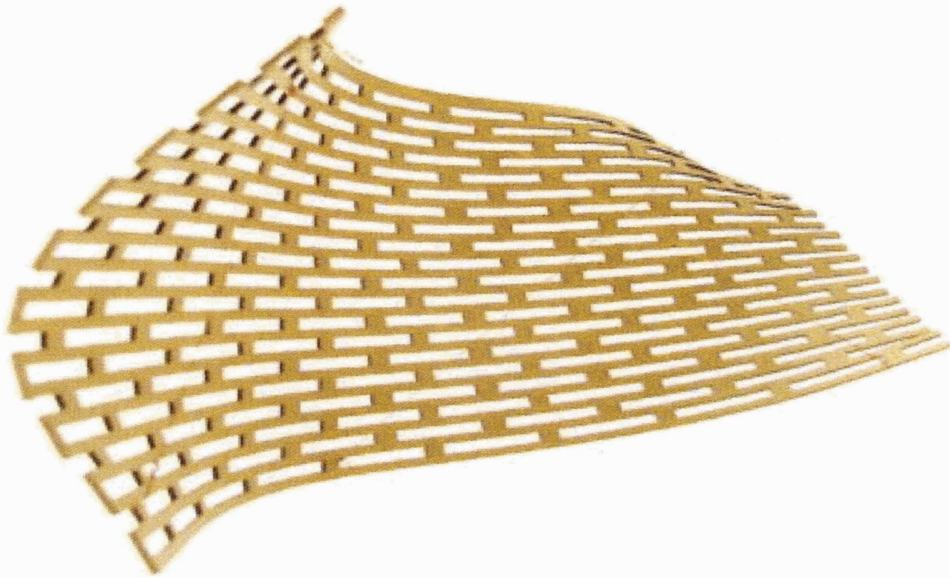


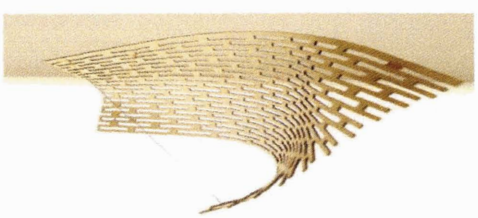


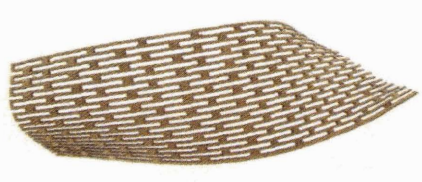


The ratio between length and width of the pattern influences the direction of highest elasticity

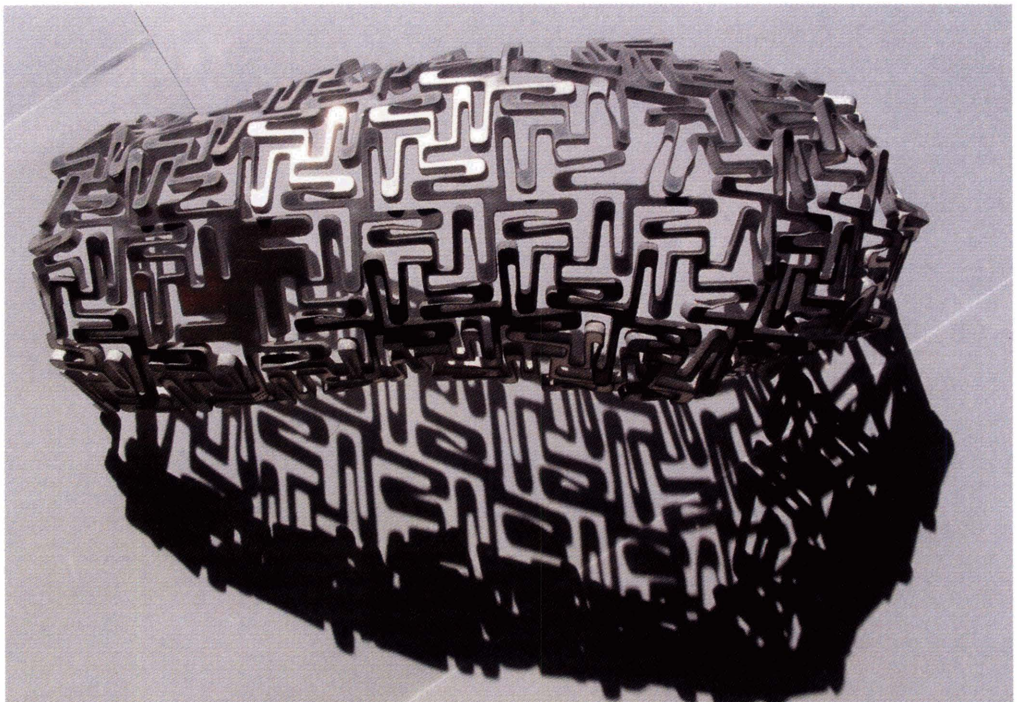


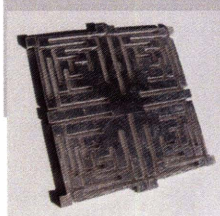


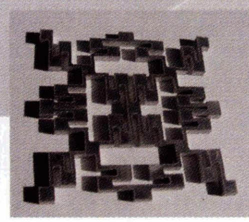


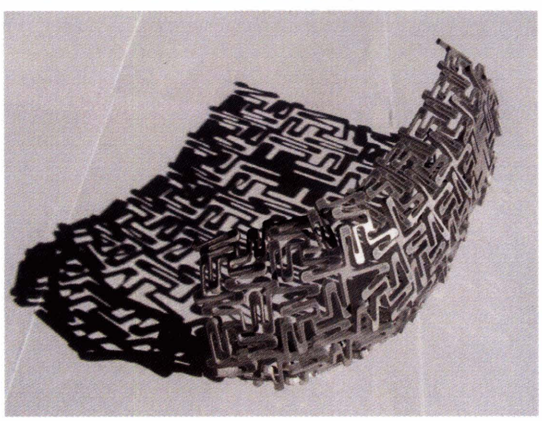


Double curved shapes obtained form a rigid panel of plywood with little tensile force applied. If tensors were supressed, the panel would return to its flat state. The next step in this process is to use continuous joints to produce the local deformation, having then no need for tensors.

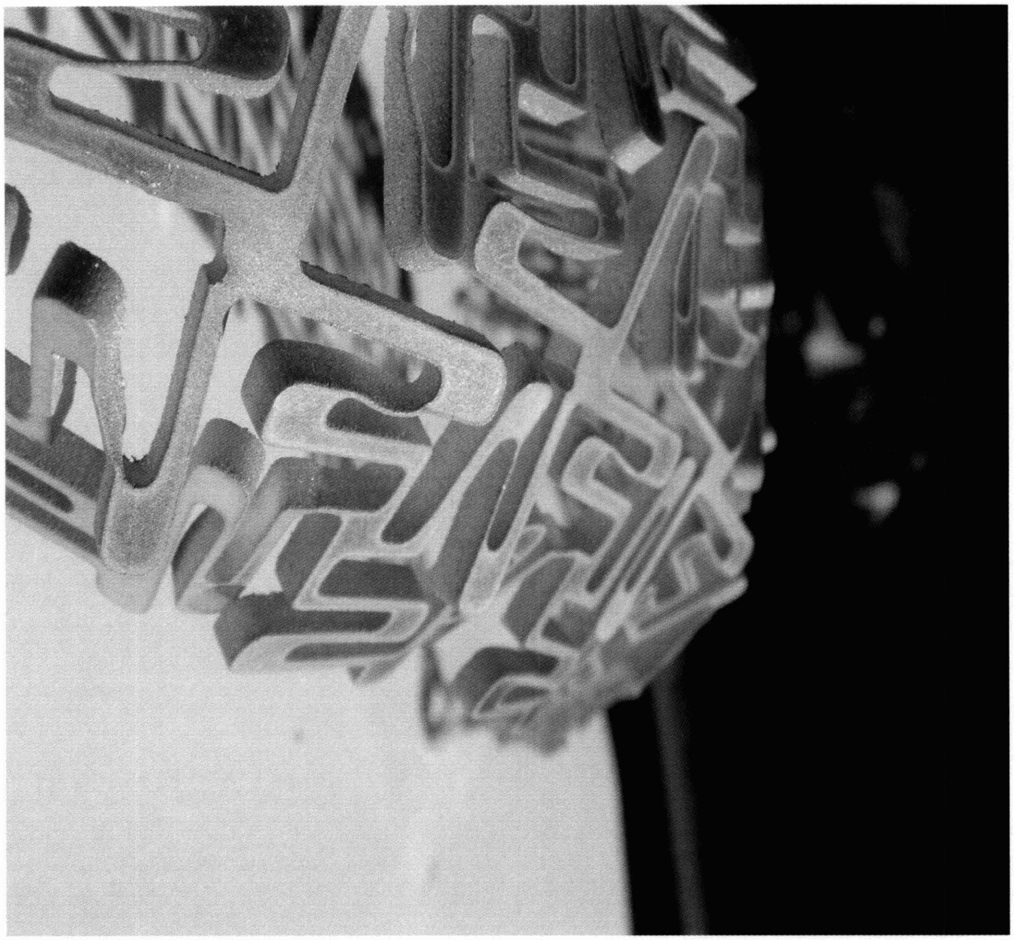








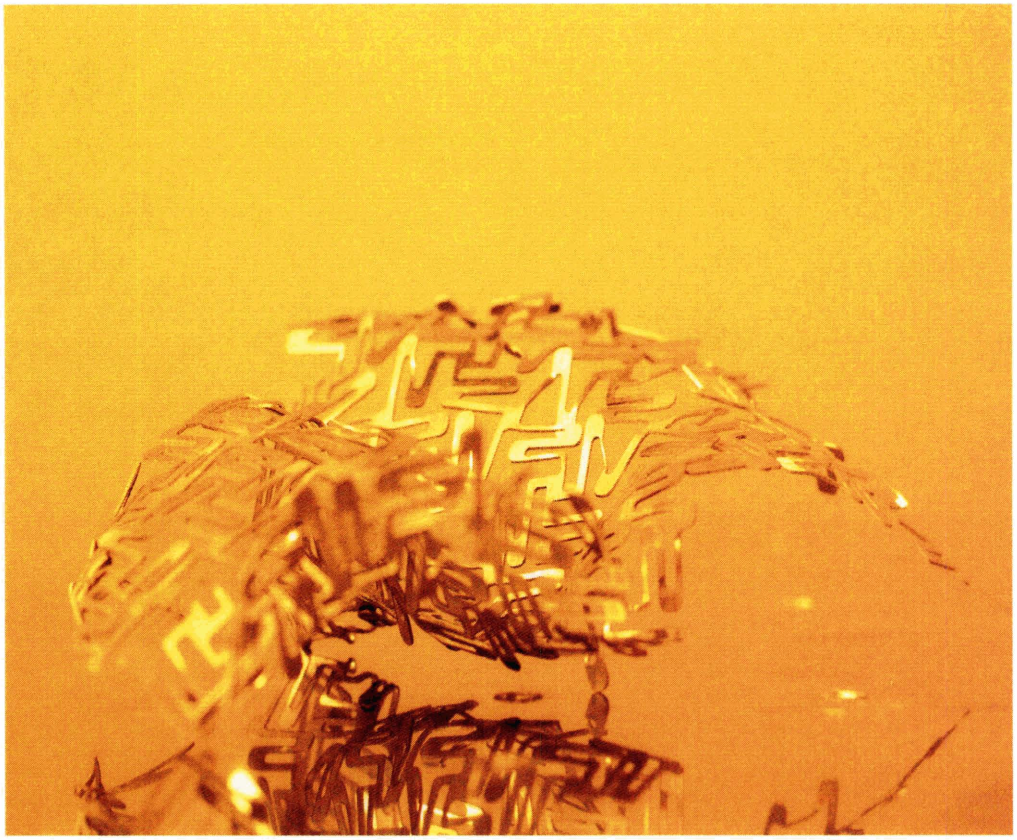
Flexure patterns cut form rigid aluminum panels. In this case I experimented with bending the stucture beyond it threshold of elastic deformation, assuming that I would not require to return the panels to their previous flat state



Double curved structure constructed using flexural patterns to increase elastic behavior on rigid material. This method allow to obtain curved shapes from solid rigid pieces without construction assemblies

The most critical points are the points where the curvature is higher, requiring a different ratio of material removal to be able to stretch properly. In the case of this structure, the smaller sudvidision mantain the same ratio of material removal than the larger ones.

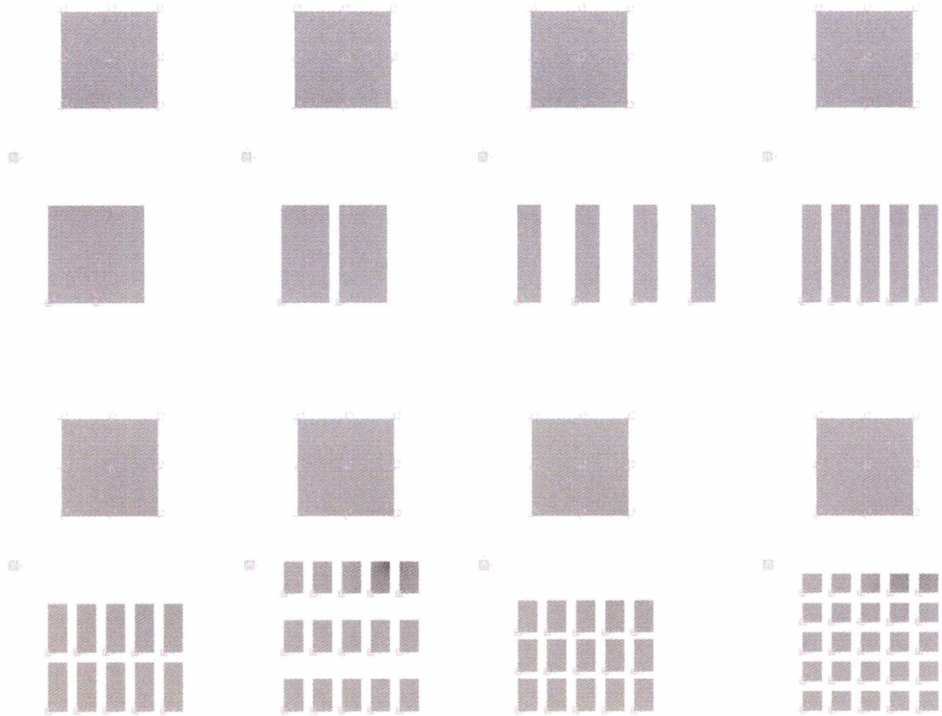
Another possible strategy would be to assign different patterns, based on their ratio of material and removed material in relation to their elastic performance, and the specific local geometrical conditions of the curvature of the structure.



Progressivevly higher levels of elastic behavior can be obtained from rigid metal panels depending on the ratio between the length of the flat spring flexural pattern. In spiral behavior the highes elasticity resides towards the exterior cycles of the spiral due to its proportional longer dimension in relation to the constant width of the structure.

In this structure in particular, some parts of the shape have been permanently deformed, beyond the elastic deformation threshold of the material, and some are curved flexuraly but mantain their curvature due to the force implicitly applied byt the parts that are permanently deformed.

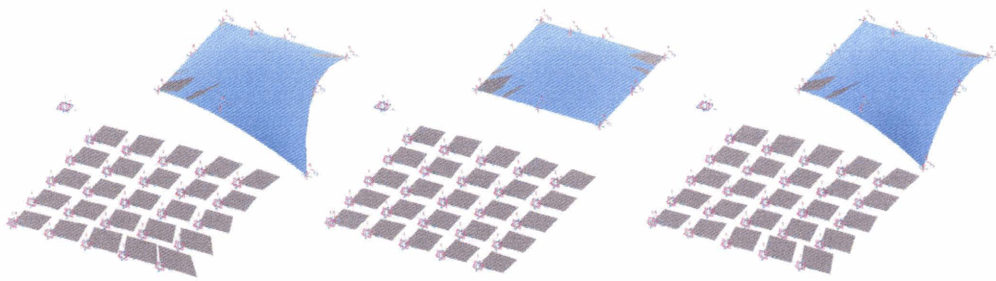
This appears as a potential strategy which combines both permanent and temporary form, given the specific characteristics of the shape and the material involved.

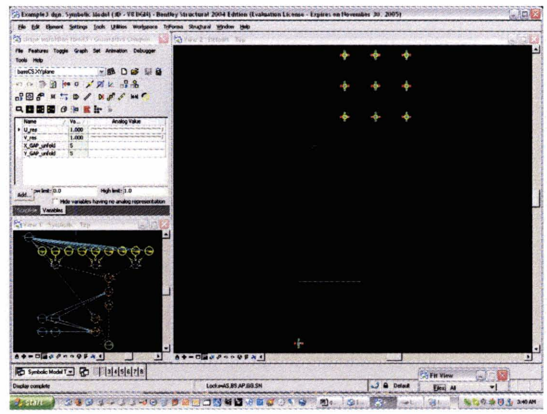


Double curve surface decomposed into smaller unrolled components, parametrically controlling the subdivision number and the nesting of extracted pieces

The second strategy was by nesting parametric components in Generative Components (GC). This first procedure turns a bspline surface with double curvature into a parametric faceted surface by applying a triangulation method via a script. The script locates a series of points on the surface based on its UV values. These points sampling the surface are translated, rotated and aligned in another plane, effectively unfolding the points.

As each facet is created by grouping four non colinear UV points on the surface, the resulting facets are quadrangular, which can be reduced to two triangles sharing a side in common. The first triangle is translated into a plane, then the second triangle, takes the common edge of the first unfolded triangle and aligns its third vertex to be coplanar with the vertices of that first triangle. The result is the unfolded quadrangular facet. An optional procedure is included to unfold the second



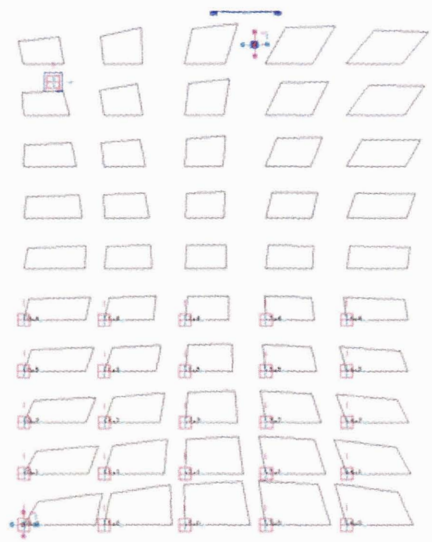


The decomposed and unrolled version of the double curved surface updates each small component as the shape itself is changed, allowing for design iterations and evaluation regarding both shape design and component design.

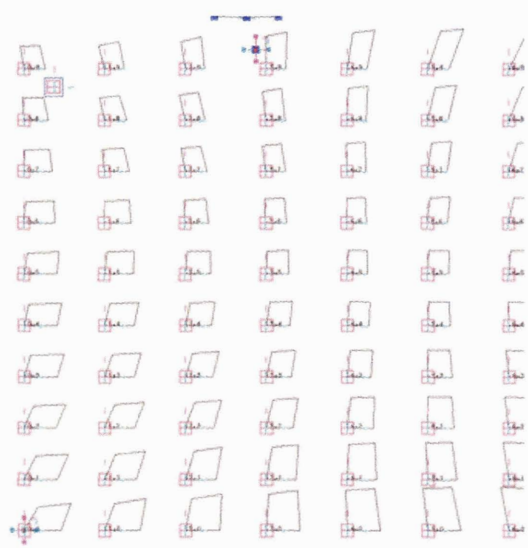
The function in charge of the unrolling performs a triangulation and then aligns both triangular facets on the same plane

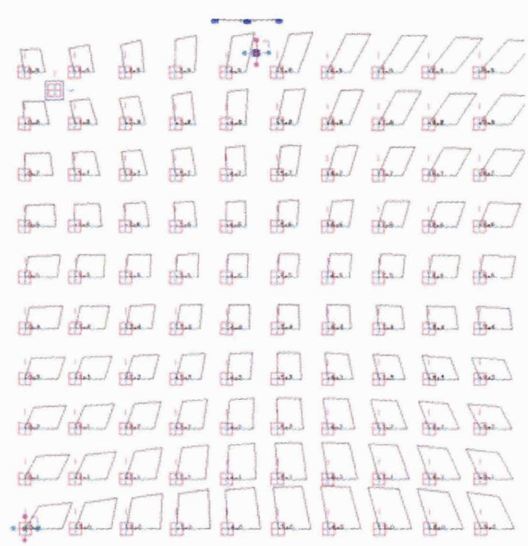
facet, using the common edge with the first facet, either in the U or V directions, creating a continuous facetted strip

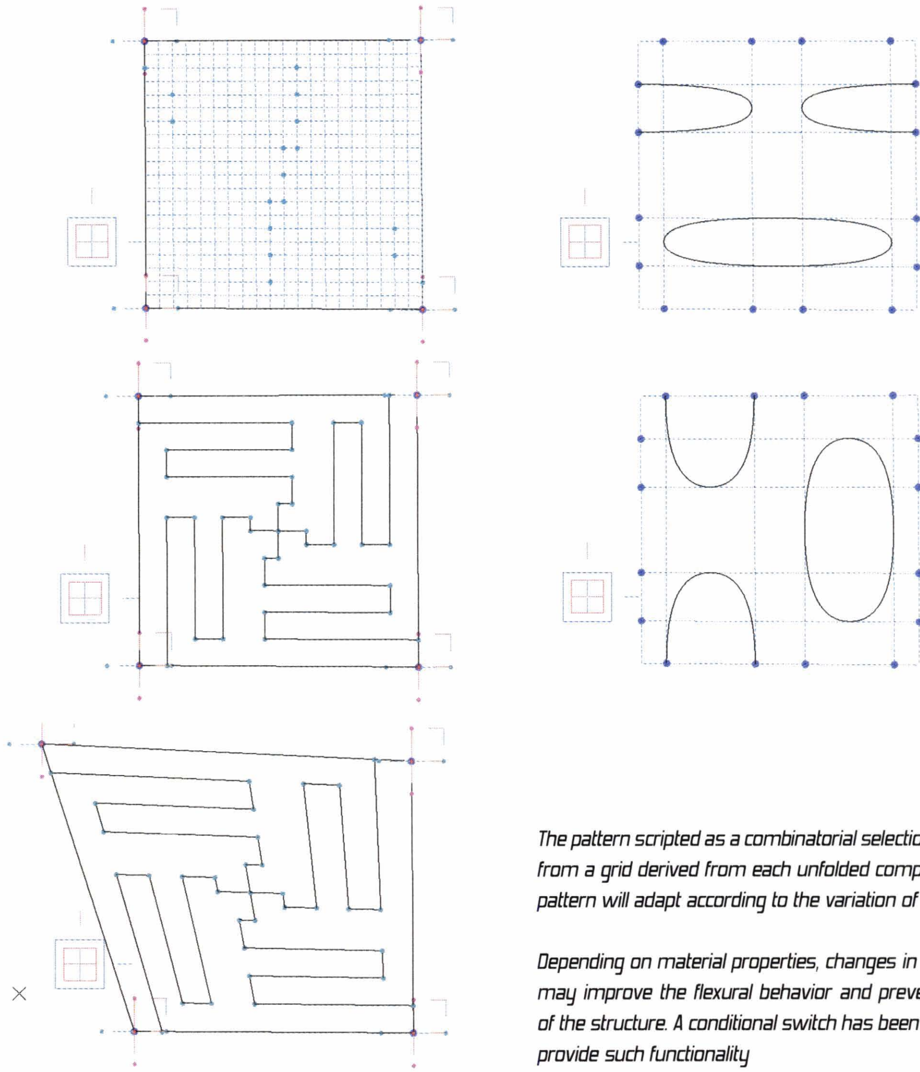
I created a flexure pattern feature, based on an array of points supported by a basic quadrangular shape. The feature is populated over a point grid placed on a spline surface. A global variable controls the number of points used to subdivide the surface, adjusting the resolution of the flexure surface. The shape grid used as vehicle for population is unfolded in a different model. After re importing it to GC, the unfolded shape array can be promoted to GC and can then be used to reconstruct a shape grid. Finally the flexure pattern feature is applied to this unfolded surface, obtaining the cut sheet which can now be exported as a regular 2D CAD drawing to be machined.



parametric adjustment of the number of subdivisions and their nesting optimization to provide a cutting sheet withou excessive material loss





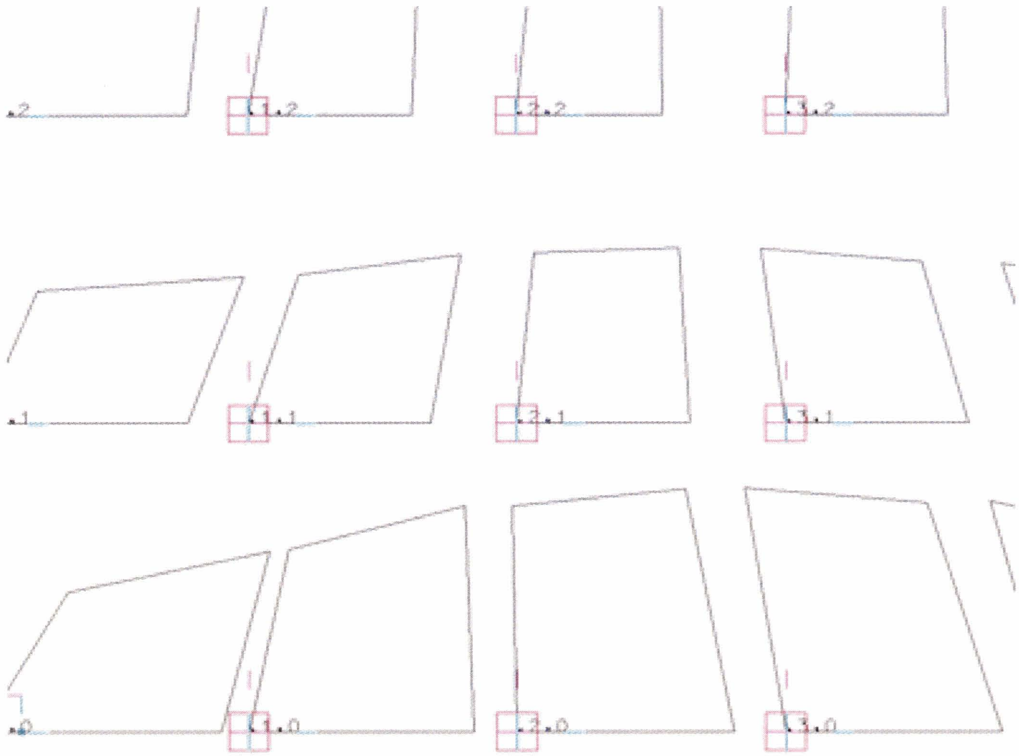


The pattern scripted as a combinatorial selection of points from a grid derived from each unfolded component. The pattern will adapt according to the variation of the shape.

Depending on material properties, changes in orientation may improve the flexural behavior and prevent rupture of the structure. A conditional switch has been scripted to provide such functionality

8. 11 PATTERNSCRIPT

The strategy explored to model these flexure pattern designs consisted of creating a parametric feature in Generative Components (GC), and populated an unrolled portion of the surface with it. The creation of the flexure pattern "feature" was based on four points, supporting a basic quadrangular shape. The feature is populated on a shape grid placed over the bspline surface. The shape is used as a vehicle to group and order sets of 4 points in order to insert the parametric feature on the surface, or in the unfolded version of it in this case. A global variable controls the number of points used to subdivide the surface, adjusting the resolution of the flexure surface. The shape grid used for population is unfolded in a different model. Finally the flexure pattern feature is applied to this unfolded surface. Global variables were exposed to be able to control the nesting of the unfolding shapes as a cutsheet, optimizing the material use and reducing the cutting time.



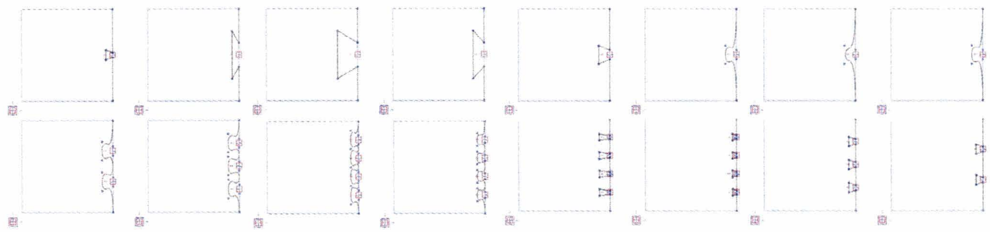
the scripted function runs through all the surface and tags each unrolled component according to its row/ column position.

8. 12 TAGGING

A common difficulty when dealing with large number of different pieces to assemble is how to match the pieces, usually requiring an assembly diagram. The script includes a tagging feature that labels each quad patch obtained and unrolled from the original surface. The tag also works as registration mark as it is located always in the lower left corner of the piece, facilitating its alignment. Furthermore the tag can also be applied to the subdivided surface, which acts itself as assembly diagram explaining where each tagged patch goes.

8. 13 SCRIPTED JOINTS

If a design is to be fabricated as parts or components to be assembled, careful consideration has to be given to the way these components will be joined. The algorithm proposed for the series of exercises conducted for this research uses a common starting join concept, which is developed and adapted according to each specific fabrication method. I started using the common dove-tail joint detail, usually used in carpentry and woodwork. I use this detail as it provides an efficient yet simple press fit joint which could be later modified to different extents as different designed assemblies would require.



Parametric variation of the scripted joint function, controlling:
-:> the number of joints placed

-->the dimensions and proportions of the joint (width, length)

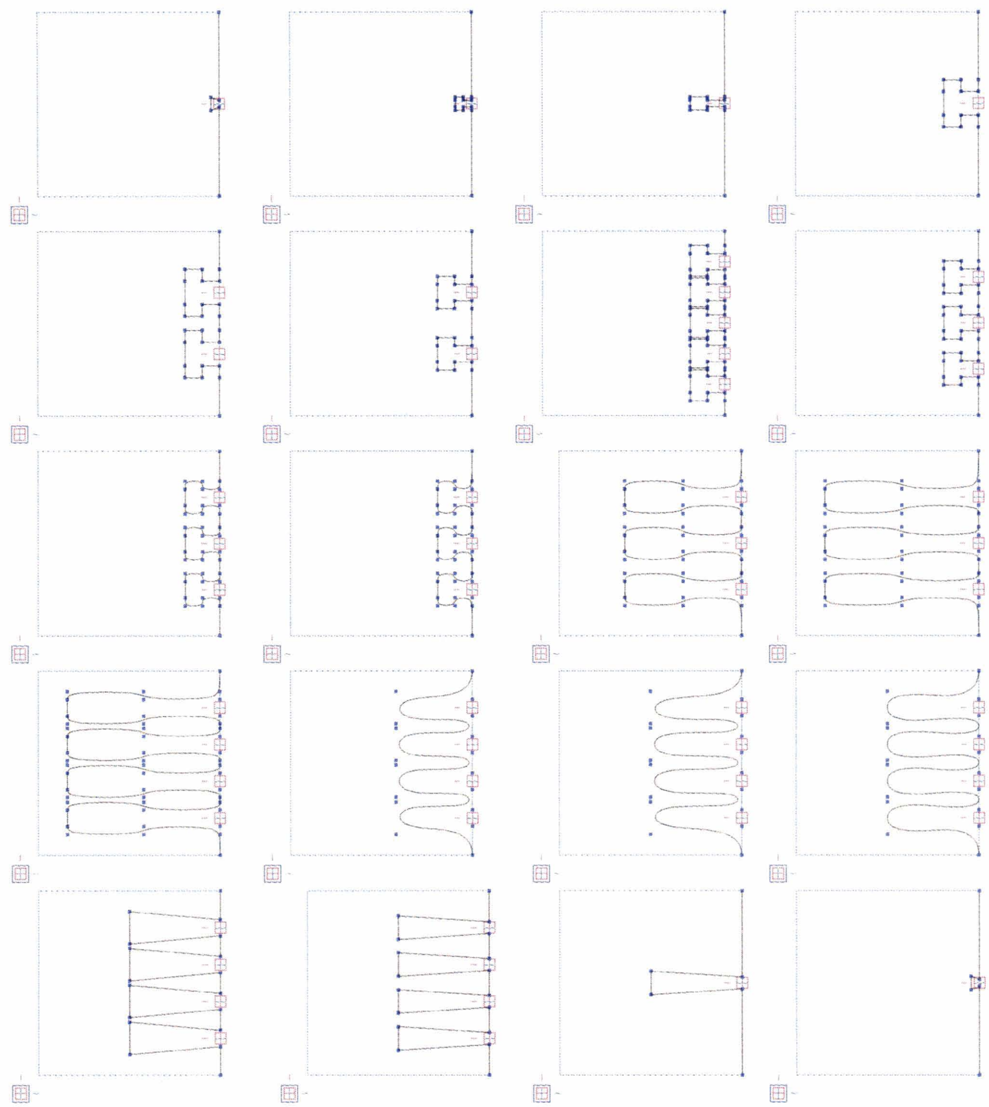
-->the type of joint used (Ithere are 16 hardcoded variations but it is allowed to enter custom patterns in case a new design is desired)

-->the level of smoothness of the joint (required to prevent rupture on the joints depending the material used)

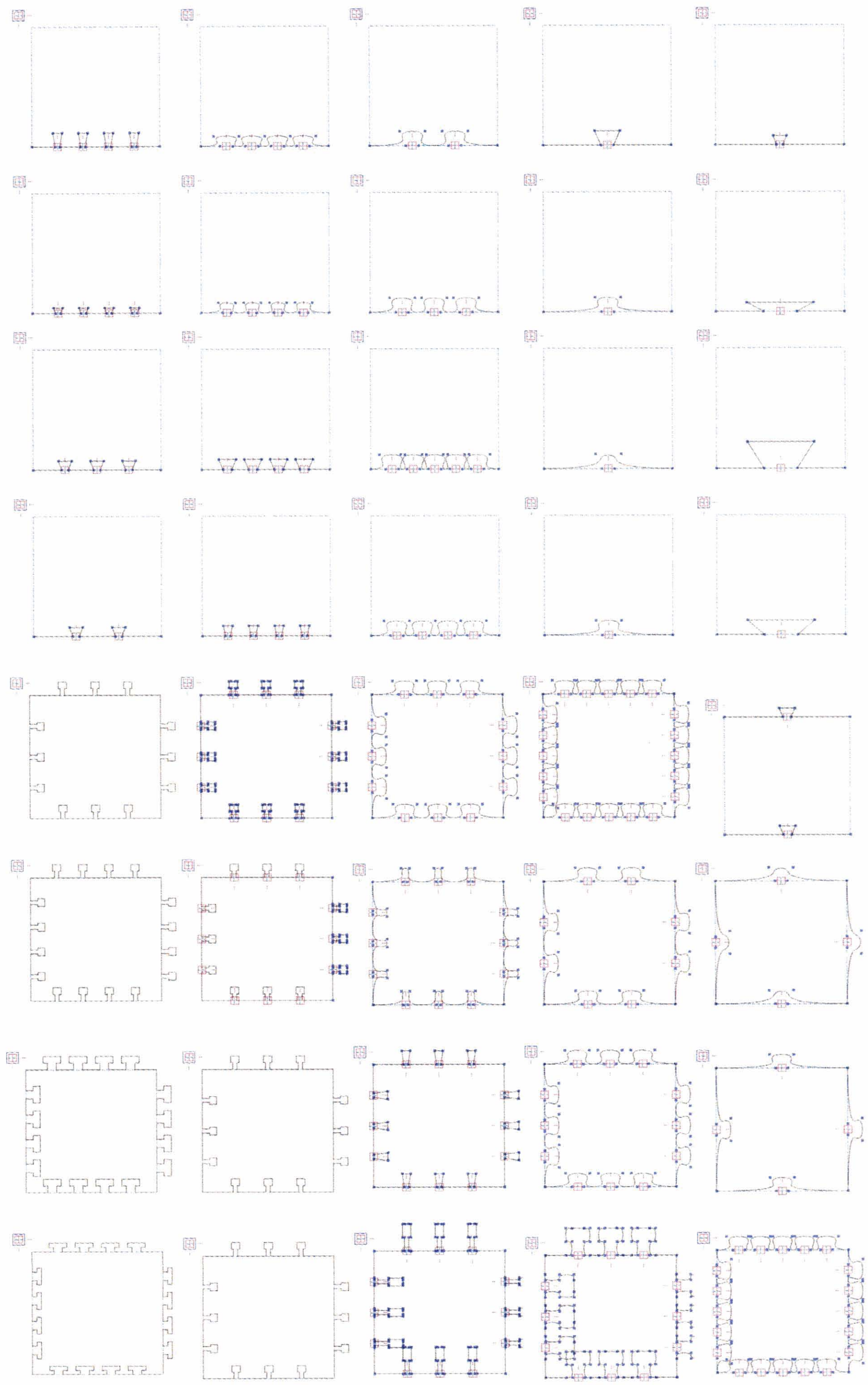
-->and the tolerance between the concave anc convex part of the joint to facilitate loos or press fit joints and adjustability to different machine processes.

The joint detail was scripted as another parametric feature in GC, which could be nested on top of the series of other features to provide a complex modular component design yet maintaining control over the individual features that control the component. The points used to drive the dovetail detail are placed using the planes defined by the triangles obtained by the subdivision function. Every dovetail tenon has a correspondent dovetail mortise. For the joint to work on different materials and with different machining processes, a tolerance value was included, reducing the tenon in size, in a ratio that can be controlled globally. Global variables were exposed to control the size and shape of these details.

Another concern was the location and frequency of these joints, therefore the parameter that controls the number of joints populated on each side of the quadrangular patch was exposed as a variable, redrawing the bspline line that defines that particular edge of the patch to take any number of tenons or mortises. This method provides a flexible solution that ranges from individual joint details for each quad patch up to a continuous joint seam.



Joint type variations using some of the 16 hardcoded types, dovetail, fingerjoint, etc.
Beyond its joint functionality, the self registering geometry also facilitates the post fabrication alignment and assembly of each piece.



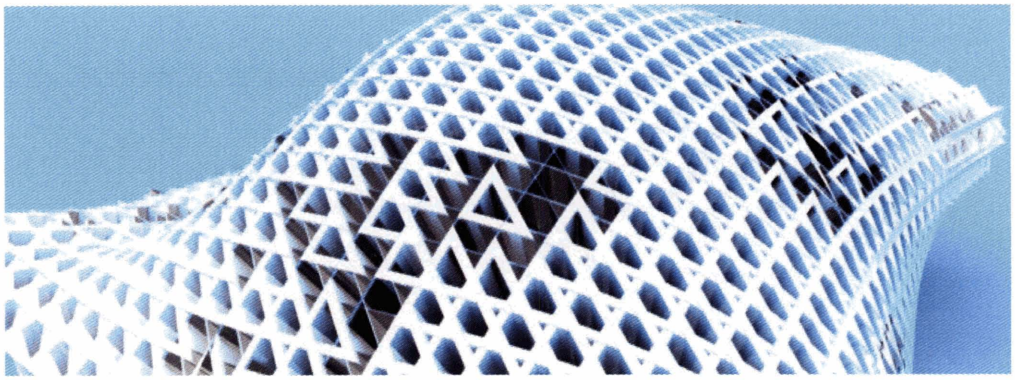
Posible variations and replication methods for the scripted joint system

8. 14 PARAMETRIC CONSTRUCTS

Removing material from a flat board weakens its structure. If this operation is performed according to the material flexibility of the panel, it is possible to obtain degrees of flexion from it, even from the most thick and rigid panels. Different patterns can be applied to cut and or remove material from flat panels to be able to flex them and obtain curved geometries. Furthermore, I will show how different patterns can be applied to obtain different performance from the original panels and therefore, different surface effects. Two different materials have been tested for this purpose, to investigate the incidence of the material properties in relation to the material removal process.

I used 2 mm plywood on a laser cutter to test different results derived from a script. The wood panels were semi rigid, allowing to be slightly bent along the longest dimension, but completely rigid (for hand applied force) in the short dimension. The cut sheets were imported directly from the dwg file where the script was executed. The speed and power of the cutting were related to the resolution of the pattern, so they had to be adjusted every time to avoid burning the wood and creating flames. Even though the script was very simple, the results obtained were very different, depending on the values of the variables that control the script. The wood acquired the desired material elasticity in order to bend not just in one direction, but in both, obtaining double curved structures, from original, semi rigid panels. When the deformation force was ceased, the panels return to its flat state.

A second test was performed on an Omax Water Jet machine, to cut flexure patterns on 4 mm aluminum. This panel was absolutely rigid in both dimensions. Several test using different patterns were conducted to study the results of varying lengths and thicknesses, comparing removed material percentages and elasticity acquired. A more complex but still regular 2D pattern was applied. The result is that material elasticity was achieved, although the ranges of plastic deformation were several times smaller, given the material properties. Nevertheless, the aluminum panel became ductile enough in order to be shaped by hand into a double curved structure. The flexure pattern applied, gave enough elasticity to the material to allow plastic and non plastic deformation. When the plastic threshold is overcome, the structure does not go back to its original state.



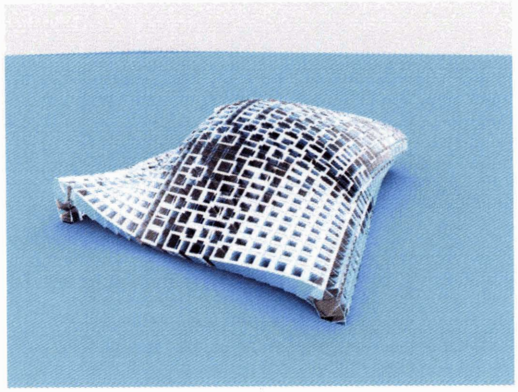
Initial exploration in extending these scripting procedures towards the fabrication of threedimensional interlocking blocks

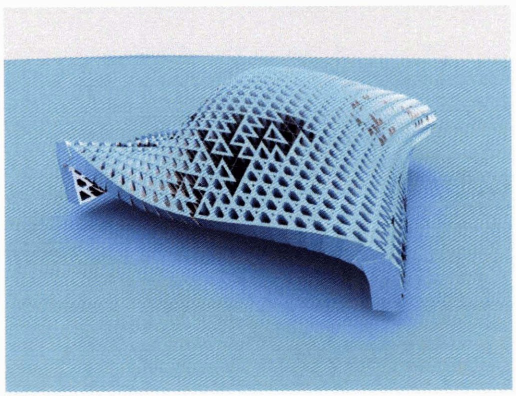
8. 15 MACHINING

The actual fabrication of the components required adjustments according to the machines and the materials utilized. These adjustments were granted by the variables scripted in order to control the tolerance of the joints and the nesting of the shapes in the cutsheet. The tolerances for the laser cutter had to be bigger than the other machines like the waterjet, where given the toolpath it is possible to specify the side of the cut, requiring only small adjustments in the tolerances to obtain press fit precision. The ratio between the speed of the machining and the cutting power was used to provide a smoother or rougher finish, which can also be used to increase the friction between components ensuring a better assembly. It was hard to calibrate the tolerance when pieces to be matched were processed in different machines. In general the strategy that proved to work best was to provide at least on one of the pieces, a rough edge in order to help the press fit assembly.

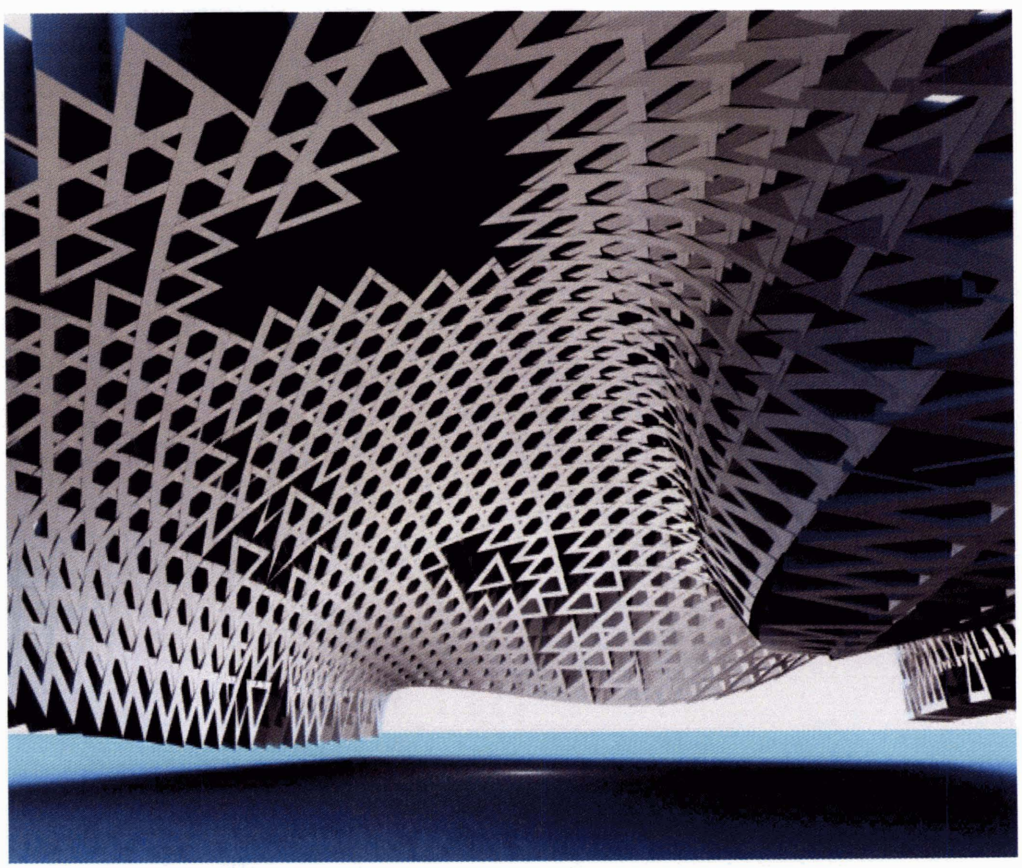
8. 16 PRINTINGBRICKS

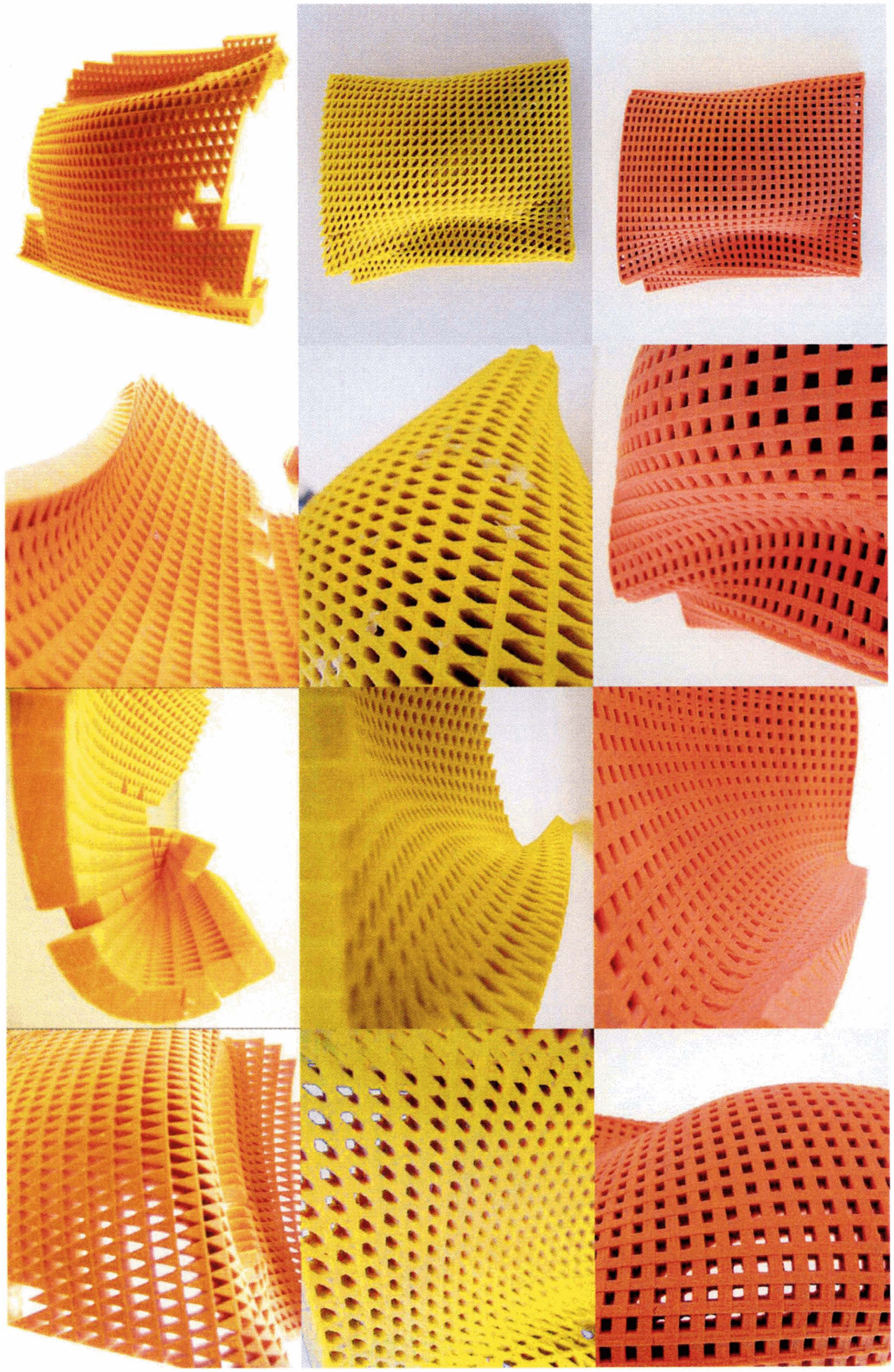
Even though the purpose of this paper was to explore fabrication on flat panel, I detoured from the original line studying other fabrication methods that could be implemented from the development of the scripted routine. I wrote a function to create solid extruded modules using the pointgrid obtained from the previous script. Global Variables were defined to control the height of the extrusion. More functions included in the final script were developed to provide a hollow module, and control on the number of sides that the module would have, I tested pyramidal and cubic modules. This result was fabricated using 3D printing process on a ZCorp machine. This line of research has the potential to develop as a separate study, developing complex structures using a non standard modularity approach.





Initial explorations towards the design and fabrication of threedimensional interlocking blocks





ZCorp models of first explorations on block surface designs

8. 17 CONCLUSIONS

The research described in this project is still in progress, but the results obtained so far are interesting and promising.

The script files developed prove that the geometrical logics of parametric design environments can be used to drive fabrication models.

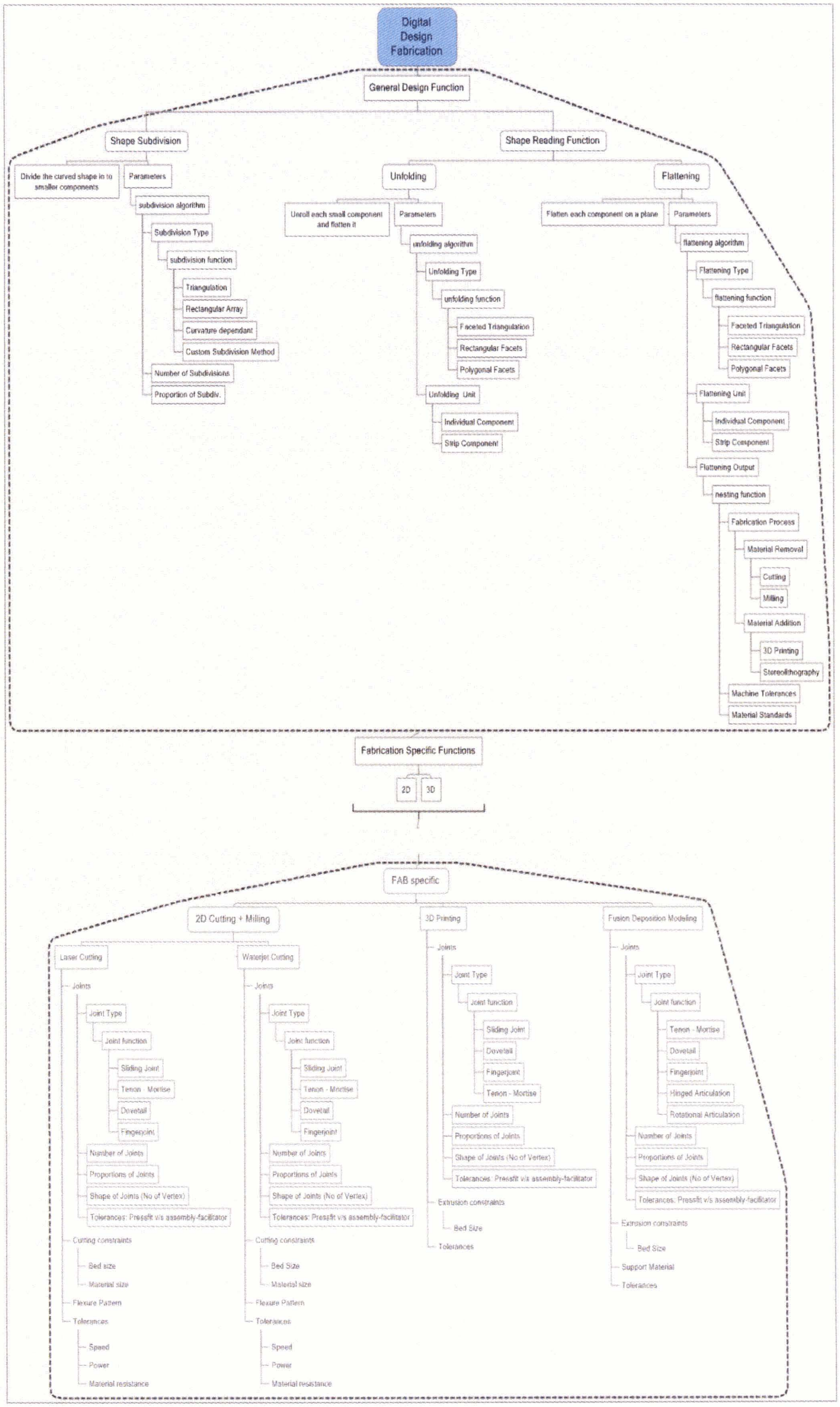
The tests performed for this research were at model scale, and further testing is required at real scale with real materials. Nevertheless the results obtained from the model tests, prove that this techniques could be performed using standard materials. The Water Jet test in aluminum shows that it is even possible to obtain complex curved structures form rigid materials, through these techniques.

Comparing the results from scripting to previous tests achieved by modeling, the performance of the script is several times better. Scripting in GC combines the speed and performance of programming and the adaptability and flexibility of parametric design

Finally it is promising to note that large structures could be develop by this way, reducing the number of pieces required to be assembled, providing a range of deformation to adjust in place the continuity of the curvature between assembled pieces. They could be eventually, while performing with plastic deformation, be unstressed and laid out flat again for transportation advantages.

8. 18 FURTHER RESEARCH

The results shown in this results are preliminary and further research should be done to accomplish more precise and universal results. In depth exploration using parametric components should be performed to demonstrate further functionality of decomposing complex features into cut sheets for fabrication. This opens a wide spectrum of possibilities for architectural design and building technologies, providing a technique to streamline the production of complex components.


Digital Design Fabrication
General Design Function
Shape Subdivision
Shape Reading Function
Divide the curved shape in to smaller components
Parameters
subdivision algorithm
Subdivision Type
subdivision function
Triangulation
Rectangular Array
Curvature dependant
Custom Subdivision Method
Number of Subdivisions
Proportion of Subdiv.
Unfolding
Unroll each small component and flatten it
Parameters
unfolding algorithm
Unfolding Type
unfolding function
Faceted Triangulation
Rectangular Facets
Polygonal Facets
Unfolding Unit
Individual Component
Strip Component
Flattening
Flatten each component on a plane
Parameters
flattening algorithm
Flattening Type
flattening function
Faceted Triangulation
Rectangular Facets
Polygonal Facets
Flattening Unit
Individual Component
Strip Component
Flattening Output
nesting function
Fabrication Process
Material Removal
Cutting
Milling
Material Addition
3D Printing
Stereolithography
Machine Tolerances
Material Standards
Fabrication Specific Functions
2D
3D
FAB specific
2D Cutting + Milling
3D Printing
Fusion Deposition Modeling
Laser Cutting
Joints
Joint Type
Joint function
Sliding Joint
Tenon - Mortise
Dovetail
Fingerjoint
Number of Joints
Proportions of Joints
Shape of Joints (No of Vertex)
Tolerances: Pressfit v/s assembly-facilitator
Cutting constraints
Bed size
Material size
Flexure Pattern
Tolerances
Speed
Power
Material resistance
Waterjet Cutting
Joints
Joint Type
Joint function
Sliding Joint
Tenon - Mortise
Dovetail
Fingerjoint
Number of Joints
Proportions of Joints
Shape of Joints (No of Vertex)
Tolerances: Pressfit v/s assembly-facilitator
Cutting constraints
Bed Size
Material size
Flexure Pattern
Tolerances
Speed
Power
Material resistance
Joints
Joint Type
Joint function
Sliding Joint
Dovetail
Fingerjoint
Tenon - Mortise
Number of Joints
Proportions of Joints
Shape of Joints (No of Vertex)
Tolerances: Pressfit v/s assembly-facilitator
Extrusion constraints
Bed Size
Tolerances
Joints
Joint Type
Joint function
Tenon - Mortise
Dovetail
Fingerjoint
Hinged Articulation
Rotational Articulation
Number of Joints
Proportions of Joints
Shape of Joints (No of Vertex)
Tolerances: Pressfit v/s assembly-facilitator
Extrusion constraints
Bed Size
Support Material
Tolerances

9 THESIS CONCLUSIONS AND CONTRIBUTIONS

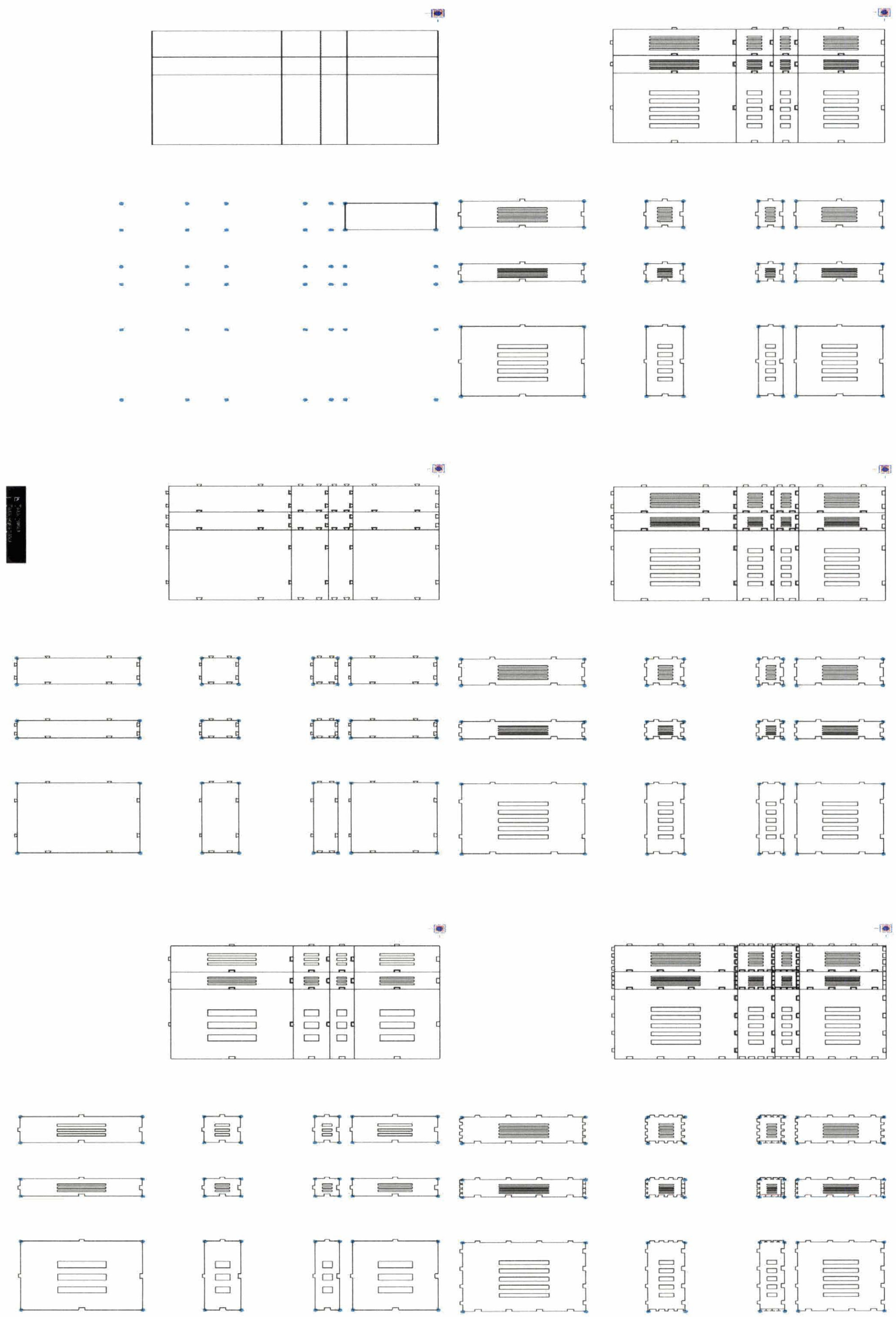
MULTISCALING The gradual process of fomalization and definition of the design process implies also a gradual shift of scale, from an overall scale of design to that of accurate detailing. Incorporating fabrication logics into the early stages of design allows to think of that design in different scale levels and different levels of accuracy simultaneously.

PART AND WHOLE. Together with bringing multiscaling, these proposed methods allow thinking and conceiving design simultaneously envisioning the overall project form and the embedded components and parts that conform such design. This multilevel conception is intuitively addressed by the designer, but has not been incorporated by CAD technologies beyond the use of identical cloning of blocks or standard parts.

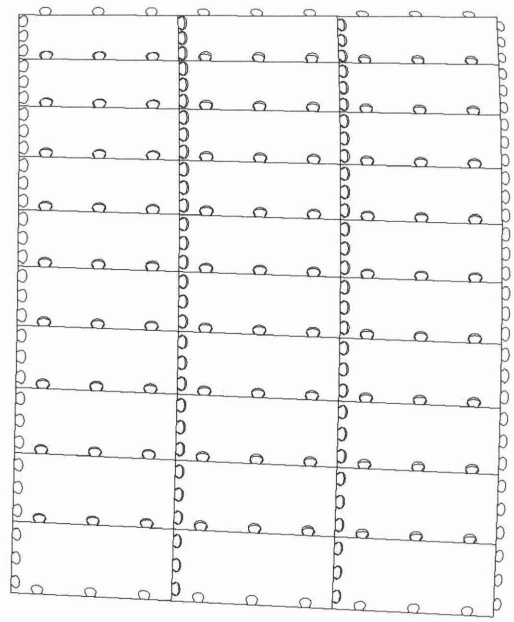
DESIGN COMPUTING. The integration of both design techniques and computing programming enable several levels of imbrication towards designing appropriate techniques and tools for design purposes. Each approach has its own strengths and limitations and the crucial relevance of their implementation in an ensemble is to target specific functionalities towards the achievement of specific design objectives, beyond the actual tool implementation.

REDISCOVER TRADITION. I believe that this research proves that traditional methods and techniques can be very valuable to advanced digital modes of work. It is imperative to learn how traditional methods operate and what are there contributions and shortcomings to be able to extend and even enhance some of these procedures by actualizing them using new tools, or even serving as a base to implement new innovative methods of work, both in terms of design and fabrication.

NESTING PARAMETRICS. One of the contributions of this thesis is the technique by which nesting parametric features may allow to build complex structures and behaviors with robust and simple control over each level of nesting. This technique also allows the reverse approach, explained in the last part of this research, which is the extraction of particular level of components. This enable a parallel design opportunity visualizing both the assembled or disassembled version of the component, or merely storing the local geometrical data, required to rebuild the spatial conditions for such instance to occur, allowing for flexible exchangeability of parts and components.



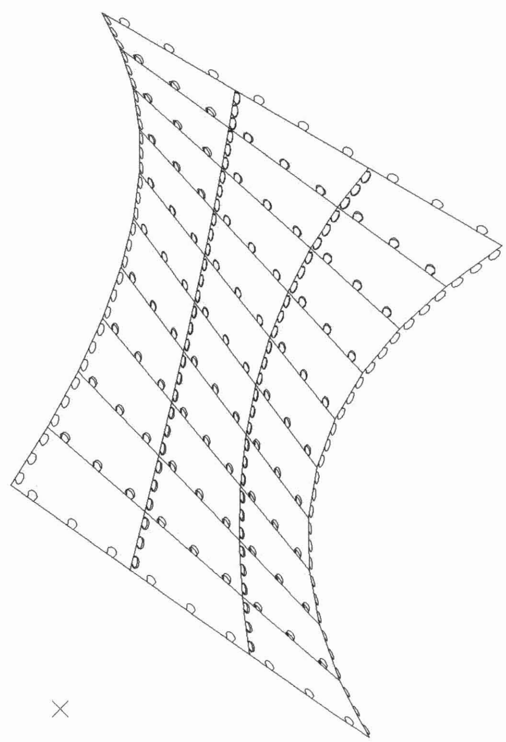
component reading and extraction, pattern embedding and joint variations

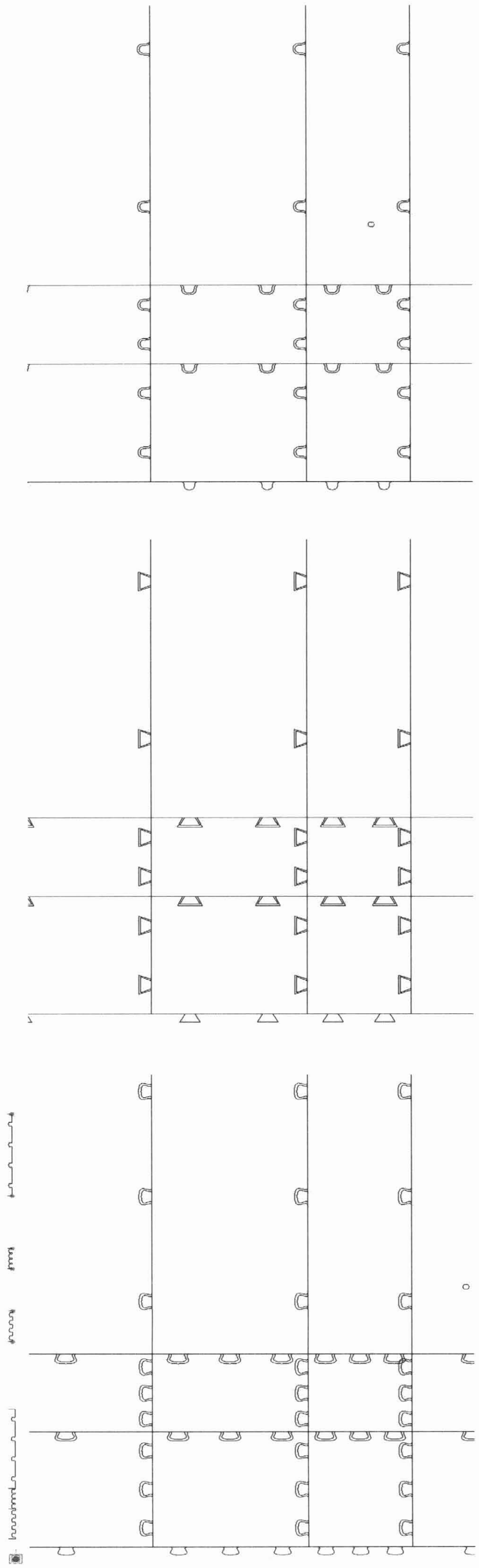


After completing the projects I started a new iteration appying the CCCS scripts on the previous projects to test their appliaction and performance. The examples shown below describe how these scripts have been nested onto Ichtyomorph design, allowing not only to extract the components but to further decompose each sub structure into levels of detailing.

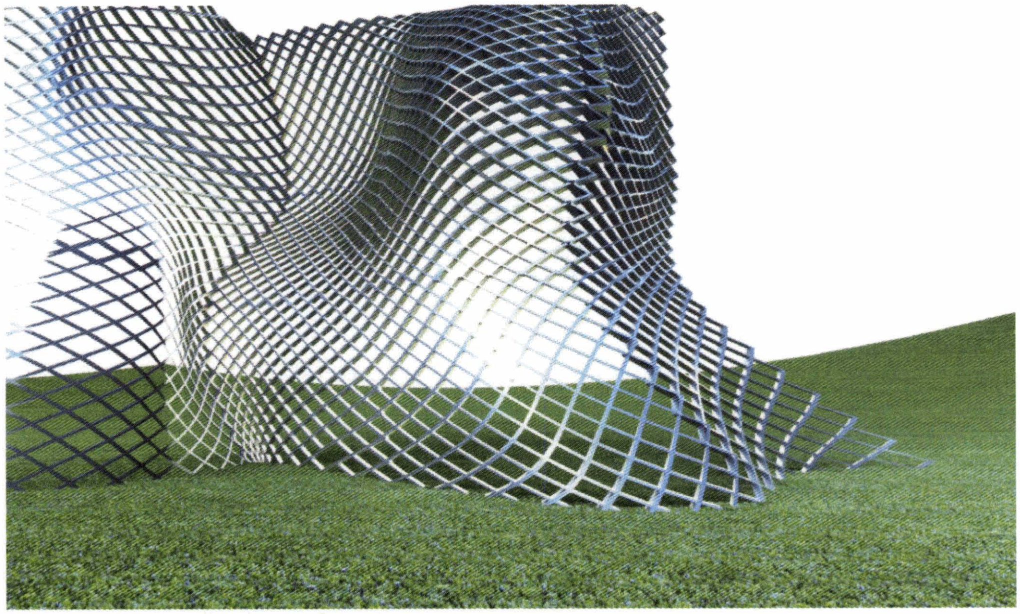
This presents a valuable oportunity for understaning and conceiving a design both bottom up and reverse way. This also allows tho design and conceive the design in multiple scales

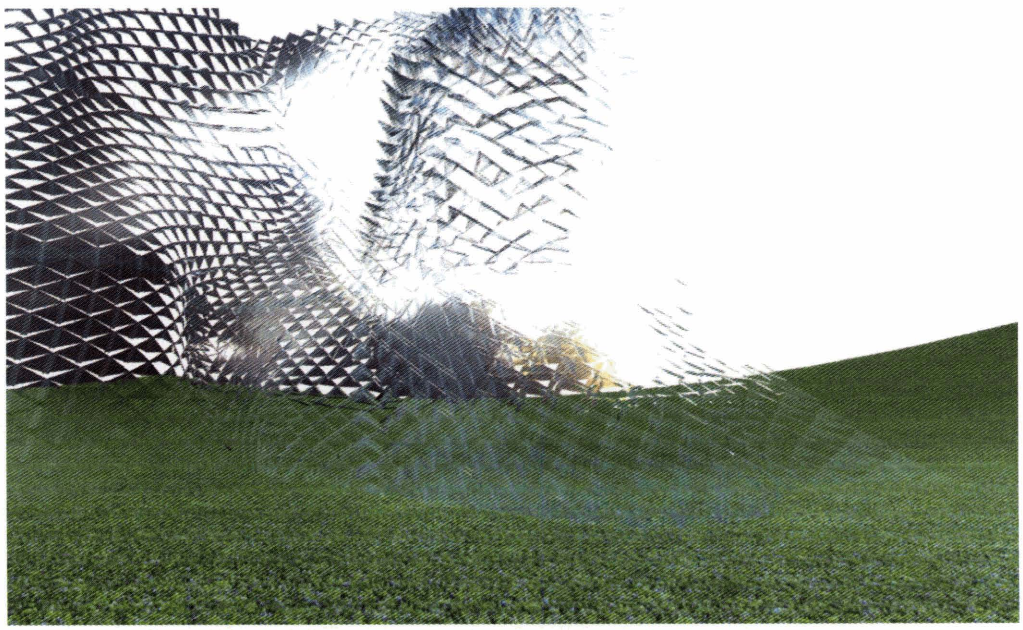
JOn the right is the Joint system with adjustable tolerance evaluated on the surface before extracting the components

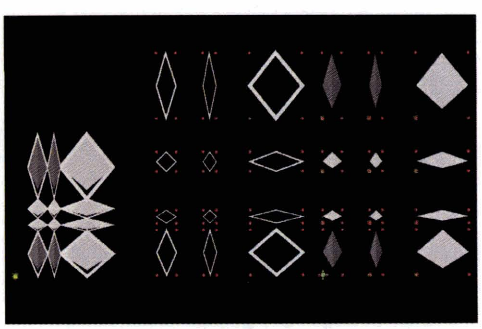




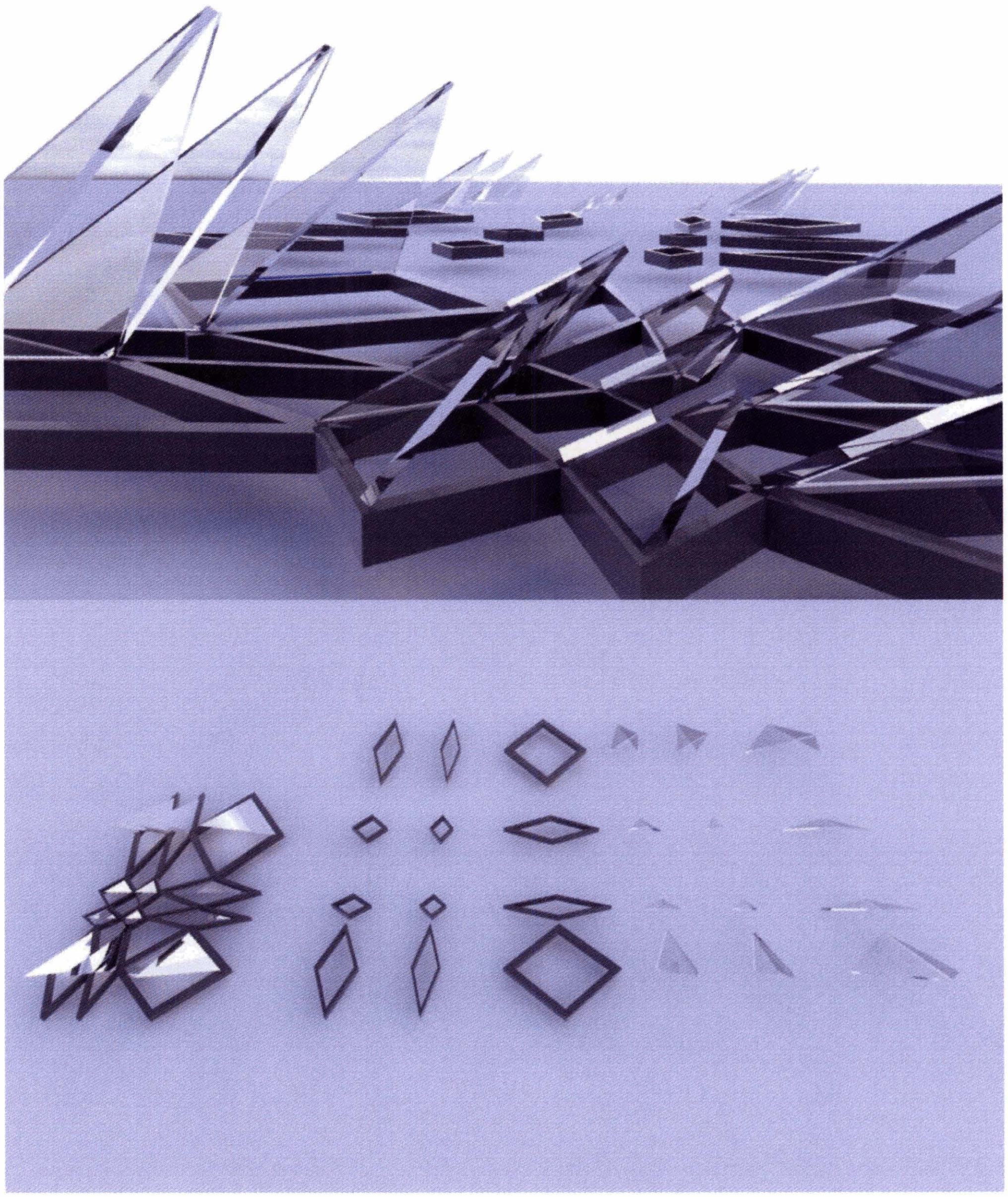
Parametric variations of the joints with adjustable tolerance between mortises and tenons for press fitted or loose joints







Reworked ICHTYOMORPH surface for re iteration using CCCS scripts.



A first re iteration using the CCCS scripts with the ICHTYOMORPH project components. The extraction function can be applied independantly of the unrolling function allowing for simple nested extraction of sub-components, in this case extracting a set of shapes from the curved facade, then extracting the structural frame and later extracting the glass panels. Thiese could then be unrolled or unfolded independantly, using the function that reads the triangles and aligns them on a plane. This nesting procedure could be a powerful technique to manage complex assemblies simultaneously at multiple scales and levels of detail

10 PROJECTIONS OF THIS THESIS

RE ITERATE THROUGH DESIGNS AND EVALUATE

Further experimentation and evaluation of the scripts and parametric function developed should be performed iterating on the same research projects to compare

EXTEND RESEARCH TO FULL SCALE

Necessary experimentation and evaluation using larger CNC machinery and real scale mock-ups should be performed to evaluate the scalability of these procedures to be fully applicable to architectural design fabrication.

EXTEND DESIGN ALGORITHM TO ADDITIVE FABRICATION SYSTEMS

Although the initial results are promising, further investigation should be performed in order to extend the funtionalities of this work towards the design and fabrication of real scale interlocking block systems for an innovative custom parametric masonry system

EVALUATE MATERIAL BEHAVIOR AT FULL SCALE

Deeper and more exhaustive research and evaluation regarding real scale material behavior should be conducted. Specially regarding composite material which can not be scaled down to prototype size

EXTEND RESEARCH TOWARDS RESPONSIVE SYSTEMS

One of my biggest and deepest interest is towards designing and building complex smart responsive systems. These work has partially entered into that field but there is much more to learn and try. In many ways these work is trying to build a base and a foundation for deeper adventures into this type of work.

12 BIBLIOGRAPHY

Banham, R. (1967). Theory and Design in the First Machine Age. 2nd ed., Praeger, New York.

Mitchell, W. J. (1975). "Vitruvius Computatus," in Models and Systems in Architecture and Building, D. Hawkes, (ed.), The Construction Press, Hornby, Lancaster, pp. 53-59

William J. Mitchell (2001)."Vitruvius Redux" in Formal Engineering Design Synthesis, ed. Erik K, Antonsson and Jonathan Cagan. Cambridge /university Press, USA, pp 1-19

Stiny, George (2001)."How to Calculate with Shapes" in Formal Engineering Design Synthesis, ed. Erik K, Antonsson and Jonathan Cagan. Cambridge /university Press, USA, pp 20-64

Loukissas, Yanni (2003). Rulebuilding, Exploring Design Worlds through En-User Programming, SMArchS thesis, Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA.

Shelden, D. R. (2002). Digital Surface Representation and the Constructibility of Gehrys's Architecture. PhD thesis, Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA.

Killian, A. (2003). Fabrication of Partially Double-curved Surfaces out of Flat Sheet Material using a 3d Puzzle Approach. PhD candidate, Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA.

Loukissas, Yanni (2004). A Generative Approach to Modelling Architectural Designs Using a 3D Printer. PhD candidate, Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA.

Rafael Sacks, Charles M. Eastman and Ghang Lee, (2005) "Parametric 3D Modeling in building construction with examples from precast concrete", Automation in Construction, Volume 14, Issue 2, pp 233-240

Merleau-Ponty, Maurice (1975). "Fenomenologia de la percepcion": Editions 62 SA, Barcelona, Spain.

Howell, Larry L (2001). "Compliant Mechanisms": John Willey & Sons, New York, US.

Sass, Lawrence (2003), "Rapid Protoyping Techniques for Building Program Study", CAADRIA Conference.

Banham, R. (1967). Theory and Design in the First Machine Age. 2nd ed., Praeger, New York.

13 IMAGE SOURCES

Figure 1 "Sketchpad: A man-machine graphical communication system" http://www.guidebookgallery.org/articles/sketchpadamanmachinegraphicalcommunicationsystem

Figure 2 "dactylfractal" http://zapatopi.net/

Figure 3 mages on this page by V. Ryan © 2002-2005 http://www.technologystudent.com/index.htm; Keith S. Rucker website; http://pages.friendlycity.net/□krucker/index.htm; Frank Campbell website http://www.sawdustmaking.com/index.htm General%20Information; V. Ryan website http://www.technologystudent.com/

Figure 4 Patterns presented here as example, Isoloc Patterns, are produced by Leigh Industries Ltd. http://www.leighjigs.com/about.php

Figure 5 Images extracted from http://www.new-technologies.org/ECT/Civil/psk.htm

Figure 6 Images extracted from http://www.terraforce.com/

Figure 7 Images from this page extracted from http://www.ottobock.com (robotic prosthetic leg); http://en.wikipedia.org/wiki/Category:Mechanisms (articulated joints schemes); http://www.zoho.

nl/zoho2.html (articulated sculpture robot); www.centres.com/nuclear/manip/models/modh.htm (articulated robotic arm); http://www.hephaist.co.jp/e/index.html (rotational joints)

Figure 8 http://www.ulsinc.com/english/laser_systems/laser_systems.html

Figure 9 Image extracted from http://www.omax.com/machines_model_2652.php

Figure 10 Image extracted from http://www.zcorp.com

Figure 11 Image extracted from http://www.stratasys.com/sys_main.html

Figure 12 Image extracted from http://www.3dsystems.com/products/sls/sinterstation_hiq/index.asp

Figure 13 Images on this page extracted from http://www.isi.edu/CRAFT/CC/modem.html

Figure 14 image extracted from http://www.solidica.com/

Figure 15 image extracted from http://www.solidica.com/

Figure 16 image extracted from blog website http://blabla.blog.lemonde.fr/photos/uncategorized/christophet2005_104.jpg

Figure 17 Image extracted from http://www.0111.com/lud/pages/architecture/archgallery/foa_yokohama/pages/foa-yokohama_01.htm

Figure 18 Images in this page extracted from http://www.unrealaircraft.com/classics/pages/T167393.php and http://www.airchive.com/airline%20pics/Airbus/thumbnails/A320%20FUSELAGES.jpg