Exploring Layered Freeforming in a Design and Architectural Context

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by

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Abstract

By Thomas Modeen

The work considered and presented in this thesis was catalysed by the potentials of the additive fabrication processes, usually referred to as Rapid Manufacturing. These fabrication methods connect its theoretical assumptions to its designs.

The thesis was developed around a number of designs which were progressed in conjunction with its evolving theoretical components, the latter which entailed the formation of a bespoke taxonomy and accompanying bespoke terminology to describe the various distinct features and processes involved. The thesis questions the current detrimental schism dividing the act of computing based designing from the act of making something physical, and makes a case for a more inherent role for the material, sensory and tacit properties in the process of designing something through Rapid Manufacturing. The focus of some of these designs were developed around the physical domains of full-scale, additive builds, where innate sensory and tactile qualities were explored. The resulting designs provide a link between computing based conception and a sensorial and haptically perceived components.

The main contribution of the thesis is the novel use of the additive fabrication technologies in a manner which is intrinsic to the fabrication methods and exploits process characteristics, and would be very difficult if made by alternate means. These explorations take the form of both the use of actual material qualities and patterns particular to these technologies.

The resulting factors formalize design grammars that aim to provide the foundations for furthering additive fabrication methods from conception to making in a design and architectural context.

Submitted test components:

- Snakeskin Haptic Interface
- Sense Sticks (Snakeskin tests)
- Finger Run

Key words:

Layered Freeforming, Rapid Manufacturing, Buildware, Rapid Prototyping, Haptic, Tactile, Senses, Architecture, Design

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Last but not least I would like to dedicate this dissertation to my family, my parents Peter and Riitta Modeen, my parents-in-law Ali and Kasmia Al-Mumin, and my wife and daughters, Maysaa Al-Mumin and Andia and Amalie Modeen, who are my 'there-theres'.

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Glossary of Terms

Below is a summary of some of the more uncommon words used in the thesis. Some of them are explained in more detail in the thesis, however, as a quick reference, an abbreviated rendition is provided below. The words marked with a '*' are unique to the thesis and cannot be found, or aren't used in a similar fashion, in any existing source material. All the existing words are based on the descriptions found at 'dictionary.com', which sources its material from a number of established sources such as Encyclopaedia Britannica, Random House Unabridged dictionary or the Oxford English Dictionary. Any alternate sources are listed within brackets at the end of the reference.

A

Additive Fabrication (AF) — Refers to the additive CAD-CAM processes themselves. Can be applied to RP, RM and LF.

Aggregate — Formed by the conjunction or collection of particulars into a whole mass or sum; total; combined.

Ambulatory — Of, pertaining to, or capable of walking.

*Avaterial** — Stands for 'Avatar-Material'. It describes a material condition unique to particularly additive CAD-CAM production where the properties of a material are equally determined by both the virtual and analog realms of conception. It is usually used in conjunction with roughly object size artefacts.

B

*Buildware** — Is an alternate term for the CAD-CAM technologies, and sets their value and use on equal footing with Hardware and software.

C

CAD — Stands for 'Computer Aided Design'.

CAM — Stands for 'Computer Aided Manufacturing'.

Claytools — Is the software that accompanies the SensAble device.

*Clicks** — Are elements of the *Snakeskin* design. They provide a constant, metric and generic, pattern along the *Snakeskin's* path.

Cutaneous — Of, pertaining to, or affecting the skin.

E

Epidermis — The outer, nonvascular, nonsensitive layer of the skin, covering the true skin or corium.

Exteroception — Sensitivity to stimuli originating outside of the body.

F

*Finger Run** — Is a design, a tactile folly, conceived through the use of a SensAble device.

*Fire Spine** — Is a component of the *Snakeskin* design. Its sole purpose is to provide a friction based guide (to follow the direction of least friction) for directing its user to the closest fire exit.

Freeform Construction (FC) Is a term used to describe the use of the additive fabrication methods to make architecture and larger sized things. A term introduced my Dr. Rupert Soar.

*Freeform Fabrication (FF)** Is a term used to describe the use of the additive fabrication methods to make things that are sizeable, large objects, but smaller than architecture.

H

Halbzeug Semi-finished product, semi-finished part. [www.babylon.com]

*Handscape** Is a key element in the *Snakeskin* design, consistent of a directional friction surface that amplifies the *Tactile Spine's* more literal tactile messages. Its means of communication are thus more subtle and intuitive in their format.

Haptic Of or relating to the sense of touch; tactile.

I

*Intro Info** Forms the beginning of a *Snakeskin* stretch. It provides a synopsis of features along the path of this particular stretch of the design.

L

*Layered Freeforming (LF)**: Is a particular conceptual interpretation of Rapid Manufacturing where such means are not only used to make final completed designs, but the particular idiosyncrasies of the related technologies are included as defining features in any designs produced.

*LF-Model**: A model using the AF/ RM means of conception as defining criteria in t he making and definition of a taxonomy for LF.

M

*Magent**: Stands for 'Material-Agent'. It is a programmable agent which behaviour is based on particular material properties.

Manuductory: The act of directing or guiding, as if by hand.

*Materix**: Is a portmanteau of the term 'Material-Matrix'. It relates to the micro scale material arrangements and patterns possible through a select number of Rapid Manufacturing technologies which allow one to control and manipulate the properties of a design's meso and macro scale use.

*Maxel**: Is a 'material voxel', - defining the resolution of a rapid manufactured build. The size of a maxel is dependent on which fabrication technique is used, and/ or at what resolution a build needs to be.

*(Meta) Block**: Is the follow up, one step bigger or more complex, increment from the *(Meta) Brick* in the *Metature* taxonomy.

*(Meta) Boulder** Is the follow up, one step larger or more complex, increment from the *(Meta) Block* in the *Metature* taxonomy.

*(Meta) Brick** Is the initial, smallest, increment of the *Metature* taxonomy.

*Metature** Stands for 'Meta-Architecture', and is similar to *Avaterial* in its application, only here in reference to designs of an architectural scale.

*(Meta) Rock** Is the follow up, the largest and most complex (and the last sub-categorization before the 'total' architectural design), in the *Metature* taxonomy.

*Mether** Is a portmanteau of the words 'Material' and 'Ether', and is the term general term used when referring to either *Avaterial* or *Metature.*

N

Neology A newly invented word or phrase.

*Nunod** Stands for 'Nucleus Node', and is the initial and simplest composition of a set of *maxels* in the *Avaterial* classifications.

P

Phantom A particular type of haptic interface device by SensAble.

Portmanteau A new word formed by joining two others and combining their meanings.

*Proc**	Is a term combining the words 'Property' and 'Cluster'. It describes a composition of elements made up of *Nunods* in the *Avaterial* taxonomy.

Q

*Quivers**	Are feature elements in the *Snakeskin* design. The provide bespoke tactile patterns and demarcate a particular area or space according to use or classification.

R

Rapid Manufacturing (RM)	Uses the additive CAD-CAM processes to make the final completed design.
Rapid Prototyping (RP)	Uses the additive CAD-CAM processes to make a representation or a prototype of a future product.

S

SensAble Device	Is a commercially available haptic interface that allows one to manipulate virtual elements on a computer screen through touch.
*Snakeskin**	Is a design that informs its user about his or her approaching environment through the sense of touch.
Somatic	Of, relating to, or affecting the body.

Somatosensory System	Of or pertaining to sensations that involve parts of the body not associated with the primary sense organs.
Stereognostic Sense	The ability to determine the shape and weight of an object by touching or lifting it.
Syncretic	The attempted reconciliation or union of different or opposing principles, practices, or parties.

T

*Tactile Coax**	Is a type of *Tactile Icon* which 'coaxes' or encourages its user to follow a particular type of action.
*Tactile Icons**	Are component of the *Snakeskin* design. They are a limited set of icons, perceived through touch, used to communicate various key nodes or prompts for actions along the path of the *Snakeskin* strip.
*Tactile Node**	Is a type of *Tactile Icon* which informs about a particular approaching feature along the path of the *Snakeskin.*
*Tactile Spine**	Is the lead means of tactile communication in the Snakeskin design. It occupies the centre of the design and uses a set of *Tactile Icons* to relay its message.
*Tactile Tail**	Is an end or final element of a stretch of *Snakeskin.* It informs the user that end of a *Snakeskin* strip has been reached.

*Tactile Tides**	Describe the level undulations of the *Handscape*. Divided into ripples, waves and swells.
*Trac**	Is a portmanteau of the term 'Trait-constellation'. It is the largest and most complex (and the last sub-categorization before the 'total' artefact/ object), in the Avaterial taxonomy.

V

*Voigent**	A programmable void (a 'Void-Agent'). The opposite of a *Magent*. A term suggested by Mr. Christian Derix.

1.0 Introduction

The introduction describes the background and rationale to the research as well as its aim and objectives. It also provides an overview of the research methodology and the research work presented, and establishes the originality and achievements of the research. Finally, a guide to the thesis is presented, which includes descriptions of chapters' contents.

1.1 Background and Rationale of the Research

Rapid Manufacturing (RM) as a practice is in its ascendancy (Wohlers, 2007) gaining ground as an effective way to realize bespoke designs (Leftieri, 2007), and is, in comparison to Rapid Prototyping (RP), with the advancement of the technologies and materials related to Additive Fabrication (AF), expected to gain a more substantial position in the future (Wohlers, 2007). The use of RM in the production of design and architecture, however, is currently at most nominal, occupying the fringes of practice and academia (Thompson, 2007; Leftieri, 2007; Hara, 2007; Wohlers, 2007).

The research argues that the RM technologies, by being inherently linked to both the digital (CAD) and the physical (CAM) aspects of fabrication, provide a natural means to resolve the rupture currently dividing the way we conceive computing based designs from the way we construct them (Park, 2008), that has come about due to the present pervasiveness of computing (McCullough, 1998, 2001), and the inevitable ocular bias such means lead to (Pallasmaa, 2005), in the conception of design and architecture (Sennett, 2008). It contends that by allowing for a more inclusive sensory paradigm to 'enter the picture', when conceiving designs through RM, a more complete and congenial take on design, regardless of scale, can be achieved.

The thesis used the technologies affiliated with Rapid Manufacturing as defining components in the conception of its designs. Such aims were explored through the execution of a number of case-study designs which were conceived by utilizing particular qualities of the technologies which are unique to RM, and would be difficult or senseless to be made by alternate fabrication methods. This process, which acted as an inherent reflection of the fabrication means, was referred to as Layered Freeforming (LF). It was within this framework the case-studies are formulated, fabricated and appraised.

1.2 The Aim and Objectives of the Research

The aim of the research was to use additive fabrication methods as a defining components in the conception of its designs, and to conceive such designs by applying a design approach which considers both the computing based as well as fabrication and material centred factors in their realization. These objectives were formulated through a more inclusive sensory and perceptual perspective. In order to achieve this the following objectives were developed.

1) Build a clear understanding of comparable design based projects and research.
2) Review and define the scope of existing literature relating to the thesis aims.
3) Develop a methodology which is reflective of the particular processes and fabrication methods involved.
4) Develop a design taxonomy related to the methodology.
5) Develop a set of case-studies that reflect the unique qualities of the additive fabrication processes.
6) Develop design based case-studies which are founded on a particular sensory paradigm.
7) Choose a particular paradigm to develop further.

1.3 Overview of Research Methodology

The methodology adopted in this research endeavoured to achieve the research aims and objectives. Based on the revision and analysis of the research process and various research approaches, the methodology adopted the qualitative method of analysis, which were applied through the exploratory as well as basic research approaches.

The methods used for data collection were observation, literature review, unstructured interviews and case-studies. The methodology used a more bespoke take of the qualitative research approach by adopting the notion of 'pragmatism' as a key element in its development. This approach allowed for a more hands-on and intuitive research approach to develop. As a parallel and ancillary act to this, the notion of a syncretic approach was advanced. This position, which blends together two or more different systems into an unified symbiotic unit, was also encouraged in the inception of the case-studies.

In addition a number of charts were included to further elucidate the thesis methodology. These were presented through a sequence that provided examples of how the thesis' various considerations interlinked. These are shown on a more general level by the 'Design Correlation Chart', which shows how various case-study designs interweave; a more specific level through the 'Snakeskin – its Related Taxonomies and Neologies' chart, which provides an example of the conceptual, material and process based interconnections of a particular design; and on a detail level by the 'Development Progression Chart', that shows how the design's material based features developed.

Images and illustrations were considered a key means of communication, and played a key role in elucidating the thesis' explorations.

1.4 Overview of Research Done

Following the introduction to the research background and rationale, the establishment of the research aims and objectives, as well as an outline of the research methodology, it is appropriate to present a overview of the research work done.

Based on the notions outlined in the methodology, a theoretical paradigm, based on concepts by Vattimo (1988) and Pallasmaa (2000), was proposed for conceiving designs through additive fabrication. This was formulated as an adaptable and open-source taxonomy referred to as the Layered Freeforming Model (LF-Model), an original term used to describe AF based design processes where the resulting designs are directly generated by such means. The LF-model provided a system and terminology for defining and classifying AF based designs and builds.

Eleven case-studies were developed based on these foundations. These were divided into two groupings. The first group, consistent of six case-studies, included designs that were generated by features and processes exclusive to RM, and which would be difficult or senseless to be made by alternate fabrication methods. These case-studies were:

- *SLA & FDM Bowl(s)* – utilize the default support scaffolding of the fabrication processes as an integral part of the final design.
- *Adaptable SLA Material Matrix* – develops a system for customizing the support scaf folding to serve a variety of different material purposes.
- *Ghost Tile* – uses the burnishing marks that result from the SLA process as controllable features in a design.
- *Alice Cups* – utilizes the parametric 'sliding-bar' control features of a CAD software as an attribute in the bespoke adaptations of a tea-set.
- *Bead Pavilion* – adapts the advantages of the abovementioned feature in the design of a pavilion.
- *PaperCuts* – makes use and combines the advantages of a subtractive fabrication technique with those of AF.

The second set of case-studies expanded the paradigm of the initial group by contextualizing the first group's aims into a format generated directly from perceptual and sensory concerns. These five case-studies, which were derived from a desire to make designs for three of our five primary senses which lent themselves least easily to computing based design, included one gustatory (taste and digestion based), two olfactory (smell based), and two haptic (touch based) case-studies. These case-studies were:

- *Architectural Tidbit* – explored the sense of taste and digestion by adapting a particular AF process to make an edible design.
- *Fragrant Tower* – provided an olfactory an mnemonic device used to subtly release an amalgamated fragrance.
- *Fragrant Mobile* – a balancing mobile used to affect the ambience of a space through a faint but crafty aroma.
- *Finger Run* – A tactile folly which explored the various dimensions of touch.
- *Design Ground* – a textured floor pattern used to provide understated cues to its ambulatory users.

The last category was used and expanded into a more comprehensive design study, which introduces a novel way for communicating data through tactile means. The design, titled 'Snakeskin', utilized various touchable textures and patterns to inform its user about key features in his or her surrounding. The design, due to the variability of conditions it has to adapt itself to, would be very difficult to realize through other fabrication means than AF.

The case-studies provided the backbone of the research, and provided the impetus for the thesis theoretical components.

1.5 Research Originality and Achievements

The notion of originality, in the context of a PhD, is not well defined (Phillips and Pugh, 1994). According to Phillips and Pugh, it doesn't require a massive breakthrough, or a paradigm shift in the thesis' discipline. Instead in entails making a synthesis that has not been made before, using known materials but with a new interpretation, bringing evidence to bear on an old issue, and adding to knowledge in a fashion which is distinct from before (Othman, 2004). The originality and achievements of this thesis are summarized as follows:

1. The act of identifying and defining the research subject, which involves reviewing the prevalent perceptions and shortcomings of current practices, is in itself a contribution to knowledge. Through research observation and first-hand empirical experience with the related technologies and relevant disciplines, a thorough literary review, and through the use of the applied research methods, the thesis was provided with a novel Definition of a subject matter. Here the notion of '*architecture*' is not necessarily considered according to more traditional spatial terms, but through more immediate perceptual means, in which ones various somatic and kinaesthetic forms of awareness were used in the conception and understanding of a vernacular. This entails a '*space*' senses through the skin; perceived through the nose and ears, and read through kinaesthetic motion and proprioceptive cognisance before allowing vision to partake and influence the outcome. Here classical and modernist ideas of visual proportions and orders are acknowledged, but were not considered as defining constituents. How could

the notion of a tactile spatiality be delineated and how could architecture be perceived and understood without the benefit of the eyes? These were some of the initial queries around which some of the included designs provided suggestions for.

2. The research was innovative by providing theoretical framework reflective and bespoke to the RM means of conception. This agenda provided the foundations for how RM could transcend into LF.

3. Accordingly, a customized taxonomy and accompanying terminology was developed. Titled the LF-Model, it provided a system through which a LF build could be composed and described.

4. In the formation of some of the case-studies and designs a haptic interface (SensAble's 'Phantom' device) was used in the investigation of tactile textures realized through RM. Here the device, which retains the advantages of CAD software whilst providing an added dimension through which they could be utilized, was used to explore, through the sense of touch, the palpable textural aspects of a RM design.

5. The research resulted in a number of case-studies that used methods and features unique to the AF processes as defining components in the conception of designs. An approach which inevitably made the resulting designs reflective of the production means.

6. The research also applied the aforesaid approach in an adapted manner and context to conceive hybrid (digital and analog) designs which took into account a more comprehensive and inclusive realm of perceptual and sensory considerations in their formation. Here the AF processes ability to builds directly from digital files, and to shape and manipulate a material at a minute as well as a larger scale, was key, and provided a means for creating, exploring and expanding the resulting designs' physical and sensorial, qualities.

7. The research produced a design which provided a culmination of many of the key considerations described in the thesis. The design, titled 'Snakeskin', performs as a tactile textural mapping, which provides its user with a tactile synopsis about the approaching surroundings. The setup involved establishing a touch based taxonomy that introduced a novel touch based classification of signs. Its fabrication involved numerous, larger and smaller, full scale builds, which culminated in an almost eleven

meter long sample strip of the design made through additive fabrication.

8. Three conference papers were written, presented, and published in the conference proceedings.

1.6 Guide to the Thesis

The thesis comprises nine chapters in total. A brief summary of each chapters contents is presented below.

Chapter 1: Introduction

This chapter explains the background and rationale of the research. It establishes the research aims and objectives and presents the adopted methodology. In addition it presents an overview of the research work done and its originality and achievements. It concludes with a guide to the thesis.

Chapter 2: Research Methodology

This chapter includes the literature survey and a breakdown of the thesis methodological foundations. It outlines the research process and research approaches. It also explains the reasons for choosing the research methodology and provides an adapted rendition of such methodological approaches.

Chapter 3: Background and Context

This chapter includes a brief introduction to the relevant technologies, which is followed by a breakdown of some of the key comparative projects and research that have recently been completed or are currently being developed by various practices and institutions. It also includes a breakdown of how the haptic sense and tactility, a key perceptual realm explored in this thesis, can be classified.

Chapter 4: A Classification Method for Material Led Digital Design

This chapter provides a conceptual framework of the thesis' accompanying theoretical foundations from which its themes have materialized. These include the LF-model, which provides the affiliated design process with a reflective taxonomy. This chapter also provides a descriptive breakdown of some of the new terms that have sprung up during its development, and examples of applications which are specific to this mode of conception.

Chapter 5: Case Studies - Exploring Characteristics of the RM/ LF Process Through Design

This chapter consists of case-study designs which all explore various features and processes specific to Rapid Manufacturing. They apply them in a context which aims to use such features as defining elements in the design. This chapter includes six case-studies in total.

Chapter 6: Case-Studies – Exploring Aspects of Sensory Perception through LF Designs

This chapter expands on the remit of chapter five, and adapts it into a sensorially derived paradigm where three of our five senses which lend themselves currently least naturally to computer based conception are used as catalysts for the designs. These are taste, smell, and touch. This chapter includes five case studies in total.

Chapter 7: Snakeskin – A Manuductory Interface

This chapter provides an in depth description of the Snakeskin design – a wall based tactile mapping which, in a similar way to Braille, allows its user to 'read' about his or her immediate and approaching surroundings.

Chapter 8: Discussion

This chapter discusses some of the features outlined in the thesis. It summarizes its aims, context and achievements.

Chapter 9: Conclusion and Recommendations

This chapter is the final of the thesis. It comprised the conclusion and contribution to original knowledge. It also provided recommendations for further research.

1.7 Naming the Discipline

In the context of the aforesaid, one of the early quandaries involved with this project was deciding what to call this still evolving discipline. Using 'Rapid Prototyping' (RP) was out of the question, as the term reflects aims long ago surpassed and is in its basic portrayal inaccurate, as the aim here was not to only prototype things (although that still plays a key role in any related conception), and anyone who has used the additive technologies to make something are keenly aware that as a fabrication process it is anything but quick. This also, through affiliation, disqualifies 'Rapid Manufacturing' (RM) as it, although a step closer to the intended aims, still carries too much of the shortcomings and baggage associated with RP. 'Direct Manufacturing' was again a degree closer to an accurate description, although it also in its abruptness fails to communicate the finer nuances and, worse, saturated potential, of this mode of conception. In many ways using 'Three Dimensional Printing', or 3D Printing (3DP), due to its directly illustrative quality, would have been ideal, however, it was already linked to a particular sub-technology of the discipline (a powder based fabrication technology made by Z Corporation). As summarizing expressions 'FAB' and 'Fabbing'[1] have a suggestive succinctness about them, however, particularly when considered in a British context, do have a somewhat derogatory connotations[2]. 'Solid Freeform Fabrication' is perhaps the term closest to the mark of all the idioms currently in use. However, it also is a bit of a mouthful and cumbersome, thus usually resulting in it being

1 http://www.ennex.com/~fabbers/publish/200102-Napster.asp

2 As a colloquial term for 'fabulous'...

abbreviated into 'SFF' which, by being a degree removed from its more explanatory core, lacks the evocative impact that the term's, particularly two last words, call to mind. More recently the term 'Additive Fabrication' has become more common, however, this term suffers from the same shortcomings as the previous one. It is, however, here in the cross-roads of the two aforementioned terms, where the solution might lie, for if one takes the abbreviated rendition of SFF, and call the practice 'Freeform Fabrication', a term that preserves the catalytic, as well as descriptive qualities of the practice, whilst retaining the mnemonic attributes of a more evocative phrasing and a shorter term, that one is provided with a more symbiotic and thorough term for what currently is done and what it will hopefully eventually evolve into. This term, Freeform Fabrication (FF) can also be made to act as a key element of a larger context when placed adjacent to the already established term of 'Freeform Construction'(FC)[3], where the former is used to describe designs and builds that fall into the realm of objects, here described as things roughly the size or smaller than, or within the grasp, of a generic human torso and extremities, and the latter to things that are of a larger, more architectural, scale and function – things that are beyond the immediate grasp of a individual's reach.

Considering all the aforementioned, a fitting term that describes the collective act of both Freeform Fabrication and Freeform Construction would be Freeforming, a term that has phonetic and mnemonic qualities of both. This term that is already in use by a number of different contexts, the one that is closest related to the interests of this study being the 'FreeForm System' used in conjunction with the SensAble haptic device, can be further tailored to befit the additive CAD-CAM processes by adding the word 'layered', an attribute common to all the relevant technologies, before the term Freeforming, resulting in the final amalgamated term of 'Layered Freeforming' – a phrase that retains the illustrative quality of the former term, whilst still preserving the open ended characteristics of the latter terms abilities and promise in this still evolving technological domain. Thus the term 'Layered Freeforming' was used to express the actions, processes and related designs contained within this thesis which were directly dependent of, or catalyzed by, the various additive CAD-CAM processes and were not necessarily and alternative, but a parallel way to make things in comparison to the more traditional fabrication methods.

3 A term introduced by Dr. Rupert Soar.

2.0 Methodology

The Finnish architect Alvar Aalto was claimed to have stated, "I'm sceptical about experts. They seem to know more and more about less and less."[1] In a similar manner Maeda (2006), the 'guru' of computational graphics and accompanying logistics, describes that during his studies he was advised to be more of a light-bulb than a laser-beam, i.e. instead of intensely lighting a single point, use the same light to brighten everything around you[2]. This project aimed in its methodology to be an example of the latter, to be a 'light-bulb' rather than a 'laser' in its approach. In a sense this thesis was an ode to enlightened generalization, an approach that in concept refuses to distinguish or prioritize the macro from the micro, the conceptual from the practical, the analog from the digital, whilst still involving all of the aforementioned. It was an open ended process that generates more questions than it can to answer, a method with perforated blinkers[3] guiding the way - allowing for alternate relevant paths to be acknowledged and even acted upon whilst still striving forward.

Thus this thesis was about a particular set of design projects, explored through case studies, and about an evolving approach and narrative for how the additive CAD-CAM processes could be included and considered in the course of conceiving and making designs. It was a thesis about making things, through the use of very particular means, that, whilst in the process of making these things, revealed why such means were valid. Attached to this core was also the notion that the aforementioned methods are used to make things in a way that would be very difficult, if not impossible or even meaningless, by any other building methods than those related to RM/ LF (Fig. 2.1).

2.1 Research Aims and Objectives

This chapter explains the research methodology used to attain the research aims and objectives.

1 A quote from a wall at the 'Alvar Aalto – Master of Finnish Functionalism' exhibition held at the Finnish Design Museum in Helsinki, Summer 2004.

2 An alternate analogy of similar lines, its source which cannot currently be recalled, compares the western and eastern forms of research, where western research is similar to a mountain peak, an approach where the research gradually gets more and more specified. This is compared to the eastern way of research where the mountain is of a similar volume, but much shallower and wider, entailing a form of information assimilation that allows for a much wider scope of information to be absorbed, but is less focused in its application. The process of this thesis is probably located somewhere in between – a shallower volume with occasional sub-peaks poking out along its ascent...

3 Occasionally also referred to as 'blinders' – used in a horse & carriage to control the peripheral views of the horse(s) and thus saving them from any distractions.

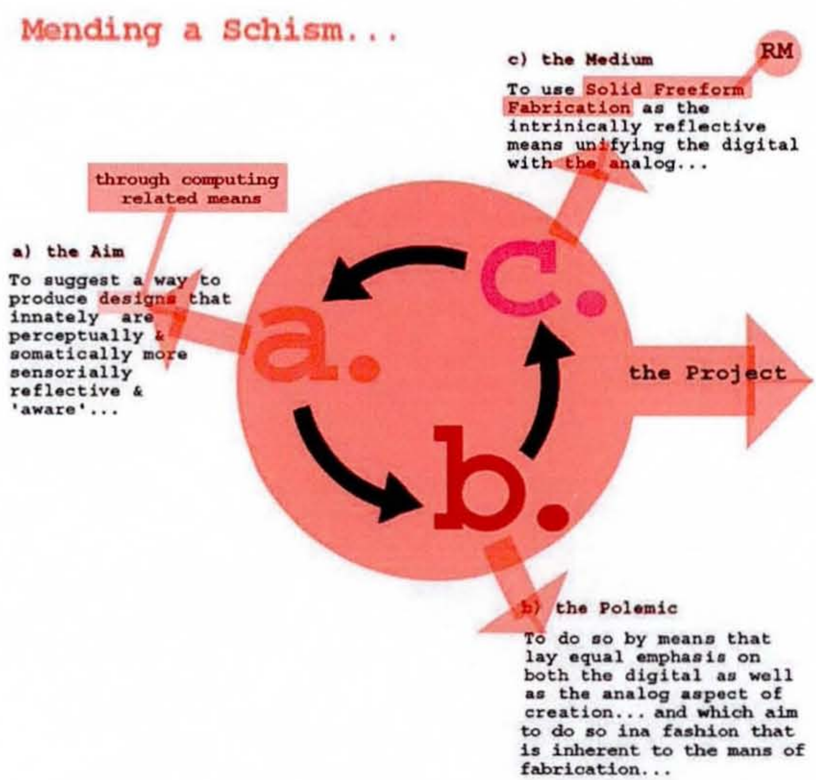


Figure 2.1 An early rendition of the thesis' guiding principles...

To make sure an apt approach fitting the aims of the thesis is defined, the key considerations involved in choosing the research methodology were determined and the affiliation between the research objectives and the research methods were represented.

2.1.1 Research Approaches

The approaches to research can be classified into group based on (A) what the research is aiming to accomplish, and (B) how it will be used (Othman, 2004). The former set can be classified as *exploration*, *description* and *explanation*; whereas the latter group can be defined as *basic* and *applied.*

2.1.2 Exploration Approach

The exploration approach is used to explore a new topic. It structures and identifies new questions. The less mature the area or research is, the more likely its use becomes. It is a less systematized approach, and allows the research to progress according to a more open-ended agenda, and often plays a role at the commencement stage of a study (Adams and Schvaneveldt, 1991). It may be a exploratory study that provides the foundations for a more in depth and extensive study that follows. It deals with the '*What*' of a research question (Othman, 2004) and applies qualitative research techniques which allow for a less defined, and consequently encourages a more 'creative' approach to research (Groat and Wang, 2002).

2.1.3 Description Approach

This form of research begin with an already well defined subject matter, and proceeds to describe it accurately. It requires extensive empirical knowledge of the topic at the commencement of the research, and performs as an opposite format to that of the exploration approach (Robson, 2002). Much of applied research is descriptive. Its driving aim is not to explore new issues, but to focus on the 'how' and 'who' queries (Othman, 2004). Both qualitative and quantitative research techniques are used in descriptive research.

2.1.4 *Explanation Approach*

Explanation research expands on the notions provided by exploratory and descriptive research through looking beyond the either act of defining a topic or providing an outline of it. It aims to understand 'why' something exists or functions in the way it does. Experimental work, qualitative and quantitative techniques are used in explanatory research (Neuman, 1997).

2.1.5 *Basic Approach*

Basic research (also called pure research) progresses fundamental knowledge. It concentrates on either refuting or supporting hypothesis' and is usually pursued without a clear outcome in mind. It is often driven by the researcher's interests, and even intuition. Basic research is the chosen format of most new ideas and ways of thinking. It can be exploratory, descriptive, explanatory, of which the exploratory is the most commonly used (Powell, 1997; Othman, 2004).

2.1.6 *Applied Approach*

Applied research is a less theoretical approach to research. It applies a particular research community's accumulated knowledge for a specific, usually externally (client, state, commercial) driven purpose. It usually takes the form of descriptive research (Neuman, 1997).

2.2 *Choosing a Research Methodology*

The research aims and objectives according to which the choice of the research methodology is based on are:
The research aims to:

Use RM as a defining component in design, and to develop a more sensorially inclusive conceptual process and framework for conceiving such designs.

To achieve these aims the following objectives were developed:

1) Build a clear understanding of comparable design based projects and research.
2) Review and define the scope of existing literature relating to the thesis aims.
3) Develop a methodology which is reflective of the particular processes and fabrication methods involved.
4) Develop a design taxonomy related to the methodology.
5) Develop a set of case-studies that reflect the unique qualities of the additive fabrication processes.
6) Develop design based case-studies which are founded on a particular sensory paradigm.
7) Choose a particular paradigm to develop further.

2.2.1 Applying the Qualitative Method

This research applies an adapted rendition of the basic and exploratory approach to research. The research method was advanced by both empirical collection of data regarding the relevant technologies as well as applying the technologies in the realization of designs. Such practices when applied to disciplines like design (here interpreted as items of a smaller scale than architecture - things directly manageable by an individual), and architecture (here understood as something of a more substantial size – manmade entities, which are habitable and larger than those which can be physically manipulated by an individual) entail that at least a part of the assessment remains subjective to the individual making the judgement (Groat and Wang, 2002), and consequently remain difficult to measure according to quantitative research methods. Thus, as seen in figure 2.2, the research applies a degree of the 'what', 'how' and 'why' of all three of the aforementioned approaches of exploration, description and explanation research. It also aimed to acknowledge external and internal influences that affected the outcome.

The specific qualitative methods used during the cource of the research were: observation, literature review, unstructured interview and case-studies.

2.2.1.1 Observation

All good research begins with observation (Edwards and Talbot, 1996). This practice, along with the accompanying literature, conversations and case-studies, formed the core means for aquiring

Design Affects Chart

Figure 2.2 An illustration of the various elements that affect the process of making something through the means affiliated with Layered Freeforming...

relevant and verified information. It was through daily involvement and extended observation that the thesis' initial polemic was catalysed. It was also through the availability of access to additive fabrication related technogy which enabled the author to directly observe and discover the latent potentials of these methods of manufacture.

2.2.1.2 Literature Review

The literature review established the conceptual foundation upon which the study was constructed. It aim was to introduce and summarize the main literary influences which catalysed and directed the research, which, as to the research was based on the explorative and basic methodological formulations, entailed the any precedents were inevitably inferred rather than based on existing examples or standards. The updating of the literature review was an ongoing process during the research. A number of sources were used for data collection to unsure a thorough review of the relevant work. These included textbooks, professional journals and magazines, conference proceedings, the publications of various organizations, dissertations and thesis', workshops, technical reports, CD-Roms and the internet.

The review has been divided into five main headings, each representing a conjectural notion that signifies a particular literary paradigm and influence from which the study has been derived. These headings are in some sense self-referential and will not be referred to in the main text.
The chart below (Fig. 2.3) illustrates how the various headings are positioned in regards to each other, with the *Corporeal (sensory)* is placed as the polar opposite of the V*irtual (conceptual)* – and the *Digital* defines the reverse of the *Analog*. A number of key authors are also positioned alongside the main headings to provide a context for the aforementioned headings. The five topics move diagonally across the chart (from bottom left to top right), from subject matters dealing predominantly with 'fully' analog and the physical qualities and properties of realising design and architecture (bottom left), to schools of thought prescribing the virtues of the more digital and virtual realms of the related disciplines.

The headings are:

- '*Architecture and the Senses*' - explores the way we perceive our built environment.

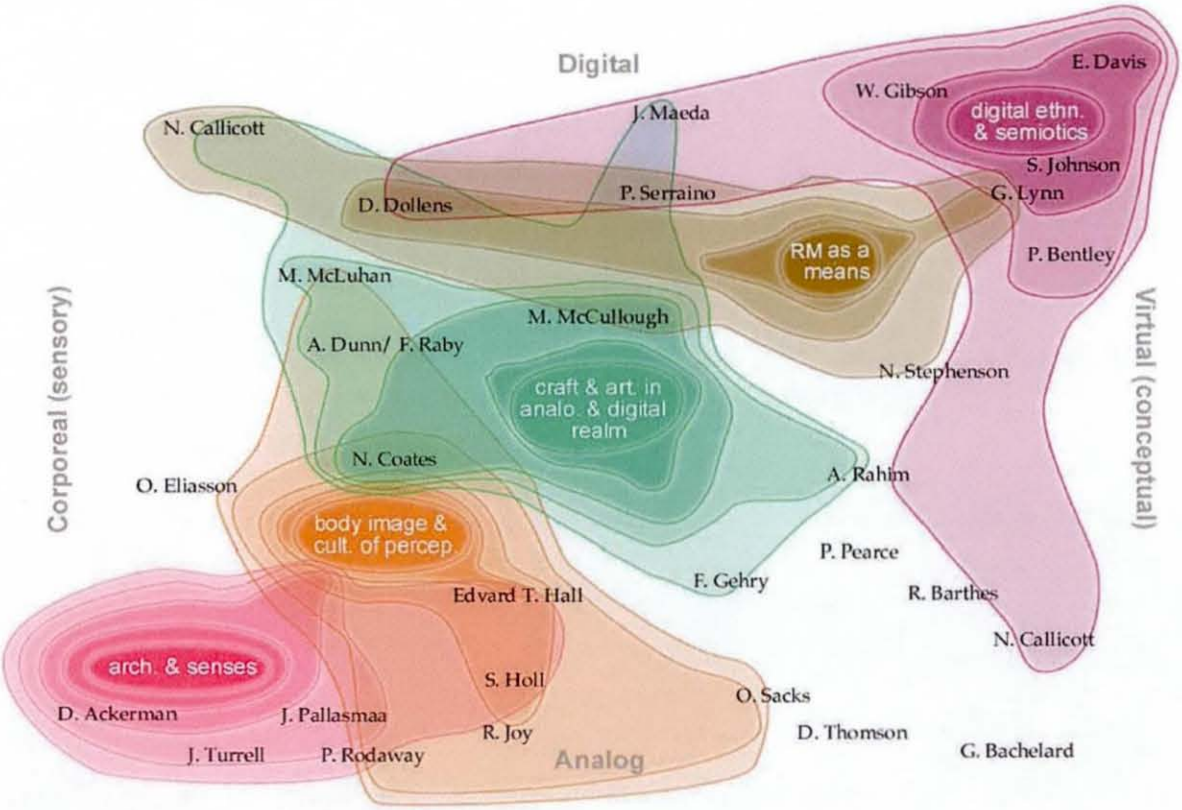


Figure 2.3 Literature Review 'topographical' Chart. The coloured 'topographical' curves provide a suggestion of how the various categories overlap in influence...

- '*Body Image & Cultures of Perception*' - furthers the initial category and contextualizes it in society and within particular cultures.
- '*Craft & Artistry in the Analog and Digital Realm*' - presents writings that take a shot at trying to breach the somewhat imposed gap between how we design and how we experience those designs.

  This heading occupies the middle ground between the two (seemingly) opposing polarities.
- *Rapid Manufacturing as a Means...*' - deals primarily with the logistical and technical

  aspects of LF, but still involve all of the aforementioned headings, particularly the two preceding it...
- '*Digital ethnologies & Semiotics*' - explores the realm of digital theory and logistics in the context of this project.

* *Architecture and the Senses...*

The texts included in this section explore the perceptual side of how we know and understand our built environment. All the texts expand beyond the notion of architecture as a predominantly visual language into the realm of the tactile, auditory, olfactory and even gustatory. These include work by Ackerman (1996), who explores the rich perceptual landscapes of our various (five) senses, as well work dealing with sensory and the parallel connected cultural impressions and idiosyncrasies of specific senses such Corbin's (1986) work the *Foul and the Fragrant*, that considers nineteenth century Paris from an olfactory perspective, or Watson's (1999) book, *Jacobson's Organ*, that debates the more intuitive and emotional role of fragrance in society, and how the more, call them, 'limbic' or emotional aspects of our beings play a surprisingly defining role in how we perceive our surroundings. Other related books worth noting are Rodaway's (1994) *Sensuous Geographies* creating a discourse on how geographic and sensory landscapes entwine, *Sensory Design* by Malnar and Vodvarka (2004), who provide an extensive and in-depth analysis of how our senses respond to our built environments, and Bloomer's and Moore's (1978) book, *Body, Memory and Architecture*, which considers architecture from a more somatic point of view, along with the seminal texts by Pallasmaa (1991, 1996, 2001, 2002, 2005), who has perhaps had the most profound affect on the author from all the writings included.

* *Body Image & Cultures of Perception*

This segment has a fundamental connection to the initial heading. How we perceive is as much depended on cultural, habitual and mnemonic information as it is on sensory input. One could almost claim that we are culturally programmed to perceive in a particular way - we 'learn' to see certain things and ignore others, find particular physical or sensory qualities more appealing than others, etc.. This applies particularly to vision, something which is particularly the case when considered from an occidental perspective, but it can certainly also be applied to the remaining realm(s) of sensory perception.

Hall, a (cultural) anthropologist, has been a decisive influence in the formulation of the foundations for this heading. With books such as *The Silent Language* (1959), *The Hidden Dimension* (1966), or *The Dance of Life* (1983), exploring the cultural and social particularities that we often consider generic, but which in fact turn out to be, according to Professor Hall, culturally inscribed. Sacks' (1985) book, *The Man Who Mistook Her Wife for a Hat*, puts forth some truly provoking suggestions for the underlying taxonomies that guide our behaviour - patterns with their own, occasionally contradicting, rationales and stuctures.

* *Craft & Artistry in the Analog and Digital Realms*

It is here, in the apparent twilight between the analog and digital realm of conception, that the foundations of the thesis are rooted. Most of the authors included here provide various suggestions for how one could potentially deal and formulate a more comprehensive elucidation of where we are, where we need to be, and where we should be heading.

Dennis Dollens' books explore a variety of design processes generated and catalyzed directly by the various CAD-CAM processes he's involved with. McCullough's (1998) *Abstracting Craft*, a noteworthy and influential book, was amongst the first texts exploring the craft aspect of realizing designs through digital methods. His book was also fundamental in recognizing the innate tactile aspects in almost anything we produce, regardless of means. Two books with collections of essays, Kolarevic's (Ed.) (2003), *Architecture in the Digital Age – Design and Manufacturing*, and Sheil's (Ed.) (2005), *Design Through Making*, have both been important in reinforcing and confirming ideas related to those put forth in this dissertation.

* *Rapid Manufacturing as a Means...*

This section is predominantly concerned with literature dealing with the technical and logistics aspects involved in producing a design through Rapid Manufacturing related technologies. However, this section is still inescapably linked to all of the preceding headings. The source materials here were also, one could claim, in constant 'flow', as the various facets of the related technologies (hardware, software, materials, etc.) are regularly being altered and updated. It places high emphasis on some of the more accessible mediums of information, such as web-pages (http://home.att.net/~castleisland/home.htm), internet based user groups (majordomo@rapid.lpt.fi), academic journals and conference publications - all mediums with immediate revising capacities and shorter turn arounds.

In *Computer Aided Manufacture in Architecture – The Pursuit of Novelty*, Callicott (2001), a member of a team of CAD-CAM designer-makers called Sixteen Makers*, provides a very succinct and considered introduction as well as analysis of the CAD-CAM craft as it stands. As a designer himself, his examinations derive from a more directly empirical perspective, rather than from a viewpoint ascertained from the sidelines, consequently making his deductions all the more convincing. Another worthy publication is the annual *Wohlers Report (annual)*, which every year provides a synopsis of the trials and tribulations of the Rapid Prototyping and Rapid Manufacturing trades. Additional samples of relevant publications would be *Manufacturing Processes for Design Professionals* by Thompson (2007), and *Digital Design and Manufacturing* by Schodek et al. (2005).

* *Digital Ethnologies & Semiotics*

It is interesting how, regardless of how 'formulaic' and stringent one tries to be, the intuitive always manages to 'seep' in through one of the hairline fractures catalyzed by the doubt accompanying most endeavors. Many of the text in this section tackle some of the evolving ethnographic and cultural tangents that have begun to evolve and establish themselves in the both conscious and subconscious realm of 'everyday' urban existence. We are emotionally driven beings, as Evans (2001) claims, regardless of how rational we claim to be. Post-rationing and covert impulses seem to guide most of our decisions, be they made in the canteen during a lunch break, or in the highest echelons of public office. Such modes of conception also apply to how we conceive and use technology; occasionally with some perplexingly peculiar results.

There is also an underlying language evolving in regards to the digitally conceived crafts. A language with its own sub-texts and sub-cultures, saturated with nuances, conceptual nooks and crannies. The notion of technology as something clinical and precise has by now been proven inexorably utopian. Technology seems to be as 'carnal' as the rest of our activities and exploits. Davis' (1998) book, *TechGnosis*, communicates such aforementioned technological notions through an amalgamated collection of anecdotes. Dunne's and Raby's (2001) book, *Design Noir*, provides, along with offering an insight into our technologically derived psyche, a provoking set of relevant responsive or reactive designs. Some of the analogies conjured up by technology are touched upon in Bentley's (2001) book *Digital Biology*, and in Johnson's (2001) book *Emergence*, that explore the way similes and metaphors often act as catalysts of various, technology related or other, epiphanies. Also worth a note is Balmond's, one of the principal engineers at Ove Arup and Partners, (2002) book, *Informal* which outlines some of the collaborative architectural projects he's been involved with during the last decade or so. Again, it is interesting how, call it, 'intuitive' his process of (engineering) conception seems to be. The justifications for some of his structural arrangements, be it the floor plates of a Rem Koolhaas structure in Holland, or his thoughts regarding the, seemingly sporadic, tectonic arrangements for Toyo Ito's pavilion for the Serpentine Gallery, seem to be justified much more through an emotionally and instinctively motivated language than the 'cool' and rational idioms found in engineering text books.

2.2.1.3 Unstructured Interview

The unstructured interview entails here the more casual discussions that took place during the development of the thesis. These were conducted with individuals related to a variety of related disciplines, ranging from architecture, design, engineering, computer-science, biology, art, philosophy, social-sciences, constuction and project management, physiology, and psychology. The unstructured interview is a potent research tool, which is capable of yielding valuable data

(Punch, 1998).

2.2.1.4 Case-Studies

The case-studies of this thesis are made up of designs which utilize specific features, or processes affiliated with rapid manufacturing as defining considerations in their execution. They perfom a key role in the thesis through which its assumptions, assessment and proposals have been tested and developed. They also, due to the physical engagement they inevitably entail, provide a powerful means of rationalizing and validifying an assumption. Each case study included an introduction to the design theme, an outline of the objective, an explanation of the method used to realize the aim, and a description of the results.

2.3 Adapting the Methodology

Qualitative research which as a format of inquiry crosscuts disciplines and subject matters (Denzin and Lincon, 2005), is here adopted and adapted into a material, practical and process based framework (Flyvbjerg, 2006) which subscribes to the "thinking through doing" school of though. This approach is comparable to Pragmatism which, according to Sennett (2008), aims to make "philosophical sense of concrete experience" and provides a fitting rendition of the qualitative approach. Pragmatism, when defined as a methodology, requires subjects to be explored through empirical means, and which, according to Sennett (2008), "addressed the quality of experience as well as the sheer facts on the ground," which, he continues, "animating impulse remains to engage with ordinary, plural, constructive human activities". This hands-on approach has played a key role in how the activities involved in this thesis have been pursued. Even though the computer, and its affiliated paraphernalia, define and are fundamental to its aims, they still remain tools which are in need of supervision and guided effort. The technology may form the language and the alphabet of the work, but what is said and made with it is where its essence lies.

This adapted notion is further revised through the *foundation of craftsmanship* (Sennett, 2008) into, "the ability to *localize*, to *question*, and to *open up*", a sequence of actions of which the initial one (A) entails the building of a foundation and core understanding for what is to be practised, the ensuing point (B) strives to debate what is now known and establishes a polemic, and the final point (C) combines the initial efforts to build and expand on them through practices intrinsic to the discipline. How these notion were reflected in the thesis can be observed in *Figure 2.3*, where its various case-studies are applied and correlated according to perceived influences. It shows how transition and links between the designs, and how, even though conceived as singular entities, they affected each other as the thesis progressed.

The illustration following (Fig. 2.4), provides a more detailed picture of the factors shaping a particular design example. Here the 'Snakeskin', a tactile information pattern which informs its user about the surroundings through a Braille like touch based relief texture (explained in detail in chapter seven), is used as an example of how the various key elements are interlinked. In the chart the design, placed in the centre, is surrounded by defining influences. These are *Fabrication Means*, which describe the technological elements involved; *Conceptual Foundations*, which explain the key perceptual, social and cultural aspects involved; *Conceptual Taxonomies*, that recount the particular bespoke classifications applied; and *Design Elements*, which recount the various features of the design itself. A further breakdown of this latter category's material evolution can be observed in Figure 2.5. The chart shows the means through which the design's tactile qualities were investigated, starting with a plasticine and wood model, and gradually developed through a sequence of full-scale prototypes of increasing size and degree of refinement, to eventually result in an almost eleven meter long physical rendition of the design. This advancement is depicted in the illustration's base, where (from left to right) some of the key material stages are shown.

2.3.1 Method of Approach - Constructive Conflict

Key to this approach, formulated as a hybrid based course of action, an amalgamation of intersecting disciplines, was the application of *syncretism* (the union of different or opposing principles or practices), which allowed a dynamic balance to evolve between the various, seemingly discordant, issues that arose during the realization process of both thought (theory), and action (design). In this sense it formed a rendition of *gesamtkunstwerk* (a synthesis between the different arts and disciplines) of the CAM age, where the different branches and occasinally conflicting elements that were involved in realizing a physical design through RM were acknowledged, as well as on a conceptual level considered as a fused collective from the beginning.

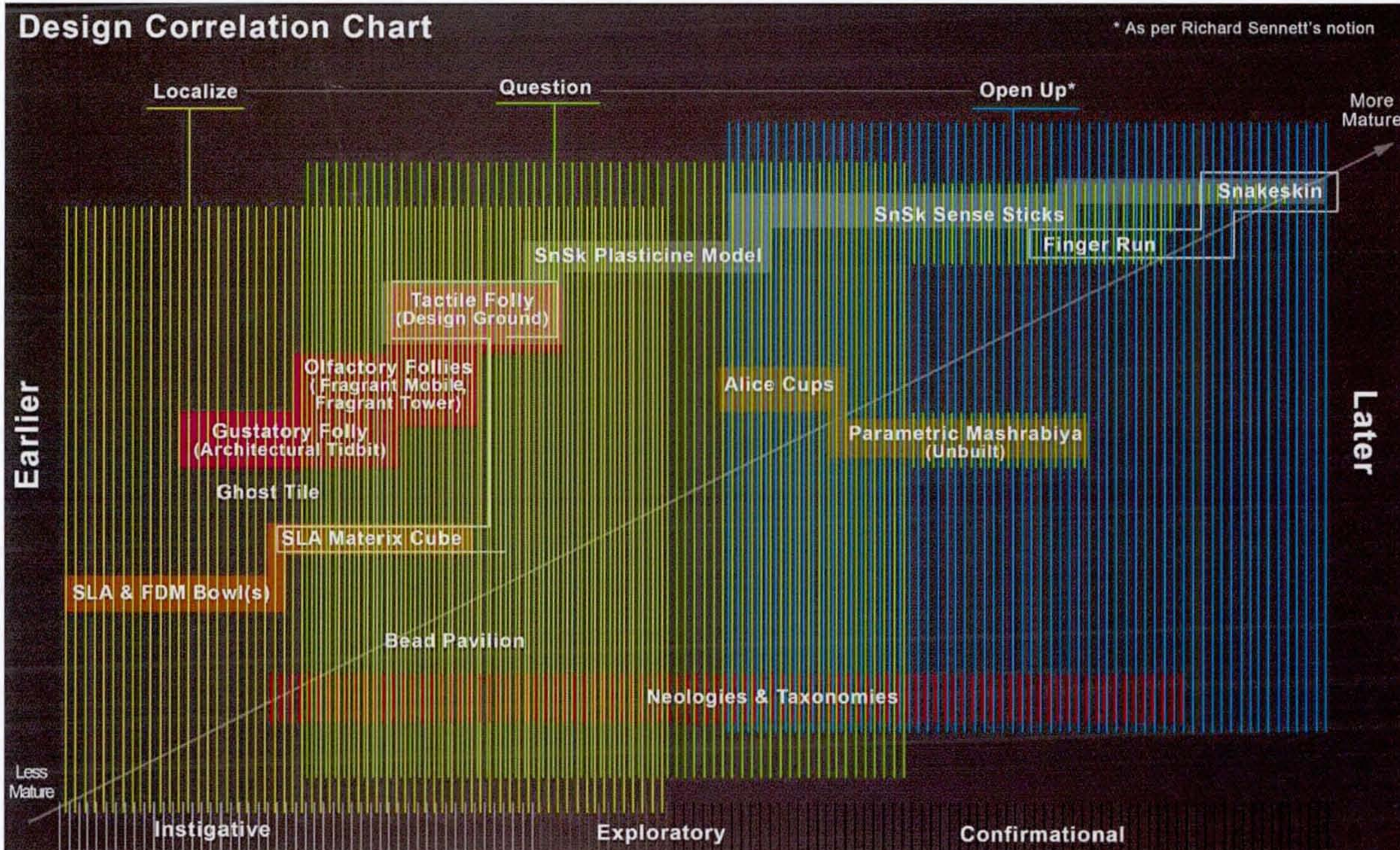


Figure 2.3 A correlative chart showing how Richard Sennett's notions of Pragmatism correspond with the various designs realized during the thesis' development, and how some of the case-studies are conceptually interlinked.

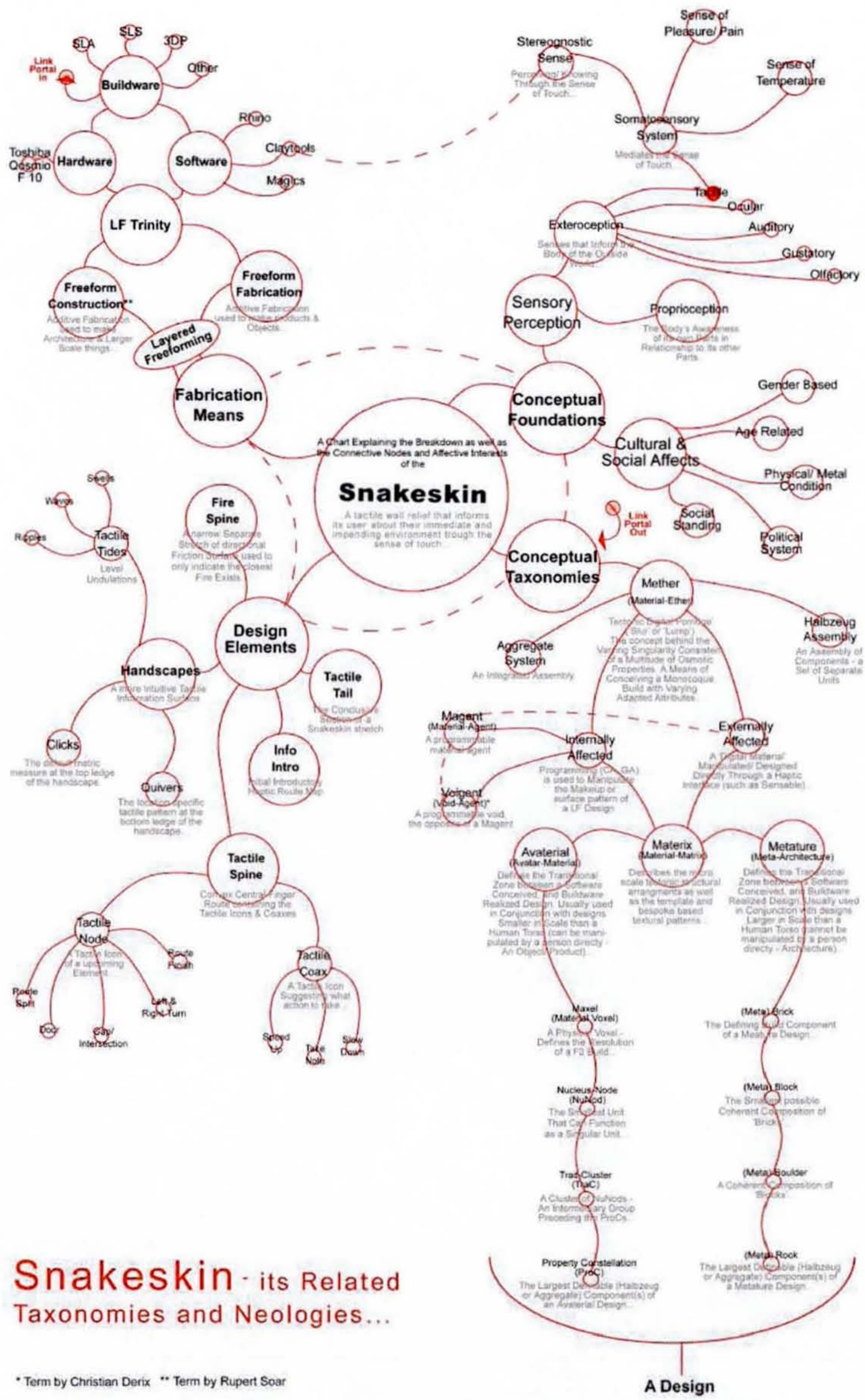


Figure 2.4 Combination taxonomy - showing how the various interests and elements of a design are interlinked.

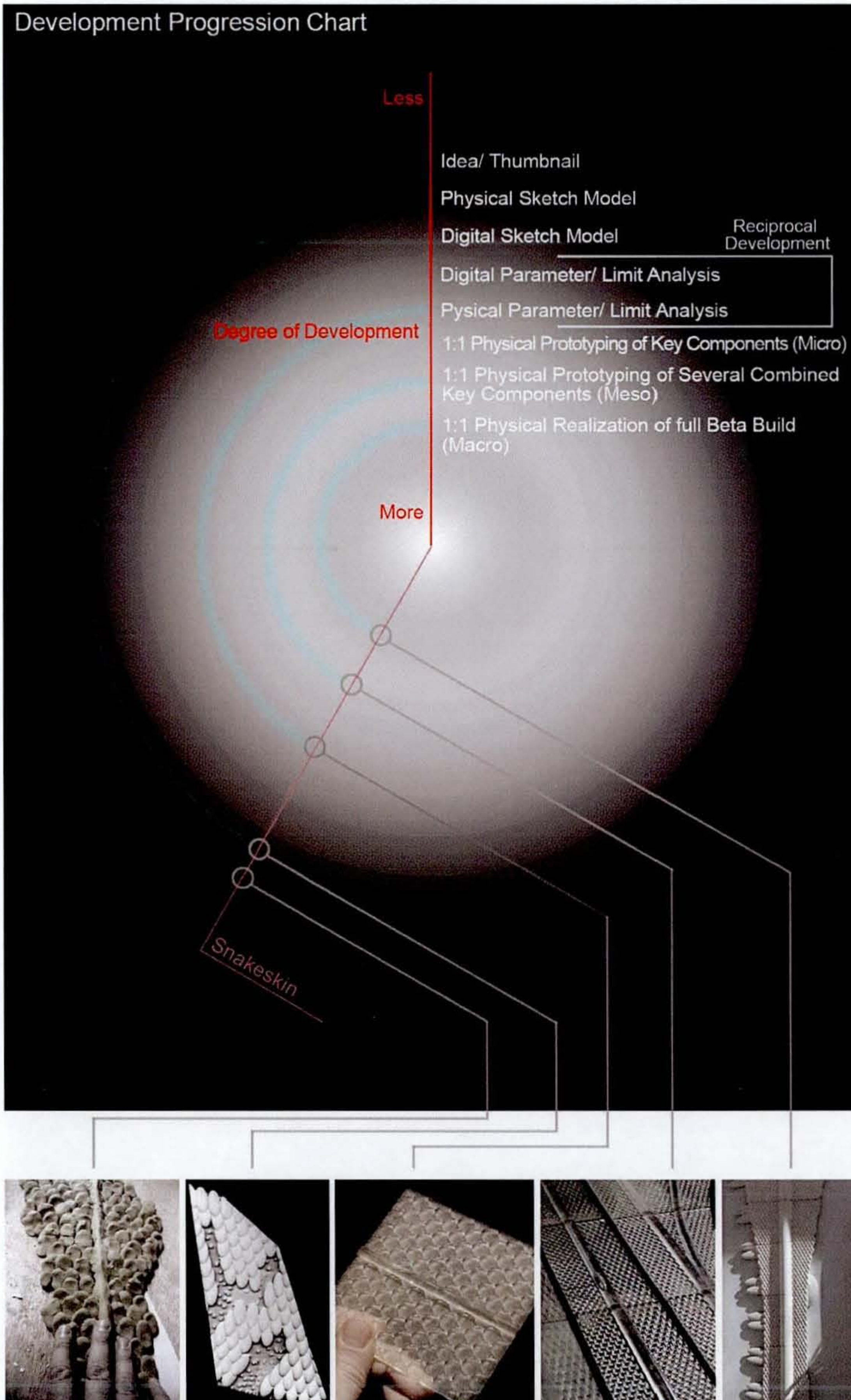


Figure 2.5 Chart of a particular design's, the Snakeskin Tactile Relief's, various material development stages.

This latter point, an approach alluded to by Komonen[4] (2006), and Miessen[5] (2007), both who discuss using the notion of (cerebral) conflict as a positive and generative tool in the advancement of a cause. This approach, that ventures to develop a position by amalgamating seemingly opposing approaches into a dynamic syncretic singularity, a, as Miessen defines it, 'critical platform of engagement'[6], hold on to the idea of progressing and maturing an idea without necessarily reaching a collective consensus between the various sub-components of which it is composed. This inherently elusive position concedes that the bias contained in an evolving hypothesis' constituents become, when exposed to the presence of alternate polemics, stonger due to the originally opposing idea's conflicting or ineffectual components annulling each other during extended exposure, resulting in a manifestly more non-partisan primary polemic. Thus, to retain and even encourage such a dynamic, it becomes important to be on the look-out for things that seem somehow related, but might (initially) rub one the wrong way. Or as Komonen (2006), whilst quoting the ex-president of Estonia Lennart Meri, puts it, "...extremes are of course necessary, for the most fertile soil builds up in the fault line of collisions; even more fertile is the accumulation of collisions at the edge of a field."[7] This should not be considered a justification for the slapdash, but an attempt to avoid the research becoming entrenched in a form of hermetic groupthink where the outcome is second guessed rather than allowed to evolve and develop according to what a project needs, instead of based on what was initially envisaged. Keeping a watch on things that dwell outside ones regular comfort zone, and allowing such influences to, if deemed useful, influence the outcome, can only be a good thing. Such procedural 'sways' have, whilst establishing and defining a methodology sensitive to the aim of this thesis, played an important part in establishing its semantic structure[8]. Architecture in particular is saturated with these forms of strange amalgamations. These incipient analogies, similes and adapted meta-

4 Komonen's essay, titled Snowball Fights in Finnish Architecture – The Counter Tradition, can be found in: MacKeith, Peter (Ed.) – Archipelago – Essays on Architecture. Rakennustieto, 2006, pp. 114-118.

5 An essay by Markus Miessen titled Conflict as Practice, found in: Bouman, Ole/ Khoubrou, Mitra/ Koolhaas, Rem (Eds.) – Al Manakh. Stichting Archis, 2007, pp.464-469.

6 Ibid. p.464.

7 Ibid. Komonen, 2006, p.115.

8 Another, somewhat wry, reference, suggested by Irwin (2004) to this notion is taken from the film, *The Third Man*, where Orson Welles' character Harry Lime states, "In Italy for thirty years under the Borgians they had warefare, terror, murder, and bloodshed, but they produced Michelangelo, Leonardo da Vinci and the Renaissance. In Switzerland, they had brotherly love; had five hundred years of democracy and peace - and whar did that produce? The cuckoo clock."
The aim here is not to suggest that warefare, even of the cerebral sort, is an encouraged approach for advancing a course, but that the insertion of new, foreign and even conflicting ideas and concepts into the stream of thought can only strengthen the 'argument' - a term which in itself is suggestive of the inherent need for benevolent conflict in any astute proposal...

phors[9] that from a set cultural standpoint might seem initially strange, nevertheless provide catalytic venues for dynamic discoveries that might not been apparent through any alternate, perhaps more tested, methods. Aspects of this syncretic approach are evident in all the included case-studies. Examples of this can also be found within the realm of philosophy, where notions that began as purely philosophical reflections were assimilated into architecture, resulting in works of architecture that were based on ideas which weren't necessarily intended to provoke physical or volumetric expressions. Whether the resulting constructions and buildings classified as either post-modern or deconstructivist do the original cerebral concepts justice, or are even capable of truly reflecting their sources, is beside the point as such syncretic outcomes did induce new genres of classifiable architecture which have by now become established in their own individual rights, and are seen as clearly defined and unique entities different from their initial provenances. Alternate examples of such ongoing fusions are taking place between architecture and biology (Soar, 2008), architecture and ecology (Weinstock, 2006), and architecture and nano-technology (Gans and Kuz, 2003), to mention a few...

2.4 Images and Illustrations

If the adage that an image is worth a thousand words holds true, this thesis was approaching half a million words - images, illustrations and charts occupy a fundamental role in the expression and summary of its positions. In some sense images provide a more direct link between ideas expressed and interpreted through words, and the actual design(s) presented. They, through their inevitable choices of fonts and subjective stylistic preferences, provide a more particularized and nuanced expression of where and how the thesis' positions itself.

In its layout, the images were assigned a page of their own, usually on the page or pages that follow the text page affiliated with a statement or claim. This arrangement allows for the images and charts to be judged on their own merit without having to become subservient to the text, and provide the illustrations with, both from a compositional as well as format related standpoint,

9 Which require a condition where embellishment is possible, and the more primal requirement of a 'roof above our heads' is surpassed into a situation where elements that are non-essential for survival are allowed for. This usually has entailed a circumstance that, where before the local climate and available construction materials have determined what the structure or habitat should be, have now been, usually along with the development and relocation of our habitable environments from an agrarian to a predominantly urban context (a move that is accompanied by advancements in construction based processes and materials), transcended into a more, call it, 'aspirational' state where more aesthetic interventions are allowed for.

more clarity and flexibility than when integrated with the writing. Images, in comparison to text, also carry a closer and more direct affinity with the sense of touch[10] (Kennedy, 2007), a key ingredient in this project.

The aim is thus to provide an means of communication that transcends beyond what either text or images could convey by themselves. By symbiotically linking the two modes a more lucid picture of the thesis' aspirations is imparted.

2.5 Conclusion

The methodology adopted for this research was devoted to the development of RM as a defining component in design, and to form a sensorially more inclusive conceptual framework for conceiving designs. A number of objectives were defined to enable the achievement of the research aims. A brief description of the research process and research approaches were explained to establish the appropriate approach to the research. This research adopted the explorative and basic approach to research and used an adaptation of the qualitative method in its execution. The research methodology consisted of four activities: observation, literature review, unstructured interviews and case-studies. The case studies in particular fulfilled a fundamental role in the basic exploration approach to the research. The methodology used a more bespoke take of the qualitative research approach by adopting the notion of 'pragmatism' as a key element in its development. This approach allowed for a more hands-on and intuitive research approach to develop. As a parallel and ancillary act to this, the notion of a syncretic approach was advanced. This position, which blends together two or more different systems into an unified symbiotic unit, was also encouraged in the inception of the case-studies.

Images and illustrations were considered a key means of communication, and played a key role in elucidating the thesis' exploration.

The specific premises and context from which the methodology is derived is discussed further in chapter three.

10 There seems to be a closer perceptual link between visual representations and touch, than between written text and touch. The, call it, synaesthetic connections between these two sensory modes seem to have a number of qualities in common.

3.0 Background and Context

This chapter provides an introduction to Rapid Prototyping and Rapid Manufacturing processes and examples of comparative projects and research that use such technologies to make architecture and design. It concludes with a section explaining precedent systems for classifying the various aspect of touch, and puts forth an rendition of haptic categorization titled 'Tactile Gestalt'.

3.1 The Potentials of Rapid Manufacturing

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

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

3.1.1 Methods of Making

Rapid Manufacturing and Prototyping fall primary into two main categories: the subtractive and the additive methods. The initial entailing a process in which usually a router 'subtracts' material, through the use of a variety of different routing-bits, from a, usually wood or foam, block which is gradually reduced into a physical replica of the original CAD model. Examples of this kind of production are: CNC (Computer Numerical Control) milling, routing centers, and plasma & laser cutting (Fig. 3.1).

In the case of the latter, additive, method, a physical model is sequentially constructed, layer by applied layer (a process referred to as 'stair-stepping'), to finally form an analog facsimile of its digital (CAD) origin. It is this latter additive process this study is exploring.

Of the thirty (Kwon, 2002), or so, additive RP processes four seem to have become more prevalent than the rest. These four are: stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), and 3D printing (3DP).

3.1.2 The RM/ RP Process

In short, the primary steps in the additive process are:

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

Here the use of CAD solid modelers, that tend to represent 3D more accurately than wire-frame modelers, is a safer bet. Due to the variety of different algorithms used to denote such solid objects the STL format has been adopted as the standard by the rapid prototyping industry. This format represents the design as an assemblage of connected planar triangles (like the facets of a cut diamond). Since such planar elements cannot represent curved surfaces exactly, one has to increase the number triangles to improve the approximation of 'smoothness', inevitably resulting in a larger file size. The third step involves a pre-processing program that slices and prepares the STL file to be built. Most of these programs allow one to adjust the size, location and orientation of the design (Kwon, 2002). This ability is important since how, and where the design is placed on the build platform influences both the piece's strength as well as the time

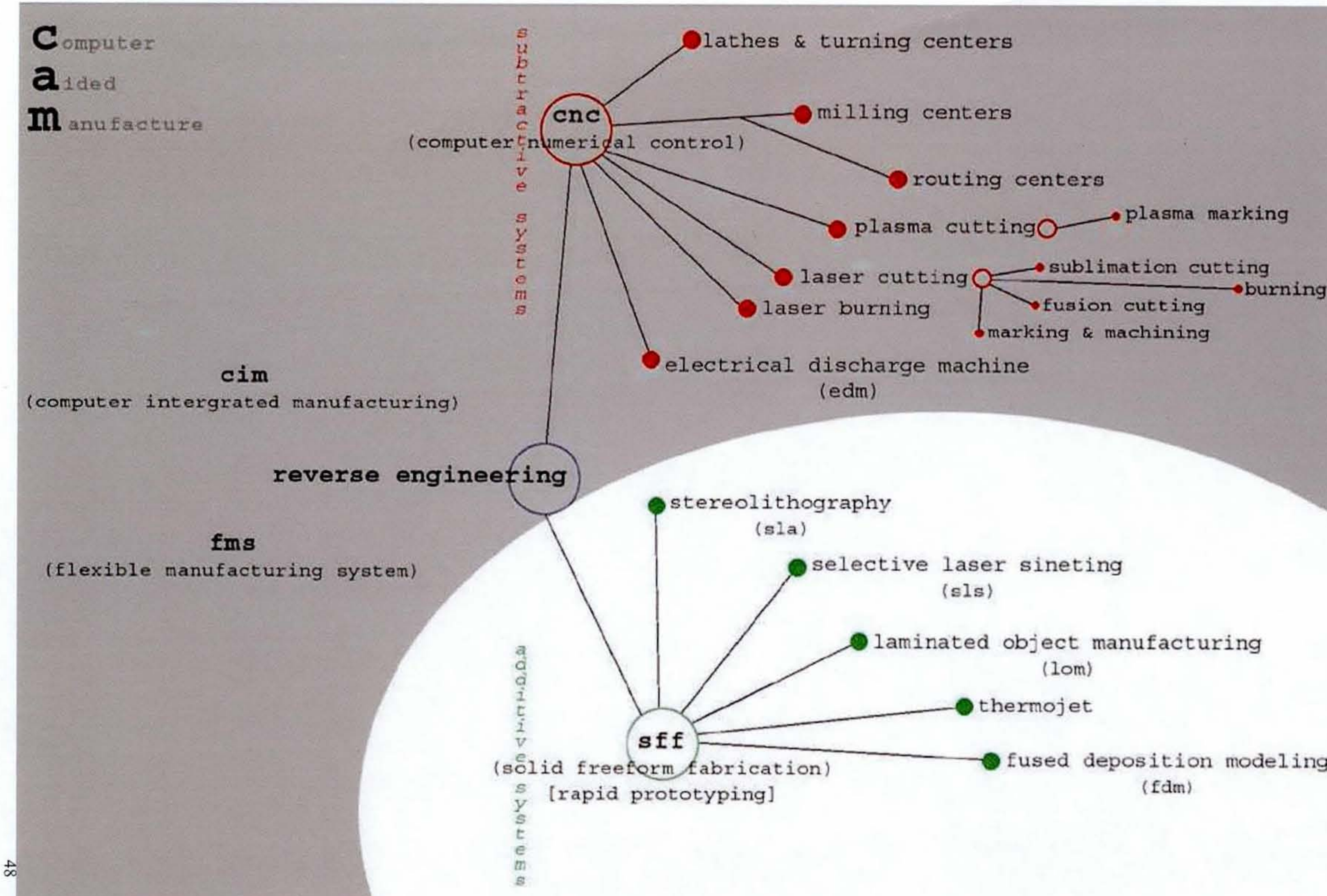


Figure 3.1

A chart, based on the descriptions and sequences provided by Nick Callicott (2001), outlining the main CAD-CAM technologies. The white area shows the technologies of particular relevance to this study.

required to build the model. The fourth step is the actual construction of the design. This phase is fairly autonomous, needing little human intervention. The final stage is post-processing. This involves removing the design from the machine and the detachment of any support structures. Some of the photosensitive materials need also to be cured before being used. Most objects may also need some additional cleaning and surface treatment.

3.1.3 The Cons and Pros of the Additive Technologies

Some of the disadvantages of the additive process are:

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

Some of the advantages of this procedure are:

- The ability to produce complex and detailed three-dimensional forms. The additive process allows for deep undercuts as well as features such as building pieces within (even enclosed) other pieces, properties that would be very difficult, if not impossible, to produce directly by any other means.
- Reduce lead times for unique parts (Callicott, 2001). Unlike in many machining operations, no jigs, moulds, or other external support devices are needed to fabricate the

object.

- As most RP processes are completely enclosed, thus producing very little noise and waste, a clean production environment is produced that allows for the installation of the machines into non-industrial environments (Callicott, 2001).
- The choice of processes and materials seems to be increasing at an exponential rate. Currently anything from metal to medicine or food-stuff can be produced through the additive processes.

3.2 A Reluctance to Engage

There is an abundance of architects and architectural practices already utilizing the additive processes for making scaled down representations of architectural proposals(Chaszar, 2006) [1]. However, this practice entails the production of an intricate architectural scale model (Kieran and Timberlake, 2004). It seems to be more of a desire to create volumetric illustrations, than something that would be innately reflective of additive processes as a catalyzing means of expression as well as fabrication.

There seems to be almost an avoidance, or at least a conflict or confusion of interest, in how some of the individuals and practices involved with digital design approach the physical realm of digital design. Examples of this would be Frank Gehry's approach, in which he, an acknowledged 'CAD-phoebe'(Lindsey, 2001), is intrinsically entwined with and dependent on the computer aiding him to realize his somewhat cacophonous, almost anti-tectonic, compositions[2]. Or a theoretician such as Markos Novak (2003) who, whilst very much involved with issues dealing with the micro-scale in conjunction with rapid-prototyping, still occupies a domain where the architectural components are somewhat hermetic and self-referential, and a number of degrees removed from the actual actualization of a 'real', physically interactive, full scale, constructs.

[redacted]

1 http://home.att.net/~castleisland/faq/faq440.htm (Accessed June 2005)

2 "The logic of the drawing has superseded the logic of the building, resulting in buildings that aspire to be like drawings [...] during construction, the uninhibited freedom of such drawings will often translate into a building that is very difficult to construct, and so the logic of the building stands in direct contradiction to the logic of the drawing that inspired it". Bruce Lindsey quoting Dan Willis from his book emerald City, Lindsey, B. Digital Gehry - Material Resistance, Digital Construction, Birkhauser, 2001, p 23.

3.2.1 RP in Architecture

On a slightly different tack, would be the work of Laurence Sass at MIT, Department of Architecture (2003), Mark Burry, professor of Innovation (Spatial Information Architecture) at RMIT University of Melbourne[3], and Dennis Dollens, professor at the Genetic Architectures program at ESARQ, UIC, Barcelona (Dollens, 2001). All three of them, in their own way, whilst still relying on using the RP process for the production of models, have allowed the process to transcend beyond a representational device into something that is intrinsically connected to the physical outcome of the process, and that would have would have been much more difficult to discover without utilizing rapid prototyping as a key ingredient in the realization of their designs.

In regards to the subtractive and formative[4] means of shaping things one should include individuals such as Gregg Lynn[5], Bernard Cache (2002), and Achim Menges and Michael Hensel (Menges, 2004), as well as the group of like-minded individuals called Sixteen *(makers) (Callicott, 2001), who are all directly involved, immersed even, in the CNC (subtractive) fabrication, as well as allowing the more physical aspect of the digital conception process to influence the outcome.

Procedural traces, similarities in interests, if not directly involving additive fabrication as the main catalytic protagonist, can also be found it the work of people such as Mike Weinstock (2002), Ocean North[6], Office da[7], Mark Goulthorpe (2002, 2008) (Decoi[8]), Kas Oosterhuis (2002), Lars Spuybroek (Zelner, 1999), Peter Testa[9] and Francois Roche[10] to mention a few, who are all exploring various methods in which the digital component is intrinsically linked to a physical outcome…

3 Theme discussed in person with professor Burry in Barcelona, October 2007.

4 The subtractive process entails shaping techniques such as milling, turning, or electrodischarge machining (EDM). The formative means that no material is either added or removed, but opposing pressure is applied to the material to modify it into the desired shape. Examples of this technique are automated bending and reconfigurable molding. http://www.Ennex.com/~fabbers/intro.asp (Accessed April 2005)

5 http://www.glform.com/ (Accessed April 2005)

6 http://www.ocean-north.net (Accessed June 2006)

7 http://www.officeda.com/ (Accessed June 2006)

8 http://www.newitalianblood.com/progetti/695.html (Accessed Jaunuary 2007)

9 http://span.vox.com/library/post/a-conversation-with-peter-testa.html (Accessed February 2007)

10 http://www.new-territories.com/ (Accessed March, 2006)

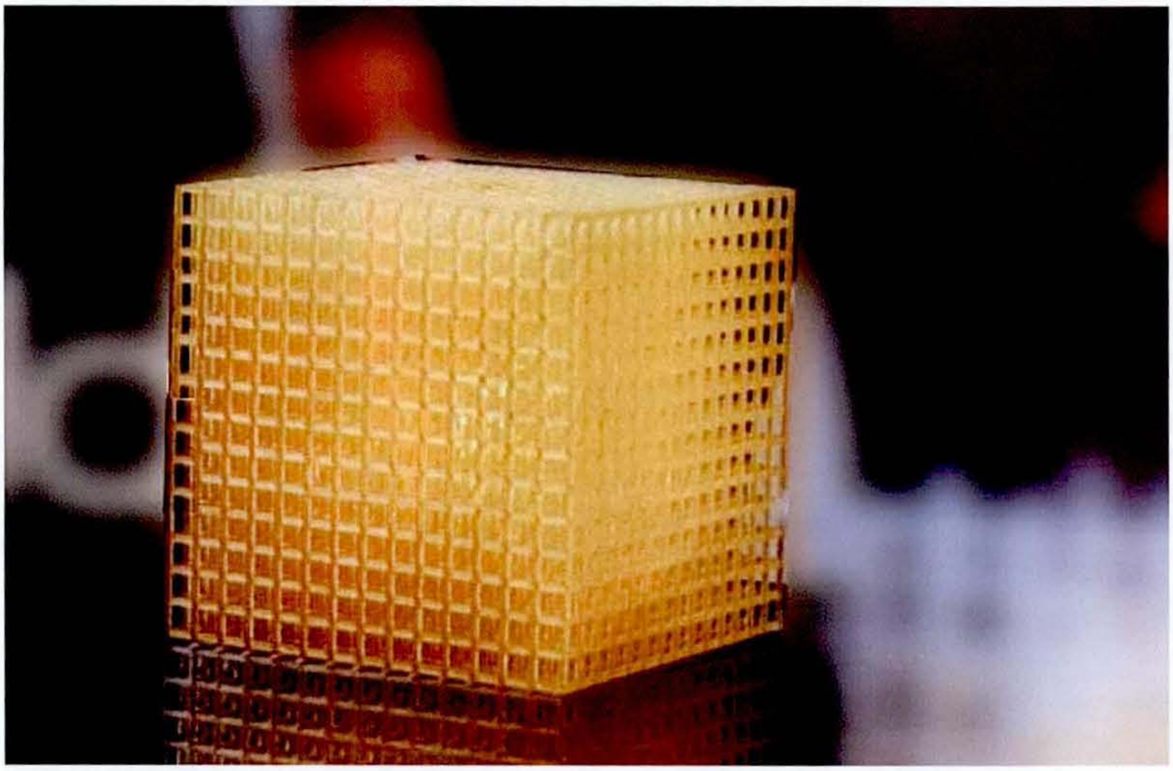


Figure 3.2 A light design by Freedom of Creation, made by using stereolithography...

3.2.2 RM for End Users

If not strictly architecture, there are a number of instances where the RP/ RM process is already used for both the conceptual development as well as the physical execution of a design. 'Freedom of Creation' is an Amsterdam based company started by by the duo Janne Kyttänen and Jiri Evenhuis, which design and produce designs using exclusively the additive processes (Fig. 3.2). They've produced a number of, mainly lighting designs, using both stereolithography and Selective Laser Sintering (SLS). Recently, however, they've expanded their 'repertoire' to include an RP/ RM based, chain-link like, textile, as well as tessellated SLA seat[11]. Their work has adopted a intrinsic textural and translucent qualities of RM materials and processes as elements in their designs. Similar pursuits, in a slightly larger scale, have been realized by Assa Ashuach[12] (Fig. 3.3), Patrick Jouin[13] (Fig. 3.4), and the Swedish collective Front[14] (Fig. 3.5), although most of these work on a conceptual level, and, as a stool, chair, table, aren't robust enough to fulfil their intended function.

Additional projects with a kinship to the design approaches above, are the Interaction Design Department at the Royal College of Art[15]; by Fiona Raby and Anthony Dunne[16]; work by Random International, a London based collective involved with, as they state on their web-page, exploring the "friction between the digital and analogue domain"[17], and a project titled 'Orpheus Filter' by the Canadian Architect Philip Beesley and the artist and scientist Diane Willow, who have managed to produce an, almost textile-like, pattern of interlinking feather like mechanisms (CNC-cut mylar, latex and acrylic components) that together form a 'living wall' that slowly converts surrounding material into a living and fertile surface[18]. This project manages to fuse the processes of both entropy and organic transference with the digital fabrication methods, a notion the final fabricated exhibit display encapsulates in a surprisingly intrinsic and moving fashion. In a somewhat similar fashion, where the layering processes themselves

11 http://www.freedomofcreation.com. (Accessed November 2004)

12 http://www.assaashuach.com/ (Accessed October 2005)

13 http://www.patrickjouin.com/ (Accessed April 2005)

14 http://www.frontdesign.se/newsupdate_JAPAN_TOKYO%20WONDER%20SITE_02.htm (Accessed November 2007)

15 30. http://www.interaction.rca.ac.uk/ (Accessed May 2007)

16 http://www.interaction.rca.ac.uk/ (click 'research studio' heading…) (Accessed May 2007)

17 http://www.random-international.com (Accessed March 2005)

18 The project was displayed at the 'Digital Fabricators' exhibit at the 'Interbuild' exhibition, held at the NEC, Birmingham, 25 - 29 of April, 2004.

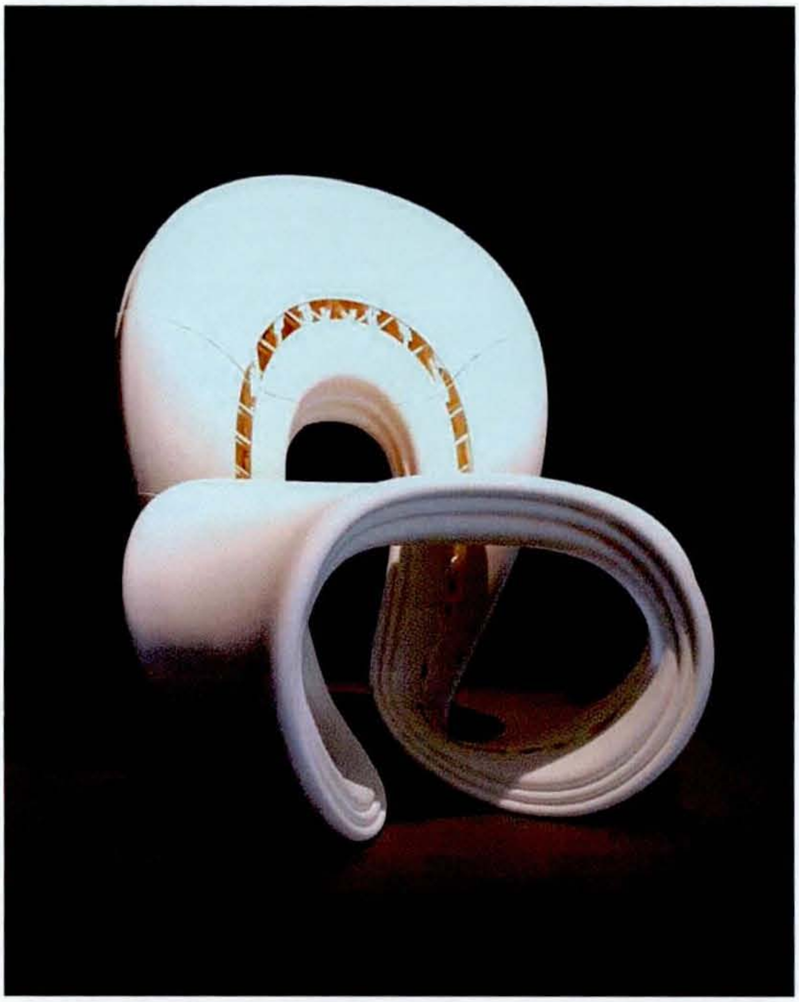
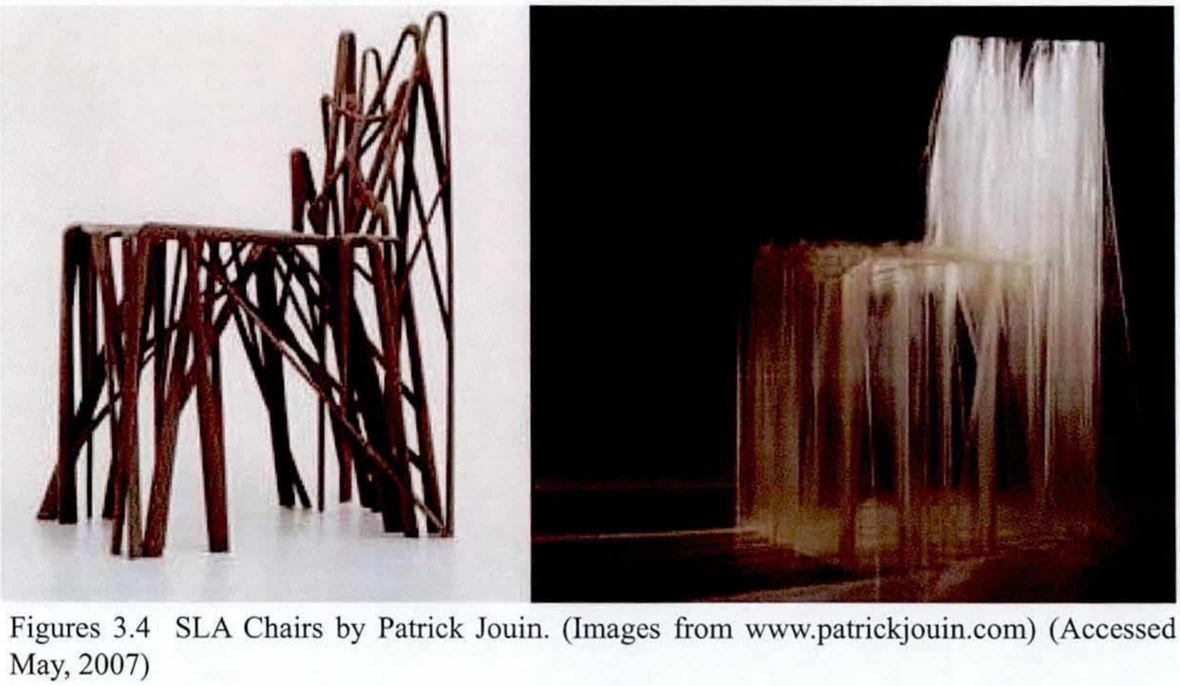


Figure 3.3 SLS Chair by Assa Aschuash and Complex Matters. (Image from www.assaschash.com) (Accessed November, 2007)



Figures 3.4 SLA Chairs by Patrick Jouin. (Images from www.patrickjouin.com) (Accessed May, 2007)

Figures 3.5 3D motion scanned and rapid manufactured furniture pieces by Front. (Images from www.frontdesign.se) (Accessed June, 2008)

are applied as a catalyst, a modest project by the the designer Itay Ohaly[19] displays a sensitivity to the basic core qualities of these means of fabrication. A layered stratum of thickness is created by painting onto a wooden table a layer of acrylic paint a day, thus block of layered matter is consequently cut out and re-shaped into a variety of smaller objects (mostly jewelry).
As a more directly RM related reference a project worth a note is the REPRAP project[20], initiated by Adrian Bowyer, which sole aim is to create a machine that can reproduce (a copy/ clone of) itself. Future Factories[21], a project initiated by Lionel Dean which explores the notion of 'mass customization' within the realm of product design (lighting, pendants), has somewhat similar ambitions, only with a twist.

Examples of two current ongoing schemes which interests correspond, on a more conceptual level, with those of this study are, firstly, research being conducted at MIT by Neri Oxman, who, according to the author Bruce Sterling, is practising something he refers to as 'New Materialism' (Sterling, 2008)[22]. Ms. Oxman's work deals directly with the material qualities and fabrication means involved with the various additive as well as subtractive processes, and hybrids thereof. Similar explorations are conducted by Andrew Kudless, whose company Matsys,[23] and the practice 4M Group[24], both in their owns ways are expanding what the link between the digital and analogue realms.
A project, which was developed in conjunction with, and catalysed by, some of the earlier schemes affiliated with this study, are currently taken forward in a commercial sense by an UCL affiliated company called Complex Matters[25]. Here the aim is to apply some of the inherent advantages of scripting and combine and configure them according to parameters set by additive RM technologies and the materials they use. Catalysed initially by the SLA scaffolds which, in most cases, is removed and discarded at the end of a build, here would be customized, through changing the consistency, shape, angle and thickness of the minute scaffold's branches, to accommodate particular physical and textural needs of the overall design. During the time of the author's involvement, a number of tests were fabricated, which allowed one to

19 http://www.ohaly.com (Accessed August 2008)
20 http://reprap.org/bin/view/Main/WebHome (Accessed April 2007)
21 http://www.futurefactories.com/ (Accessed January, 2007)
22 Sterling, Bruce, The New Materialism, Abitare 482, May 2008. p. 138-145. See also: http://www.materialecology.com (Accessed May, 2008)
23 http://www.materialsystems.org/ (Accessed July, 2008)
24 http://www.4mgroup.co.uk (the author is affiliated with this company).
25 http://www.complexmatters.com (Accessed March 2007)

experience first-hand how the physical properties varied between various material and programmatic configurations.

3.2.3 RM in Construction

Projects that are utilizing the various additive fabrication means seem to be expanding exponentially, be its use applied in design architecture, engineering, medicine, fine art, or any of the additional more and less related disciplines, and new venues of use published almost daily. However, most of them are still, as of yet, realized at the scale of product design, i.e. the things made through the additive CAM technologies can still best be described as belonging to the family of 'objects' rather than fitting within the realm of architecture (if one excludes architectural models from consideration). Larger scale fabrication processes can mostly still be found only within the realms of academia, an example of which the Freeform Construction[26] venture at Loughborough University would be a prime example, and some of the research conducted in Switzerland, at the ETH Zurich, Department of Architecture, under the guidance of Professors Fabio Gramazio and Matthias Kohler[27]. As examples of other large scale techniques currently under development can be mentioned the Monolite process[28] developed by Enrico Dini in Italy (Fig. 3.6), and the much published large scale additive process of Contour Crafting[29], developed by Behrokh Khoshnevis at the University of Southern California (Fig. 3.7). The Mammoth SLA by the Belgian company Materialise, which allows for single over two meter builds alos provides a means suggestive of an architectural scale[30]

3.2.4 An Evolving Domain

Most of the latter aforementioned examples are still in the process of being developed, and thus in many ways a true reflection of the stage and state this still budding discipline is currently - still not yet settled and in lack of established generics, is nevertheless saturated with potential. What format(s), or taxonomies will be used to guide its progress and practice remains to be

26 http://www.freeformconstruction.co.uk/ (Accessed March 2007)
27 http://www.dfab.arch.ethz.ch/?lang=e&loc=AF&this_page=lehre (Accessed June 2008)
28 http://www.monolite.org/ (Accessed June 2008)
29 http://www.contourcrafting.org/ (Accessed November 2006)
30 http://www.materialise.com/materialise/view/en/91687-Mammoth+Stereolithography.html (Accessed June 2008)

Figure 3.6 The Monolite system by Enrico Dini. (www.monolite.org. Accessed October 2007).

Figure 3.7 The Contour Crafting process by Behrokh Khoshnevis at USC. (www.contourcrafting.com. Accessed September 2006).

seen. This is also the realm where its potential lies, as each stand or approach will not necessarily have an already set standard or logistic structure, and currently such configurations can be customized according to the needs and objectives of the project, rather than according any pre-established tenets. Considering the exponential growth in the use of these technologies within the academic community, as evident from the more recent architectural and design end of the year shows that take place usually at the beginning of the summer season at the various academic institutions, such expansion of how the current use of RP can expand into RM and LF, is only a matter of time.

3.3 Tactile Topographies – the Gestalt of Touch

Pallasmaa (1996) states that "the hands are the sculptor's eyes. […] The skin reads the texture, weight and temperature of matter. The surface of an old object, polished to perfection by the tool of the craftsman and the assiduous hands of its users, seduces the stroking of the hand. It is pleasurable to press a door handle shining from the hands of the thousands that have entered the door before us; the clean shimmer of ageless wear has turned into an image of welcome and hospitality. The doorhandle is the handshake of the building. The tactile sense connects us with time and tradition: through impressions of touch we shake the hands of countless generations. A pebble polished by waves is pleasurable to the hand, not only because of its shape, but because it expresses the slow process of its formation; a perfect pebble on the palm materialises duration; it is time turned into shape."

Pallasmaa, a Finnish architect and academic, provides a suggestive synopsis and introduction of many of the factors that affect the way we perceive and interpret the impressions of our tactile sense, factors that include not only the directly physical or cutaneous sensations, but also the emotional and environmental factors, cultural influences, personal penchants, mnemonic notions as well as factors such as kinaesthetic conditions or the level of stereognostic awareness of the particular individual in question. This last notion, that denotes our ability to perceive objects or forms through touch (Montagu, 1986), is here of particular significance as it is this capacity that allows us to 'read' (as in Braille) and thus abstract and personalize, tactile impressions into a format and language more digestible to us – a format that allows for subjective expression and creative articulation within, and based upon, its own linguistic confines. As it will become apparent later in this thesis, such touch related notions are a defining factor in its formulation.

There is a strong link between the way we observe our surroundings through vision, and the way we perceive them through touch. Studies involving visually-disabled individuals have shown that, when asked to draw or represent an object onto a sheet of paper, a life-long fully blind person still draws the object depicted from a single vantage point and use lines to outline surfaces. They also use abstractions or analogies, such as hearts to represent affection, or curved spokes on a wheel to suggest motion (Kennedy, 2007). They use perspective and a shift in scale to insinuate location and distance[31]. This ability to represent abstract ideas through idioms that are purely tactile (which still have a pronounced 'empathy' to our visual sense[32]) is of key importance in the context of the experiment presented.

Illustrations of similar suppositions, where some concepts usually considered from a purely visual viewpoint, such as visual foreshortening that is 'neutralized' on buss-lanes by lengthening the letters[33] (Fig. 3.6 and 3.7), or the notion of the 'pan-phenomenon' – where a sequence of consecutively moving points can be used to suggest movement (as can be seen on certain 'pointing' or 'moving' neon-signs)[34] (Fig. 3.8), can also be applied to touch, and how such suggestive impressions can be made and communicated through cutaneous means.

The following segment provides a breakdown of existing taxonomies for classifying touch and its affiliated properites. These are based on research conducted by neurologists, psychologists, geographers, urban planners, architects and philosophers, to mention a few, who provide a take on the subject. The included ideas are emeshed with the illustrations that have come about whilst the thesis has evolved. The aim is to outline particular external interests that have influenced some of the designs.

31 Kennedy, John M/ Juricevic, Igor – Foreshortening, Convergence and Drawing from a Blind Adult. University of Toronto. From the authors web-page: http://www.utsc.utoronto.ca/~kennedy/ .

32 Even though this might partly also be due how we interpret the information, i.e. we perceive links between these forms of perception because we're looking for them…

33 Here the argument, however, deviates slightly from the more conventional notion of foreshortening, and, through almost reversing the observation, contends that if something haptic is perceived whilst in motion one can counteract the effect of the motion by literarily 'stretching out' the element that is being felt, i.e. if one perceives a raised dot through simple finger probing, the same dot needs to be extended in the direction of motion (changing it into an oval dot) if is to be perceived as a dot whilst moving…

34 Touching someone on their forearm at sequential points will inevitably suggest the point is 'moving'…

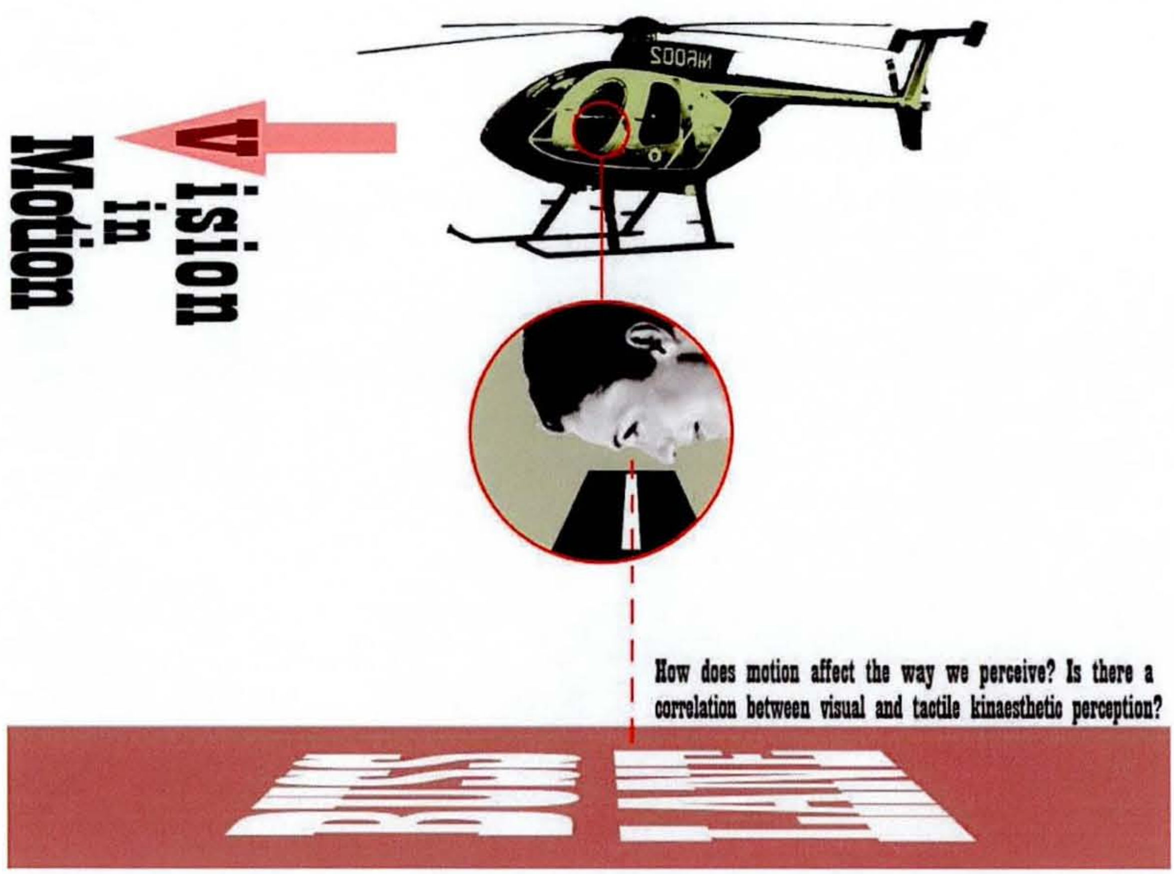


Figure 3.6 Haptic foreshortening can also be applied to touch. Here something perceived in motion through touch can be made perceptually clearer by extending/ lengthening the tactile shape in the direction of the motion...

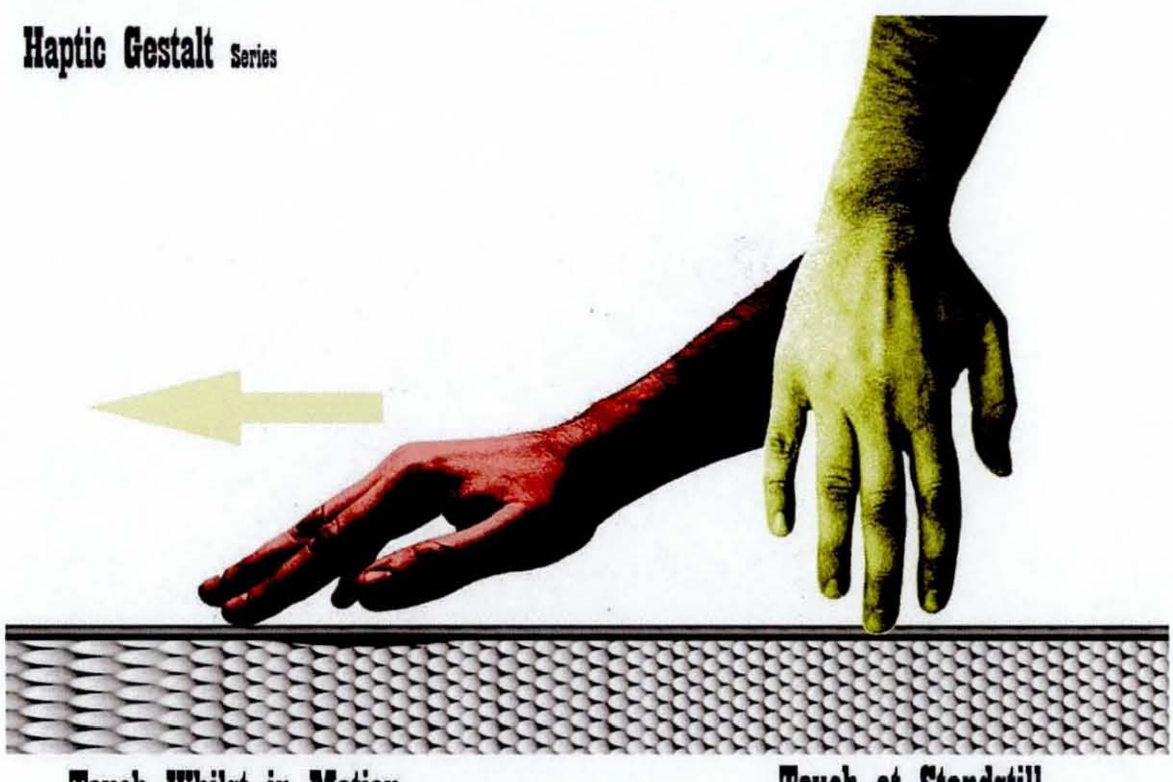


Figure 3.7 Touching whilst (body is) in motion versus 'exploratory' (doubting Thomas) touch...

3.3.1 Types of Haptic Reciprocity

According to Rodaway (1994), a geographer, there are three primary levels of haptic reciprocity in environmental experience. These are:

- *Simple Contact* – the adjacency of two surfaces against one another, usually impermanent, and often involving only one tactile sentient agent. Such contact generally involves passive touching or grazing against an alternate entity. This kind of contact is by definition simple contact with the environment but may not consciously take much notice of it. The active agent is conscious of a stream of haptic sensations giving a rich, predominantly subconsious, supply of information about the environment explored (peripheral awareness of one sitting on a chair, wearing a cotton shirt...).
- *Exploratory Activity* – One way exploration. An agent actively investigates the environment (organic or non-organic) but the environment explored is largely passive and does not respond to the touch nor appear to register its own tactile sensation (a hand exploring a surface).[35]
- *Communication* – the contact is actively intended, by one or both, but each party responds specifically to the other's tactile stimulation and messages are exchanged. This communication is generally a relationship between organisms and forms an important part of the bonding of community and the sense of establishing roots in a place (a handshake, a hug) (Rodaway, 1994).

3.3.2 Touch Formats

According to Rodaway (1994) levels of touch may be specified into the descriptive groups titled: Global touch, reach touch, extended touch and imagined touch.

- *Global Touch* – represents the body's general contact with the environment, a vernacular awareness. Global touch is the presence of the body in a context, a sense

35 An alternative classification of such levels of haptic experience is provided by Ashley Montagu, who divides them into three categories named: Social touch, Passive touch and active touch, which differ in their emphasis of the abovementioned haptic properties, but deal, more or less, with the same issues. See: Montagu, Ashley – Touching – The Human Significance of Skin. Harper & Row Publishers, 1986. p. 169.

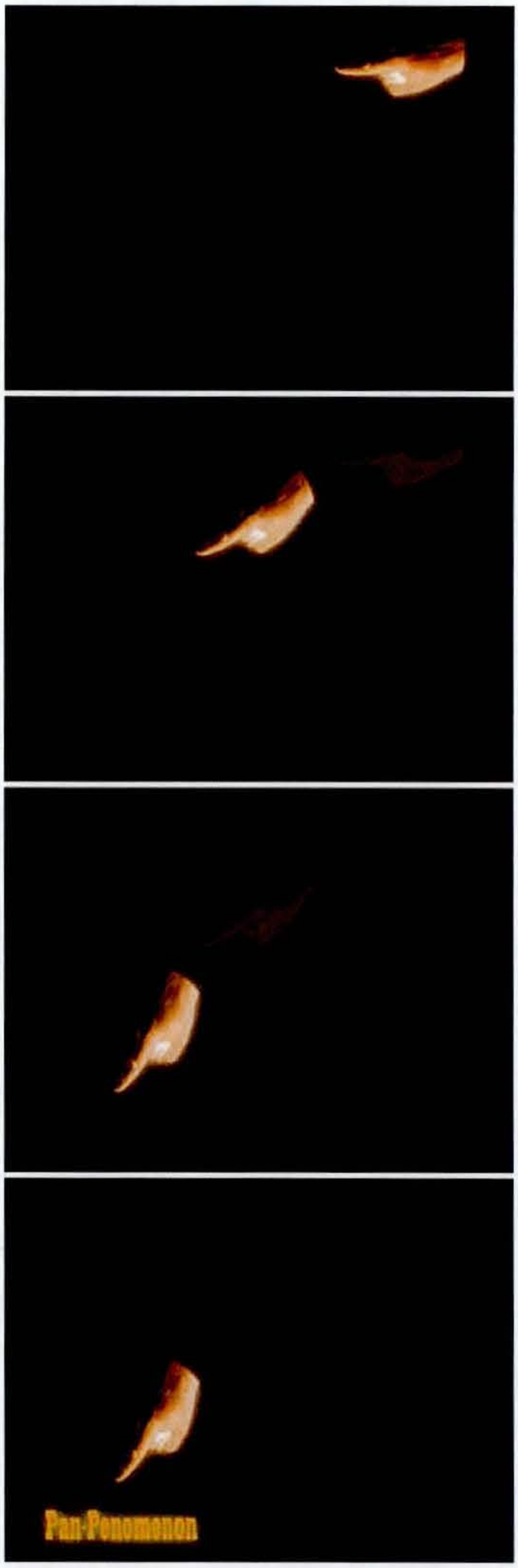


Figure 3.8 A tactile rendition of the Pan-Phenomenon...

of itself within a world. This is generally a passive experience, a general feeling of one's body and its immediate environment. This geography is not so much about distance and spatial relationships, as about a general presence such as feelings of uprightness or basic body orientation, temperature, humidity and perhaps the relative crowding or space in its most general sense[36]. The experience of global touch is quite difficult to describe. The blind frequently refer to a strong sense of the presence of objects not directly touched but nevertheless felt as a kind of pressure in the air around the body. A form of ambient epidermal perception.

- *Reach-Touch* – is the form of touch we most immediately think of in everyday use of the term. It is the touch of the hands, arms, fingers and toes. It is exploring touch which reaches out to, takes hold of or feels the characteristics of objects and their relationships in the environment around us. This is active and generally grounded in intention. Reach-touch is employed both in exploratory activity and in supporting navigation through the environment.
- *Extended Touch* – in terms of spatial experience touch can reach far beyond the im mediate geography of the body with the aid of tools. Extended reach is touch mediated by or enhanced with technology. The white cane used by the blind person is only one example of the numerous instruments used to extend the human reach. Often these instruments do not merely transmit contact information from a greater distance than our body reach but transform tactile information into other sensuous forms. The white cane not only offers vibration as it is tapped, but also sounds which can be heard and used in spatial orientation.
- *Imagined Touch* – is a haptic experience rooted in the memory and expectation. This is demonstrated both in our use of touch metaphors to describe sensuous experiences and in the creative recall of haptic experiences, as when reading a description in a novel or when remembering a treasured experience. (Rodaway, 1994)

Here the above notions of reach touch, imagined touch and extended touch are of particular

36 In an additional example a reference is made of a somewhat similar form of perception titled 'Dermo-Optical Perception' (Montagu 1986), which describes it as a an ability by certain individuals that claim to have skin so sensitive they can 'see' with/ through it. He continues to explain, "Since the skin is derived from the same embryological ectodermal layer as the eyes, several investigators have maintained that in such individuals the skin has retained some primitive optical properties, and it is this that enables them to see with skin." Montagu, 1986, p. 185.

significance as they provide summaries for design and modelling methods[37] used and grant analogous and reinforcing heading for encapsulating the qualities of touch, referring to the actual reciprocal experience and connection between the design and the tactile impressions or impact it has on its user.

3.3.3 Affective Expressions of Touch

On a immediate and intimate level, the physical, corporeal and assimilated qualities of touch were categorized in the following fashion:

- Surface – texture, pattern - that is roughness or smoothness, degree of friction and details of surface variation.
- Geometry – shape, dimensions or size, proportions and arrangement, generally relative to human scale and cutaneous perception.
- Material – the mass or weight of objects supported by the body or parts of it, and the perception of material rigidity or plasticity.
- Location – distance from us, either in terms of direct or extended reach, and directions relative to our body orientation – front, back, right, left, up, down.
- Energy – the judgment of a wide range of temperatures of both objects and environments, and their dampness and dryness (relative humidity).
- Dynamic – vibration and locomotion, that is perception of movements 'within' objects and of objects through space, relative to our own body and/ or other objects in reach. (Rodaway, 1994).

These elements all come into play and are utilized in an architectural and behavioural context. What the hand perceives can be used to suggest how the rest of the body ought to conduct itself. Through the use of the textural and qualitative features listed above (surface textures through dynamic movements) surveyed through reach-touch, one can conduct exploratory activity that, through a form of imagined touch and experience, can be used to imply a variety of ideas or actions. This involved using methods such as increasing or lessening the friction of

37 Here referring to the Sensable haptic interface that is used in conjunction with the software 'Clay Tools'.

a surface to suggest what speed one should move; skewing or increasing the oblique angle of a tacitly perceived plane to insinuate a turn; or by changing its location, height or horizontal position to reposition its user[38].

3.3.4 Tactile Gestalt

On a wider scale and framework the tactile qualities were used to support and clarify the reading and understanding of an environment.

In his seminal work, Image of the City, Lynch (1960) puts forward the notion of cognitive mapping to (Malnar and Vodvarka, 2004), define the mnemonic representation of spatial information we have stored about our physical and sociocultural environments. According to Lynch, environmental images can be divided into three components, identity, strucutre and meaning, that, for the sake of analysis can be separated (Lynch, 1960), but in reality always manifested together. Here identity, is an object that can be identified as a singular, distinct entity; structure, the spatial or pattern relation to the object and the observer, as well as other objects; and meaning, the object must retain some (practical or emotional) meaning to the observer. Malnar and Vodanka consider that these notions entail that, an image useful for making an exit requires the recognition of a door as a distinct entity, of its spatial relation to its observer, and its meaning as a hole for getting out. This idea is further clarified by John Lang (1987), who notes that, "a highly imaginable city, building, or interior is one that is perceived as a structured system of related components".

It is, however, the elements Lynch uses to form, what he calls, cognitive images, that have a distinct resonance of Jungian archetypes about them, which are more relevant to this study. He identifies these as: Paths, Edges, Districts, Nodes and Landmarks (Lynch, 1960). Here Paths are the streets, sidewalks, corridors, the passages found in our environment; Edges symbolize representational boundaries, the walls, buildings, shorelines, rivers, embankments that separate areas; Districts are usually large areas with fairly distingushable characteristics, such as business or entertainment areas, or parks; Nodes are key focal points (building or city entrances, central courtyards, stairwells); and Landmarks are clearly distingushable, dominant physical elements, the main Opera building or museum, a preeminent bridge, a central square. These

38 Nudging its user into a desired location or position by aligning the locations of the surfaces and textures so as to 'pull' the user with it.

Figure 3.9 An adapted rendition of gestalt, applied to touch...

categories were used by Lynch to describe various features relating to urban planning, however, they can also be easily adapted to other, architectural or urban (micro, meso, macro) scales and comparisons (Malnar and Vodvarka, 2004). They are also useful, and are distinctly analogous, to the elements used in this study to define the features of the Snakeskin's various tactile surfaces, as well as providing a suggestive morphology and template for the different neologies built around the process of conceiving things through the additive CAD-CAM systems.

However, on an even more comprehensive level, these conceptual models provide a foundation that can be applied to clarify and aid, in this instance through a simplified tactile language, the way in which one can read and orient oneself across or through a variety of different spaces and conditions. Here the aim is to apply and provide these conceptual generalizations with an actual and, somewhat subjective, interpretation that is proactive in its intentions rather than retroactive in its analysis. The purpose is to explore further, define and make use of the notion, as simple as it is, of a 'Tactile Gestalt', an innate and tacit language of haptic form, and to both situate and use it to corroborate the applicable designs.

However, here the notion of a gestalt is defined, different from the usually visually based tenets, according to touch based perceptual principles. This entails that, by shifting the sensory mode from the visual, a more disconnected and somewhat empirical, even abstract, sense, to a more intimate and palpable mode of perception, the format of the gestalt also switches from its customary conceptual and intangible mode into one that is more concrete, immediate and corporeal. This view is supported by Goethe, who, here quoting Hensel and Menges (2006), "… posited a crucial distinction between Gestalt, or structured form, which refers to that which is already formed and the process of Bildung, or formation, which changes structured form in an ongoing process". Here, in regards to the haptic structure of form, the more inert and cerebral format of a visual-gestalt is reinterpreted as a more active and tactile notion of 'formation' (a switch from a noun to a verb), of a 'tactile-gestalt' – a constitution of form which is inherently kinaesthetic (as no 'touching' can be done without involving some level of motion) and which naturally combines the qualities of both the more traditional reading of gestalt, with the idea of bildung (bildung-gestalt). Ultimately, in an ideal situation, this tactile format of expression would evolve into a intuitive haptic lingo that allows for things such as touch based 'slangs', 'accents' or 'dialects' to evolve, perhaps in a similar fashion to those that have grown around sign-language, where apparently to those who use sign-language ' as their mother tongue' is, it is easy to distinguish the signing of those who only use it as their 'second-language' (hearing individuals), and even to discriminate the origins of a fluent signer through their 'signing-accent' (Rée, 1991). Some traces of comparative, more cutaneous, forms of communication can be observed in the work of the Turkish, blind from birth, artist Esref Armagan, whose paintings and bas-reliefs contain, in their empathetic expression, a effortless tactility[39], or the 'Braille Graffiti', by the artist Scott Wayne Indiana, that can be found at select locations in Portland, Oregon[40], along with the more formal austere tactile vocabulary of corduroy and blister paving, found usually along urban pathways[41]. As examples of digital interfaces that allow one to use touch as an intrinsic medium in the formation of a design worth a mention would be Jeff Han's 'Multitouch' interface, that allows one to manipulate things on a large touch-screen through ones fingers and arms[42], and the Pahntom haptic interface by SensAble that, in union with its affiliated software 'Claytools', allows one to shape and mould voxel based models through touch. This latter example has also been extensively used in conjunction with this study.

3.3.5 Digital Tactility

In many ways some of the thoughts by Bloomer and Moore (1977) expand such notions into a more general tacit realm, where tactile perceptual aspect aren't relegated into a particular hermetic niche, but recognized as fundamentally key elements in our reading and conception of our environment and in defining our individual character, or as they put it, "the expansion of our actual identity requires greater recognition of our sense of internal space as well as of the space around our bodies. Certainly if we continue to focus radically on external and novel experience and on the sights and sounds delivered to us from the environment to the exclusion of refining and expanding our primordial haptic experiences, we risk diminishing our access to a wealth of sensual detail developed within ourselves – our feeling of rhythm, of hard and soft edges, of huge and tiny elements, of openings and closures, and a myriad of landmarks and directions which, if taken together, form the core of our human identity". These notions, expressed over thirty years ago, along with the other classifications of touch, provide also an

39 http://www.esrefarmagan.com/ (Accessed August 2007)

40 http://www.youtube.com/watch?v=INCGzuehIL0&eurl=http%3A%2F%2Fwww%2Ecore77%2Ecom%2F (Accessed August 2007)

41 http://www.accesscode.info/external/5_6.htm (Accessed August 2007)

42 See http://blog.centopeia.com/2007/03/21/jeff-hans-multitouch-demo-ii/ and http://cs.nyu.edu/~jhan/ftirtouch/ (Accessed August 2007)

appropriate and relevant rationale for how the haptic sense(s) need to be included as a fundamental element in any design process, regardless of aim. This applies particularly to digital and computational design[43] that, through the formats of current interfaces (mostly mouse and keyboard), and due to the expanding programmatic interests, which in many cases seem to gradually move further away from the physical realm, result in further separation between how we represent things and how we actually experience and perceive them. Acknowledging that design, any design, always involves a more comprehensive sensory affect that those provided by vision and hearing alone is crucial in this context (Fig. 3.10). How to include such considerations more fully into the context of digital design is a task that is still in the process of being established. However, the initial memes and morsels of subjects that carry and raise related issues are already permeating the ether, it should only be a question of time before such interests regain a more pervasive position within the related disciplines.

43 Especially when considered in the context of architecture.

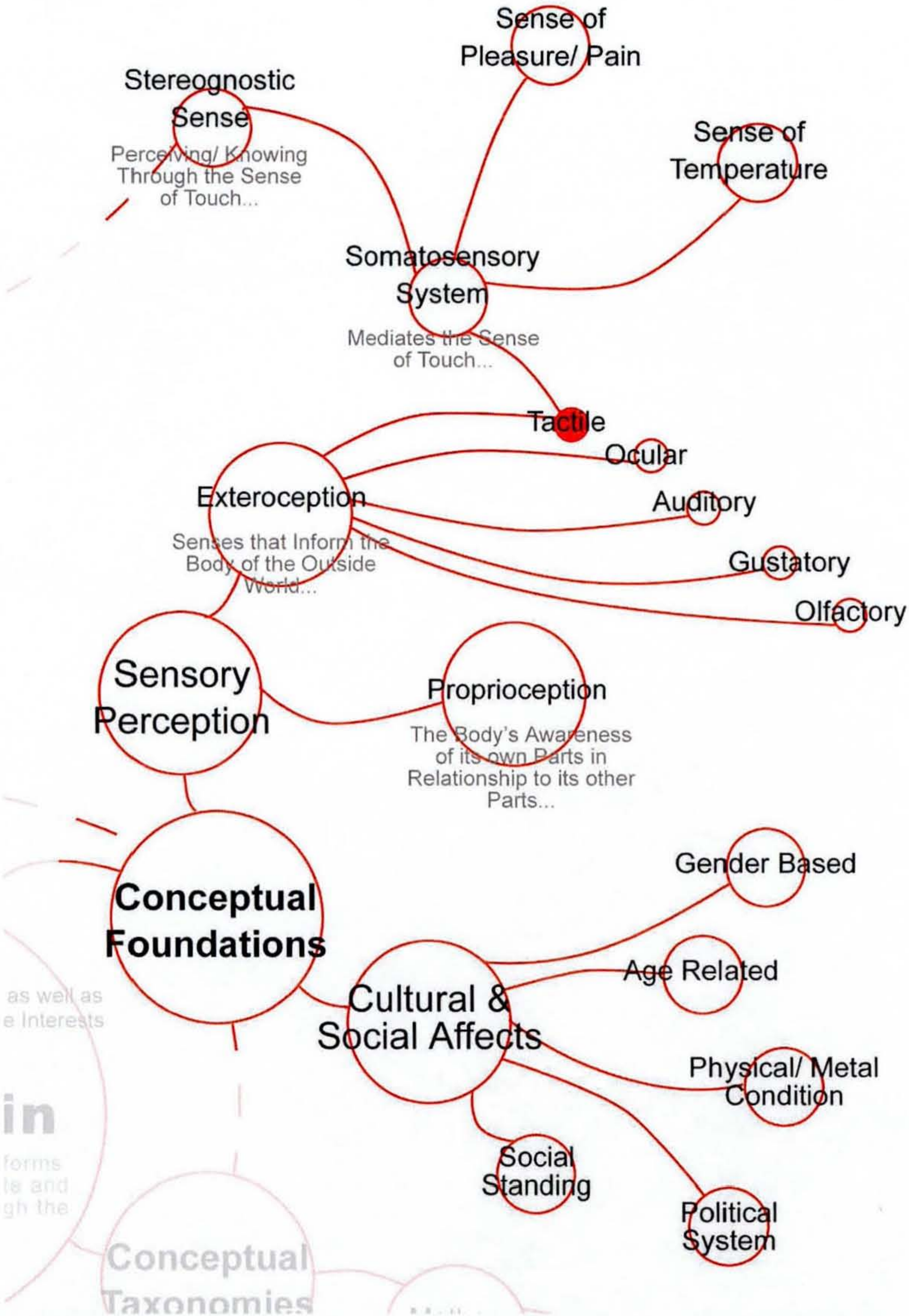


Figure 3.10 A breakdown of some of the perceptual and conceptual foundations that have been informing the thesis.

4.0 A Classification Method for Material Led Digital Design

The following chapter introduces the more theoretical foundations, both process as well as conception based, from which the thesis has emerged. It begins with a theoretical positioning of its approach, continues with a discussion about the more application related concerns linked to making things through the additive fabrication technologies, notions which are consequently expanded on through a particular application of a process reflective, made-to-fit, LF-model and terminology.

4.1 Reaching Beyond the Virtual

The thesis aimed to establish a way for using Layered Freeforming in both the conceptualization and the actualization of designs and architecture. It aimed to conceive designs which exploit process capabilities and to make designs that directly benefit (be it in something as subtle as in its texture or material consistency, or something as fundamental as its form), from making it through Layered Freeforming (LF for short), and which would be difficult, if not impossible or senseless, to make by any other means[1]. It was catalyzed by the tactile potentials that the LF introduces. As a means for producing real and physical components, which retain the advantages of CAD (Computer Aided Design) as a medium, to avoid some of the pitfalls the same medium inevitably possesses due to its 'virtuality', non-materiality. LF could reintroduce some qualities of conception, i.e. that of the cerebral and conceptual, and that of the inherently tactile and (multi) sensorial.

4.1.1 A Shift in Paradigms

The computer is a medium that acts simultaneously as an initial 'thumb-nail-napkin-draw-

1 In slightly more detail this entails that LF allows one to produce complex, asymmetrical shapes, even one with deep undercuts; but also to utilize and consider the traces that the fabrication process itself produces - the visible and tactile, usually grid-like, patterns left by the support structures in stereolithography, or the almost fingerprint like grain that results from the, layer by layer, 'stair-stepping', process. Also, as presented in Pierluigi Serraino's book titled History of Form Z*, "The debate on CAD in 1986 led Yessios [the developer of the 3D software 'Form Z*'] to claim (Yessios, 1986, Yessios, 1987) that CAD was the acronym for Computer Aided Drafting as opposed to Computer Aided Design. The crux of the contention was that if computers were unable to produce better designs, part of the raison d'etre, i.e. to "aid" design, would have failed." Found in, Serraino, P. History of Form Z*, Birkhauser, 2002, p 21.

ing' or sketchbook, as the tool for executing the various drafts and amendments, which result eventually in the final rendition of a design. It is the 'pen' (brush, pencil, crayon, etc.) as well as the 'paper' (canvas, film, background, etc.). CAM (Computer Aided Manufacture), can perform the role of a 'hand' (instrument, extension, tool, etc.), to directly shape 'matter' (material, substance, clay, etc.) which presents a fundamental shift in how ideas are introduced and conceived. This synthesis of the medium is here conceived as a positive and catalytic device. A number of degrees or stages separating the inceptive seed of a sketch from the final design are abridged, and even eliminated. By using the computer in the outline phase, as well as the final draft stage, the need to 'interpret' the drawing is removed. The sketch is the design, albeit be it still in its initial stage, that will finally result in a built design. It's a question of a *transition* over a *translation*.

4.1.2 Beyond Ocular Bias of Human Perception of Design

The project was also catalysed by a reaction against CAD based design and visually biased architecture, made "to please the eye". This it does in spite of the fact that architecture, unlike many of the other (particularly 'visual') arts, such as painting, photography, graphics, even sculpture[2], inevitably entails a multi-sensory experience. There's a risk of, as McCullough (1998) puts it, "common sense becom(ing) visual sense. Innate sensibilities - always the blessing of the artisan - become increasingly visual, and other skills slowly vanish. The experience in which most people become most practiced in no longer the workings of nature or the use of hand-held tools, but rather the reading of images - staggering numbers of images. We get the picture, or, more accurately in the era of target marketing, the picture gets us." However, there are signs that the 'corporeal' side of architectural conception and craft is starting to regain a foothold[3], in a somewhat modified format. This assertion entails an avoidance of forceful [redacted] aims to negate the excessive simplification of a concept. It is an approach that

2 Usually in a gallery one can look, but seldom touch, the displays. Outdoor sculptures are a different matter...

3 The 're' of this regain is referring to the initial, somewhat counter, action regarding industrialization in the late nineteenth century by the likes of Ruskin, Morris, Muthesius or Van de Velde and the Arts and Crafts movement, which, although not against industrialiaztion nor anti-modern, did question the process of chopping up the fabrication process into numerous simple and mundane tasks, and the lack of a more generic comprehensive understanding of the total fabrication process in question, which often resulted in designs in which the manufacturing process was dictating the end result rather than the needs of the product produced. This lack of inherent skill and craft, which was a result of the industrial process rather than its cause, was what the individuals above (each in their own way) reacted against, and which this thesis is seeing a comparative and parallel development in regards to computing and the current (mostly non-direct) resultant fabrications of such CAD based processes.

accepts the inherent polysemy of a notion and looks beyond the compulsion for boundaries that seem currently so prevalent in much of our meditations and formats of perception. This last notion is something of particular relevance, as the way we perceive is affected by social and cultural factors (Hall, 1966, 1976; Rodaway, 1994). These notions are reflected in the illustration on the following page (Fig. 4.1) which shows the five primary senses (vision, hearing, touch, smell and taste) in the centre, and breaks down their physiological, and more objective, elements above, and the conceptual, culturally derived and more subjective, renditions (Malnar and Vodvarka, 2004) of perception below. The links (or strings) of the illustration are left intentionally vague as the links between the different perceptual realms tend to involve a degree of synesthetic awareness, variability and overlap (Cytowic, 2003).

4.1.3 Homotopy and Heterotopy of Perception

According to Porphyrios (1982) there are two different forms of thought, which he has named homotopy, which entails similarities, and heterotopy, which refers to dissimilarities in thought. The initial term has a very low tolerance threshold for overlapping and confusing concepts, whereas the latter term is open to contemporaneousness. As examples of design related heterotopy could be mentioned the rich, layered geometrical patterns in Islamic architecture and calligraphy, or the fusion of structure and ornament in much of gothic architecture and design. Examples of homotopy include, in contrast, the way much art is now singled out into individual units, be this through a frame or pedestal, distinguishing itself from its surroundings; or the way much of contemporary, facade based, building construction results in default solutions where the building's message remains 'skin-deep'. Branding that lacks an understanding of the layers of interaction involved in a choreography of actions, events or features such structures inevitably will involve[4] .

4.1.4 Gothic Versus the Classical as Material Design

Introduction to their book Digital Tectonics (Leach et al., 2004) architecture as a dialectic between two different, but not mutually exclusive, ways of thinking which they describe as 'The

4 These concepts and terms were also introduced and explained in an essay by Juhani Pallasmaa titled Architecture and the Obsessions of our Times (Pallasmaa, 2005).

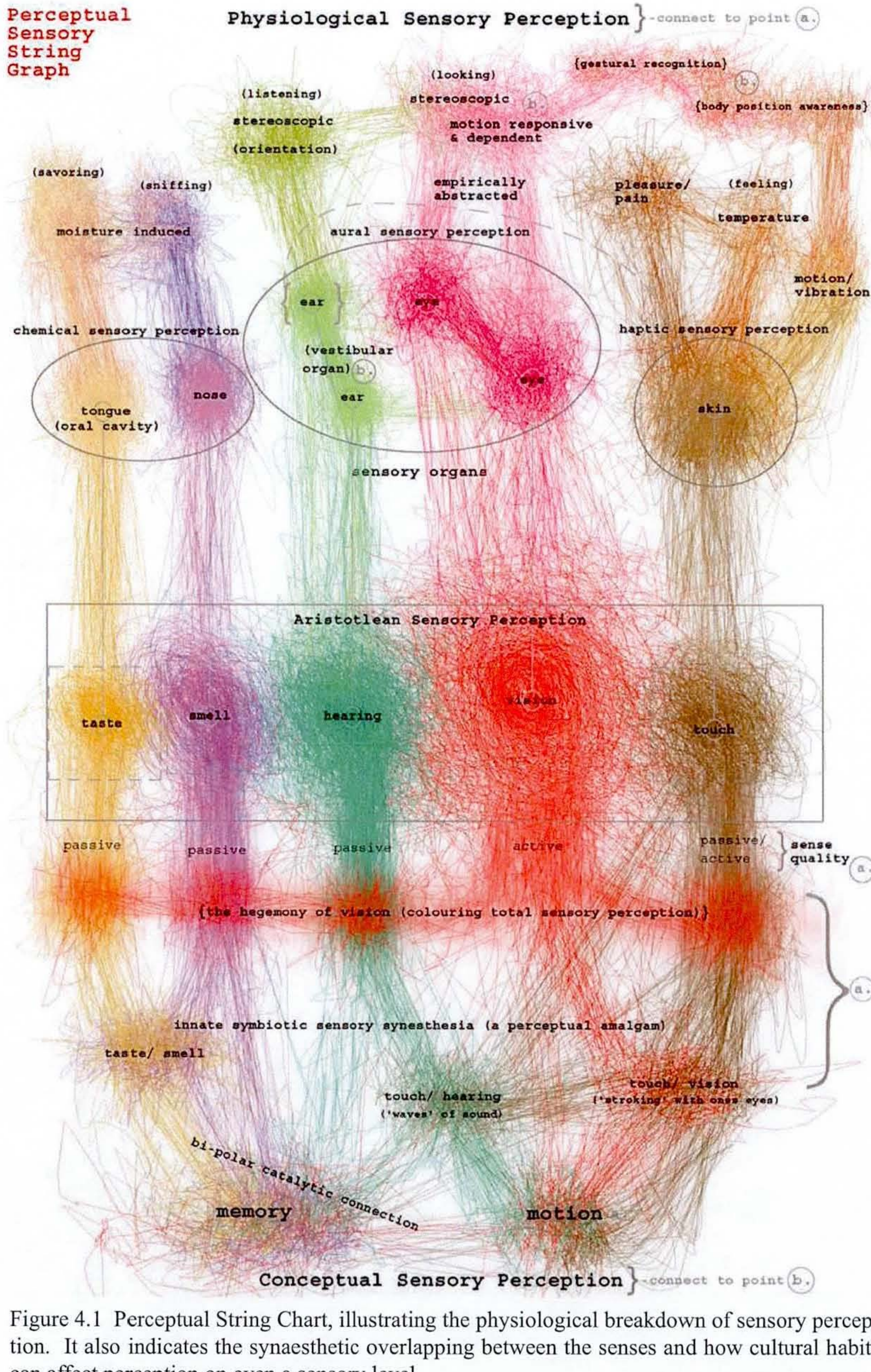


Figure 4.1 Perceptual String Chart, illustrating the physiological breakdown of sensory perception. It also indicates the synaesthetic overlapping between the senses and how cultural habits can affect perception on even a sensory level.

Classical' and 'the Gothic'. "The Gothic is based primarily on the understanding architecture in terms of materiality and structure, while the Classical is based primarily on understanding architecture in terms of visual composition." (Leach et al., 2004). The text elaborates the notions of the Gothic in the following manner, "[the] Gothic spirit in architecture, [is] a tradition based not on the formal appearance of the Gothic - as in the case of neo-Gothic - but on a certain process-oriented approach towards architectural design, that recognizes the importance of structural forces and material composition". This idea is particularly relevant in the context of this project since it, conceived with the digital (architectural) arts in mind, insinuates a shift in paradigmatic preference from the overtly visual and conceptual, to a realm where the somatic presence of material and a more craft-derived approach is allowed to flourish.

In the same book the 'material philosopher', as he himself describes his vocation[5], De Landa (2004), formalizes this idea in the following manner, "we may not be in a position to think about the origin of form and structure, not as something imposed from the outside on an inert matter, not as a hierarchical command from above as in an assembly line, but as something that may come from within the materials, a form that we tease out of those materials as we now allow them to have their say in the structures we create."[6].

These sentiments, which also need to be applied to the intrinsic fabrication processes through which such form and structure are derived, are echoed by McCullough (1998) who defines material strictures as the underpinning for conception. He states: "...[a] constraint is a source of strength. This is especially the case with respect to the nature of a material and the giving of form. Effective constraints are not explicit methods for the use of tools so much as implicit limitations learned from the behaviour of a medium. Such limitations focus the scope of process without obstructing engagement the way explicit rules do. Thus, another way of thinking of constraints is as the rigor of substance. Note that this is not necessarily material so much as structural. As we continue to note, structure is a particularly constructive source of constraint. Only though the possibilities and limitations of structured substance does expression come into being ."

5 A title bequeathed himself during his presentation in the Digital Tectonics conference held at the University of Bath, on March 2, 2002.

6 De Landa, M, 'Material Complexity', in Digital Tectonics. Wiley-Academy, 2004, p 21.

4.1.5 Fragile Architecture

When considered in the context of the additive fabrication processes, that of the material[7], and congenitally tactile, is allowed to flourish within the set and coded parameters of its process[8] into something that's innately reflective of its pedigree. At some level this suggests a reversal of the Modernist doctrine of a singular (monocock) command concept that, through the 'trickle-down' effect, affects all the subordinate components that constitute a design. How this countering of the aforesaid dogma could be formatted is suggested by the Finnish architect and theoretician Juhani Pallasmaa, who's notion of a 'weak' or 'fragile' architecture[9], is based on the sentiments initially put forward by the Italian philosopher Gianni Vattimo whose ideas about 'weak ontology' and 'fragile thought' have aroused extensive interest since the early 1980s[10]. According to Pallasmaa (2000), based on Vattimo's notions, "...we can speak of 'weak' or 'fragile' architecture, or perhaps, more precisely, of an 'architecture of weak structure and image', as opposed to an 'architecture of strong structure and image'. Whereas the latter desires to impress through an outstanding singular image and consistent articulation of form, the architecture of weak image is contextual and responsive. It is concerned with real sensory interaction instead of idealized and conceptual manifestations. This architecture grows and opens up, instead of the reverse process of closing down from the concept to the detail."
In a different text, an interview for an architectural student paper, he continues, "for me [these notions] represent an attitude towards an architecture which does not have a singular shape, or singular concept in its reading. It is a narrative which does not have a singular shape or gestalt at all, it is a narrative which can be read or experienced in a number of ways. [...] I categorize it as "fragile architecture" because it consists of separate architectural episodes; it does not have a singular image. I am simply suggesting that perhaps it is the time to begin to think of an architecture which creates an architectural narrative, or a network of possible narratives, rather than a singular image." (Pallasmaa, 2000)
It is this approach involving a multiplicity of narratives, a fragmented and emergent approach,

7 In this project predominantly photopolymers, ABS plastics and plaster powder.

8 StereoLithography Apparatus (SLA) , Fused Deposition Modeling (FDM), and Selective Laser Sintering (SLS).

9 Pallasmaa, J., Hapticity and Time (discussion of haptic, sensuous architecture.), Architectural Review, May 2000.

10 This note is in particular reference to a book of Vattimo's collected essays titled, The end of Modernity, Polity Press, 1988.

which lends itself quite naturally to the aforementioned notions. This context allows, even encourages, one to evolve an appropriate but distinctive organic craft for each design brief. In such 'fragile architecture' the analog and digital, the micro, meso and the macro, are conceived and conceptually enmeshed with(in) each other - entwined into a procedural singularity. Ultimately here the conceptual and the corporeal are united into a post-binary condition that accepts (unavoidably semiotic) categorization. It also accepts attraction and even fusions between such categories, but it does not consent to pre-set linear or hierarchical sequential narratives as necessary conditions within a conceptual framework.

In many ways this approach is echoed in a text by Hensel (2004) who, by paraphrasing Umbero Eco's notion of Open Works informs us that, "Eco describe[s] an open work as characterized by a deliberate ambiguity in meaning. According to Eco, open works must leave the arrangement of some of their constituents to the public or to chance, thus giving these works a field of possible orders rather than a single definite one. The subject can move freely within this articulated yet ambiguous field of possibilities, which serve to avoid conventional forms of expression and prescribed interpretation. At the same time Eco points out that this is not a quest for a total laissez-faire and amorphousness, but rather that there must be a guiding directive from the designer that structures the field of possibilities in some way for the subject."

4.1.6 Open Source Thinking

These means involve a new set of rules and freedoms, guides, even delusions, that all, although still predominantly structured according to binary dictates, do so in a way where practices, objects and objectives previously considered separate or even opposites, now occasionally occupy the same syncretic side of the fence. A paradigm where the various disciplines' customs and responsibilities, which formerly have been largely distinct, now enmesh duties and collaborate at almost all the different phases involved in realizing a design – be this a design for a toothbrush or a mixed use residential development.

The implication is a process without a pre-determined outcome. A process that is structured and dynamic, but also supple and adaptable enough to accept change. The exact outcome of an undetaking should not necessarily be defined at the outset of a project. A degree of 'empirical naiveté', that guide design need is needed – a form of open source thinking, if you will, which allows notions to dynamically adapt to adjusting conditions when needed. This is relevant in the present context where the options regarding how a design should be pursued and justified maybe overwhelming. Absolute certainty often leads to erroneous solutions.

4.2 Layered Freeforming as a Craft

CAD as a pervasive practice, over two decades old, is developing a touch of the prosaic. This allows the digital means of conceiving things to distance itself from the attraction of CG (Computer Graphics). The loss of novelty allows computing to evolve into a method of implementation which allows the process to reassess its foundations, and encourage the digital to reemerge with the physical...

CAM technologies are acknowledged (Steele, 2001/ Zellner, 1999) as an enabling factor in recent architectural projects (Rahim, 2002). However, this role is interpreted and actuated as almost generic, something that should enable the designer to realize even the most ambitious designs. However, CAM fabrication technologies are seldom included as a key factor in the design process, but are mostly considered as a default solution for realizing a complex computer generated model. Rarely are the specific particulars of the technologies used acknowledged in the process of conceiving a design. It is exactly these properties, however, that distinguish these means of fabrication from the other methods of making. To recognize and build upon these distinctions is vital if the, additive and subtractive, CAM technologies are to flourish.

4.2.1 Additive versus Subtractive Processes

This thesis deals with (additive) LF processes as opposed to subtractive fabrication methods, which use have dominated digital manufacture, particularly in the context of architecture (Callicott, 2001), is largely due to such techniques ability to use existing and more common, and hence price wise more cost-effective, materials; and due to the availability of large scale fabrication plants that at present out-scale anything that any additive fabrication service providers can offer (Kieran and Timberlake, 2004). However, the core differences between these two fabrication methods are also each mean's advantage. The principles of CNC based subtractive processes are still dependent on the use of default material components or units, be these standardized sizes of plywood, high-density foam blocks, sheets of canvas or glass, or even metal plates. Any production through the subtractive methods needs to start from something bigger from which something smaller is carved out or removed. This feature makes it inevitably dependent on the provisions of standardized units. Subtractive methods are also dependent on the actual 'carving' of a design, which, compared to the micron level accuracy of some of the additive processes is simply not viable through the subtractive means of making. Even though currently in a subservient position to subtractive fabrication processes, especially when making anything of scale, additive processes have an intrinsic advantage on milling in that its building matter is, in a way, shapeless, and need not be made from the outside in – a default constraint of the subtractive methods. Additive fabrication methods have the potential to determine their own make-up (establish its own micro-structure as it has the ability to build itself up from the inside-out, and has the potential to form a 'infinite build' based on wet building processes, where the extrusion of material can potentially be continuous (in conjunction with a movable print-head[11]) and fluent throughout a build - no collages of 'Neufertised'[12] (Hensel and Menges, 2006) components necessary.

4.2.2 Exploring CAD-CAM Beyond the Virtual Senses

The tools and means we use to realize designs inevitably influence the outcome. CAD is defined through analogies – iconic similes that aid and reflect our understanding and patterns. These include 'desktop' providing the default start-up 'page' of an OS system; the 'folders' we store 'files' in, as well as software icons such as hand outlines to 'move' things, buckets to 'pour' things, and magnifying glasses to 'zoom' in and out of things. Simile actions such as 'extruding', 'sweeping' or 'filleting' and 'wrapping' can also be used to manipulate virtual representations.

Such methods provide an accessible and coherent lexicon or alphabet of means for executing different complex and involved shapes (designs) and compositions. As such processes get more involved, more complex, the design in question inevitably starts becoming more and more a

11 A proposal by R&sie explores such techniques. See: http://www.new-territories.com. (Accessed February 2007)

12 The term refers to the architect's data book 'Neufert' that seems to form a core reference source for most architects and architectural students. See http://www.blackwellpublishing. com/architectsdata/neufert/pages/contents.htm .

reflection of the tools used. This isn't necessarily a problem (we need parameters to bounce ideas off) whilst the outcome is the product. The difficulty arises when additional dimensions are added, or when the means of conception and the means of production do not match. When the process involves making not merely a variation of the final outcome (an image on a screen into an image on paper) but making an image on a screen into a representation – a portrayal of a future outcome that is of a different dimension than the original source representation[13], the discrepancy becomes more apparent. Here the degrees separating the planning/ design stage from the build/ fabrication stage increase exponentially. There is an inevitable infidelity between the way we design things and how we build them[14]. Tool icons and analogies (wraps, sweeps, extrusions, etc.) are different from the physical processes and tools used (sawing drilling, lifting…), and the shaping processes (casting, moulding, joining, gluing, etc.). Here the analogies between conception and fabrication don't match. Too often architectural designs are created through CAD based means in which the physical or material fabrication and assembly has not been included as a component in the design process. Too often we're trying to build what we draw rather than draw what we plan to build. Time and again the structure is adjusted to what the designer wishes it to be, instead of the design adjusting itself to what the structure and material needs to be. This is particularly the case in many practices using CAD and CAD scripting[15].

A successful design should establish a middle ground between the two. Or alternatively and preferably, the materials and structures play a balanced and intrinsic role and provide a rich and catalytic foundation already during the establishment of a (CAD-CAM) brief. It is difficult to conceive without the use of analogies and metaphors, however, such conceptual assumptions, are debated orally or through text. There are kinaesthetic creativity (dance), olfactory ingenuity (perfumery), tactile imagination (glass blowing), to mention a few, which all provide mediums for expression that combine the way we think with the way we do and realize our artefacts. The

13 Not a direct rendition of the thing itself, as is usually the case in more large-scale, volumetric production, such as architecture.

14 It is also here where the notion of passing the info 'over the fence' enters, i.e. a set of 'drawings' are passed on from one discipline to another (from the architect to the quantity surveyor to the structural engineer, planning authorities, etc.) often resulting in the outcome and integration becoming dispersed and unfocused – a case of architectural 'exquisite corpse' – each entity have their own agendas and priorities which often are implemented in oscillating sequence without considering or including the needs of the other parties involved…

15 No formal references of studies backing up such claims could be found. Many of the included book references, however, such as Nick Callicott's Computer Aided Manufacture in Architecture - The Pursuit of Novelty, Hensel, Menges' & Weinstock's edited publication, Emergence: Morphogenetic Design Strategies, Bob Sheil's Design Through Making or Dennis Dollen's Digital to Analog (D 2 A), allude to similar notions.

engagement with materials and surfaces, which are sensed, interpreted and understood through interactions, even when such impressions are sensed through an extension (be this a dessert-fork, a chisel, glass-blowing pipe, or a digital haptic interface), allow for a dynamic awareness to develop through 'thinking through doing' (Sennett 2008) than 'writing or drawing about doing'.

4.3 Taxonomies for Layered Freeforming

McCullough (1998) informs us that the turn of the twentieth century economist Thorsten Veblen affirmed how workmanship is obstructed by mechanization. Veblen took the view that if the craftsman could retain control of the process, even within an industrial setting, technological excellence would result. To put it simply, workmanship will find a way. In this sense, a new medium could be made, even within a more abstract and technological context. Accepting this statement the following hypothesis emerges: If computing has become an innate component in the realization of design and the built environment, and the processes related to direct manufacturing (CAD-CAM) are considered key elements in synthesizing such production, how should the conceptual frameworks guiding such production be structured?
A solution may lie in a set of classifications of various scales, materials and processes of the various LF fabrication methods.

4.3.1 A Model for Classifiying Layered Freeforming

Here a model, the LF-Model, is presented which relates elements and features of Rapid Manufacturing/ Layered Freeforming fabrication methods and their specific material systems into a taxonomy. It provides a foundation for how additive fabrication processes can be described. It refers to associative positioning and scaling where groupings are sequential but not necessarily linear, entailing that one link or node can have several (different) connections or continuations. For example, the term Nucleus-Node ('*Nunod*'), describes the grouping of physical volumetric pixels,above more intricate than a Material-Voxel ('*Maxel*'), which is the basic physical component which defines the resolution of a LF design and build (these terms are explained in more detail below). Both are descriptive terms unique to this form of conception. The model is volumetrically navigated (rather than linearly sequential) and link-ups to provide a stochastic, correlation between a design's various aspects for both conceptual as well as physical composition of a design. The terms provide a vocabulary to communicate design elements which are specific to CAM related capacities and processes.

The initial cluster relate to the Layered Freeforming specific terms as 'macro' terms, from individual (micro scale) sub-units up to the more intricate assemblies (meso and macro) used to compose an *Avaterial* and *Metature.*

4.3.2 LF-Model Terminology

The terms included are:

- *Buildware* – The term refers to the various (both subtractive and additive) fabrication methods which fabricate volumetric objects directly from a digital file (Fig. 4.1). In the context of LF it is considered on similar terms and of equal value as hardware and software.

- *Freeform Construction* – a term introduced by Soar (2005), to describe the larger scale additive fabrication processes which can be applied to construction at an architectural scale. Contour Crafting and the Monolite techniques belong to parallel categories to that of Freeform Construction (FC). FC that can extrude and layer material at, a multitude of scales, a factor which exponentially increases its potential uses. The *Metature* (see below) categorization also falls within this term.

- *Freeform Fabrication* – Relates to additive builds classified as objects (as compared to architecture). *Freeform Fabrication's* qualities and logistics are specific to additive fabrication processes and would be difficult to realize by any other fabrication method.

The following terms express the precepts linked to LF fabrication. They provide craft-specific terms connected to the LF process.

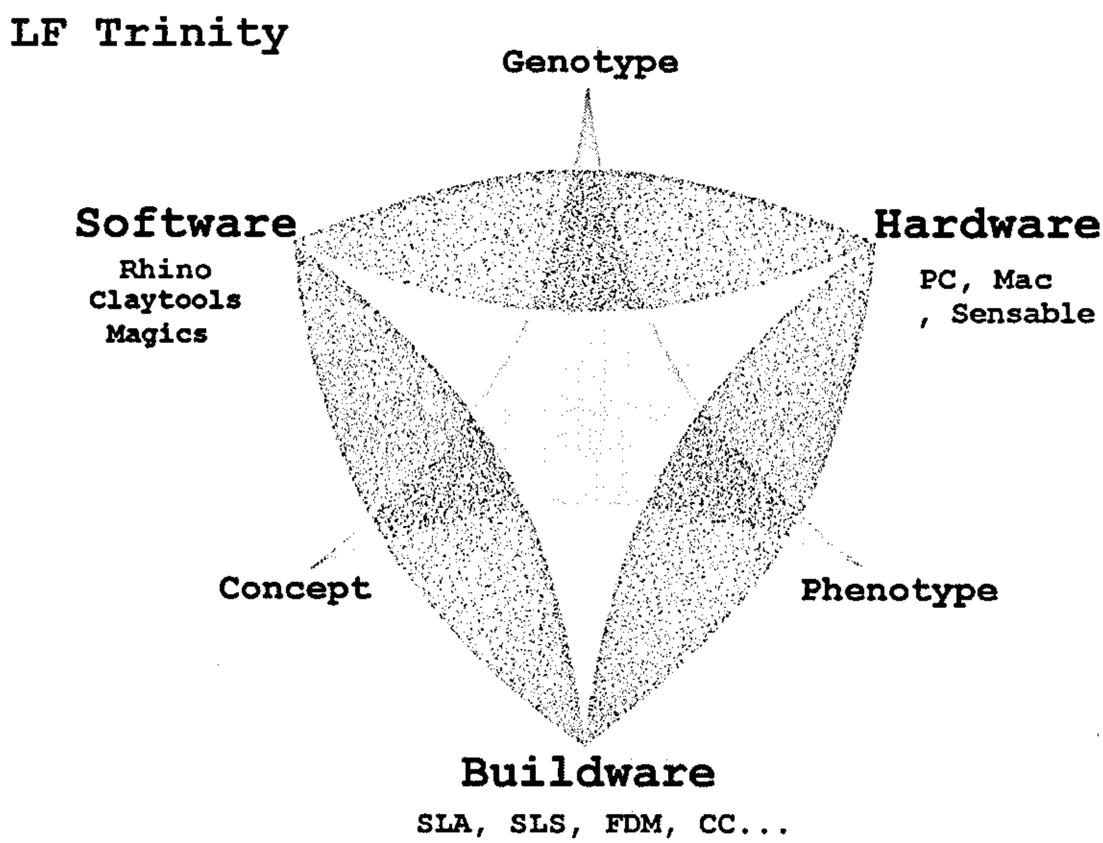


Figure 4.1 The Layered Freeforming trinity, where Buildware is included as a essential components of CAD-CAM conception.

- *Mether* (Material-Ether) – Mether encapsulates the formative material state of *buildware.* A (LF) material's specifications and performance properties can be altered and customized to fit the needs of a particular design (to make it, for example, softer at one end and more rigid at the other). The term describes a modular process, which provides a logistical framework around which a LF design can be wrapped. This doesn't entail a set of separate components or units, but provides a set of actual and mnemonic nodes, upon which the design can be explored, developed and described. *Mether* describes complex (mostly single) material composition by additive technologies, where the properties of *Mether* are expressed in the format of a verb (an action) or adjective (a quality) than a noun (a thing)[16].

- *Avaterial* (Avatar-Material) – describes a LF design's mether composition up to (roughly) the size of a human that fits within the tactual realm – within ones 'grasp'. The subcategories of *Avaterial* are listed below.

- *Metature* (Meta-Architecture) – a parallel term to *Avaterial,* describes builds larger than human scale (a magnitude beyond the immediate grasp of a set of average extremities), to entities of an architectural scale.

Although defined as separate entities, there is a link between *Avaterial* and *Metature,* in that an *Avaterial* can constitute a micro scale aspect of a *Metature* build, thus resulting in a design which has been manipulated from 'top down' (or 'bottom up').

- *Materix* (Material-Matrix) – refers to additional use of scaffolding and support

16 A corresponding term to Mether could be Functionally Graded Material (FGM) which is characterized by alterations in a pieces composition and structure that result in matching changes in the properties of a material. How this differs, however, from Mether is that whereas a mether's property variations are controlled directly through computing based means, and always realized through buildware, a FGM is usually made up of a compositional gradient from one component/ material to another. See: http://www.azom.com/details.asp?ArticleID=1592 (accesses May, 2007) . Another similar feature can be found in the capacity of the Connex500 Multi Material 3-D Printing System, developed by Objet, which can produce something referred to as a 'Digital Material'. As this machine allows one to simultaneously print a single piece out of multiple materials, it can not only build but, the system also allows its user to create composite materials that have preset combinations which, by controlling the composite's material quantities and patternings, can be provided with a variety of mechanical properties. See: http://www.2objet.com/Products/Connex500/tabid/273/Default.aspx (accessed April, 2008).

system required in LF systems. It relates to the bespoke material and textural properties that can be achieved by modifying the individual micro components/ struts that make up the structural matrix. This notion of *Materix* could also be interpreted as a bespoke rendition of a halbzeug (see below) system. A collaborative example is given in appendix two of the author's work.

Parallel to these terms are terms which describe types of patterns or systems of the *Materix* that the *Avaterial* or *Metature* are composed into. These are:

- *Halbzeug System* (Hensel and Menges, 2007) – is a pre-existing term, used to describe an assembly of semi-completed components. A set of separate and distinct units which in unison form a set of constituent parts of a composite assembly, as defined by Hensel and Menges (2007) as a semi-finished product, or sub component, lying between raw material and finished product. Sub components are available in larger sizes, e.g. as sheets, rods, hollow rods, profiles, coils, etc., and need to be cut to the required size. Sub-assemblies are created by a "design process [which] unfolds through a differentiation of the rules of assembly within narrow parameters that enable rigorous proliferation and jointing process informed by internal and external constraints. Whereas a component is described as "...a constituent part of a more complex assembly; [that] unlike the halbzeug, [...] is a fully defined, finished product" (Hensel and Menges, 2007). Such a 'designed' aggregate system can be assembled into larger systems in response to material geometric characteristics and extrinsic parameters.Formation systems need to accommodate scale affective variations when applied to either Avaterial or Metature related designs, but the overall guiding principals remain the same, regardless of size.

- *Aggregate System* – illustrates material composition, made up of a multitude of combined set of units or items, a merger process which cannot be reversed. When applied in a digital context, an aggregate or aggregation can be considered a typological composition. They are defined by the specification of the individual aggregate unit, the aggregation process and the external constraints.

> Aggregate systems are the opposite of assembly systems or composite systems, in that elements are not connected by joints or a binding matrix; nevertheless they are still systems as the interrelations of system constituents can be traced, defined and instrumentalised. Differentiation occurs through the manipulation of the individual aggregate, the aggregation process and external constraints (Hensel and Menges, 2007).

Both halbzeug and aggregate systems classify a set of subsystems (and subsystems of subsystems of subsystems, etc.) according to which a LF build can be conceived. This is achieved in a manner that aims to consider the features of a design not necessarily as separate components, but as a set of more fluid composite which (if the liquid analogy is carried a bit further) can be selectively 'frozen'. Typical aggregates such as sand and gravel, or halbzeug systems such as a box of clock-springs, a stack of chairs, or a set of programmable motes (computational halbzeugs), conceived as physical or virtual entities, exist here as scale-less. The model allows for a combination of a 'halbzeug-aggreagate' in which the detail can be customized in the context of the quantities. One can control the individual make-up, the micro structures of a build through the computing related means.

Computing allows us to consider the scales of units in a way not possible before. Computing requires us to expand Louis Kahn's dictum (McCarter, 2005) about asking the brick what kind of structure it wishes to be into a prior and more diminutive dimension, where the query needs to be reformulated into one where we need to ask the clay what kind of brick it aspires to become.

Simulation software (such as Finite Element Analysis, Computational Fluid Dynamics) inform us about the conditions (climatic, structural, utilitarian, etc.) of a design, and can also be employed as creative tools - they can be exploited as triggers in the development of a design. These methods become relevant in the context of digitally conceived design and architecture through, say, any type of algorithms (CA, EA), or biomimetic analogies, in the coding phase. They need to be conceived around some notion of a form, or idea of form, with a direct link both to material as well as fabrication related consideration (used for defining parameters set by such). Here the link between the initially separate realms of virtual and physical agents/ seeds/ units are fused into a symbiotic singularity (the *Mether*).

The two elements, agents/ units that can been used to generate such arrangement are:

- *Magent* (Material-Agent) – a scripting based agent, which properties, and consequent behaviour within a computed simulation, are based upon the actual properties of the material.

- *Voigent*[17] (Void-Agent) – The opposite (negative) of a Magent. They are agents that conjure voids within a computed simulation.

Both *Avaterial* and *Metature* can be sub-divided into four, gradually increasing, process related, 'chains of command', as they aren't linear, but interlink in multiple volumetric dimensions. Such links are correlative rather than sequential, where the phase change isn't necessarily absolute and can be formulated as thresholds.

The sub-categories for *Avaterial* are:

- *Maxels* (Material-Voxels) – defined as the resolution of a LF build. They form a physical rendition of the virtual voxel (a volumetric pixel). However, the dimensions, or size, of a maxel can be either determined by the maximum resolution set by the RM machine in use, or by the smallest unit used in a LF build. A single build can include several different sets of *Maxels*. What also distinguishes a *Maxel* from its virtual compatriots is that, unlike pixels or even volumetrically uniform voxels, it can be asymmetrical in the sense of having different X, Y and Z coordinates.

- *Nunods* (Nucleus-Nodes) – describe how (genotype) setup maxels are organized. It is the smallest built unit, the preliminary entity, that maxels can be made into. In some sense a nunod functions as the equivalent of a halbzeug component, in that it can be used as a shaped, yet primary, building component. It has a defined, even designed, shape, but requires a context in which it can be applied.

17 A term suggested by Christian Derix during discussions regarding the subject matter.

- *Tracs* (Trait-Clusters) – are the assembly into which *Nunods* can be arranged. These in turn can be congregated as:

- *Procs* (Property-Constellations) – The final 'component' assembly/ element which make up a design. A proc is a singularity which remains a part of a the final design (analogous to a table leg, or the seat of a chair).

These terms are mirrored on a larger scale by the following terms that relate to LF/ RM builds associated with builds of an architectural scale. These are:

- *(Meta) Bricks* – the initial RM/ LF building block/ element of an architectural scale. Roughly the size of a standard British Standard brick[18] - or hand size…

- *(Meta) Blocks* – describes the initial grouping of *(Meta)Bricks*. In concept an analogy to a row of bricks – a set of units that can be described as a single group(ing) – approximately equal in size and presence to that of a piece of furniture.

- *(Meta) Boulders* –The follow-up grouping from a *(Meta) Block*. A group of 'blocks' than in unison can be qualified as a singularity – described as an entity. Continuing the brick analogy this could be described as 'brick' wall, ceiling, floors, etc. Something that in itself can be justified as a unit, yet forms a part of a larger collective.

- *(Meta) Rocks* – The 'largest' cohesive singularity of a whole that can still be defined as a part or a component of a total… In architectural terms (and expanding further on the brick analogy) this could be described as a room, corridor, segment or even a wing of a building (a piece of architecture). But it could also be expanded further and be depicted as a component in a landscape, a street or square in an urban plan…

The links of the various scales is proportional rather than metric. Adjacent categories are

18 225 x 112.5 x 75 mm

defined according to 'lesser than' and 'more than', or 'adjacent to' or 'controlled by', rather than as specific quantities, positions or sizes. The proportional distribution can also be asymmetrical, with certain volumes or proportions (aspects) of the design having a larger quantity of certain sub-categories than others (i.e. a trait-cluster can have a varying set of different nucleus-nodes within a single set). Such conceptual groupings or arrangements are relevant because they provide means through which a number of adjacent and overlapping features, programmes, elements can be described and defined. They provide a suggestive and generalised system for defining something that doesn't necessarily lend itself naturally to systemization.
There was also a degree of intentional ambiguity allowed for in the above listed classifications. Their intent was to provide suggestive mind-maps without necessarily stifling subjective interpretation and usage of the terms. What they did provide was a grain or resolution for a project conceived through these means that affords it with a set of interlinked reference points, a set of logistical buoys that act as anchors for any conversations (be these internalized, non-vocal, or externalized, amongst others) about related matters. Here the 'meaning' of a classification was not built necessarily around a core spine (a centralized approach), but was instead attached to the unit, the fragment or cell (the *Mether* related terms) which makes up the body of a notion (a clustered approach) - be this the design for an idea of an artefact (Fig. 4.2).
A set of graphical illustrations using Lego as an analogue tool for the various stratum of *mether*, and of the aforementioned is examined on the following pages (Fig. 4.3 and 4.4).

4.4 Layered Freeforming Specific Applications

Here the absolute numerical valuation of links, connections or features between various elements, or the use of general or generic templates or standards, wasn't of equal importance as the technologies in question (parametric design, solid modelling, CAD-CAM) make it easy to fit various objects and features to accommodate any needed constraints. Thus the use of proportional classifications (the ascending taxonomies, from maxels to procs and (meta) bricks to (meta) rocks) make sense as they are self-referential to each other in the context of the particular task or design.
In short, the approach could be argued to entail a reversal of process, or priority and sequence of considerations, as the physical fabrication used to inform and inspire digital process(es)

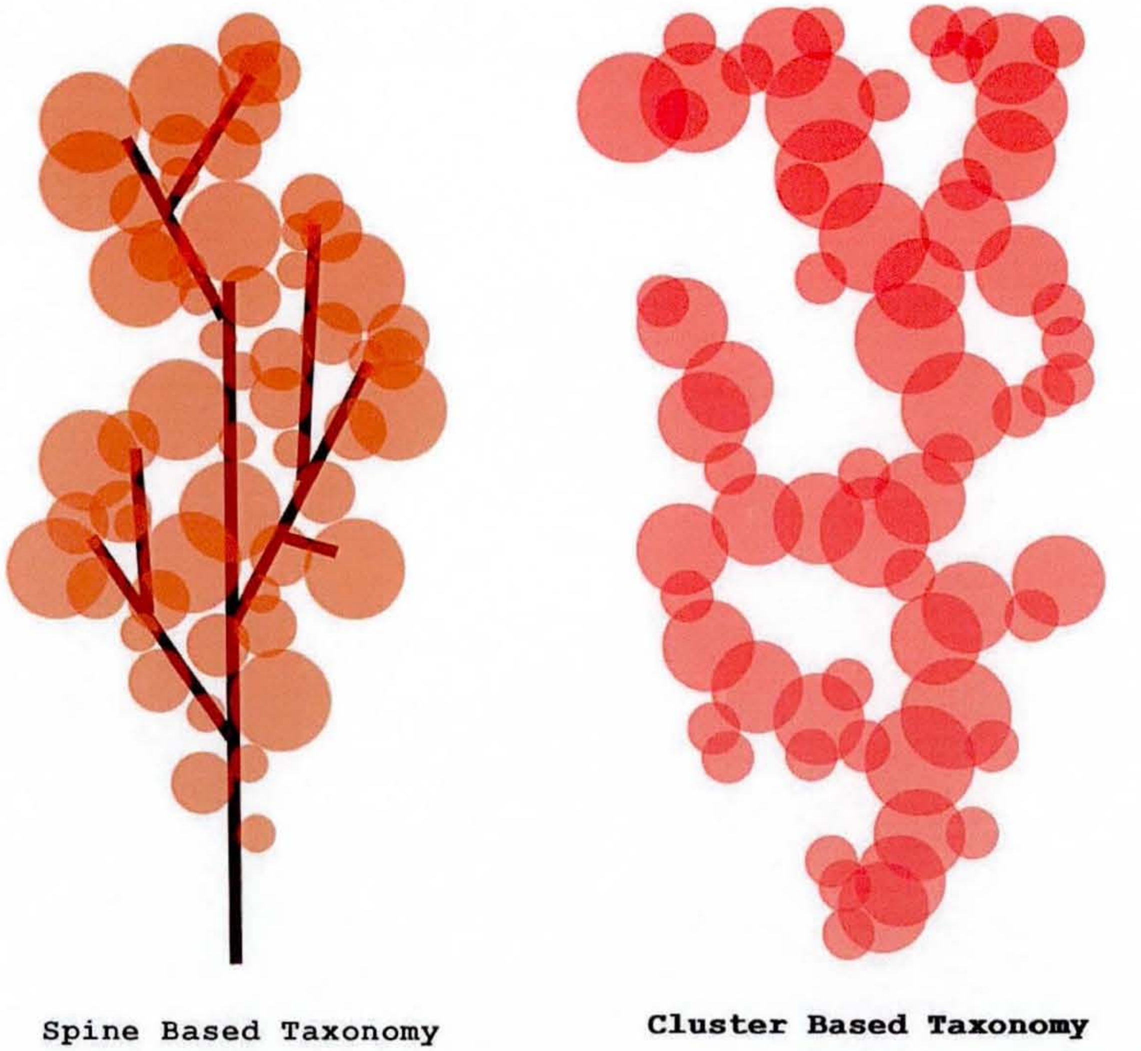


Figure 4.2 The *Spine* versus *Cluster* Based Taxonomies

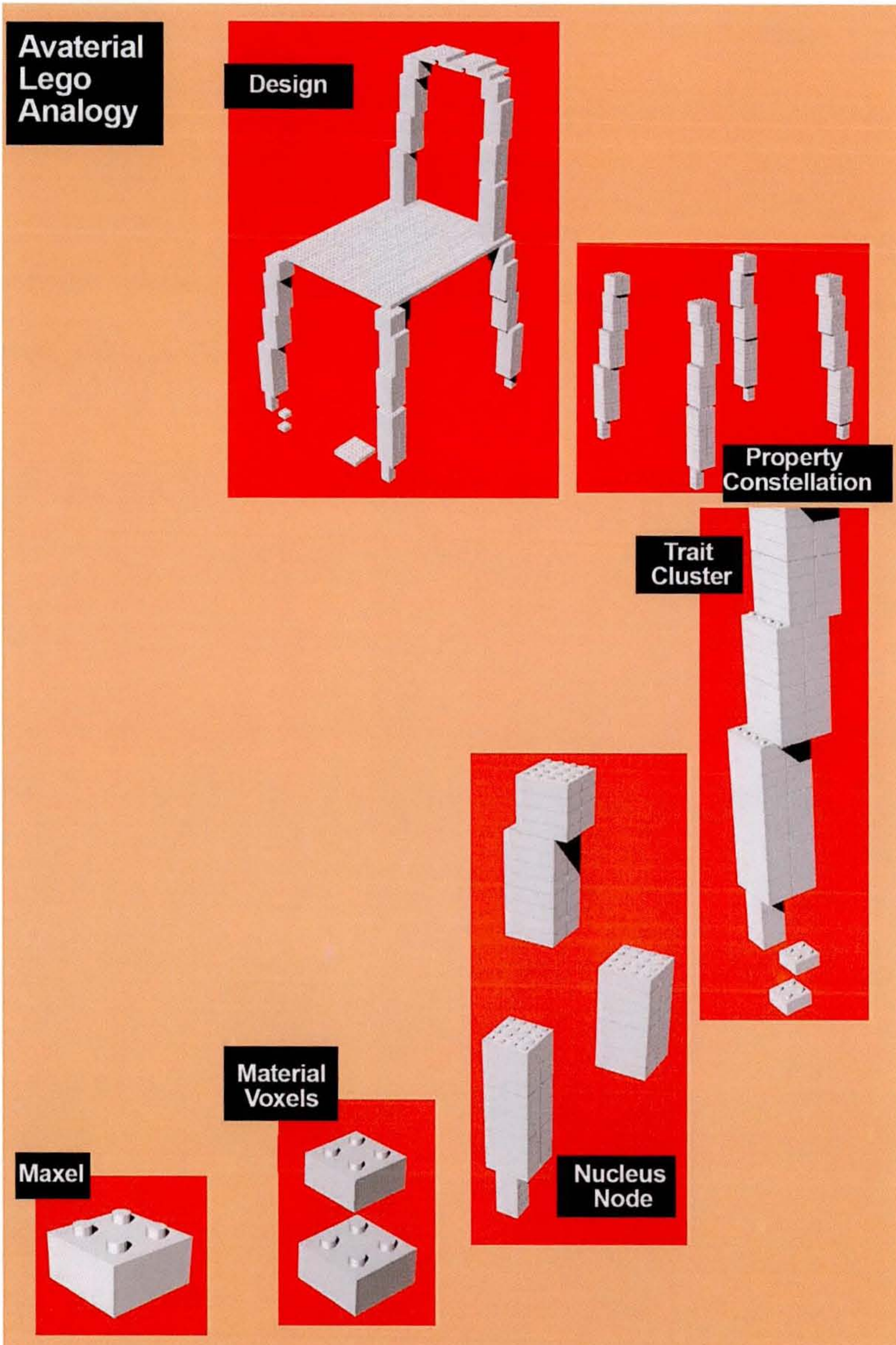


Figure 4.3 The notion of 'Lego' used as an analogy to clarify the idea of Avaterial.

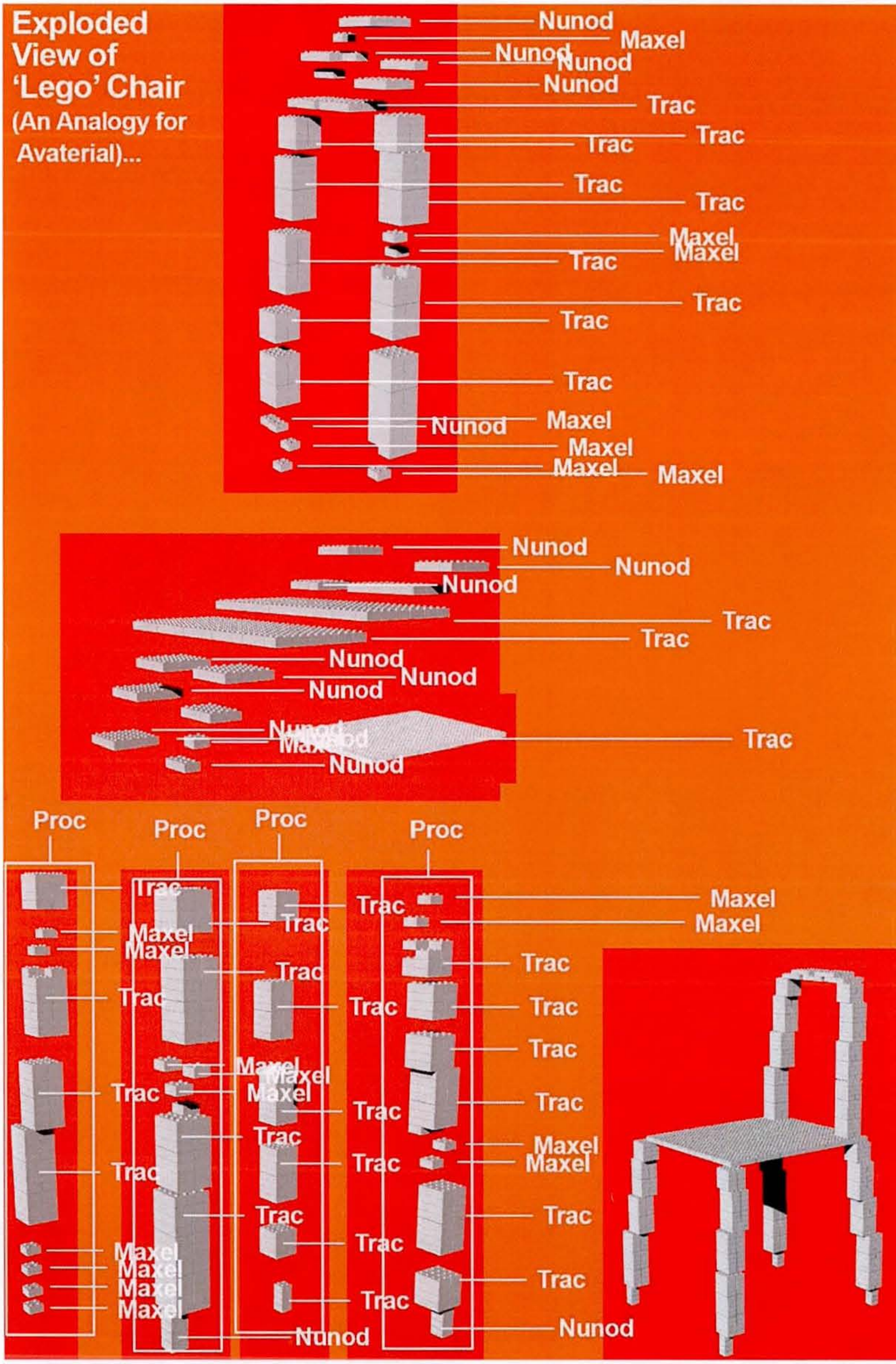


Figure 4.4 Exploded view of the 'Lego' chair.

rather than the reverse. Idiosyncrasies are often the result of failed or faulty builds, as RM fabrication processes which can be used and customized to perform in a range of unique ways. The extruded strand of Fused Deposition Modelling can be made to selectively 'unwind' through including select build errors into its STL file. The stair-stepping patterns of the Stereolithography (and other) processes can be considered and included as a feature in a design. Or how one handles the 'green' (non-treated) components that result from the 3D Printing process (the hardener or elastomer, the pace and manner in which they are applied) all influence the properties and affects of the eventual design. This approach should also be applied to evolving renditions of LF in which their particular peculiarities shouldn't be negated nor neutralized, but included as features.

4.4.1 Controlling the Model Through the Sliding Control-Bar Approach

There are also ways, however, through which some of the tools used in most CG interfaces can benefit and be applied to the ever expanding realm of RM. Perhaps the most compatible would be the way a value can be adjusted (scale, proportion, colour, tone, contrast…) by a virtual sliding control bar, usually accessible through a pop-up window or control panel, found in most illustration or CAD programmes. It is a tool that, in its straightforwardness, can provide, particularly when applied as a sequence of steps, a degree of intricacy. This type of manipulation, that could be included within parametric control, is usually used to manipulate two-dimensional qualities of an illustration, such as, say the colour saturation of a Photoshop image, or the two-dimensional representations of three-dimensional objects on the screen, such as a 3D CAD drawing, very seldom are they used to manipulate the actual physical attributes or textural qualities of a design – allow the bespokeness of the process to become a founding feature in a designs adaptation[19]. At some level this is surprising, as there are already a number of companies and individuals, such as Freedom of Creation's (FOC) Janne Kyttänen[20], Patrick Jouin[21], or Assa Ashuauch[22], who have used and to some degree specialize in the usage of the additive processes in the fabrication of their products, yet have not, as of yet, applied the

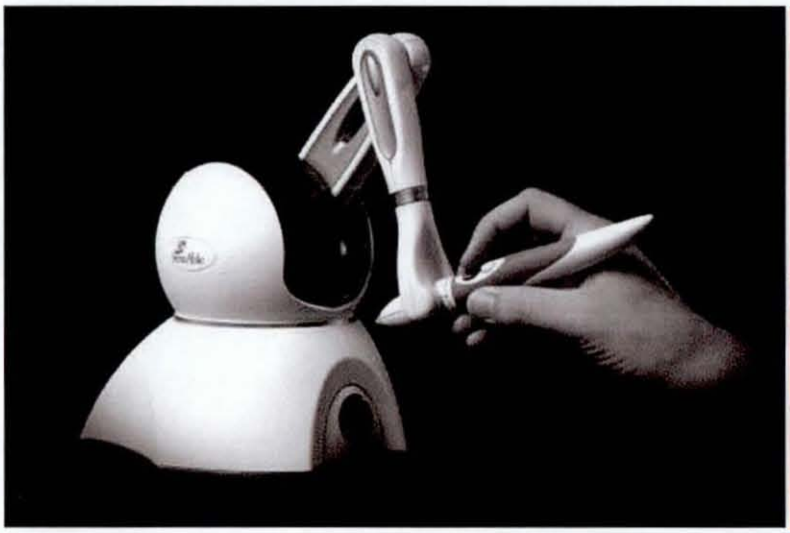
19 At the time of thesis hand-in (September 2008) the author had not encountered any acknowledged examples of such designs.
20 http://www.freedomofcreation.com/ (accessed June 2007)
21 http://www.patrickjouin.com/ (accessed June 2007)
22 http://www.assaashuach.com/ (accessed June 2007)

intrinsic flexibilities and the almost infinite possibilities to (mass) customize designs that these technologies, particularly when applied and considered in the context of the sliding control bar as a modifying tool, allow for. Nor have they used the advantages such means provide from a directly commercial perspective. As such control methods should be easy to use and adapt to a GUI (Graphical User Interface) which, say, would allow one to both progressively manipulate the size (and even x, y & z proportions separately) of a light design (to match ones kitchen niche or shape of dining table) whilst simultaneously having its price (set according to the pre-estimated quantity of time and material the piece would require to be fabricated) adjust itself to match any such revisions. This approach allows the design to still retain its core design appeal whilst providing its eventual user with a degree of influence to make it their own – in a manner somewhat similar to how bespoke suits can be acquired on Saville Row (with the 'suit' acting as the genotype of the eventual customized, phenotype, rendition of the nucleus design).
This also provides an example and an expanded rendition of (digital) craft, in which, as Cullough (1998) considers "the possibility of craft lies not so much in the technology as in the outlook you bring to it. [here the] The great paradox of computing is that the better this thinking apparatus becomes, the more we appreciate the value of a conscious human being.". Here the tool provides an alternative variant for how a thing, a physical entity, which is conceived through digital means, can expand the ambit within which such things are formed that includes the tangible and material as an inherent entity in the equation, it opens up the possibility for true user generated, mass customized, objects, which, through an intutive and already (quasi) familiar interface will allow anyone to measure and adapt various core (template) designs to fit their specific needs, be the design a chandelier, a chair, or a cup...

4.4.2 Touching Through the Screen

Another example of, in this instance, hardware that has a more natural affinity to the LF ways of making things is provided by the 'Phantom' device, made by SensAble[23], a haptic interface that allows one to 'feel' the things viewed on the screen. The Phantom device enables one to manipulate virtual entities or representations on a screen that can be felt and 'touched' through a stylus like, multi-axis, instrument that allows one to shape and sculpt things through the sense

23 http://www.sensable.com/industries-design-model.htm#overview (accessed June 2007)



Figures 4.5 The Sensable device, through which one can feel the object dispalyed on the computer screen. A variety of different stylus heads can be used to shape the digital clay, Ranging from scalable spheres, rods, points, etc. to both 'push' as well as 'pull' (and even add or build) the surface.

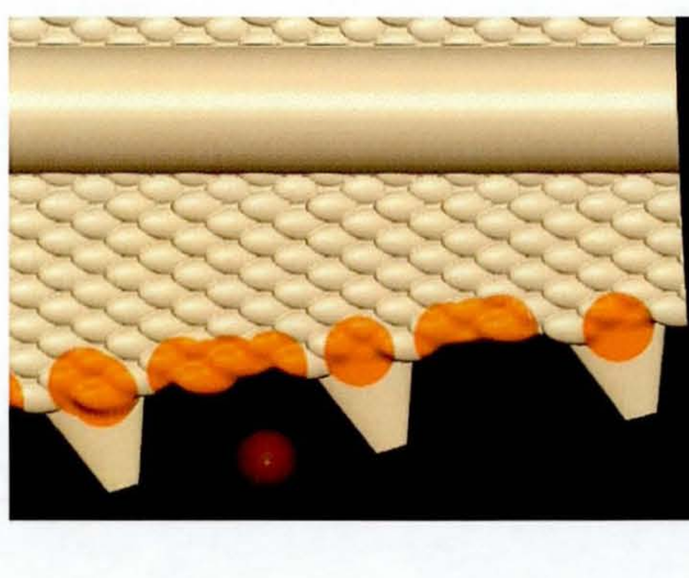


Figure 4.6 The surfaces can also be adjusted by 'painting' on a variety or textures. A similar tool can also be used to soften or sharpen a surface pattern.

of touch (Fig. 4.5). This apparatus, which seems to have initially been made for making figures for fantasy games[24], does, nevertheless, provide a very viable tool and added dimension for conceiving items, and eventually even architecture , through more direct digital means.
The function of the device is based on the manipulation of a 'digital clay', a 'lump' of material on the screen, which (voxel based) resolution, and degree of firmness (which can be controlled on a sliding control bar), is set at the commencement of a design. The foundation design to be manipulated can also be imported from an external source as a STL file. The core design on the screen can be manipulated through a variety of different means, most of which have precedents in most CAD or image manipulation packages, however, how these are applied within the framework of Claytools (the software that accompanies the Sensable device) provides, literarily, a further dimension to how these are operated, for here the results are inevitably volumetric, and not only that, but any such manipulations have also a tacit impact on the design (Fig. 4.5). The, say, texture-maps that one applies will here not only have a pattern of density and shape, but also a level or degree of, call it, articulation of such textures. The tool also allows one to 'paint' fine textures onto larger surfaces and volumes (Fig. 4.6), and one can zoom in or out of a design (Fig. 4.7), and touch or feel the object at a micro or macro level (inspect it with a gigantic or a minute 'finger'). There are a number of finer tactile nuances the device allows for, such as 'blurring' or softening sharp ridges or corners, and the ability to not only push and pull the digital material on the screen, but allows one to even 'grow' or build new material – add mass to a design according to need. This tool thus allows one to transcend beyond the front, side, plan and axonometric views of a regular CAD screen set-up, which would be somewhat useless and confusing in this context (it is easier here to have a set reference point which directly corresponds the actions of the physical device with its equivalent avatar on the screen, and rotate the object to the most appropriate angle), and allows for an analogous link to develop between the object being designed and how an equivalent physical object would be manipulated (rotated in ones hands or in space). The abstraction is here one step closer to how we actually perceive and experience things, and consequently allows the resulting design to be understood in a manner more intimate to the cutaneous means of perception. This tool allows the notion of a 'tactile gestalt', and hence a tactile form of imagination and creativity,

24 All the instruction manuals and accompanying instruction videos seem to illustrate the capacities of the device on such figurines.

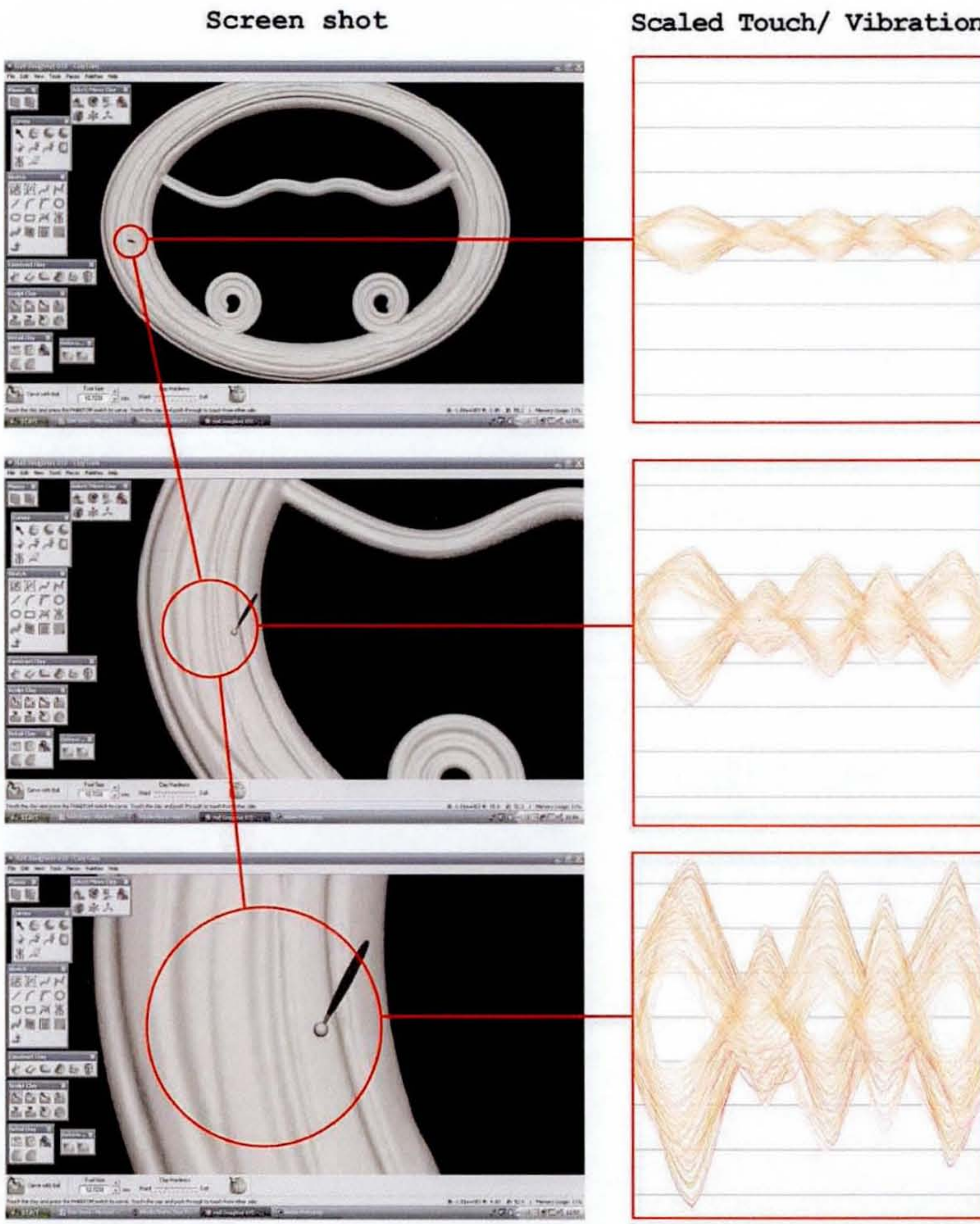


Figure 4.7 Scaled touch - here one can zoom in and out of an object, and correspondingly 'feel' the same texture at different scales. The same convexities and concavities being much larger when zoomed in closer, and equally the surface patterns reading much smaller when sensed from 'further away'.

to take root. Eventually it should be possible to design the whole gamut of related things[25] - be these the miniscule cogs in a wristwatch or the topographical nooks and crannies of a land-scape - through this type of a device for, just as we're able to envision and relate to such scale associated abstractions through visual means, we should eventually also be able to conceive such schemes through more tactile forms of imagination. This type of a more hybrid approach between different means of tools as well as sensory faculties should allow for a more saturated and comprehensive understanding to develop of any proposal under development.

Examples of how these classifications and conception methods have been assimilated is shown in Figure 4.8., which also includes a breakdown of the tactile classifications of the touch based case-studies, explained further in the upcoming chapters.

25 This should be possible, if the design is be realized on a computer with high processing capacity. (The included work has predominantly been realized on a Toshiba Qosmio F10)

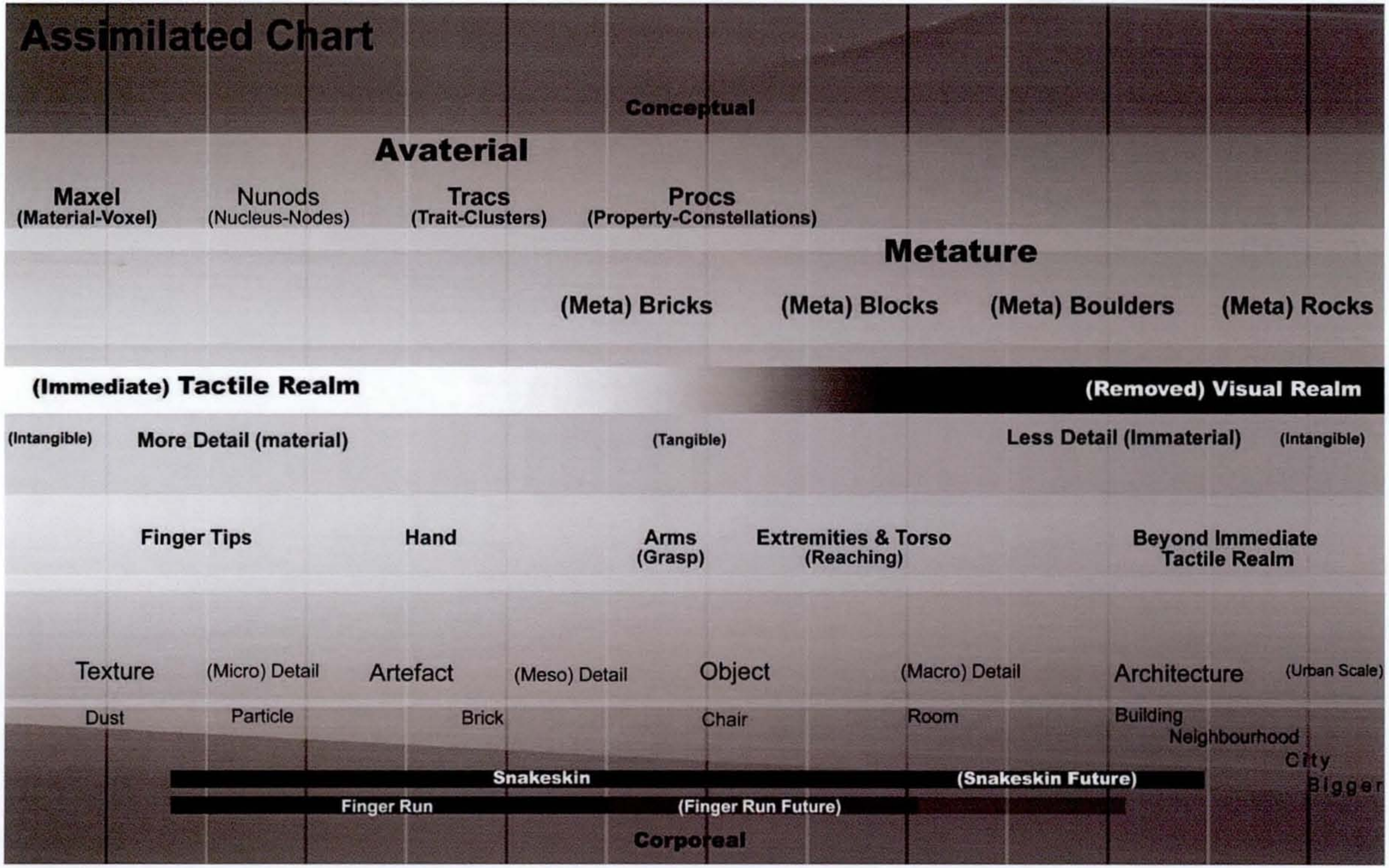


Figure 4.8 An Assimilation Chart - showing how the various classifications match and interlink with select designs.

5.0 Case Studies - Exploring Characteristics of the RM/ LF Process Through Design

The following case-studies were all derived from various features and processes unique to rapid manufacturing, which they apply as key features in the design. Each of the case-studies' *objectives* include a 'what if', syncretic component in their aims, which was used to catalyse the case-studies objectives. They all involved some full-scale physical RM builds.

5.1 The Stereolithography and Fused Deposition Modelling Bowl(s)

Two bowls are made from a single STL file through both the Stereolithography (SLA) as well as Fused Deposition Modelling (FDM) means of additive fabrication. The bowls, in size roughly 100 by 100 by 55 millimeters, are designed in a way where the default scaffolding supports of each system becomes an inherent component of the design.

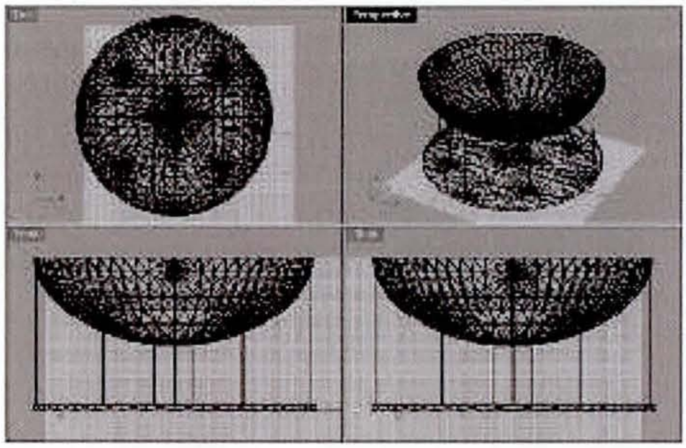
5.1.1 Objective

The aim of the bowl designs is to utilize the default supports of each respective fabrication technology as an intrinsic feature in the resulting design. It also explores the discrepancy between what is 'seen' or conceived during the design phase, and what the resulting designs will appear like, and, more importantly, how they will differ even though based on the exact same digital (STL) design file.

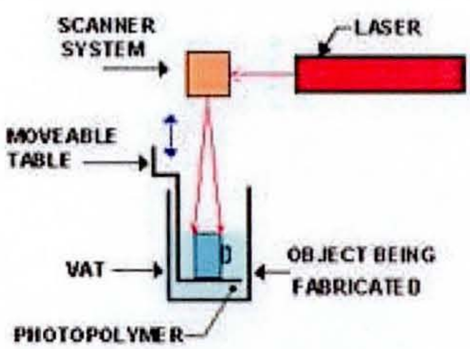
5.1.2 Method

The same design is fabricated both through a SLA and a FDM machine. When a build is made, minute layer by almost microscopic layer, the material is distributed (FDM) or cured (SLA) in such thin stratums, that any overhangs would collapse by their own relative weight before they could become thick enough to be self supporting. To counter this, the machines are programmed to automatically distribute support-scaffolding that will sustain and stabilize

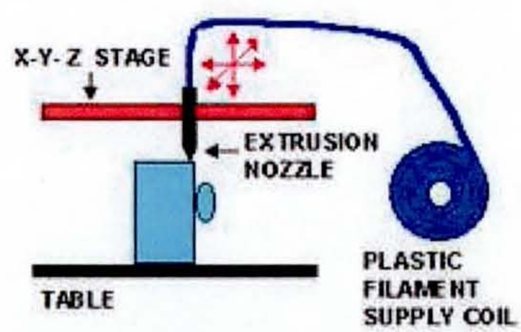
Single digital (STL) file



Two different CAM processes



The Stereolithography (SLA) Process



The Fused Deposition Modelling (FDM) Process

A pair of idiosyncratic fabrication results

Figures 5.1 SLA and FDM Bowl(s) - Two bowls originating from exactly the same STL file. One, image to the left, fabricated through Stereolithography (SLA); the other, image on the right, realized through Fused Deposition Modelling (FDM). Both design include the (usually discarded) support scaffolding as an inherent component of the design...

any overhangs until they are strong enough to support themselves. In the SLA machine this is done by forming the same resin from which the build itself is made into very light and delicate network of support-trusses. These can then be manually removed from the build when completed. In the FDM machine the supports are made out of a different material that can, in the post processing stage, be dissolved in a vat, using a liquid mixture specifically intended for this purpose. However in this instance these supports are not removed and are left to become a part and feature of the design(s).

5.1.3 Results

The aim of the project was to discover and reveal how the default support structures of the two additive fabrication processes could be utilized as constituent in a design. However, in themselves, these supports do have a certain aesthetic appeal. They are also surprisingly strong, and the way the respective materials are distributed have a distinct and recognizable patterns which can be utilized as a features in their own right. Details such as the cross-like scaffolding configurations formed in the base of the SLA bowl, or the column like supports flanking the FDM bowl on four sides. Both of the bowls also seem to distribute the material in almost oscillating staccato patterns (when viewed from above) due to the stair-stepping process, creating a somewhat wave-like, uneven, sequence of almost wood-grain like annual-rings, that seem to stretch when the angle of the curvature is reduced, and, conversely, appear to shrink when the angle of the curve increases. All such features can be appropriated and utilized as manipulative characteristics of a design. This case-study was also an example of 'what is designed (in CAD) is not what will be built (in CAM), an unique factor which needed to be included as a founding consideration during the conception of this design.

5.2 Adaptive Stereolithography Material Matrix

Inspired and acting as a progression of the aforementioned design, the SLA Material Matrix performs a system more than an object. The design is a tectonic tessellated pattern, based on the ability of the SLA system to fabricate things at a close to microscopic scale, which can be adjusted and manipulated to perform according to various different properties (Fig. 5.2). It

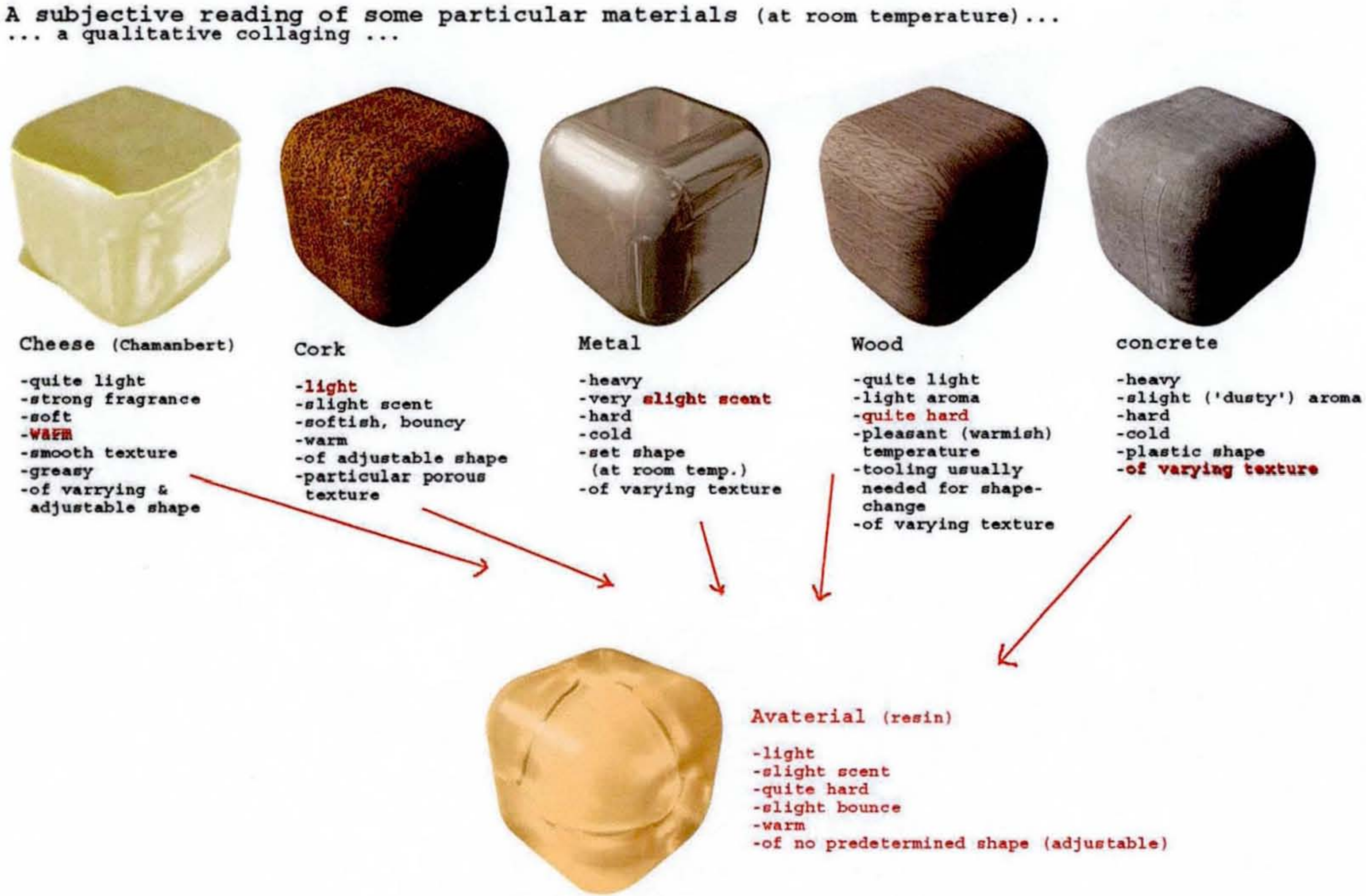


Figure 5.2 An early illustration of the process involving the definition of particular material properties and how (some of them) could be translated, through the use of the addtivie CAM processes, into micro matrixes...

aims to be, in a way, SLA scaffolding with a 'brain'.

5.2.1 Objective

The aim was to provide create a minute structural matrix with a performative purpose. It took the actual material properties of a SLA resin/ material as a starting point, and manipulated them into a variety of minute pre-determined patterns which allowed one to extend the 'intrinsic' properties of the material with a variety of additional ones based on how the micro-tessellations were arranged and distributed. The objective was to provide a set of more comprehensive properties to the material which could be controlled and 'tweaked' to perform according to the needs of a design, allowing a material to be customized based on the needs of the design rather than needing the design to adapt itself to the default materials available (Fig. 5.2).

5.2.2 Method

The method involved the production of a number of twenty five-millimeter cubes in which a genetic algorithm (GA) was used to evolve the small-scale internal structures of a material (in this instance a photopolymer) that could be manufactured through Stereolithography. The geometry of these cubes was based on a lattice connecting points in three-dimensional space, in effect a miniature space-frame structures. These were developed further in conjunction with Siavash Haroun Mahdavi, a computer scientist, and Sean Hanna, an architect and researcher, both from University College London, who became collaborators on this project. They wrote and developed the programming code for the initial rendition of the SLA matrix cube.

Initially two cubes of same structure, but different scale, in size 75 x 30 x 30 mm and 25 x 10 x 10 mm, were produced (Fig. 5.3) which provided models for physical testing.

In these initial tests the geometry was optimized for high strength under compression, and low mass. On account of to some irregularity in the structural properties of the resin at this scale (bonding between the fused layers the brittleness of thin members over time), the fitness of each generation was initially tested physically. This involved testing the twenty five-millimeter

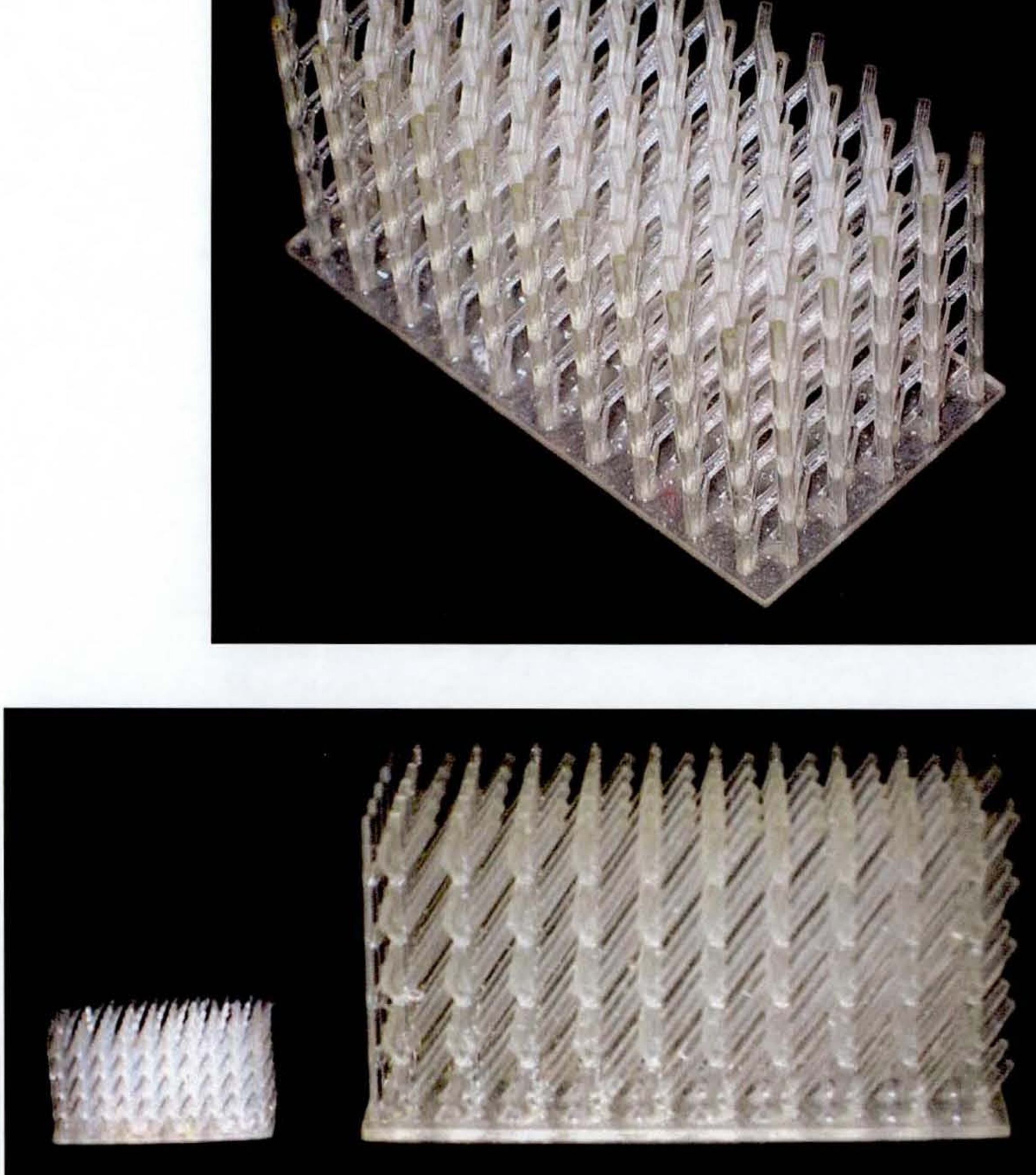


Figure 5.3 A 3/4 view and side views of the 25 mm and 75 mm SLA Matrix Cube Facades.

cubes under compression until failure, and weighting their mass. A procedural virtual model will then be derived from these tests.
After several generations of physical tests, a function algorithm could be found to map the results to a set of virtual models created by standard structural analysis software (such as Solid-Works Cosmos - a Finite Element Analysis (FEA) program. Subsequent generations of the GA used this software technique to calculate the fitness of individual cubes rather than using the physical tests. This mapping was subsequently to be used to allow for more complex forms to be evolved virtually, potentially even without the need for physical testing.

5.2.3 Results

Even these initial samples of the two differently scaled cubes managed to convey a tacit tactile thrill, particularly when the two cubes are experienced together. For even thought both cubes are, in form and structure, exactly alike, one only being three times larger than the other one , the difference in how they 'felt', was substantial. Whereas the larger cube is rigid and unyielding, the smaller one, (made from the exact same material, from exactly the same CAD model), is slightly taut and flexible. The cubes already carry traces of an affective tactile presence, that can hopefully be contextualized as a feature in future design.

The evolution of these small samples was adopted as proof of concept that may be extended to produce more complex forms, in which the internal space frame varies its geometry across the object . Conceived in this manner the fine scale structure would be optimized at every point for the inherent forces at that specific point, creating an organically evolved and responsive fabrication.
A more detailed outline of the programming related principals can be studied in the papers included in appendixes one and two.

5.3 Ghost Patterns

The design is a case-study explored how, on certain of the photopolymers used in the SLA process, the resin gets 'burnished' (a shade darker) when exposed to a number of repeated

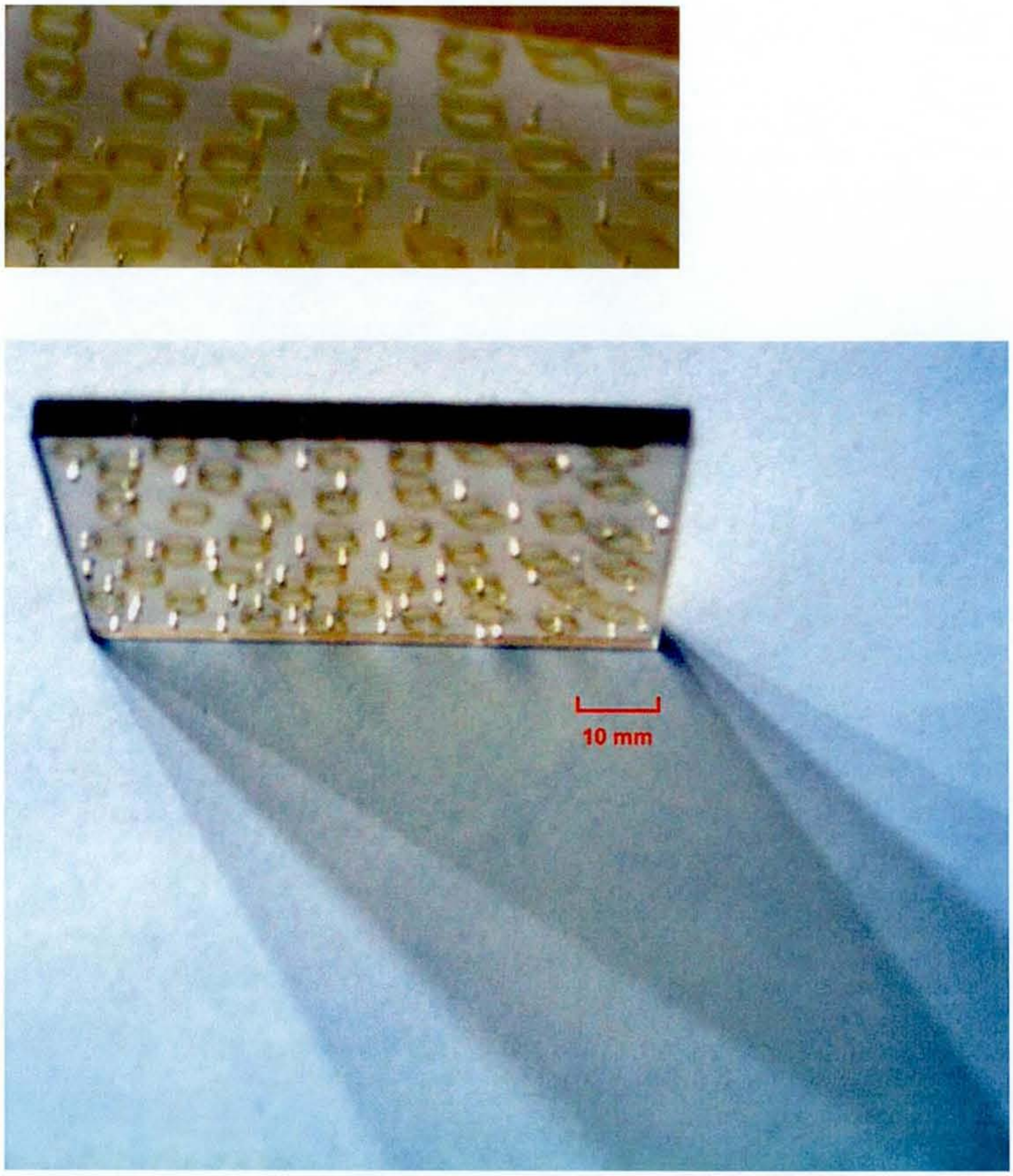


Figure 5.4 Ghost Patterns - test tile.

'sweeps' of the laser. This ability allows for the select control of the materials opacity, which can be utilized different function based purposes, such as degrees of privacy or shading control (Fig. 5.4). I.e. if the technique was to be used in the context of an architectural shade or partition, the surface's degrees of opacity can be controlled and customized to accommodate the particular locations needs by blocking certain views by increasing the surface's opacity, or, likewise, can be used to selectively shade or expose an area according to the particular locations needs and uses.

5.3.1 Objective

The aim was to explore how this quality, the ability to selectively control and vary the opacity of the fabricated surface plane, could be used in a design. The ability to selectively control the degree of opacity, as well as the volumetric 'shape' of the opacity within the material, a bespoke design can be achieved.

5.3.2 Method

The effect was achieved by overlapping or layering a number of shapes/ models (in this instance a cylinder shape) within the SLA file, causing the laser to cure the same location repetitively (how many times depends on the number of locations where, or objects, that overlap), resulting in a more dense shade on the locations where the most frequent intersections occur - a process that allows one to control the lightness or darkness of the resulting ghosted patterns by varying the number of overlaps of a shape within the CAD (and STL) file. Apply less overlaps and the resulting shade will be lighter; increase the number of units that occupy the same (virtual) space, and the shapes will appear darker...

5.3.3 Results

The design provided a suggestion for how this particular application of the SLA process could be utilized in future designs. The control of the surface's opacity depended both on the type of photopolymer resin used, as well as on the strength of the chosen laser, however, this test provided viable proof that the technique can be applied and used as beneficial means, also in an architectural context, for controlling anything from privacy to using it as a bespoke shading device in which the degree of shading (or a parametric, shadow based, chiaroscuro) can be customized to the particular location and intended function.

5.4 Alice Cups

The Alice Cups, a set of cups which were manipulated to befit a select number of beverage consumption settings. Inspired initially by both D'Arcy Thompson's On Growth and Form (1961), and the size and proportion related conditions of Alice in Wonderland.

5.4.1 Objective

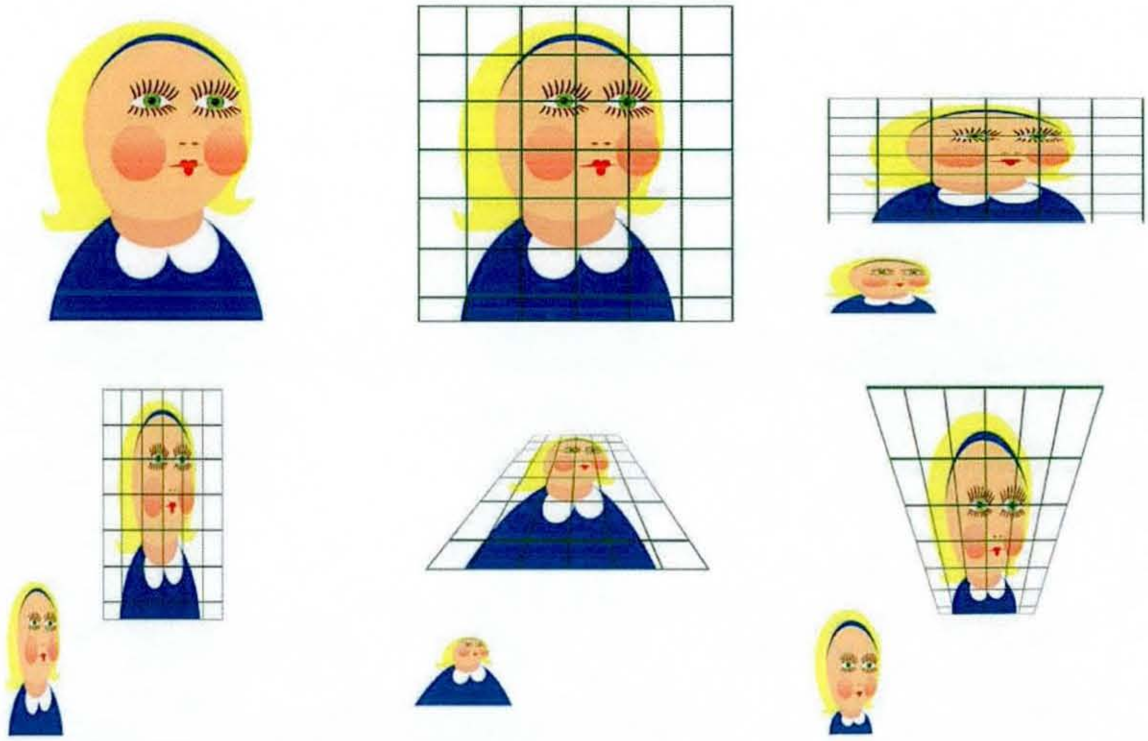
The study's intention was to use and reflect on the capacities and methods, the manual parametric abilities, of CAD in the context of CAM, and to explore how by simple acts of stretching, pulling, flattening and selectively combining a core (genotype) cup, a variety of alternate (phenotype) functions could be achieved.

5.4.2 Method

The core cup was designed in Rhino, made roughly the size of a 1.5 decilitre teacup, which was saved as a STL file, and consequently manipulated to befit a number of defined functions, such as an espresso cup (shrunk), café latte cup (stretched vertically). It was also made into a saucer (horizontally flattened and stretched), as well as a teapot (scaled up, stretched vertically and slightly flattened). These were subsequently fabricated both through SLA and SLS.

5.4.3 Results

The Alice Cups provided evidence that there is a viable way to use the technologies affiliated with Rapid Manufacturing to produce objects directly and according to, even whimsical, parameters. The methods used could easily be applied to a number of alternate household or other



5.5 Early illustration of the Alice Cup's parametric breakdown.

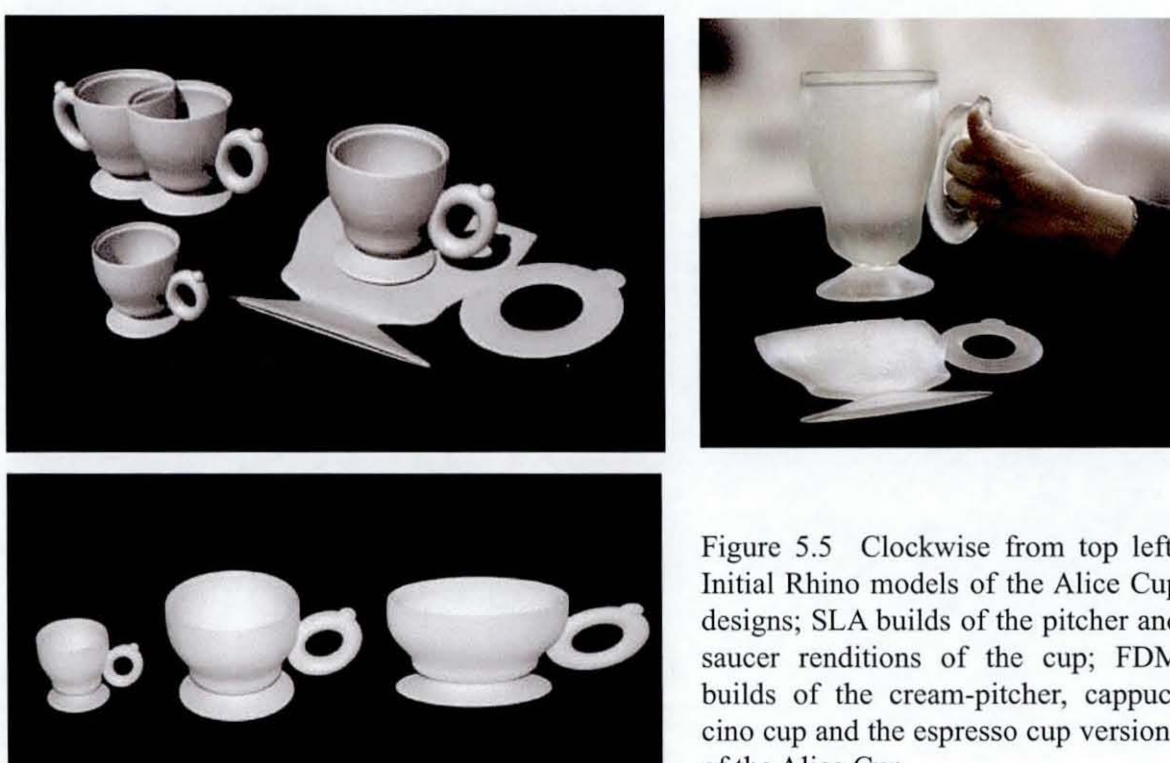


Figure 5.5 Clockwise from top left: Initial Rhino models of the Alice Cup designs; SLA builds of the pitcher and saucer renditions of the cup; FDM builds of the cream-pitcher, cappuccino cup and the espresso cup versions of the Alice Cup.

items, and provide them with a straightforward means to be customized according to need or whim.

5.5 Bead Pavilion

The designs was for a proposed 'adjustable space', here formulated under the heading of a pavilion design, due to its somewhat unspecified and generic quality of the term. The aim was to make the design multi-functional - entailing that it should be able to fulfill the role of anything ranging from a café, an exhibition area, or even a small performance space.

5.5.1 Objective

The Bead Pavilion was an attempt to design a structure by using currently available RM technologies. It expands the realm of the design described above by raising the bar, and thus the complexity, on the issues involved. The aim was to suggest a way how the additive fabrication technologies could already provide a indicative way to make things of a more substantial size, and how the abilities of the technologies in question (which includes other related forms of hardware, software and buildware) could be applied and combined in such a venture. It could also be claimed to represent a design that lacks a coherent 'image' - an appropriated notion of the weak or fragile architecture concept discussed earlier in the text (Ch. 4.1.5).

5.5.2 Method

The size of the pavilion design is approximately 10 by 6 by 2.5 meters (the height of the pavilion is somewhat variable). The breakdown of the main components of the design can be seen in the accompanying illustration (Figure 5.6).[1]

1 In this context it has become apparent that even though the current study is structured in such a way that it, call it, 'assumes' a whole architectural structure can be constructed through the use of Rapid Manufacturing, it will involve, at least for the foreseeable future, a form of hybrid construction in which alternate construction techniques will be involved in the assembly and collation of the whole. The study aimed to suggest an additional parallel alternative for how we can conceive designs, not as a superseding model replacing other paradigms of conception or construction, but as an approach which, in conjunction with other parallel means of making, can propose something new.

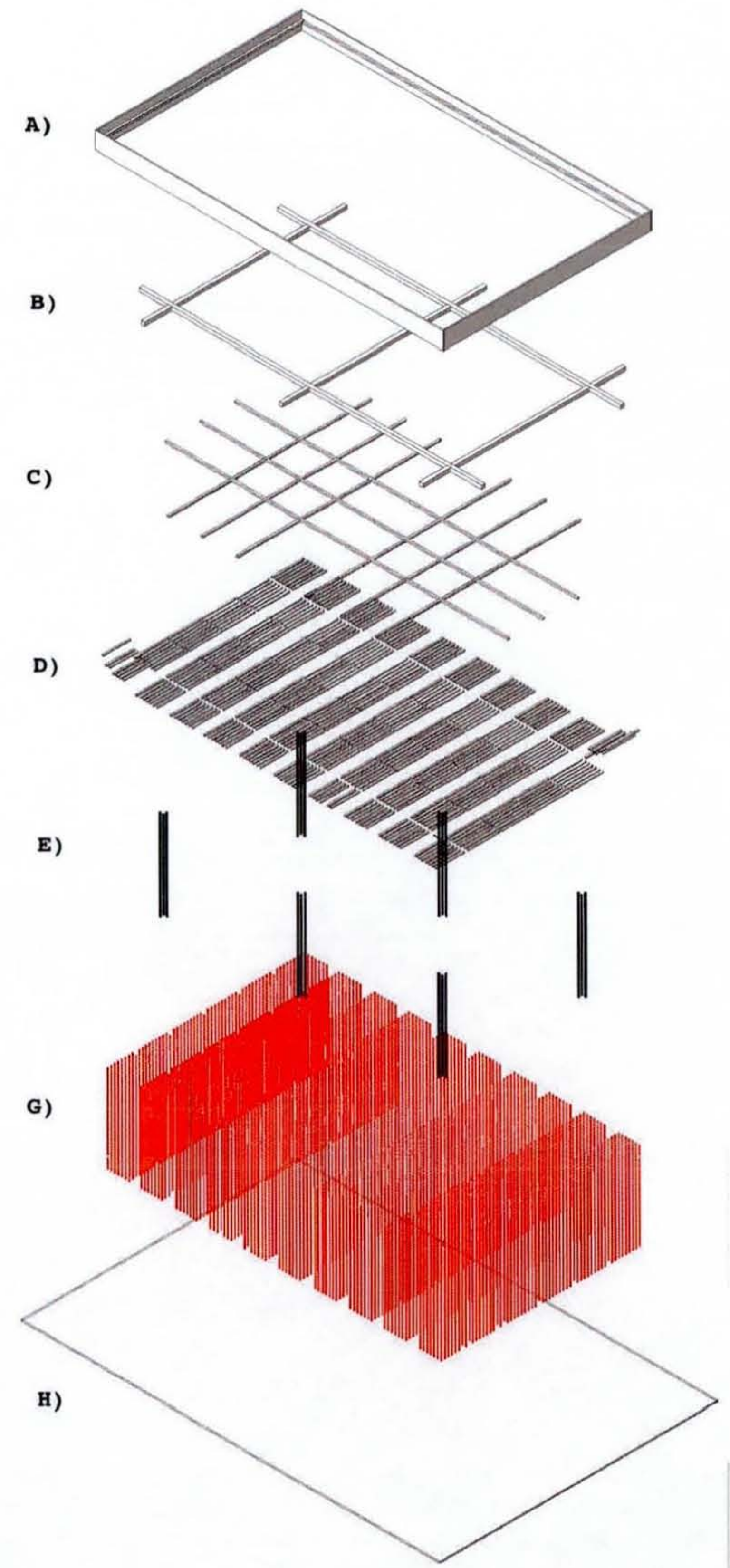


Figure 5.6 Exploded view of the proposed pavilions main components. A) Roof periphery B) Primary roof supports C) Secondary roof supports D) Bead strand housings E) Mobile piston columns G) Strand beads H) Floor.

Here the three top layers (A, B, C), form a straightforward grid-structure that is fixed and enclosed in a peripheral, half meter wide, metal skirting. The 'Bead Strand Housings' (D), support the main components of the design, the Bead-Strands. The bead strand housings are removable and can hold up to seven bead-strands each. The Piston Columns (E) perform as the pavilion's default supports. These six columns, each split, in turn, into five separate, yet connected and thus braced, narrower columns, have the ability to move slightly up and down in a piston-like housing. The Strand Beads (G) form the main, and most perceptible, component(s) of the design. The 'strand-beads' (when discussing the qualities of the individual beads), or the 'bead-strands' (when deliberating the collective quality of a whole strand of beads), are what determined the composition of the design. They were both the tools and the means by which a design is achieved. The floor (H), serves as an 'anchoring' element, a touchstone of sorts, that grounds the design and provided it with a referential constant against which any of the pavilions shifting permutations could be compared against…

The key elements were:

The Strand Beads

Formed the main building-blocks of the pavilion. They were designed, fabricated and assembled to perform, both in suspension and compression, the roles of partition or even structural 'walls'. They were also made into various kinds of seating, or desk supports. They can be made and positioned to insulate, to reflect light, to release fragrances, to vibrate, to whistle, to encourage freezing (when located in more temperate locales)...

How such a variety of qualities, properties and nuances were achieved and controlled by somewhat emergent means where slight interventions on a micro level can result, when progressively multiplied, in a potentially exponential variation at a larger, more comprehensive, scale.

The foundation to the whole set-up, as mentioned above, were the bead-housing, the connection point between two abutting beads. This somewhat conical, four-leaf-clover like, connection point was designed to provide one with four possible positional options for each of the connections between the varying beads in a bead-strand. This male - female connection is ge-

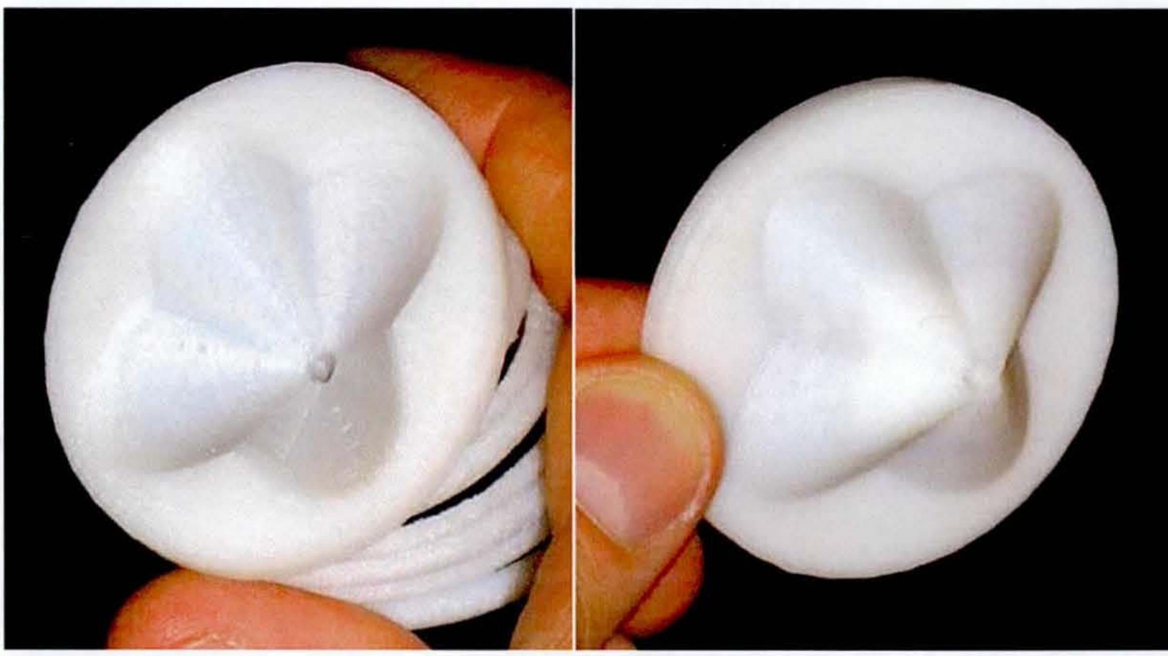


Figure 5.7 Left - The bottom half 'male' bead end-plate. Right - the top-half 'female' bead-end housing.

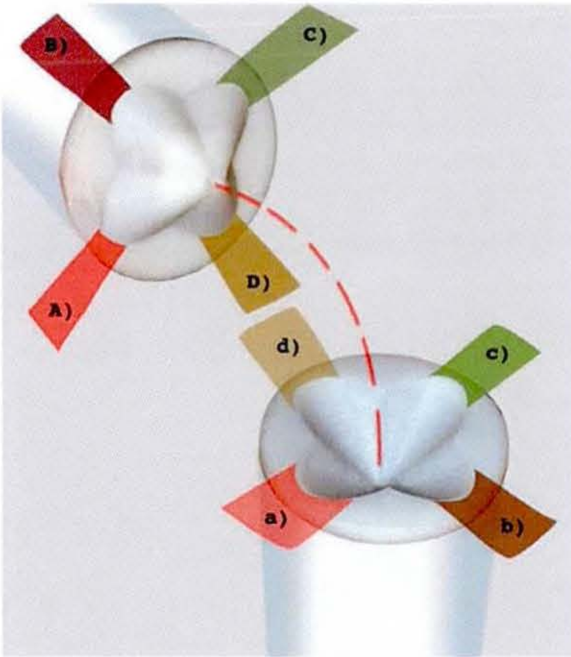
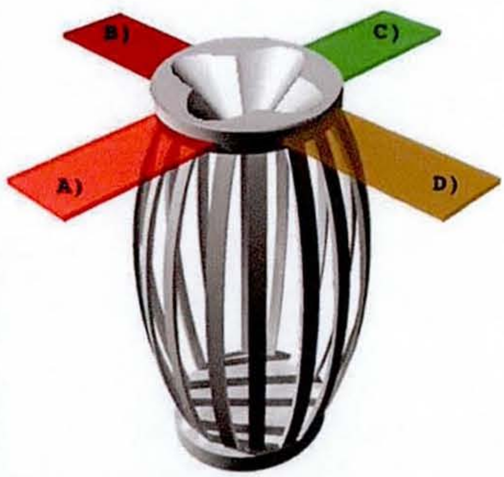


Figure 5.8 Illustration of the bead connection. Here with each of the connections 'leafs' colored and lettered.



Figures 5.9 Left - A section view through an asymmetrical bead that has thicker ribs on one side, and a bit narrower ribs on the opposite. Right - The 'legend' bead for referencing the illustrations below.

neric, whilst the bead itself (occupying the space in between the connections) varies. (Fig. 5.7)

The shape of this connection was also designed to be 'forgiving' regarding the slight discrepancies that occur due to the slight differentiation in shrinkage rates of the materials used by the various RM processes. Due to the connections conical shape, two adjacent beads made of different materials (that vary slightly in size) will still fit snuggly. (Fig. 5.8)

Based on this Cartesian framework, the design's qualities had their origin in the area between each bead's end-plates. For within this ribbed[2] area, by changing its composition even so slightly, one can instigate a variety of possible interventions, as shown in the illustrations (Fig. 5.9). In the sample bead above (Fig. 5.9) one is provided with a binary condition in which the bead is more flexible on one side than the other. When this is considered in the context of the four potential positions provided by the 'clover' connection a number of different compositions can be achieved in a bead-strand. The bead strands act and appear in a marginally different manner between being in suspension and compression. When in suspension the bead-stands act, more or less, as one could expect a, somewhat rigid strand (which can be removed by putting a oval disc bead between two interlocking 'clover' surfaces of neighboring strand-beads), to act in a 'looser' and more responsive bead-curtain (Fig. 5.13). Their performance shifts dramatically when in compression[3]. As seen in the illustrations below, by shifting each bead's positions just slightly the whole composure of a compressed bead-strand can be changed and regulated. However, in the initial images (Fig. 5.10) all the beads are facing the same direction, thus resulting in an even concave curvature of the bead-strand when in compression.

An alternate version based on the same means can be seen in figure 5.11. Here, by shifting the direction of the beads one-hundred and eighty degrees half way down, the whole strand performs in a different manner. This notion was further expanded by gradually spiraling these asymmetrical beads ninety degrees every three beads, creating an almost 'thickening quality of the whole bead-strand. These various settings can be combined, according to need, in different degrees in a single strand (Figure 5.12).

2 A compositional shape that become the default setting of the beads.

3 Also, by changing the string that passes through the center of the beads from a thin steel cable to nylon, one can manipulate the behavior of the whole strand…

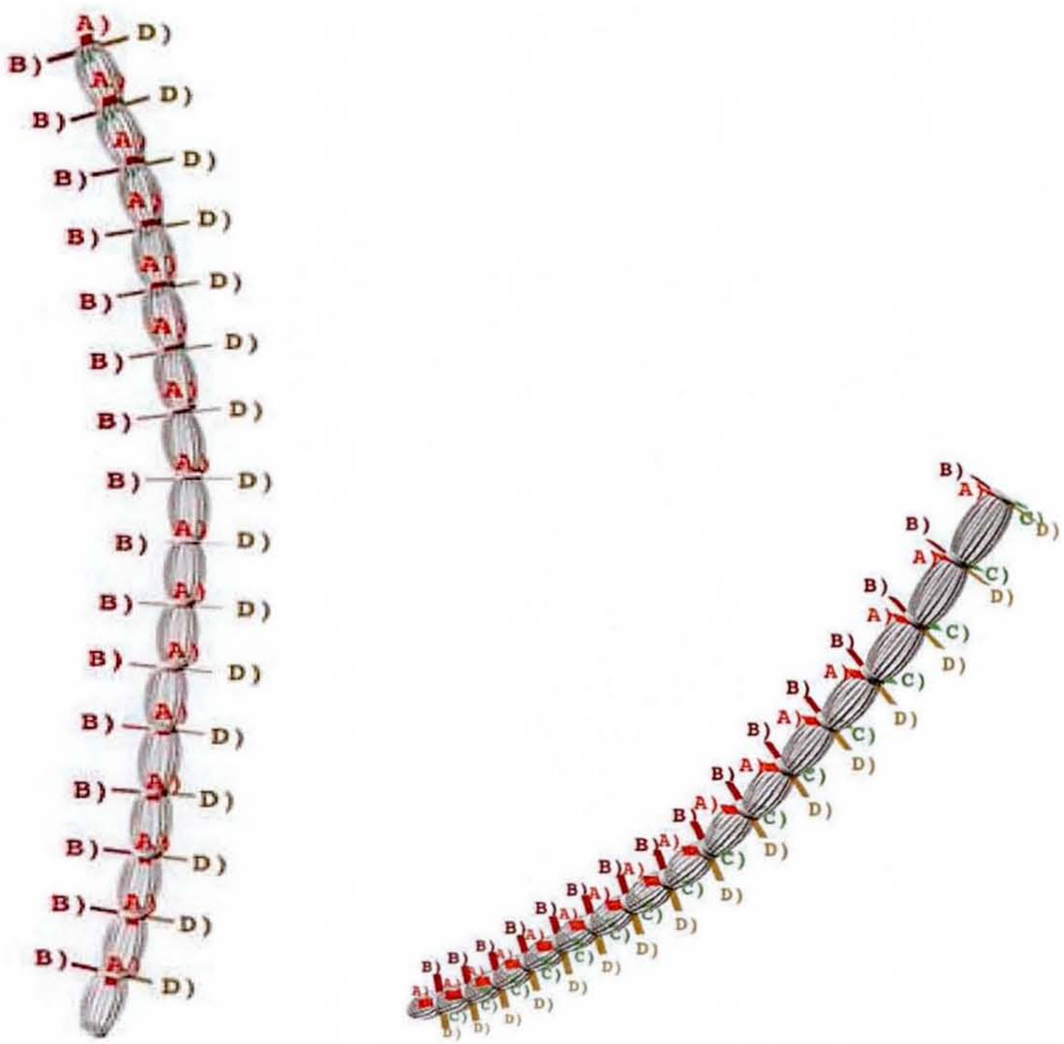


Figure 5.10 Two views of the same compressed bead-strand. Here with all the beads facing the same way. However, as the bead's are all a bit more flexible in one direction (direction 'B)'), the bead-strand flexes in this singular direction.

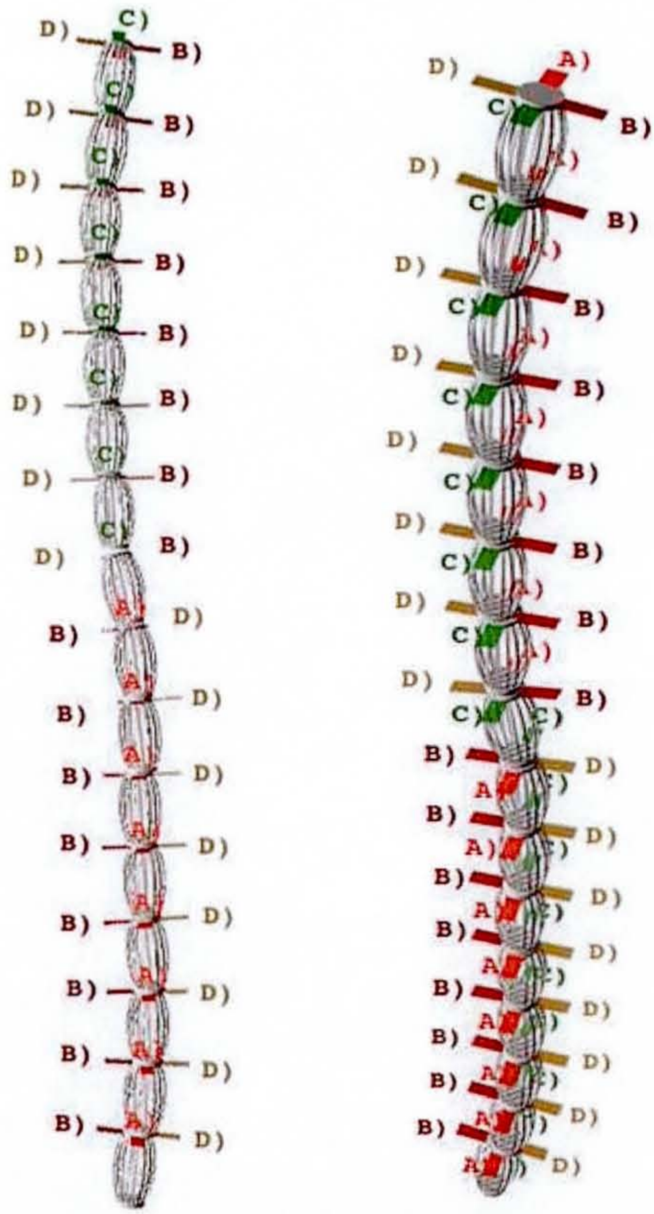


Figure 5.11 Two views of the same bead-strand, here with the direction of the flexible side switched 180 degrees halfway down the strand.

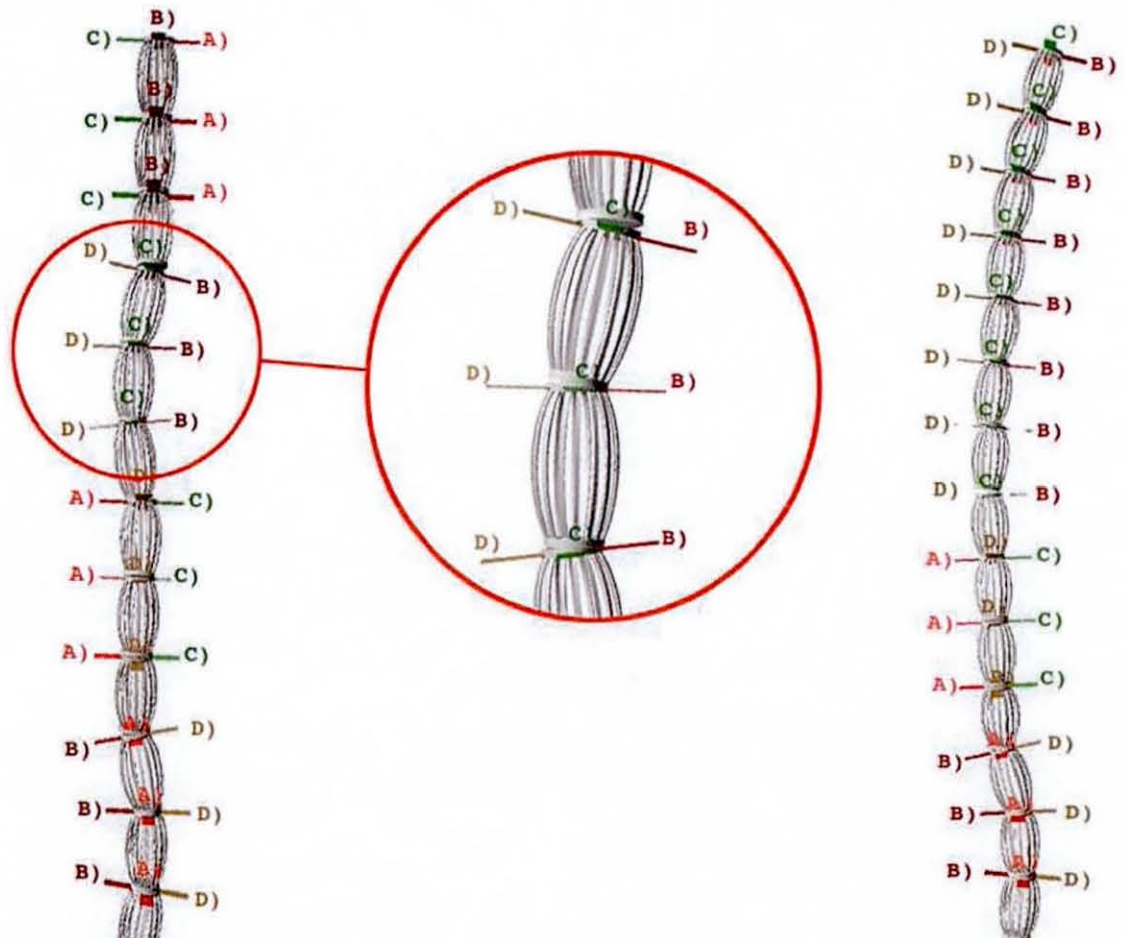


Figure 5.12 Spiralling bead strand. Here, in groupings of three which are sequentially rotated (one notch on the male-female connection) ninety degrees, resulting in the bead strand appearing to 'spiral. This composition will allow the stand to entwine itself (in a similar fashion to DNA) to other adjacent strands more easily.

This DNA like, 'play' with the various settings of the beads and bead-strands was included to demonstrate how, in this context, a very minute intervention of a simple binary condition or quality can be expanded and alternated almost exponentially with each added bead…

The beads in the strands work in symbiosis. As singulars their role in negligible. Only in groups do their true character, nuances and all, come forth.

This mode of assembly should also be considered in conjunction with the RM mode of production. For, as mentioned earlier in the text, it is irrelevant for the RM machine if it produces two items exactly alike or two items, of roughly the same volume, but which are drastically different - the effort and time to manufacture them will still remain roughly the same. Thus there was no need for an analog modular to even exist - the semiotic templates of a particular design process or parametric pattern can exist solely within the digital realm, in this instance predominantly within CAD, which can be adjusted, still based mainly on binary settings, only here these settings can be adjusted on a 'sliding-control bar', allowing one to make particular design constituents smaller or larger, more or less pronounced, longer or shorter, more or less skewed, thicker or thinner, etc. Several of such qualities can, of course, be applied simultaneously to a single component, i.e. a bead can be made taller, as well as having its member thickened or multiplied, whilst its ribs curvature can be slightly decreased, etc. How some of such variations could be classified is suggested by the illustration below (Fig. 5.14). Here the qualities of the beads were changed by applying very simple shifts to the various beads. In the initial phase, seen on the left, one can adjust the bead, in comparison to the 'median bead' on the far-left (inside the dark-pink circle), one can adjust the beads based on various binary qualities. One can make a bead taller or shorter, more or less skewed, with thicker and more dense, or thinner and a bit more sparse distribution of ribs, etc. These, in turn, can then be conceived in the context of beads that determine how one wishes the strand, or a bunch of strands, to behave; in other words, by utilizing double or triple beads on can 'bunch' up strands. By using 'transitional' or 'in-between' beads one can alter a strand's size or change its flexibility. These, again, can be contextualized according to more particular criteria. A bead, or a strand of beads, can be made more or less 'furry', to provide insulation. It can be made to rattle, float, or even freeze in

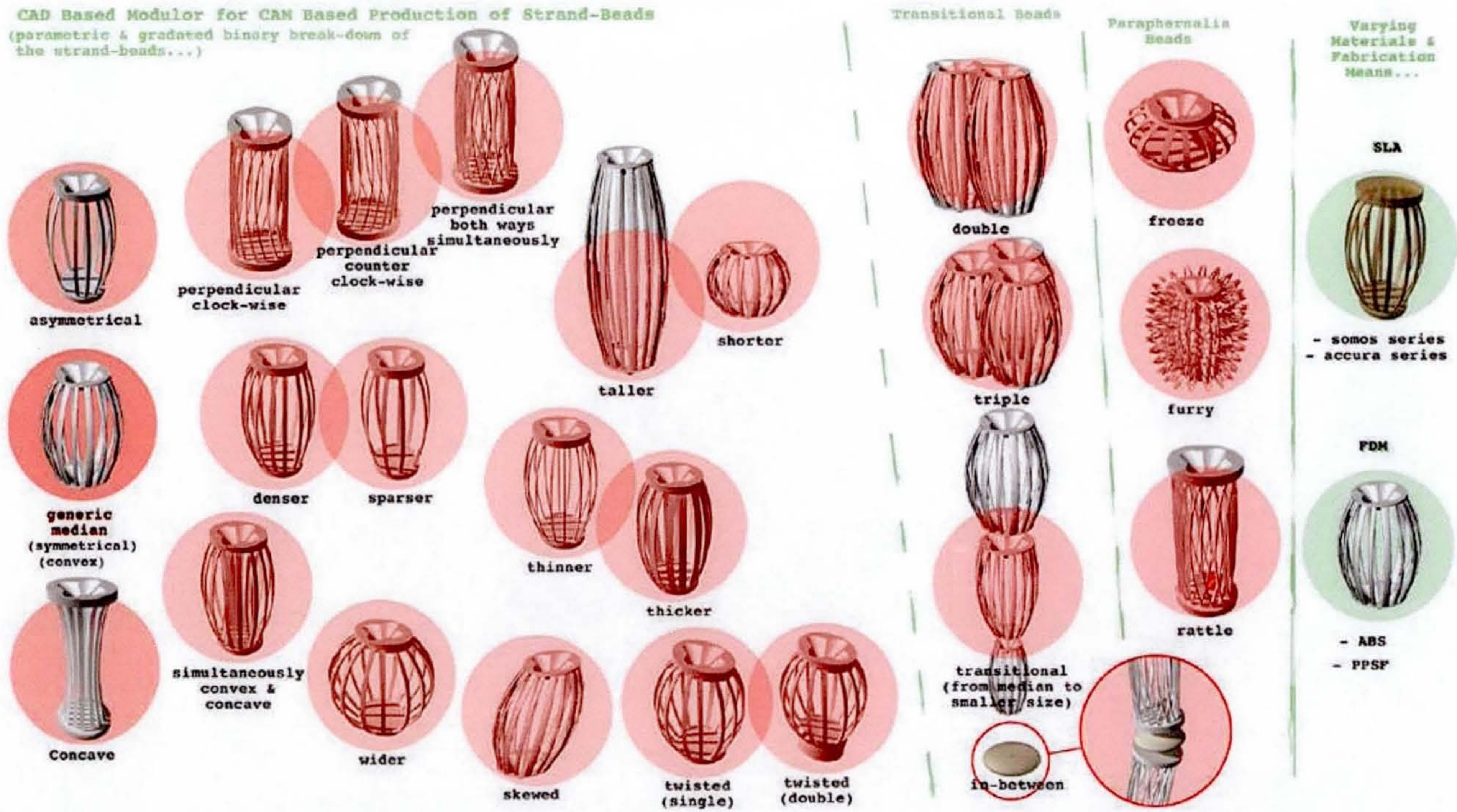


Figure 5.13 A break-down of the various bead classes.

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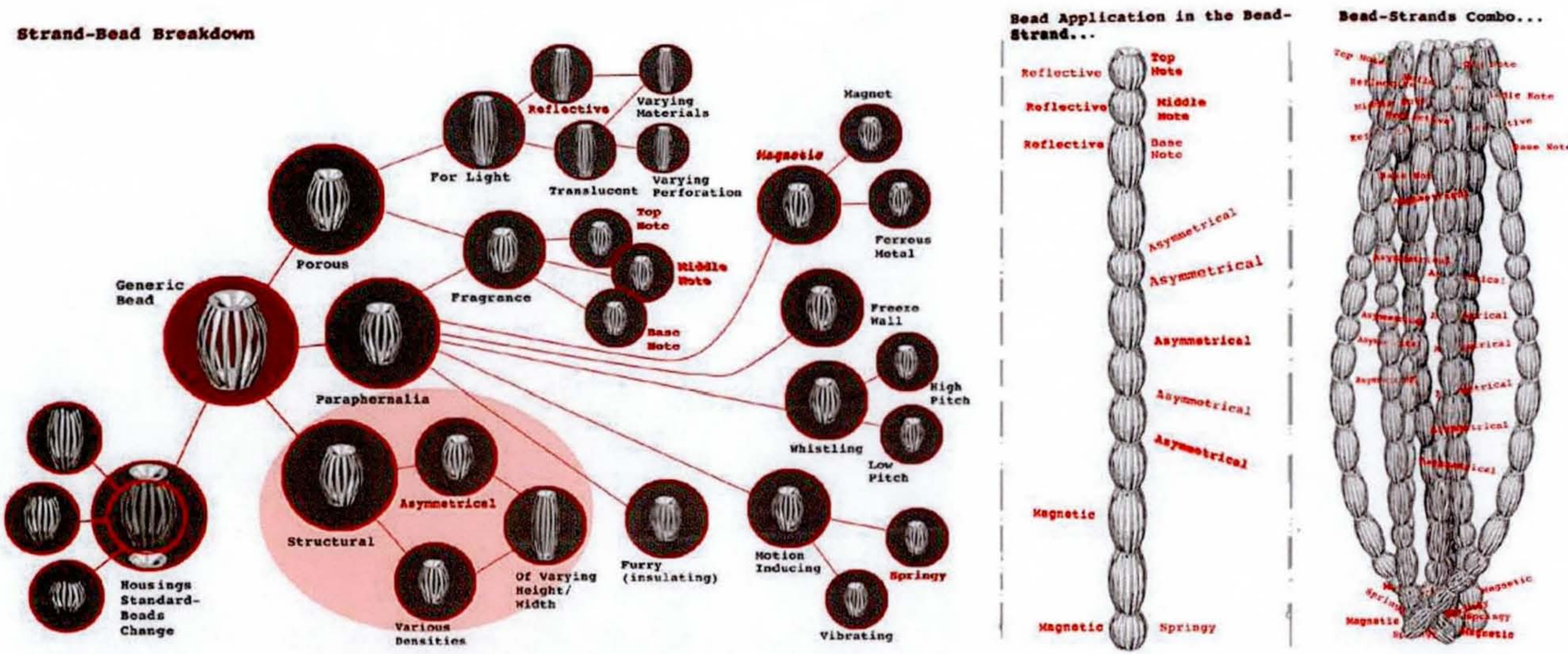


Figure 5.14 An illustration of various different bead settings, and how they could be applied in a bead-strand and how a number of slightly differing bead-strands could be, in turn, bunched up to provide an additional ‘enriched’ array of combined properties.

a particular fashion. All such considerations need obviously also to be considered in the unison with a particular fabrication method and material…

In Figure 5.14 this ascending assembly, from the beads initial formulation to its fusion into strands, which then can be combined further larger groupings according to need, is summarized. This set-up performed as an avaterial taxonomy, and provided a number of the potential analog genotypes for the phenotype settings of the bead-strands and strand-bunches. It also provided a suggestion for the almost infinite variety of properties, textural qualities and even tectonic settings that can be achieved by such aforementioned means. The beads and bead-strands can be made to act like a delineating partition, or a suspended seat, or as a supporting column, by varying the types of beads, and the combinations of such beads in bead-strands.

Box Insert *Application of Bead Pavilion*

The beads, in conjunction with the strands, provide a vocabulary and a suggestive grammar according to which a design could be formulated.

The included example was for a winter rest-stop, located on 'Hauk Lampi', a lake in Southern Finland. The site is located close to a hiking or jogging path, approximately a hours walk from the closest paved road. The pavilion would function as a resting space for the various hikers or skiers that frequent the area. It would be predominantly for winter use, although it does allow, and is also designed to accommodate, accommodation during the summer months. All its components are designed to be assembled, disassembled and carried without excessive tools or lifting equipment.

The pavilions main components are: the external self-acclimatizing shell, the inner insulating shell, the roof and the floor.

As summarized in figure 5.18, the outer shell performs quite differently during the summer and winter seasons.

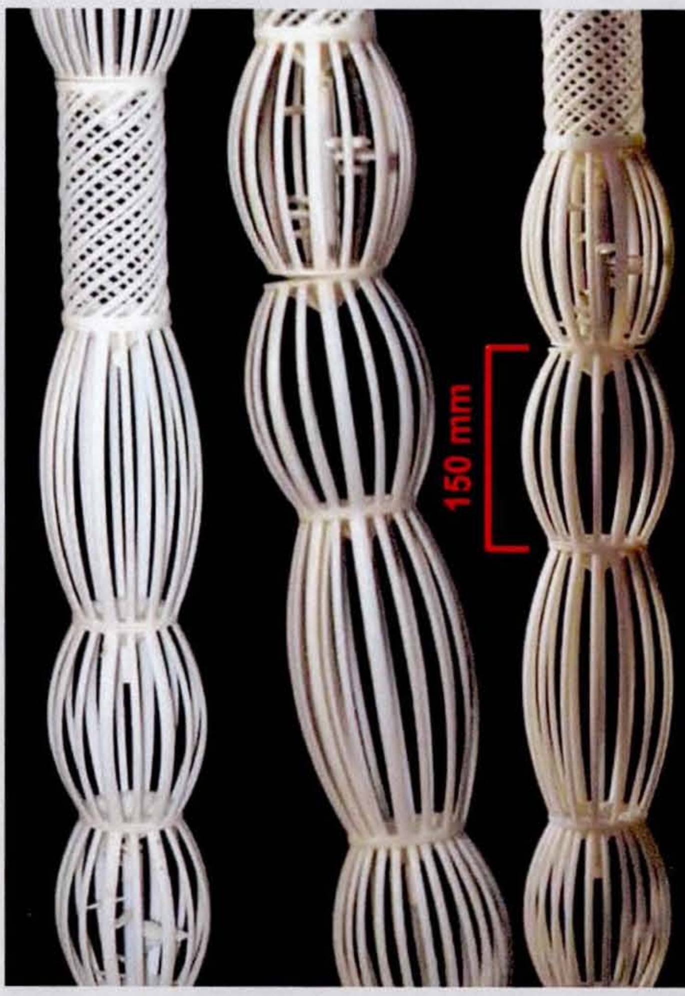


Figure 5.15 Full scale renditions, made by using FDM, of some of the beads...

The pavilions outer shell is made up of mainly two different types of bead strands - 'freeze-bead-strands' around the periphery, and 'access-bead-strands' by the intended main entrances.

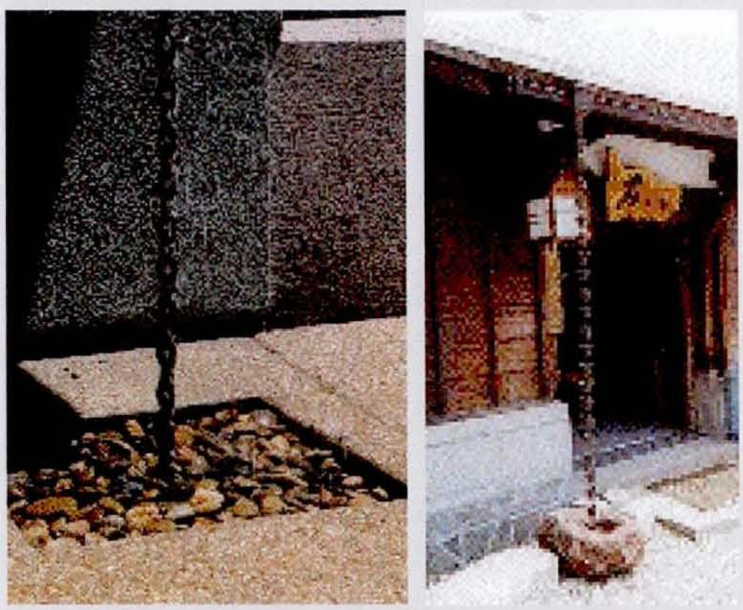
The freeze-bead-strands are what allow the outer-shell to adjust to the seasons. Inspired initially by 'rain-chains' (Fig. 5.17), a quite common feature accompanying many a gutter in Scandinavia, which are used to direct or lead rain-water into a drainage ditch. These chains, free-hanging during the warmer seasons, freeze into rigid columns during the winter. These chains, that during the early months of winter form a thin, bark-like, stem of ice around the chain's loops, can often grow into a rough 'trunk' of ice by seasons final cold months. It is this feature the freeze-strands try to accommodate.

By shaping the freeze-beads in a fashion that encourages them retain the water that runs across them during early-winter rain-fall and the 'slush' season (usually September early November), the bead-strands would gradually collect and allow ice to attach itself to the strands to form initially slender frozen stems that, as the season progresses, would grow to unite and form a solid wall. This process would reverse itself during spring[4].

This process would be predominantly self-sufficient, i.e. it would need no external intervention or energy for it to function. The pavilion would allow the warm summer wind to pass through its perforated exterior in July, and form a protective frozen bulwark against the Arctic wind in February.

The access-beads function, as the name implies, as indicative point of entry. They would be located roughly in the center of each of the pavilions four walls. They would not freeze in the winter due to their more streamlined shape. As one can observe in the beads in the illustration above one could also insert (build) a small marble into the interior of the bead to make each bead-strand function as an elongated rattle, that, as someone enters the pavilion at the access points, would make an indicative rattling-sound. During the summer months the pavilion can be entered even through the slightly stiffer, but not rigid, freeze-bead-strand (see Fig. 5.16).

4 To quicken the freezing process extra water can be poured or dripped onto the strands early in late fall…



Figures 5.16 Two images of rain-chains.

Appearance wise this external layer of the pavilion would also switch from a modest, almost covert, 'look' in the winter, when the frozen white outer shell would fade into its snow-covered background, to a very noticeable ivory during the, mostly pine-green and brown backdrop, of summer.

The inner periphery of the pavilion is made up of 'furry-bead-strands'. These are meant to provide an insulating and protective layer in the winter, and an easily adjustable, reflective skin during the warmer months (Fig. 5.17).

This layer does have a preferred point of entry, located in each of its corners (indicated by the gradual lessening of strand density as they progress towards the layers edges), however, just like the outer peripheral layer during the summer months, it can be entered at any locale by simply 'walking through' the bead-strands…

The floor is also slightly oblique, subtly ascending from the locales exterior periphery towards the pavilions center. It is covered with a subtly textural surface which has a friction pattern on it (which 'feels' rougher in one direction, smoother in the opposite) that can also be used to sense where one is moving. This feature will also aid in the drainage of the pavilion (Fig. 5.18).

The pavilions roof is simply formed by, and dependent on, snow forming a protective layer on top of the ceilings wood-joist. The forming of the roof should roughly coincide with the annual solidification of the peripheral (freeze-strand) wall.

The center of the pavilion would be occupied by an open fire, intended primarily to provide its visitors with a brief breather, and a chance to warm their hands and feet, but it would also act as a subtle beacon that could aid people to locate it in the hours following sundown, during the short winter days. The base below the fire would be of a porous ceramic material that would insulate the fire from the ground or ice below as well as provide a surface satiated enough to retain the heat, allowing it to slowly seep into its environs long after the fire sighed out. The smoke from the fire would escape through a 'self-carved' aperture (an opening made

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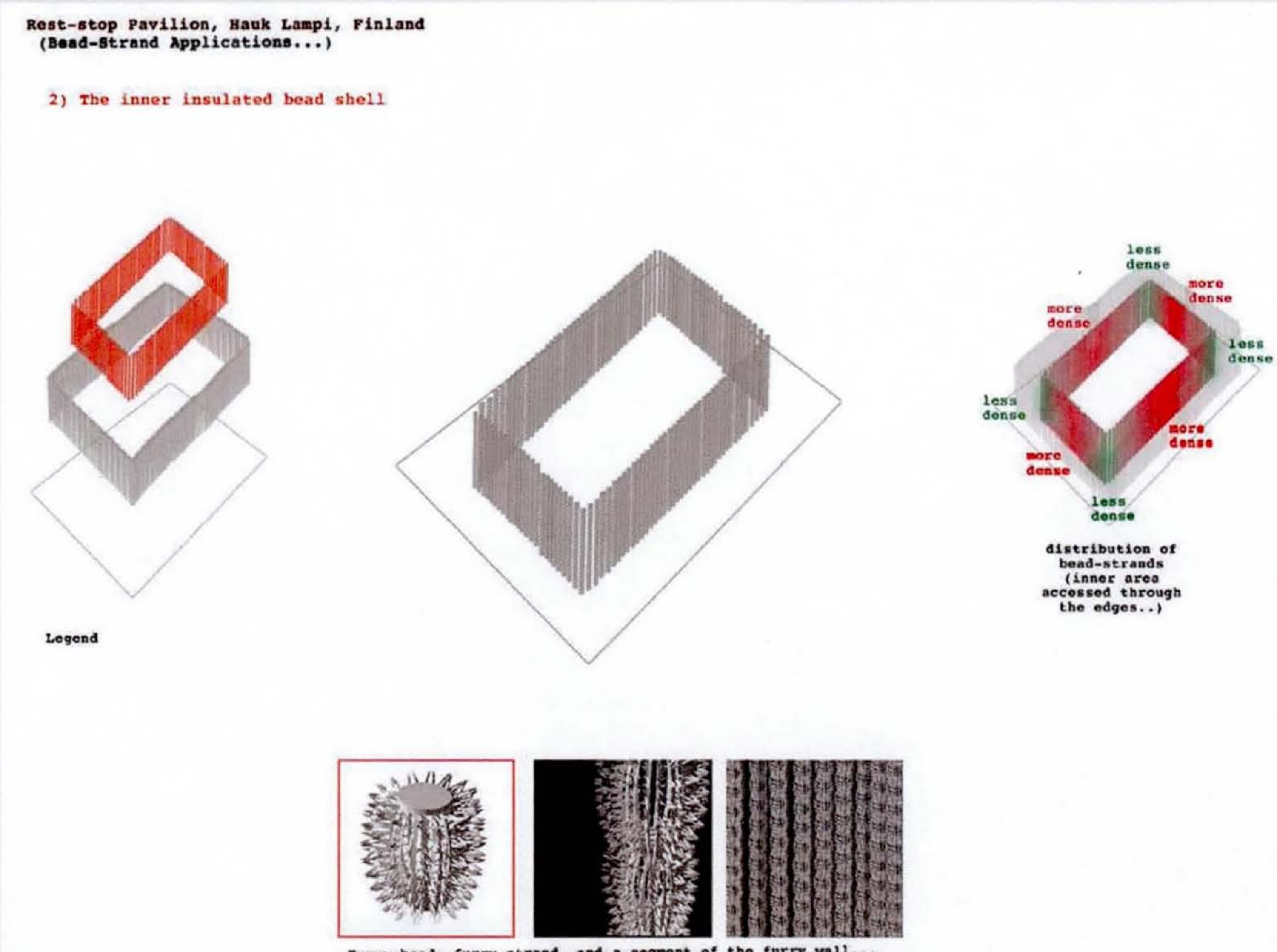


Figure 5.17 Illustration summarizing the pavilion's inner shell's components and functions, including the 'freeze-beads'.

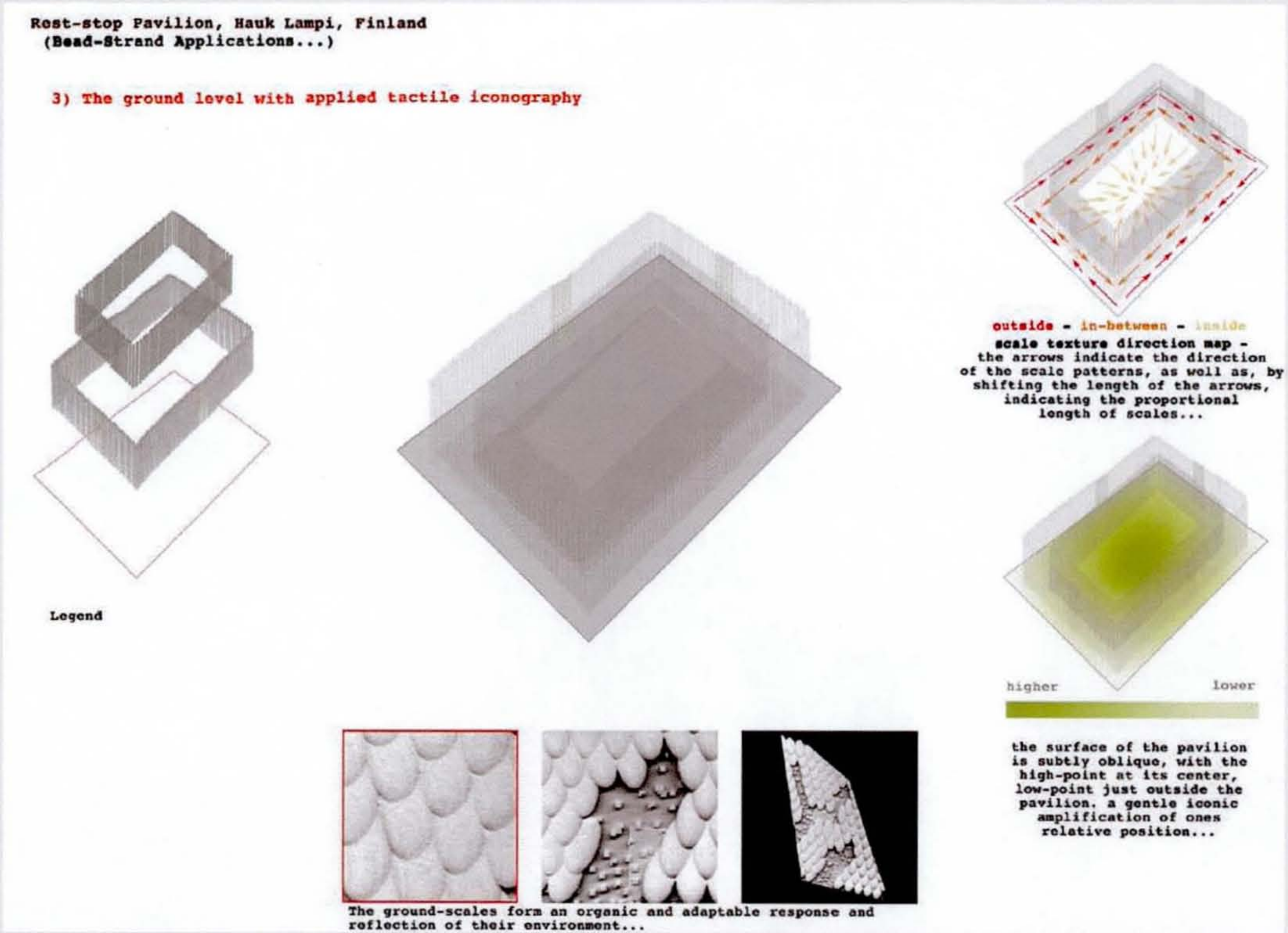


Figure 5.18 Illustration of the pavilion volume distribution and floor pattern.

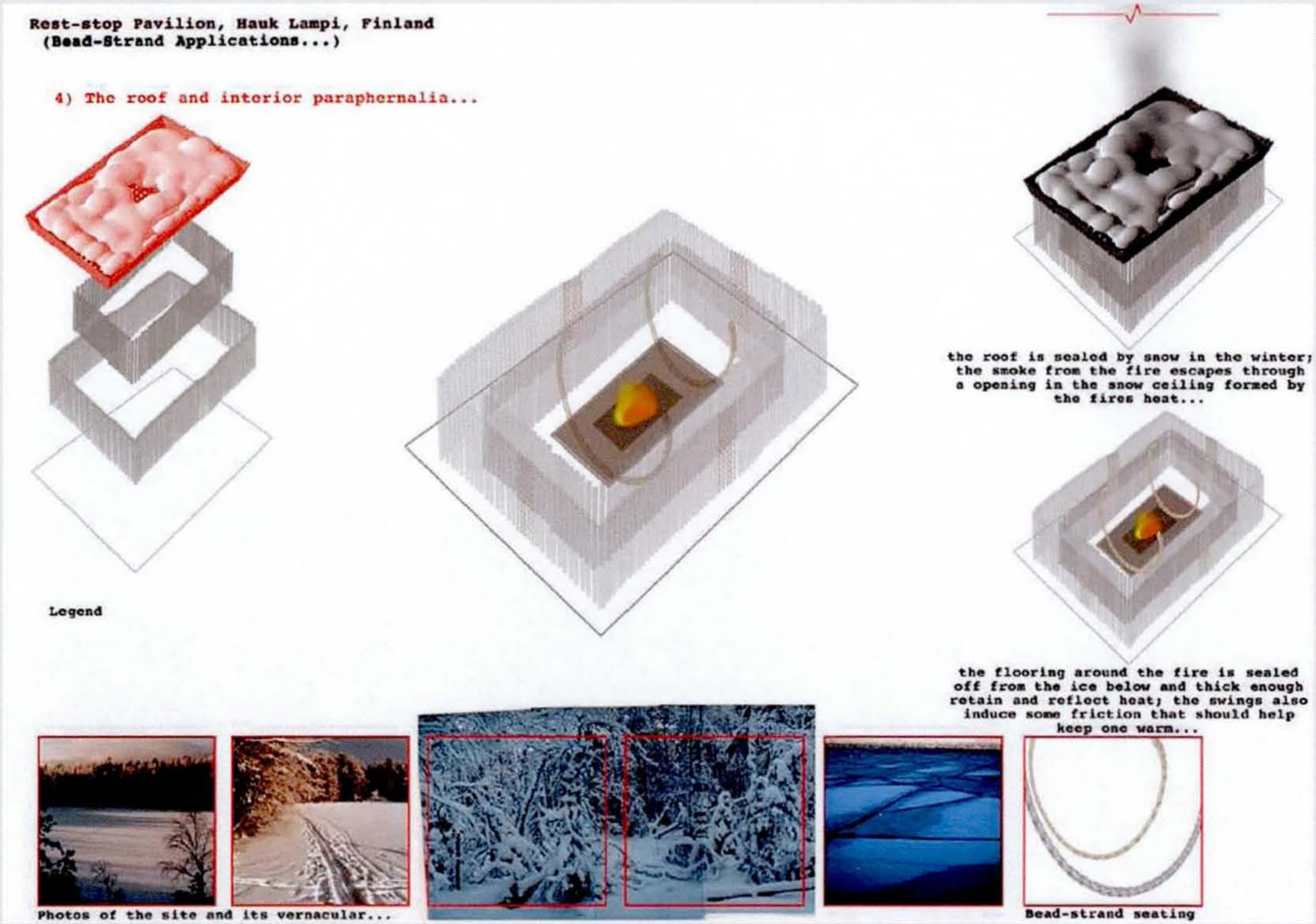


Figure 5.19 Summary of the pavilion's snow insulated roof and interior with photos from the site...

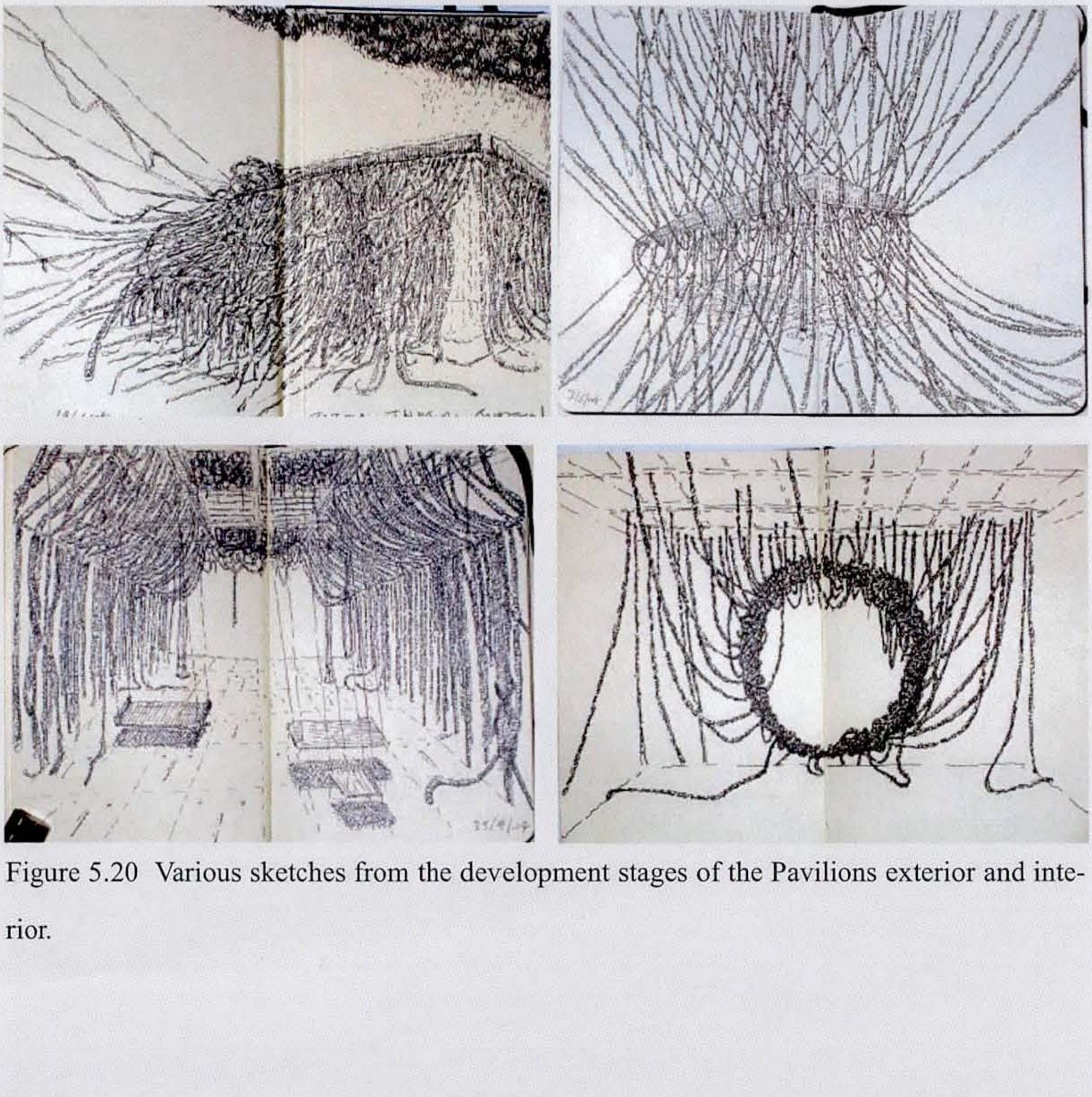


Figure 5.20 Various sketches from the development stages of the Pavilions exterior and interior.

through the snow melting where the most concentrated heat hits the pavilion's soffit) in the roof's snow cover (Fig. 5.19).

Seating would be provided by bead-strands suspended from the ceiling at both ends. These swing-like loops would also indirectly supply one with supplementary heat through the inconspicuous friction provided by the innately induced rocking motion that sitting on something that swings inevitably brings about (Fig. 5.19 and 5.20).

5.5.3 Results

The Bead Pavilion was an exercise that was aimed at exploring the adaptation of existing RM technologies in the making of an architectural project. A number of full scale beads were made through the SLS process, which allowed the viability of both the joints and the strength of the beads to be manually experienced and assessed. This particular application allowed, whilst still within their established remit, the technologies expand and be imagined beyond their usual scope, and provided a suggestion for how any why the technologies in question could be used in the implementation of larger scale builds.

5.6 PaperCuts

On a slightly different tack from the aforementioned case studies, the PaperCuts project uses the subtractive fabrication processes to make an additive assembly, a technique where, usually to create a topographical representation, a number of cut-out profiles are combined and stacked to provide an analogue rendition of something volumetric. Here this method has been adapted and expanded upon by creating a set of layered compositions where each layer does not remain a default profile, but is altered, by changing its material, or twisting, folding, weaving, saturating, soaking, painting, burnishing each laminate layer in an appropriately different fashion to provide the sandwiched composition a syncretic, and collectively considered, outcome.

5.6.1 Objective

To use the advantages of the subtractive processes in the context of the additive fabrication and (here manual) assembly methods and to create a set of more volumetric builds by such hybrid methods.

5.6.2 Method

Similar in method, only here executed manually, to LOM (Laminate Object Manufacturing), that creates physical representations from CAD based files by cutting and layering sheets of paper, the process is here expanded on by differing and individualizing the treatment of each stratum, be this by physically altering it (by twisting, folding, changing its material) or change-ing it by considering the transition between the layers (how the layers are attached to each other and how the resultant partitions or gaps - shadow or light gaps/ channels for air move-ment - can be used as defining elements in the design's realization). Here the core material's 'sheetness'[5] is taken advantage of and used to provide a hybrid approach that aims to combine the advantages of both the subtractive and the additive processes in a single build/ design.
Here also the positioning and variation of the material under the laser is altered (by shifting the material during a single build, or 'wrinkling' or selectively creasing the material so as to vary the burnishing patterns that result from the laser-cutting process by bringing it occasionally too close to the laser, beyond its intended focal point (Fig. 5.23).
A variety of different, predominantly papers but also canvas-cloths, of different weight, texture and size are cut with a CO^2 laser into a variety of different shapes and patterns which are con-sequently combined, altered according to need, and manually assembled into various composi-tions.
The pieces ranged in size from, the largest ones, being roughly 700 by 1800 by 120 millimetres (Fig. 5.22) to the smaller ones being approximately 300 by 420 by 150 millimetres (Fig. 5.21 and 5.23).

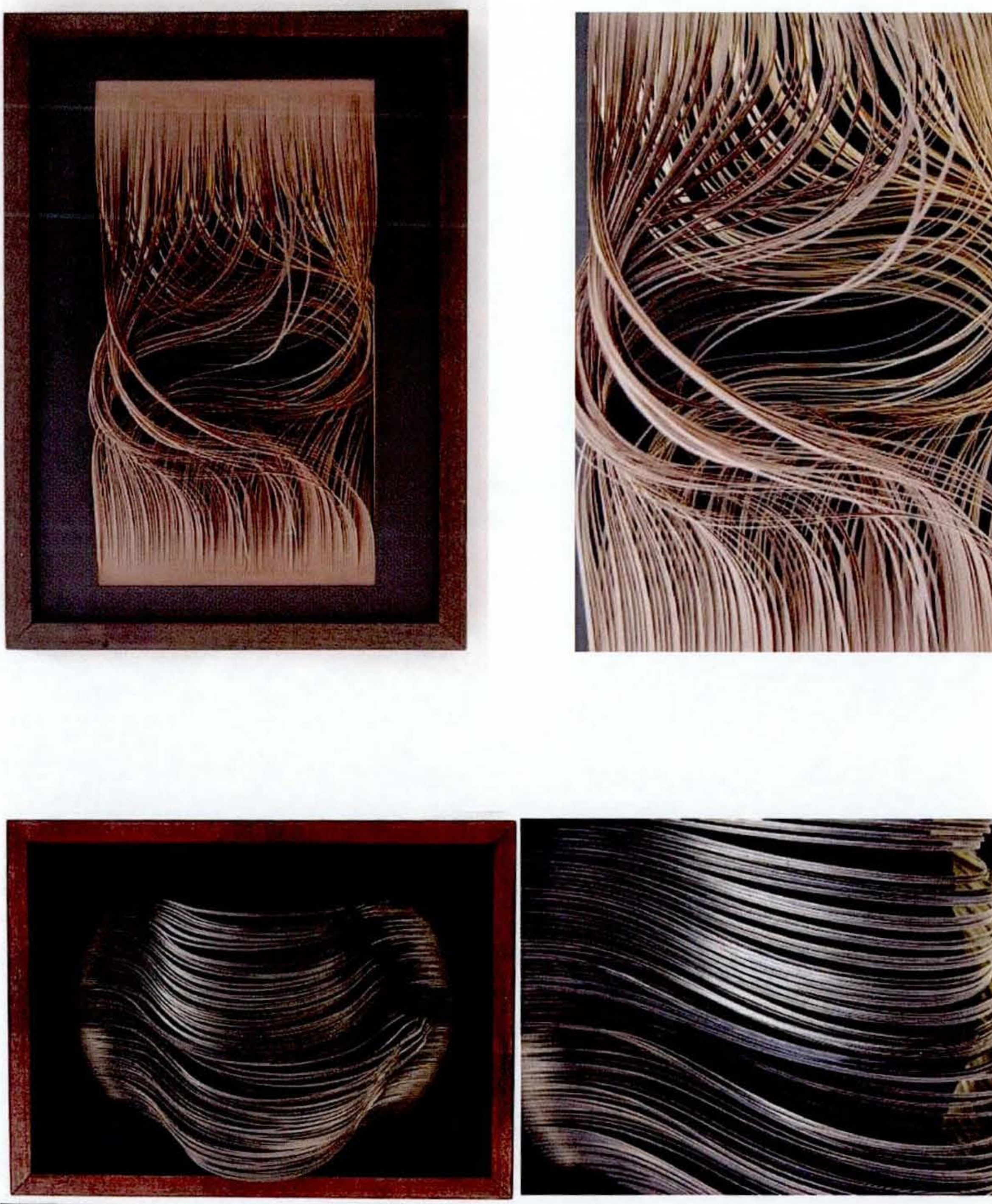
5 Strong enough to perform as a single unit, but still thin enough to be layered and allowed to function as a component in a collective.

5.6.3 Results

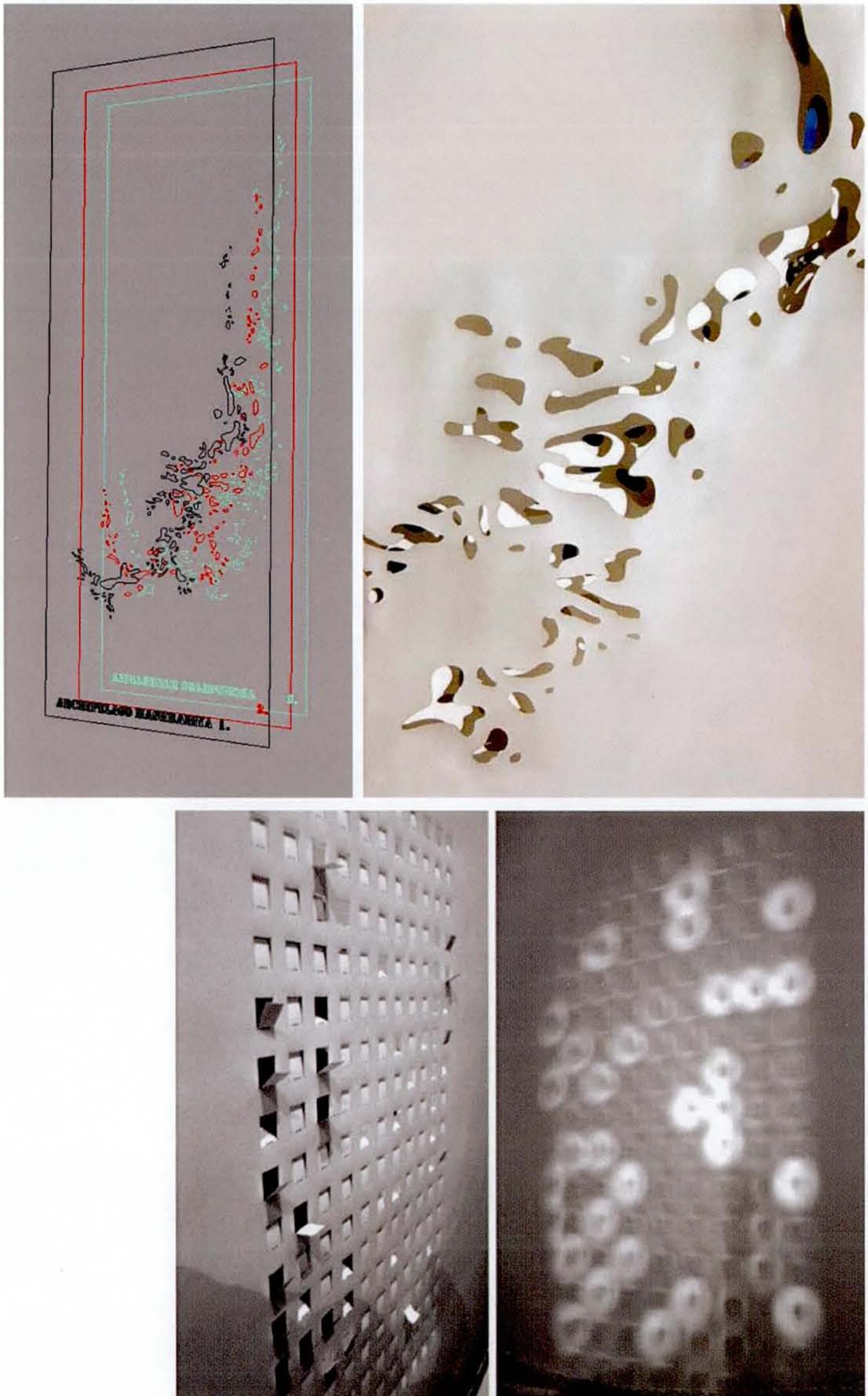
The designs provided a suggestion for how the seemingly opposing CAD-CAM fabrication methods can be combined. Engaging directly with all the facets of the process, from the original CAD based digital design, to the actual laser cutting of such a pattern (usually based on two dimensional either a DXF or Adobe Illustrator file) as well as the final combination and composing of the layered design, provide one with an empirical and literarily 'hands-on' experience and feel for what can be done, as well as how such related affects were be achieved. Here the notion of craft, from the initial making of the original digital file, to the cutting of the patterns with a laser, followed by the composing of the, usually layered, final assembly, and the reciprocal repeat any such process inevitably entails, provided one with a more fundamental understanding between the make-up of a design and its whole, from the burnished nunod cuts, to the texture of the trac sheets, to the consistency of the compiled procs. Here the rendition of the additive process through the manual assembly of different profiles provided one with a more intrinsic understanding of the processes involved and the potentials and avoidances of such fabrication methods, something of particular importance when using computers to make physical things.

The case-study also acted as a valuable conceptual foundation and testing-ground for how these techniques could be applied in architecture by providing essential information regarding the material parameters and considerations which needed to be applied when built at a larger, more architectural, scale. The way the material behaves did not always correlate in a proportional manner (i.e. the proportional scaling up of a design as well as the thickness of the cut material did not necessarily match), nor did what is drawn in CAD always correspond, even within the allowed tolerances, directly with was produced in CAM, as variations in the seemingly uniform materials used only revealed themselves during the cutting process. Factors such as slight variations in thickness of the material being cut, or the subtle level undulations in the surface being cut all had an impact in the quality of the outcome.

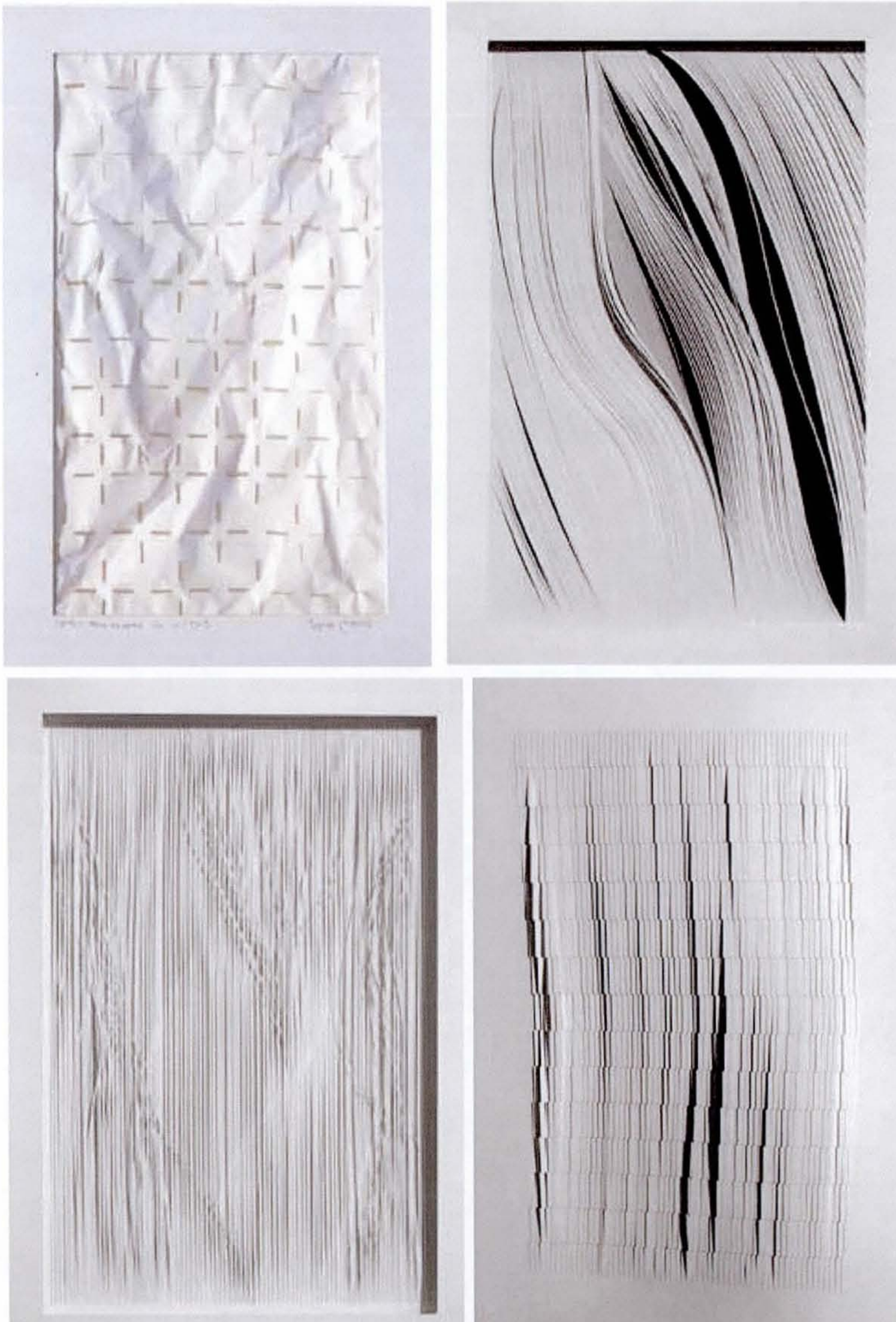
The PaperCuts were displayed at the Asia House Gallery, London, March - April, 2008.



Figures 5.21 Examples of smaller scale PaperCuts. Here the burnishing marks of the laser-cutting process were used as planned and defining features of the designs. The pieces were made of multiple stratums of paper, where the various layers were, whilst still corresponding and composed as a collective, differed from each other.



Figures 5.22 Examples of larger scale layered laser-cut designs, with the 'Archipelago' design above, and the 'Flap' design, inspred by middle-eastern mashrabiyas, below (both roughly 700 by 1800 by 150 mm). Here the shadows and reflections, both on the pieces themselves as well as on the surroundings were allowed to flourish.



Figures 5.23 A3 size PaperCuts clockwise from top left: PaperCut in which the paper was crushed before set onto the cutting bed, resulting in the grid distorting where the paper came too close to the laser during the cutting process; the remaining paperCuts all explored ways of cutting, weaving, handling and hanging the pieces that allowed for a variety of subtle responsive compositional variations (developed in conjunction with Maysaa Al-Mumin & Paul Brady).

6.0 Case Studies - Exploring Aspects of Sensory Perception Through LF Designs

6.1 The Sensory Follies

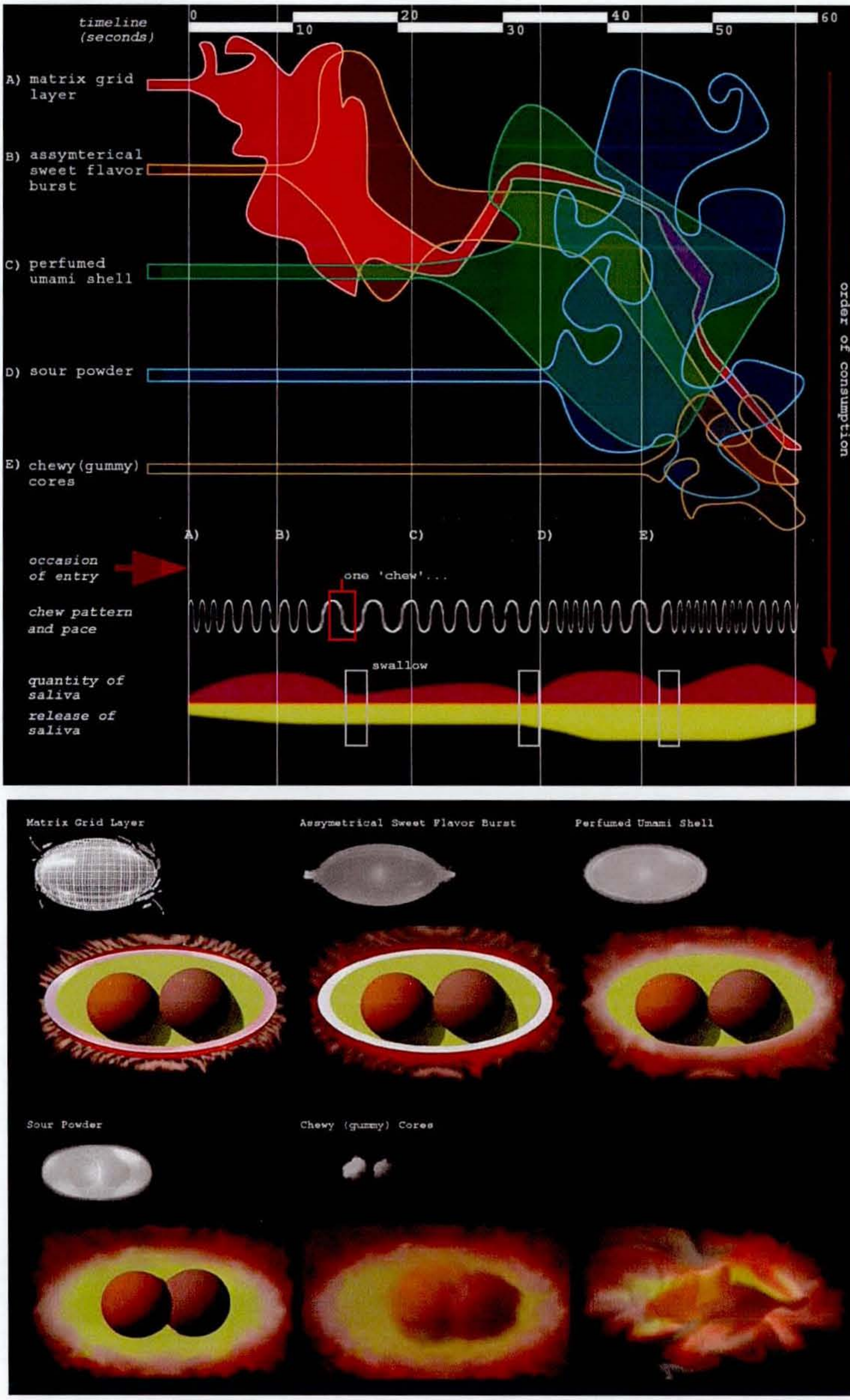
This chapter aims to apply sensory considerations within the LF- model. The designs discussed were catalysed by a polemic that questions the predominance of vision and hearing, and the conceptual realms that accompany them, in the things done through computing related means. The designs included here all aimed to realize designs that are directly reflective of the Rapid Manufacturing related fabrication methods, but do so by producing designs that are based on the three senses **least** affiliated with computing, which are taste, smell and touch. The designs are titled The *Sensory Follies*, and include the *Gustatory Folly* (taste/ digestion), *Olfactory Folly* (smell) and the *Tactile Folly* (touch). They each present a distinctive take of a physiological or human feature which are unique to Rapid Manufacturing and some of the technologies related to it.

6.2 Gustatory Folly – The Architectural Tidbit

What would happen if one switched the colour cartridges on the Z Corp's Z510 System to distribute flavours instead of colours? And instead of using an epoxy as a binder use something digestible, perhaps a glucose mix or a digestible polymer, to bind the powder particles together. The idea is not too far fetched as similar techniques have been used in the customization of pills, which can be made bespoke to a particular individuals medical needs[1]. This Three Dimensional Printer (3DP), uses either a gypsum or starch based material, the latter which is edible, to fabricate its objects.

The project was also interested in touching upon the idea of food consumption as entertainement, or as an experiential event. As much of what we eat, particularly today, has very limited nutritional value. Candies, pastries, soda-pop, various titbits and sweet-meats, as well as different 'diet' product which boast about their lack of calories, all involve oral intakes which are much more about the experience of consuming flavours and textural compositions rather than

1 For a related example of chocolate being printed see: www.youtube.com/watch?v=PTdiTe5G40Y&feature=related (accessed in August, 2008).



Figures 6.1 Top, a graph and, bottom, an sectional illustration of the Architectural Tidbits digestion and breakdown.

their dietary attributes. They are, in a sense, more about a limbic and (flavour based) aesthetic craving than a dietary necessity. A case of a more folly-esque, sensory and sensual experience, than a utilitarian one. It is within this realm the 'Gustatory Folly' dwells…

6.2.2 Objective

The project endeavoured to explore the gustatory qualities through the use of a specific additive fabrication process which allows for an edible piece to be built. It also examines the literal process of digestion of the design - how different flavours can be released, intermingled and sequenced (Fig. 6.1).

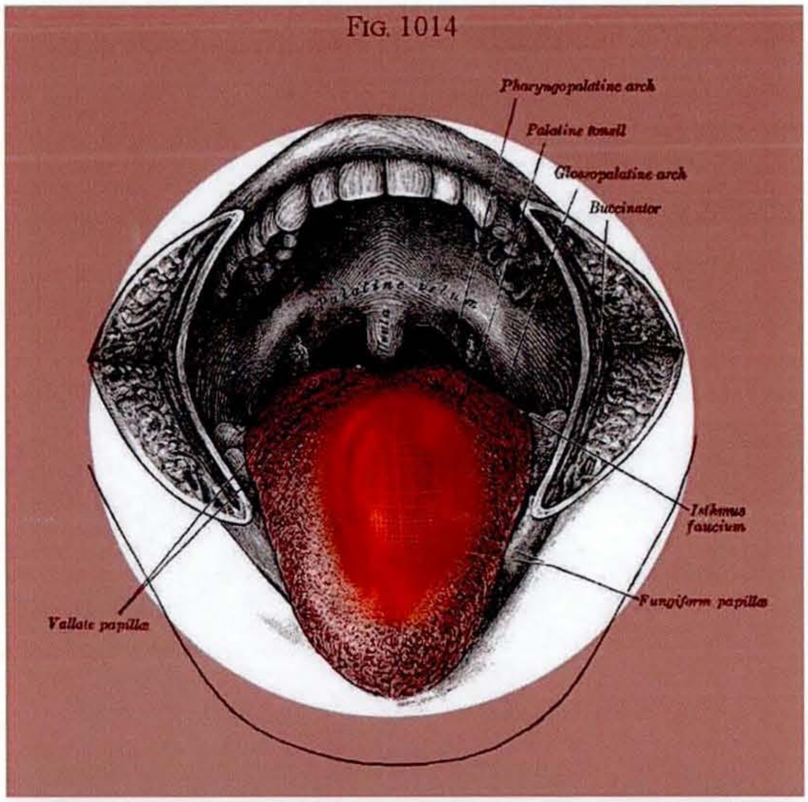
6.2.3 Method

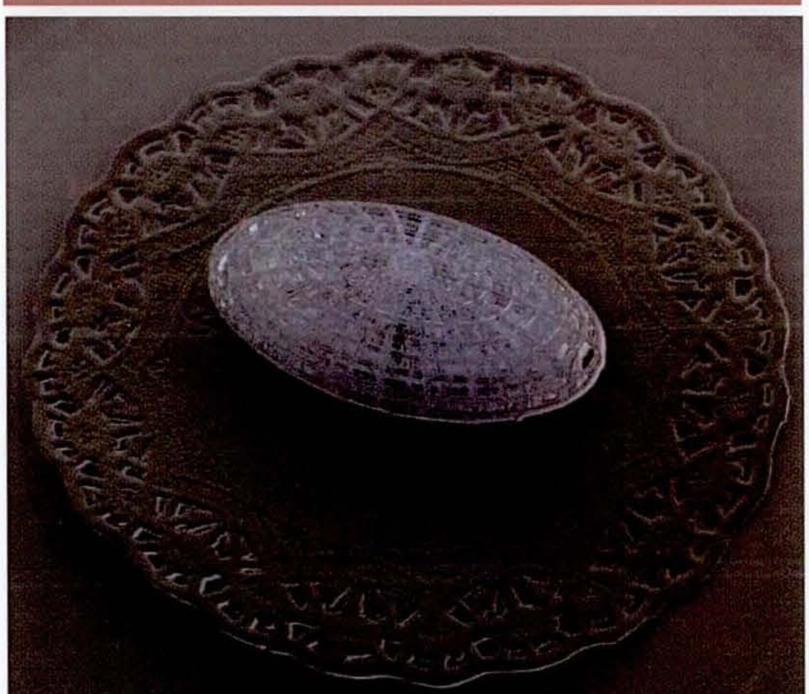
Using the model a new design can be envisaged. Taking the standard CMYK colours, Cyan, Magenta, Yellow, Black, and replacing them with the generic flavours of Salty, Sweet, Bitter and Sour, and with the doughy nuance of Umami (sometimes considered the fifth flavour) added as an gustatory catalyst, one could add a new idiom into the annals of conceiving things through RM.

These flavours would be applied into a multi-layered 'architectural-tidbit' (a chewable and digestible item) you put in your mouth, the site onto/ into which the architectural brief is applied (Fig. 6.2). Here the gustatory logistics are analyzed from a more spatial, procedural, mechanical, tactile, olfactory, and culturally semiotic (architectural) tack. This entails exploring how the various layers of the tidbit will dissolve and collapse, and how they consequently blend and interact with each other. The project also considers how saliva, the pace of chewing and breathing, the motility of the tongue, and how the disparate flavours and senses would commingle and interact.

6.2.4 Results

An initial stereolithography (inedible and sour tasting) model was produced of the tidbit to get





Figures 6.2 Above - illustration of the Architectural Tidbits 'site'. Below - A Stereolithography rendition of the Architectural Tidbit.

an physical manifestation of the tidbit. Its size, weight, texture and consistency seem, on the surface, appropriate, and according to initial expectations. However, further testing would be needed to bring about a satisfactory example of the tidbit which would allow for a more truthful assessment to take place. The process also benefitted (the charting of the mingling flavours and the reflected physical aspects of the tidbit) from the more adaptable sequencing of the Avaterial model, which in its suppleness and interlinking of the conceptual and the physical fabrication aspect managed to converge into a coherent experience.

6.3 Olfactory Follies – The Fragrant Tower and Mobile

The Olfactory Follies are designs, both fabricated through SLA, which, in a similar fashion to some of the earlier designs, used the default scaffoldings of the system as components in the design. Here, however, the support matrix was utilized to retain the fragrant oils which are used to saturate the torsos of the designs. The designs aim to subtly affect their environments through the limbic means of smell, distributing noticeable, but subtle, aromas into the spaces they occupy, leaving fragrant mnemonic traces onto passers by, thus allowing them to bear their influence far beyond the realm their modest sizes might initially suggest.

6.3.1 Objective

The aim was to make a design as subtle and discrete, yet as expressive and catalytic as a fragrance. A design that could be experienced without being seen. A design that is sensed before it is comprehended.

The designs form discrete interventions that interact with its surroundings through evocation rather than provocation. Like a symbiot parasite they aim to conjoin with existing conditions, buildings and beings, stealthily adapting themselves to what is there. Powered and spread by the a breeze, air conditioning, the turbulence from a swinging door, even a sneeze, the designs distribute their subtle aromatic memes. The designs are 'mechanical' in the sense a termites-nest, a spiders-web or a beavers-dam is mechanical, aiming to fulfil their aims in a comparably congenital manner.

As we inhale, we smell. As we exhale, we don't. There's an inherent binary pace and rhythm to experiencing something olfactory. Here the design is not the protagonist, but the ethereal experience of the scent actually takes place 'in' its audience, as the fragrance enters their bodies through their nose, mouth and pores. The experience of the design becomes an internalized event, where the usually optically derived formulation of semblance is forgotten.

However, a fragrance is not always just a subtle backdrop to other activities, it can also be used as a somewhat illusive means of suggestive control. It can be used to either repulse or to attract. A person exiting from a foul smelling public toilet will inevitably be afflicted with a reflective degree of spite that is directly proportional to the level of olfactory repugnance emitted from his recently exited cubicle. Or, in an comparable but opposite fashion, the way we can be influenced to take action by the exposure of the smallest whiff of aromas released by newly cooked food.

All such considerations formed the backdrop to the design development of the Fragrant Follies.

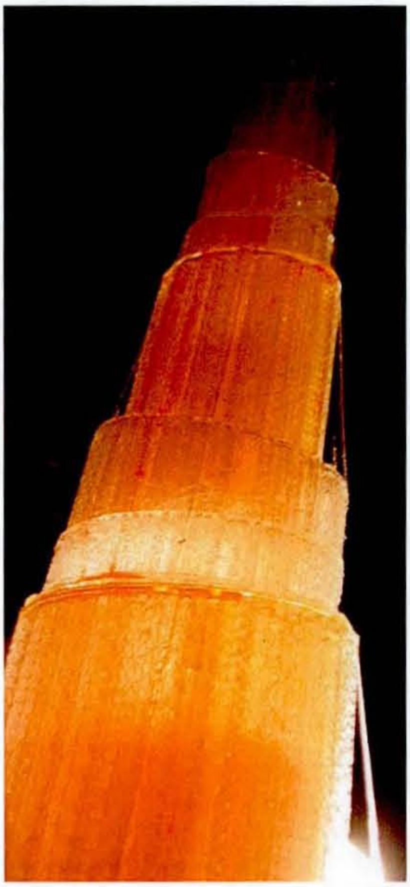
6.3.2 Method

Usually there are three levels to a fragrance - a bottom (base), middle (heart), and top (head) note. The top notes are the most volatile, these are initial 'layer' of an aroma one usually smells first. The middle notes diffuse more slowly, and are usually floral essences. They provide the fragrance with a body. The base notes are the most fixed of all the fragrances. They provide the foundations for the initial two levels.

In all the Fragrant Designs the bottom and middle notes were the same (Base Note - 'Vanilla' with 'Benzoin Tincture' as a catalyst. Middle Note - 'Rose Absolute'). Only the top notes were varied (both from the citrus family), with one being 'Orange - Sweet' (Citrus Sinensis), and the other 'Grapefruit' (Citrus Paradisi), this was done to provide some variation to their olfactory-scape.

Fragrant Tower

Due to both its eventual size and fact that the design intended to use the default scaffoldings to create both the bulk of its torso (in a similar fashion to the SLA bowl explained earlier in



Figures 6.3 Fragrant Tower - Top two images showing the outisde elevation. Bottom image shows a corss-section through one of the stackable segments...

chapter five), as well as to entrap the oils which were used to emanate its subtle affects, the fabrication of the Fragrant Tower required five attempts before a sufficiently robust rendition was produced.

Made up of three stacked components, with a shallow male-female link between the components, the tower's total height 720 millimeters. Its shape and aims were loosely based upon on the makeup of termites nests, wind-scoops and wind towers, which all provide different means to distribute air, and thus provide suggestions for transferring fragrances (Fig. 6.3).

To better understand how the various viscous liquids containing the fragrances would move and occupy the tower, a test was made in which various coloured inks were poured into and through the tower segments. Beyond this action simply having a certain aesthetic appeal , it was quite an informative exercise and did provide suggestions for how to apply and disperse the various aromas through the tower segments.

Fragrant Mobile

Designed as a mobile (Fig. 6.4), that would slowly sway on a the ledge of a shelf, table or perch, the design, differently from the Fragrant tower (which in purpose is the same), also uses the ability of the Materialise Magics software to manually distribute support scaffolding across a build, here to selectively make the makeup of the design denser, and thus enabling it to retain the fragrant oils saturating its torso for longer.

6.3.3 Results

The designs of the case-studies were displayed in a domestic as well as a public context. Both designs functioned as intended, distributing their subtle affect into their environments and did evoke a notable affect on the ambience of each space, as in each instance numerous visitors did enquire, and did try to discover, the sources of the subtle citrus scented perfume that went with the space[2].

2 Feedback was provided, in the form of unstructured interviews, by visitors to the *nous Gallery* exhibition, that took place between April - May, 2008, where the pieces were displayed.

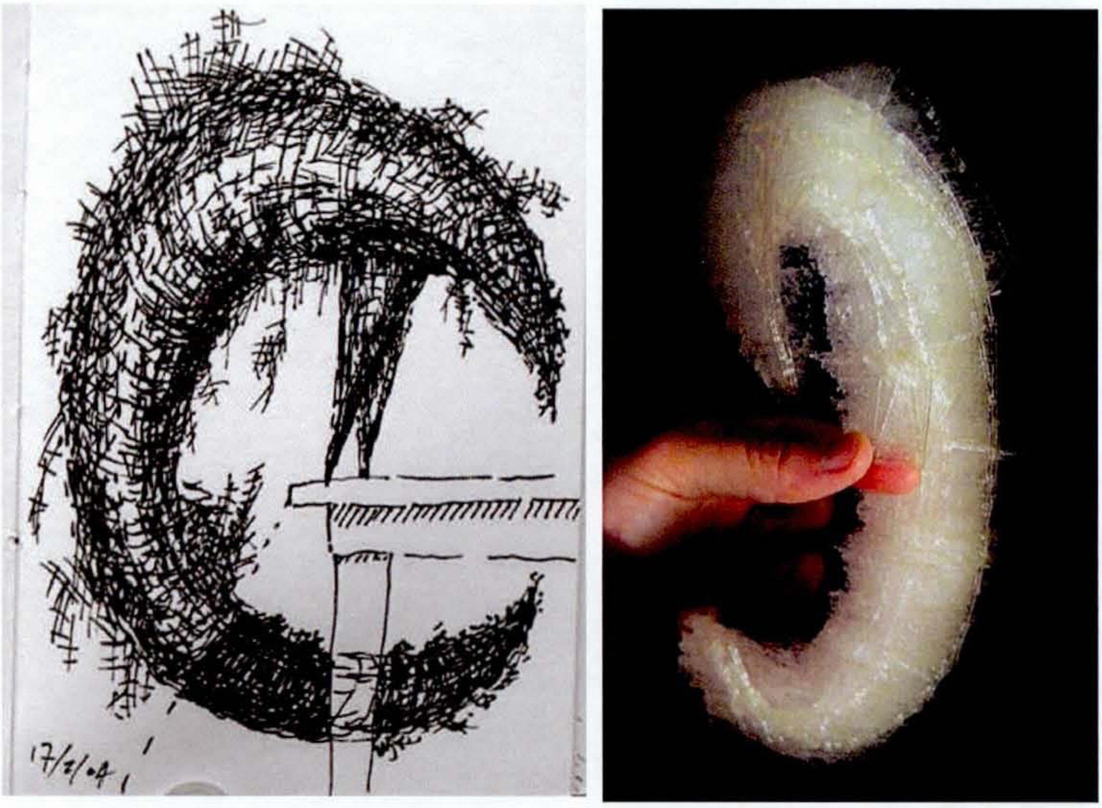


Figure 6.4 Initial sketch and Final Model of the Fragrant Slug. The 'density' of the support scaffolding that makes up the mobile's torso has been manually 'thickened', selectively applying more body where needed.

6.4 *Tactile Folly – Finger Run*

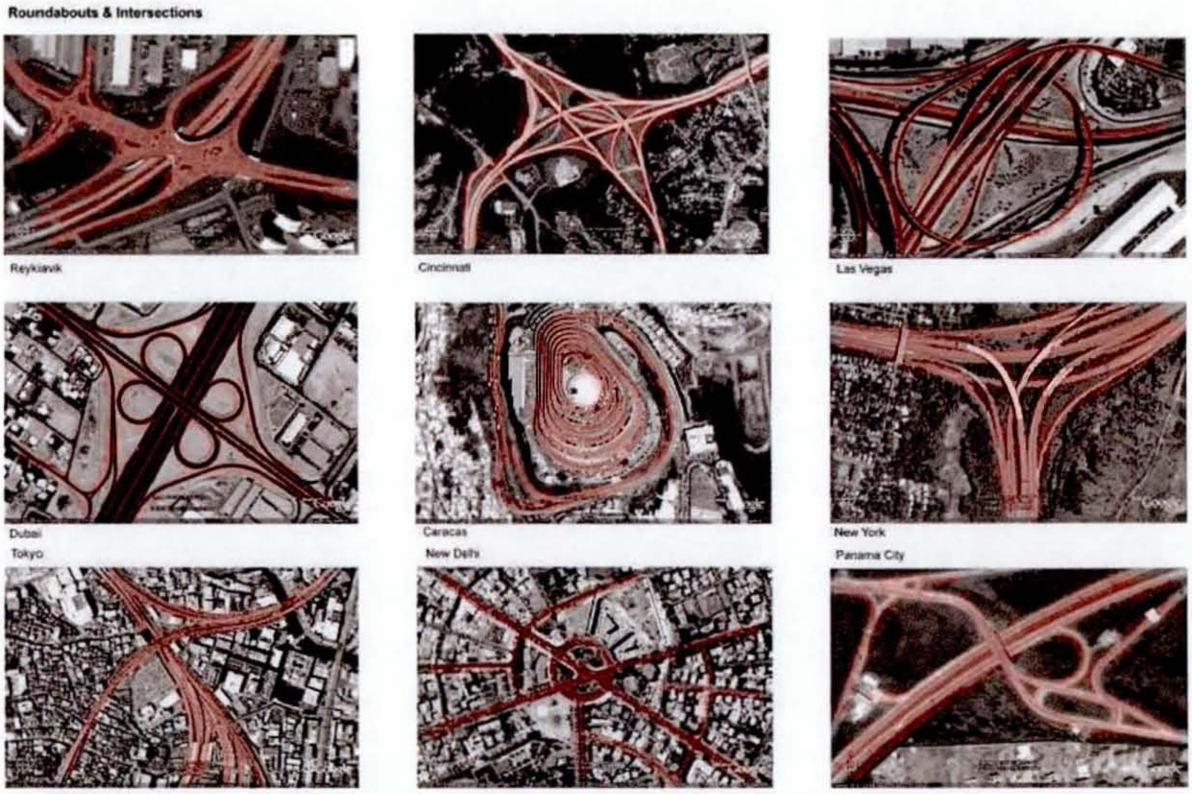
The Finger Run Tactile Panel design was derived from a desire to use available computing based means that included a haptic component as a key element in its application. Allowing for this form of more immediate interaction regarding how we conceive things and the way we actually realize them, when using the digital means, is crucial if a more intrinsic understanding and reflection of the aims are to be encompassed in the eventual design. It appreciated the congenital link between vision and touch and its role in how we craft things, and aimed to include such an enriched palette into the digital (& tangible) processes involved in shaping our artefacts and environments. This type of 'senseware', to somewhat inaccurately appropriate a term introduced by Manabu Akaike (Hara, 2004), and which the SensAble device (discussed in chapter four) is an example of, will undoubtedly become increasingly important as the digital trades mature.

6.4.1 Objective

The design sought to, through the use of SensAble's Phantom device, make something to be experienced and explored through the sense of touch. Its aim was to explore how the haptic interface could be used to design things (through computing based means) which are designed through the sense of touch to be perceived through touch.

6.4.2 Method

The Finger Run design was made up of two, A3 size, rectangular panels, which, within their rigid, defined, and upright frames, contained what initially read as a textural cornucopia, but which on closer (tactile) inspection, revealed a number of intermingling stratums which each corresponded to a particular texture, pattern or touchable route. Their aim was to provide a variety of tactile impressions, which interacted with the various exploratory haptic dimensions, be these sensed through the kinaesthetic actions of the fingertips, fingers, palm, hand (wrist), forearm, arm (shoulder), or even torso. Inspired by the apparent tactile qualities of various inter-



6.5 Some of the intersections and roundabouts, found on Google Earth, from around the world, which provided the initial catalyst for the Finger Run project...

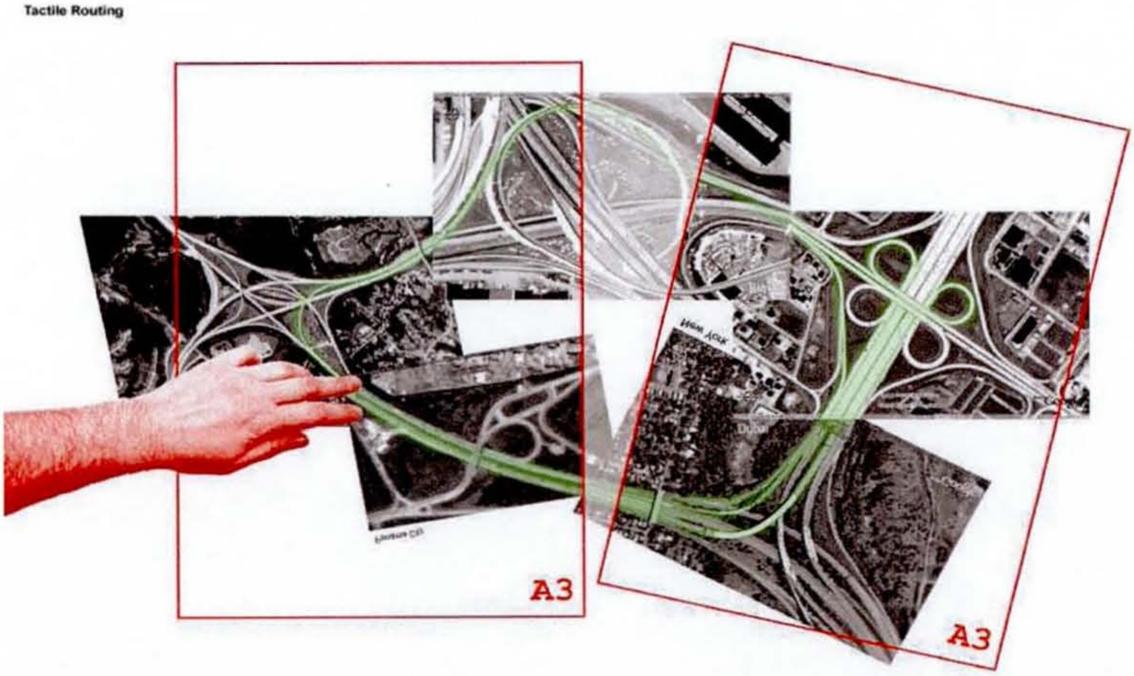


Figure 6.6 A number of the roundabouts were re-appropriated and assembled into a suggestive pattern and route...

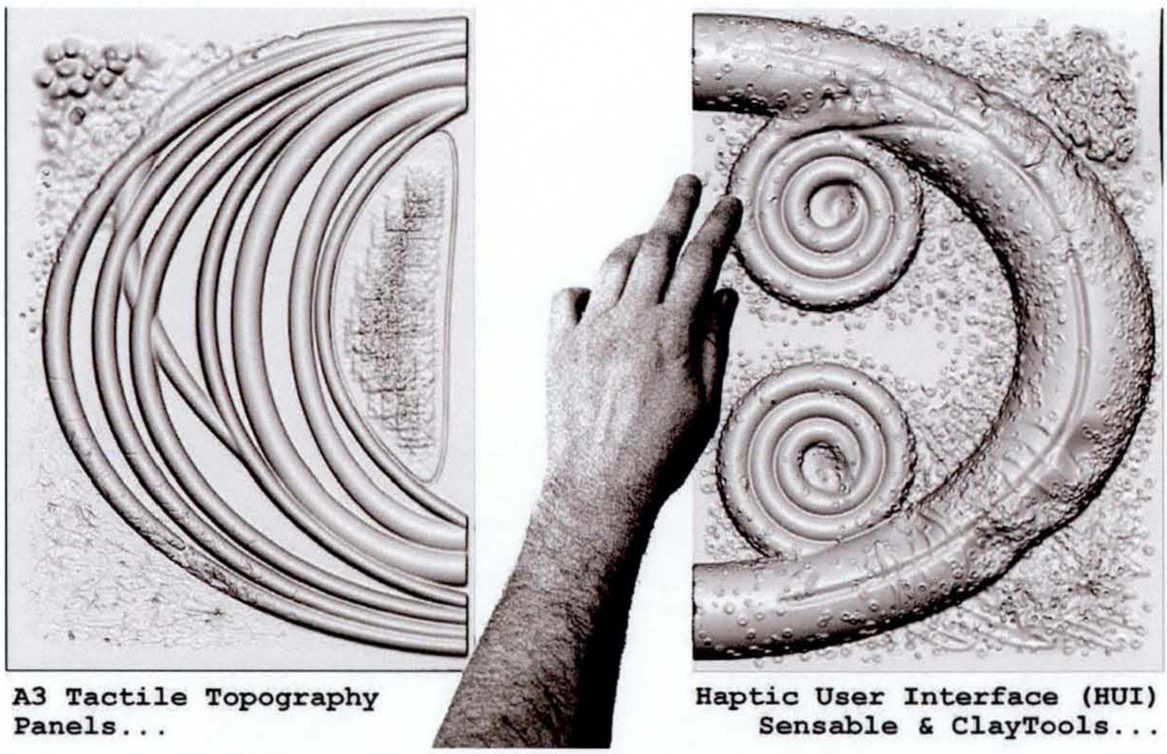


Figure 6.7 The appropriated routes and roundabouts were translated through haptic means into a tactile rendition of such a route, perceived through fingertips, fingers, palm, hand, and arm...

sections and roundabouts found on Google Earth (Fig. 6.5 and 6.6), the design could be used/ explored through any chosen means, however, it was designed to be experienced through the fingers and hand (Fig. 6.7), and at various kinaesthetic paces, which allow it to sense its diverse more subtle and delicate textures and patterns, read through the fingertips, usually inspected at a more slow and cautious (Doubting Thomas) pace, to its larger elements, which required one to move the hand and arm (usually quicker) along the quasi-oval path that runs across both panels. The distance between the two adjacent panels was twenty centimetres – small enough to allow them to be read as a unit, but large enough to allow for a 'Trick Finger Jump' over the (imaginary) gorge separating them (Fig. 6.8).

The design intended to be a manifestation of the Sensable tool's abilities of conceiving a tactile topography according to a set ambit of constraints, that through the notion of 'thinking through doing' explores and develops a materialization and a personification of a number of embedded tactile attributes which are specific to the means, yet still provide an adaptable haptic vocabulary. Here the physical textural patterns, from the maxel stage upwards, was utilized and allowed to fluently interlink on a haptic level[3].

The device retains all the advantages of the usual graphic interfaces, only here with an additional dimension. The ability to touch, or feel, the surface of a design under development, while retaining the software related, more abstract, but by now to many almost second nature like, capacities like - zoom, pan, texture-map, the 'undo' key, removing and adding (here virtual) material, etc.., - a level of 'tactile finesse' and refinement was achieved which would be almost inconceivable through the use of any alternate (particularly digital) methods - the 'distance' or indirectness between how things are made usually in CAD, and the way this device allows

3 There is here a similarity in approach to certain mid-twentieth century painters, the likes of Cy Twombly, Jackson Pollock, Franz Kline or even Morris Louis, ocassionally classified as 'Action Painters', where their ways of making the work and such methods', call them, 'parametric freedoms', have been exploited to their sporadic limits within their own corporeal and tool based confines. The resulting work retains the innate and literal markings, topographies, scratches, (tool/ hand) prints, and more, of their makers, but also act as reflections of the artists' physical beings through the aforementioned markings' shape and form, which allow one to 'read' the maker's finger, wrist, hand locations and motions in the arched shapes and arm-radiuses evident in the paintings. In many ways similar, call them ergonomic or physiological, features are also evident in many more 'engineered' objects, like bike-handles and seats, cutlery, keyboards, as well as the variations of such things whether designed for a child, an adult (male or female) or an individual closer to the Autumn of their life.
The Finger-Run design aspires to similar sentiments, aiming to combine spontaneous and control based factors within a singular conceptual framework in a fashion where the intuitive and cerebral are allowed to intermingle. A case where the notion of a 'weak' ontology (as subscribed by Vattimo, explained in chapter four) is allowed to influence the eventual outcome of the work.

Figure 6.8 Haptic textures and routes - clockwise from top left:

- Finger and palm kinaesthetic route (with finger jump).
- Exploratory corner textures - A. Craters (manually realized), B. Rustication (manually realized), C. Veins (manually realized combined with a route template applied), D. Termite pattern (manually applied).
- Clockwise and counter clockwise spirals.
- Neutral planes - touchstones made up of the default textures of the fabrication methods. Sets a point of comparison against which the texture patterns can be compared.
- Coral pattern - a texture that 'bleeds' across and over some of the other patterns and elements.
- Central gravel texture - an applied texture map - a manipulated default texture map provided by the Claytools software.

one to 'directly' manipulate a (digital) material, is diminished. The degree of tactile empathy or imagination, between what is being conceived and how the eventual design is actually perceived, is, though not the same, much closer. It was the development of this breed of qualities - virtues which combined not only the facilities to delve into and control the slight textures sensed through ones finger tips, and also to discover (through zooming out and experiencing the design from a, virtual, 'distance') how it would feel from a more comprehensive kinaesthetic view point - that introduce a fresh paradigm for how designs can be realized (Fig. 6.9)... However, was is important to also recognize that even though one could claim that the processes through which the actions were achieved were analogous to actual physical actions, they were still not the same. The range of motion was more limited and the way the physical interface behaved, the 'form' of ones hand and arm motion and positioning, was controlled and determined by the joints and axis length of the device. These factors, in unison with the linked software, provide a unique mode of making things through the digital means that was a step, or dimension, closer to how the eventual design will be perceived (Fig. 6.10), and, in some ways superior, to actual cutaneous, one to one, sensing, as the device affords access to dimensions, angles and locations in the design which would otherwise be difficult to penetrate, manipulate or understand. It is also important to realize that the process should not be considered as something replacing an existing process, but something that performed rather as an adjacent way of conception (an additional or modified extremity or temporary capacity) which one can use when making something worthy.

These methods were a means to an end. A way to make and understand better something that would ultimately be used, perceived, and thus judged by direct physical contact and interaction.

6.4.3 Results

The case-study's two panels were fabricated through SLA (Fig. 6.11), and did provide a viable rendition and reflection of what the original intentions of the design. The two physical panels, made through a semi-transclucent stereolithography photopolymer, 'feel' very much as assumed, the only difference perhaps being that the 'digital-clay', the analogous 'substance' within the Calytools software through which the panels were designed, provides a slightly softer tactile impression that diverges a tad from those of the eventual physical builds (Fig. 6.12).

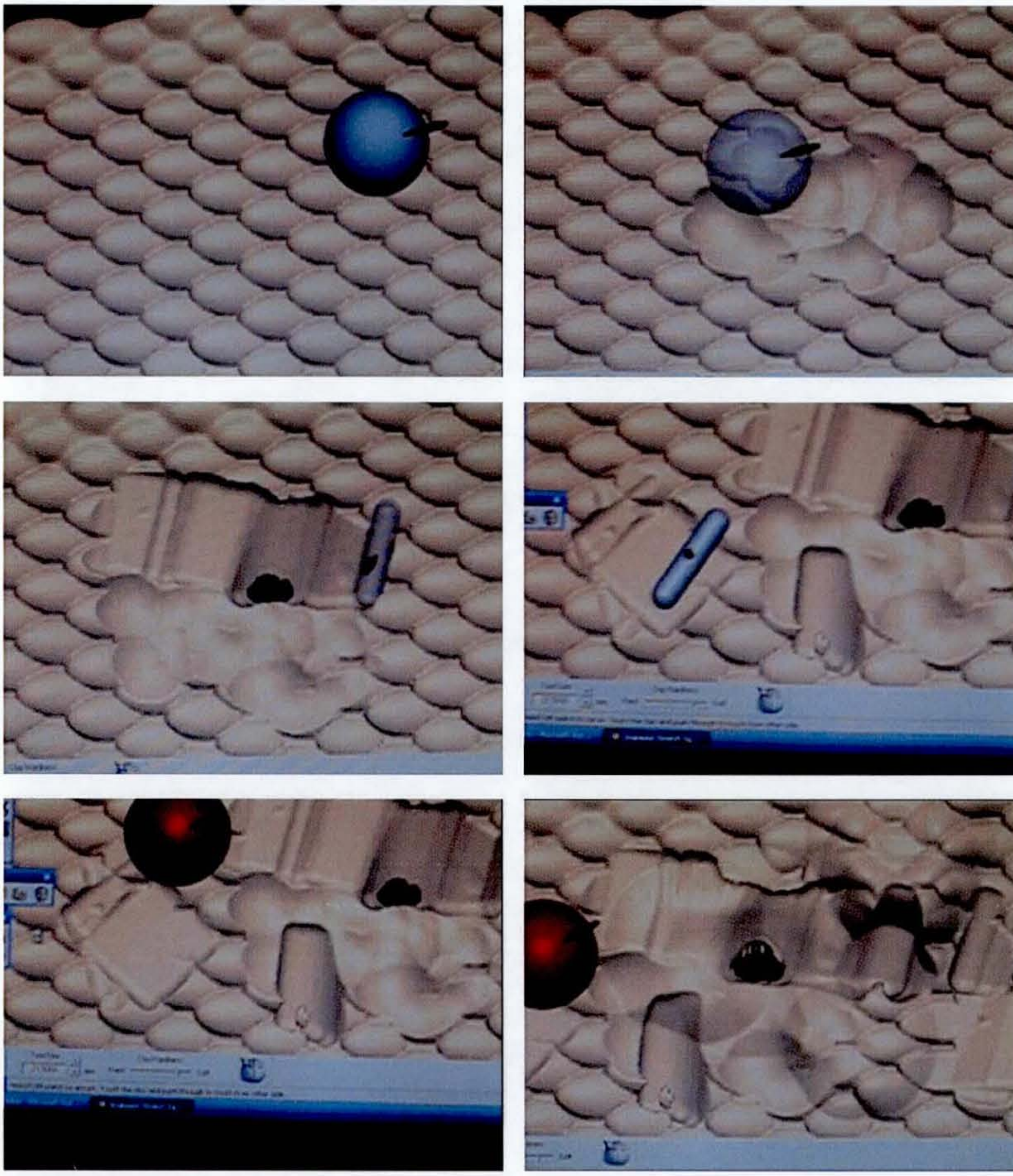


Figure 6.9 Screenshots of the 'Claytools' software, controlled through the Sensable device, in action...

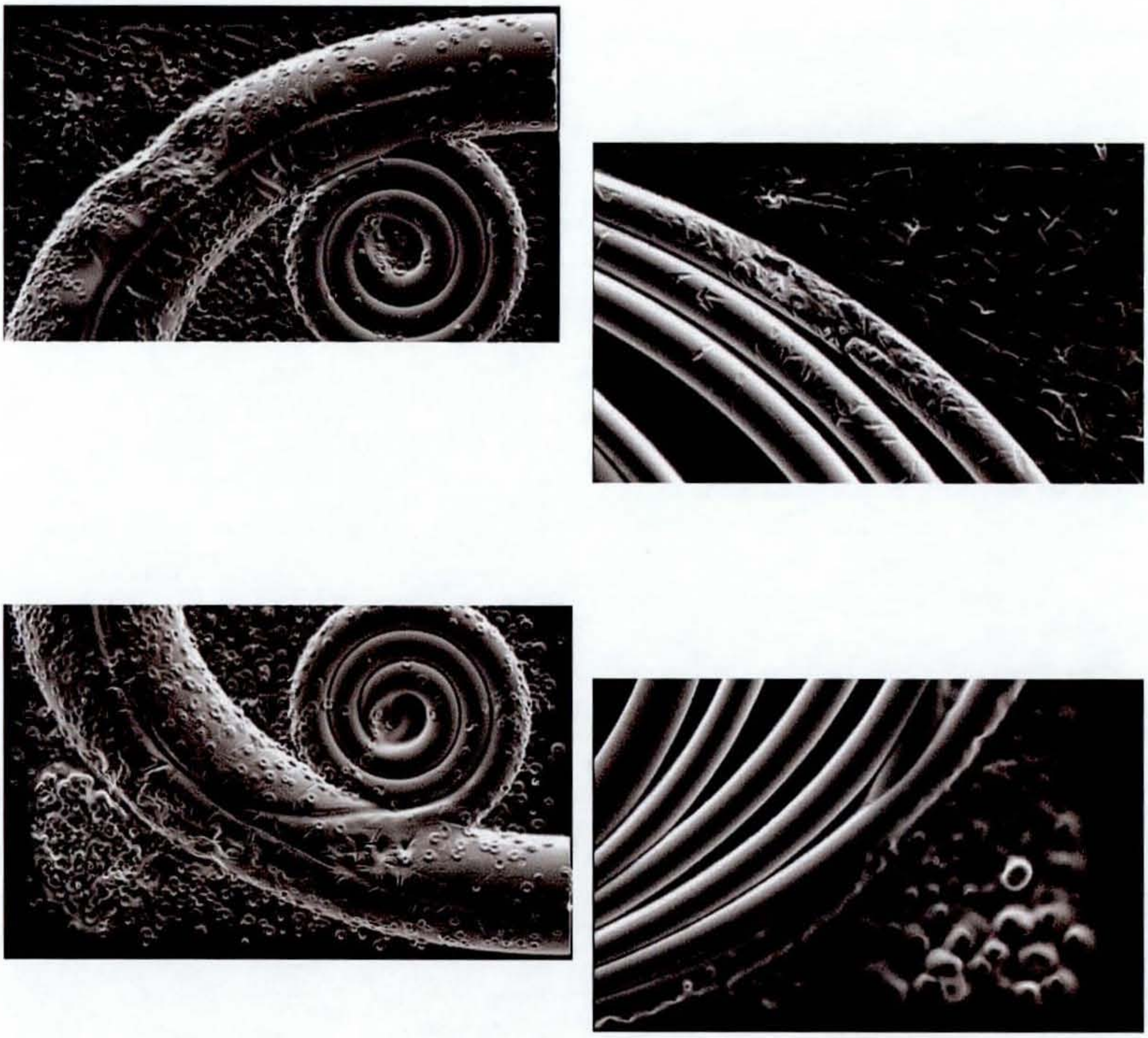


Figure 6.10 Detail images of the 'Claytool' software images and manipulations of the Finger Run panels...

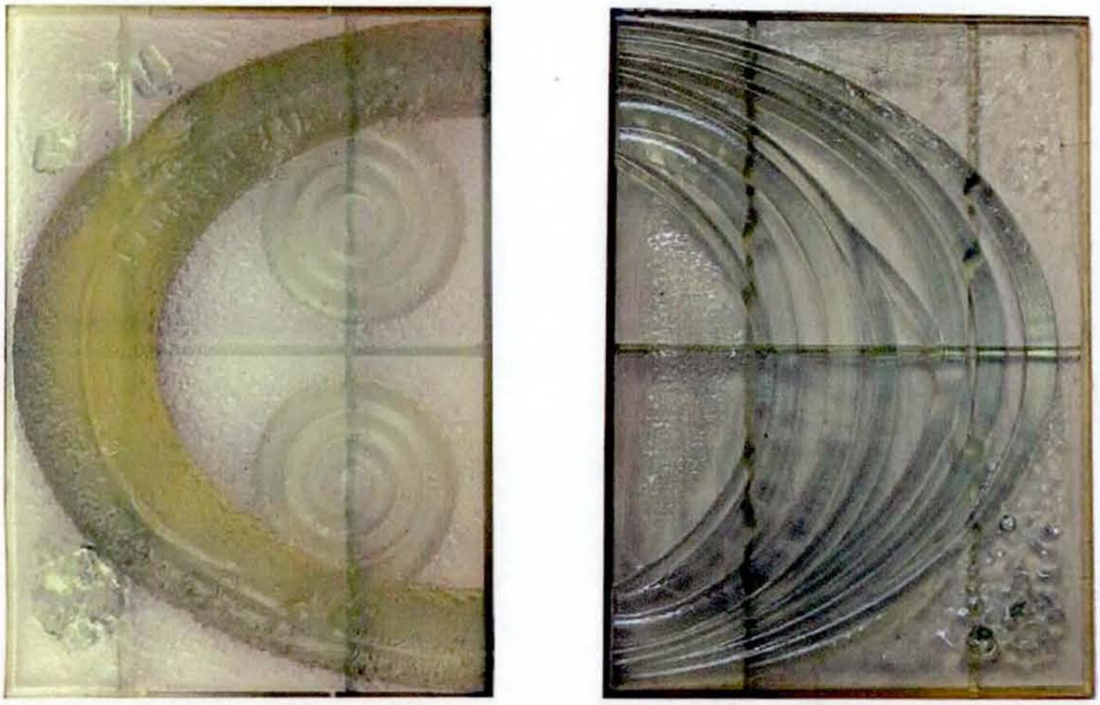
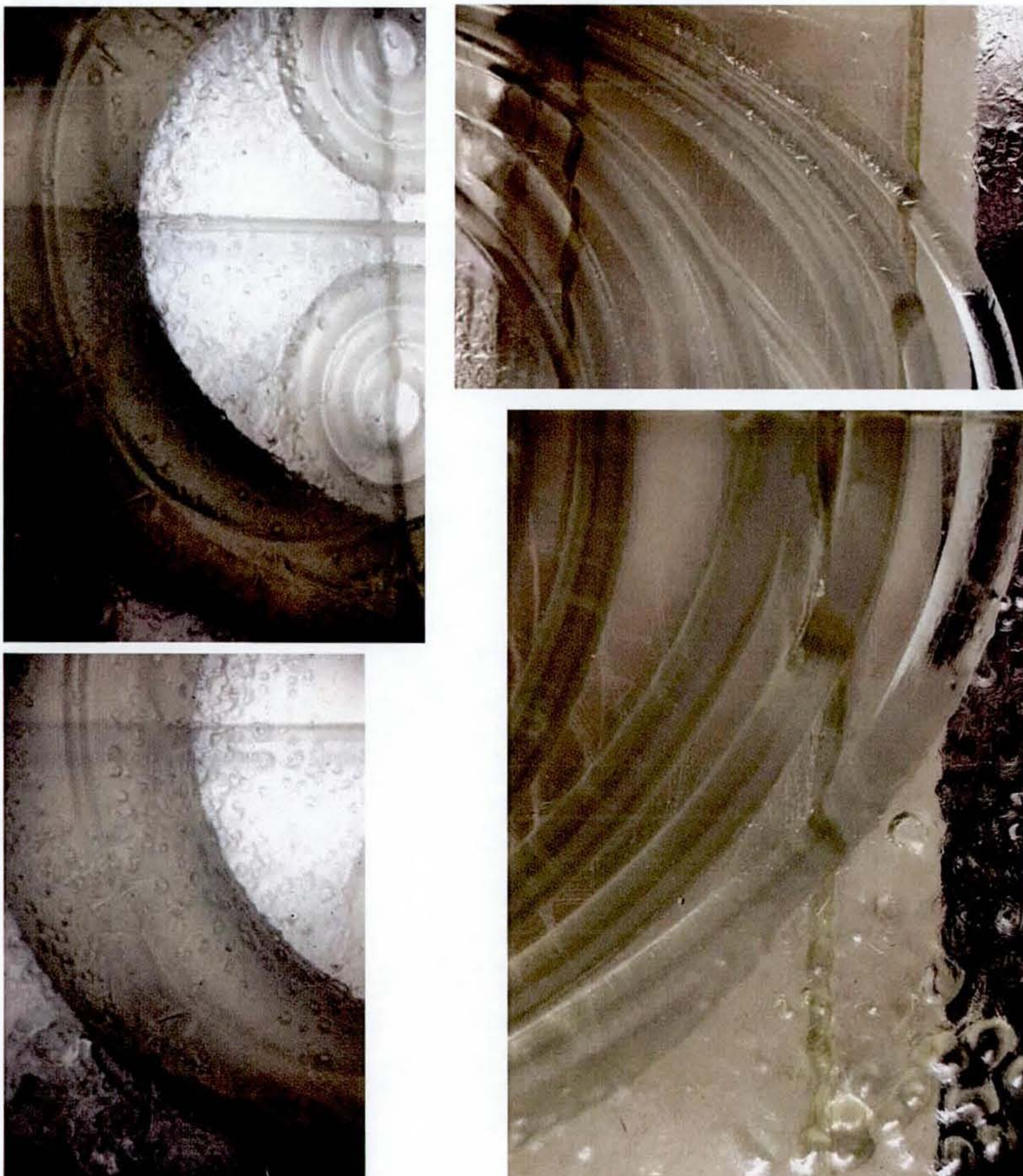


Figure 6.11 An SLA rendition of the Finger Run's, roughly A3 size, panels...

In the realized piece the panels were displayed turned around 180 degrees, as it seemed like most (right-handed) people explored and ran their hand across the panels clockwise, which in this arrangement turned out to be more natural and comfortable...



Figures 6.12 Close up details of the SLA rendition of the Finger Run panels...

Figures 6.13 Images from the Syn_athroisis Exhibition held in Thessaloniki in January 2008. For this event the Finger Run panels were reproduced onto high-density foam through a multi-axis CNC milling machine. This rendition of the design were never actually, beyond through photographs, viewed (perceived) by the author. The STL files were sent through ftp directly to the exhibition and fabricated locally. However, even though the files sent were the same, tactile impressions inevitably did differ from the panels produced through Stereolithography.

But the scale and roughness of the textures were fabricated as anticipated, and the 'flow' of the hand and fingers across the panels is natural and lends itself to the aimed arch-like, elbow centered, motion. On more extended tactile exploration, done without the benefit of vision, the design's layers of different forms of textures and patterns become palpable, and do provide an emphatic refection of their process of making. Here the refined maxel size, which allows the finer designed textures to reveal themselves, does also provide a smoother transition into the nunod resolution of the design, permitting one to conduct much of the exploration solely through the fingertips.

A CNC-milled rendition of the design was also fabricated for the 'Synathroisis' exhibition that took place in Thessaloniki, January 2008 (Fig. 6.13).

6.5 Tactile Folly - Ground Design

The project was initially constructed around a competition brief provided by the Swedish flooring company 'Pergo'. The brief was left somewhat undefined, requesting its participants simply to design something 'innovative', and that such novelty should happen in/ on the plane below ones feet…

How such an open brief was developed for this particular project was initially prompted by the, to some extent peripheral, qualities of the paved surface around the neighbourhood of London's Exhibition Road in South Kensington, an area occupied by number of the city's main museums and galleries. However, it wasn't necessarily the more, call it, 'highbrow' aspects of this locale that were of interest, but the more peripheral marks of human/ urban occupation – the blots of discarded chewing gum that seemed to saturate the streetscape. There must have been thousands, tens of thousands, hundreds of thousands of these, predominantly off white, specks carpeting the main segments of the road and flanking sidewalks.

Observing these blots closer it was interesting to note how one could decipher their approximate location on the road simply by their shapes and the patterns they formed. They were very dense around and just outside the sidewalk curb. Dense, but more pronounced, by pedestrian crossings; less dense and elongated by the main or central footpaths (where the gums had been stretched in the direction of the footpath by a multitude of pedestrians); and sparse by the inside (building side) of the sidewalk (Fig. 6.14).

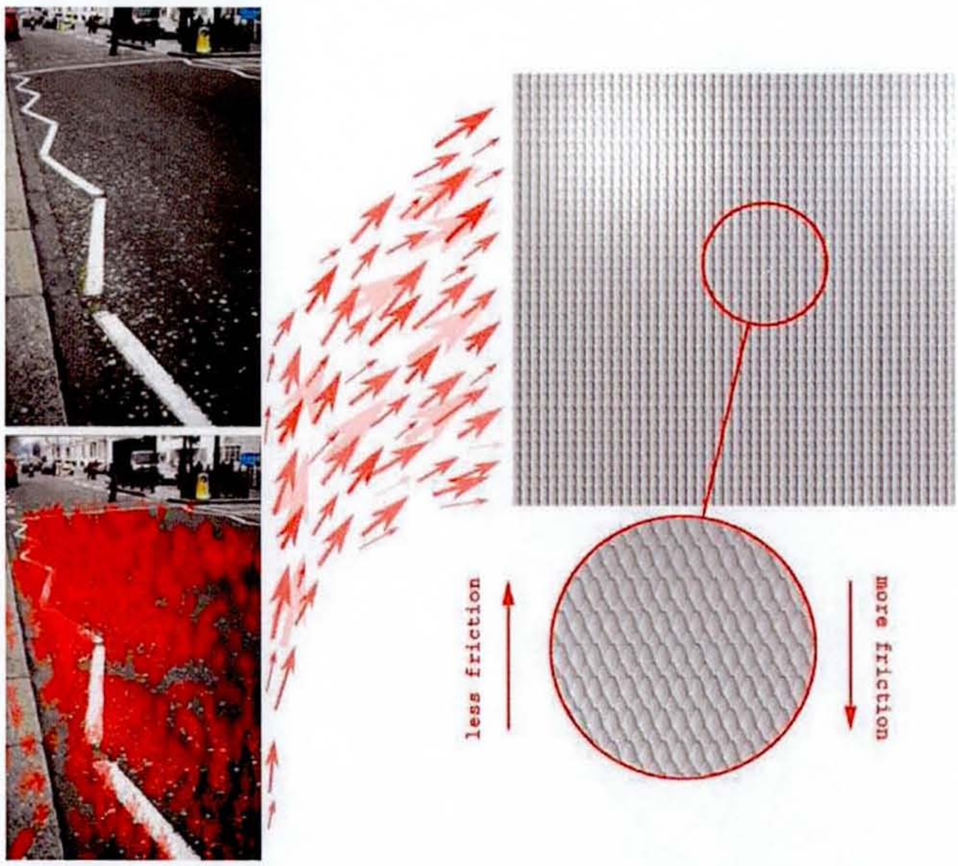


Figure 6.14 The project was catalyzed by the 'field' of discarded chewing-gums on London's Exhibition Road. These patterns were used to suggest how the consequent patterns of the surface should be implemented.

These patterns, somewhat suggestive of Braille (the tactile reading and writing method used by the visually disabled), provided the initial clue for how to proceed…

What if, instead of merely passively interpreting these aforementioned patterns, one would provide them with meaning, immerse them with performative attributes that could inform one of their immediate vernacular on a more planned and specific level? Could one, by manipulating such patterns' surface and consistency, create an additional strata of, non-intrusive, sensory stimuli that, ideally, would not only enrich the streetscape on a purely perceptual and affective level, but craft something that could also act as a functional tool for conveying empirical information to those with, and without, a sensory disability? Could the surface be made to perform an amplifying role in clarifying the features of its immediate environs? Could it, as McCullough (1998) states, be a permeated example of the entire body eventually 'knowing' a dance, becoming an example of an instance where knowledge is all the more likely to be physically inscribed, without an overtly intellectual component? An approach that acknowledges that how we perceive intrinsically entails a more comprehensive realm of considerations that reaches beyond the mere conceptual and needs to include the body in all its varied and intricate details and customs.

6.5.1 Objective

The project was instigated based on two defining parameters…

- Firstly, to produce a sensorially inclusive design. To produce a design that 'looks' beyond visual, or visually derived, stimuli. To allow the haptic (touch), auditory (sound), kinaesthetic (motion), and all the substrata of such perceptual formulations (temperature, vibration, pitch, treble, rhythm, obliqueness, texture, friction, etc.) to play a more involved role in the conception of a design. To produce a design framework within which such aims can be achieved…

- Secondly, to use Layered Freeforming in the formulation of the designs conceptual foundation as well as for final physical fabrication. To suggest how the technologies could be formulated in a way that reflects and utilizes its intrinsic qualities instead of merely mimicking

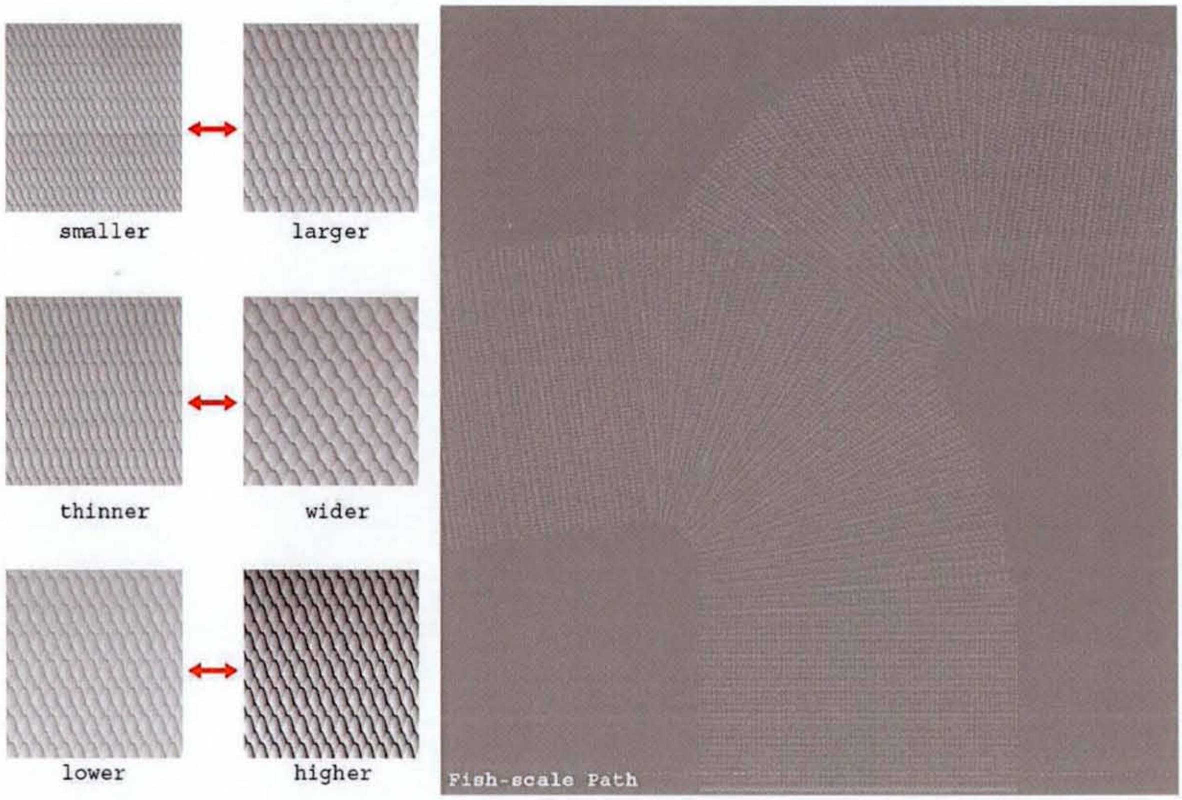


Figure 6.15 Illustrations of how one can amplify the affective qualities of the surface by simple binary means – making it more or less pronounced, wider or narrower, smaller or larger, etc.. The scale pattern can also be made to curve or/ and angle towards various relevant nodes in its vernacular…

alternate fabrication methods…

How such concerns were put into practice required that the aforementioned gum-patterns be conceived within a formal framework. Here randomly distributed gum-blotches were conceived as a fish-scale like array of small tactile components that allow for a surface with a binary and directional pattern - the surface is smoother in one direction, and 'rougher' in the other (Fig. 6.15).

The texture was 'enriched' by applying simple binary 'deformations' to the core pattern. The scales of the surface were made (gradually, as on a sliding scale) smaller or larger, thinner or wider, more or less pronounced, etc., according to various predetermined and intuitive haptic iconographies. The fish-scale pattern was also curved towards, and obliquely angled, to show and insinuate various surrounding features (say, the entrance of a building or an approaching pedestrian crossing).

By manipulating the consistency of the fabrication material through to the minuteness and accuracy at which one can control the composition of a material, outlined in the chapter four, to change its tactile and auditory qualities. By making the surface more or less dense, and by patterning according to various utility and performance configurations, from this 'feel' and sound different (when walked upon) at various locations (Fig. 6.16)…

Here it is worth noting that the paradigms within which the aforesaid notions have been conceived in have all been guided by a framework set by what the relevant technologies (software, hardware and buildware based) allow for. This entails that the size, patterning and modulation of the designs become dependent on a set of criteria different from those that have been used until now – for to fabricate the design(s) it is its mass and volume, not its complexity or the repetition of a set formulae, that matters. Here there is no need for a fabrication template (entailing a set of identical pieces) as for the RM/ LF machines it is equally laborious to produce two (or more) alike physical pieces as it is to produce a number of, roughly equal in mass and volume, but still drastically different components. This is both the processes advantage and its crux, as the seemingly almost infinite freedom this means of production seemingly entails, it

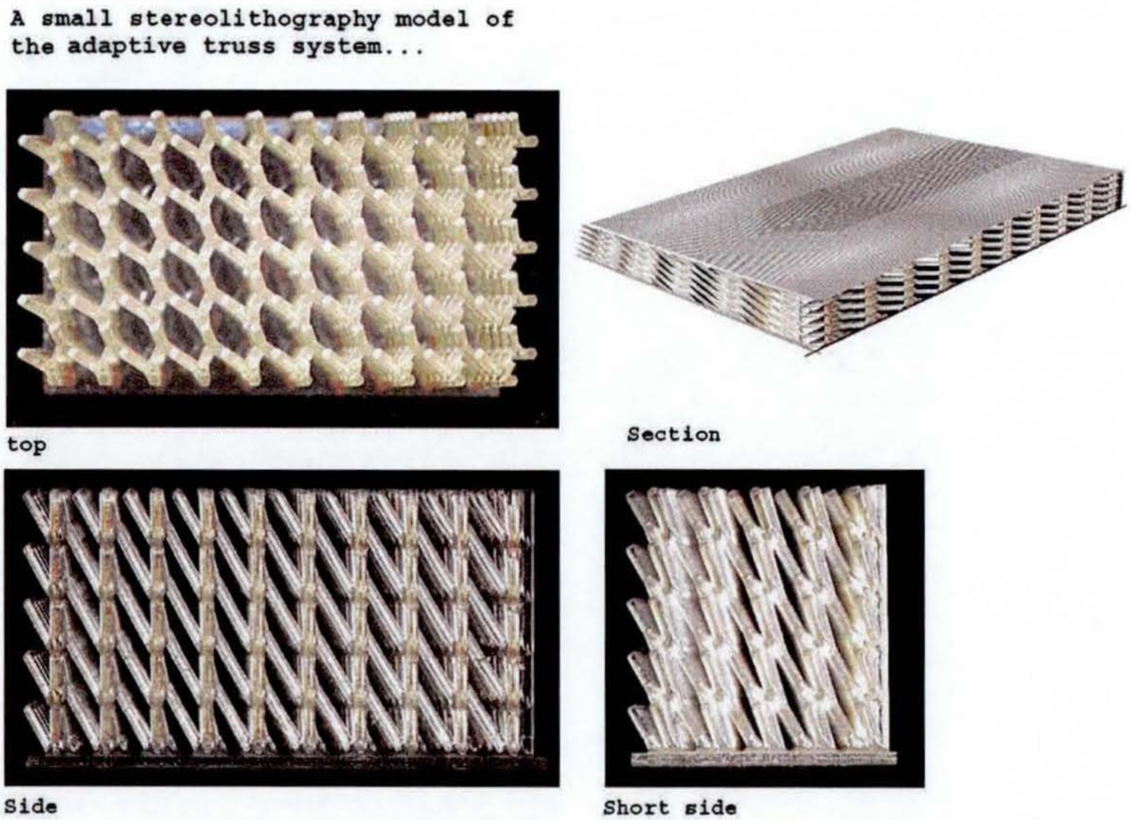


Figure 6.16 Illustrations of how the consistency of the surfaces thickness could be customized according to the principles outlined in the Materix section, i.e. here not only the surface texture is made reflective of a pre-defined tactile vocabulary, but the 'feel', the softness and hardness, as well as the epidermis' auditory impressions (what it sounds like to walk on the surface) can be adjusted according to need by controlling its materix patterns...

still needs to be defined and thus confined, according to some form of predetermined parameters – a protocol that Mether aims to suggest an adaptable modus operandi for.

6.5.2 Method

How such aforementioned interests could be applied in a design is illustrated in the example following.

In a generic streetscape four key nodes of a pedestrian sidewalk are recognized: the main (or 'spine') path of the sidewalk, the entrance to a building, the curb, and the area of a pedestrian crossing (Fig. 6.17).

Applying the aforesaid principals to each of these four key locales the various surface properties could differ as follows (Fig. 6.18)…

- The main path of the sidewalk:

    - Directional (fish-scale) pattern applied along the main spine of the pedestrian passage.
    - 'Medium' porous consistency.
    - Level, horizontal, surface.
    - Surface sound 'A' (generic surface sound).

- The entrance to a building:

    - Directional fish-scale pattern towards the entrance of the building.
    - More solid surface consistency than along the main path.
    - Slightly convex slant (surface obliqueness) towards the building entrance.
    - Surface sound 'B' (a 'harder' sound than sound 'A').

- The curb:

    - Directional, skewed, fish-scale pattern.
    - Higher, more pronounced, texture.
    - Surface level slightly higher than along the main path (the surface is oblique down towards the main spine of the sidewalk).

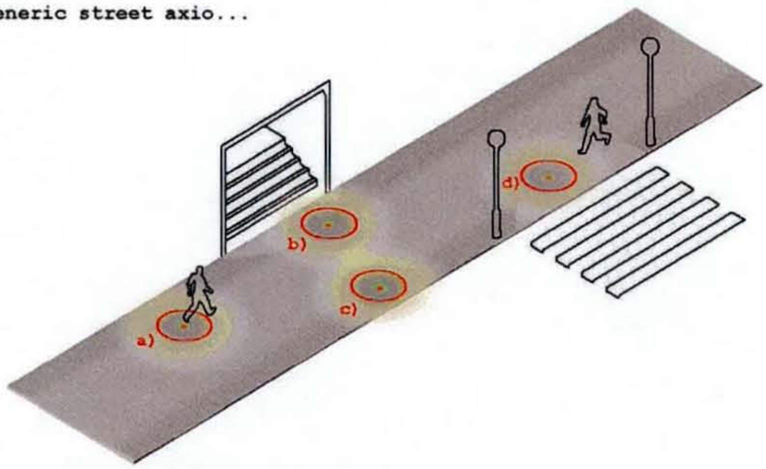
Application of aforementioned principles within a design (exterior)...

Thus, to illustrate how such concerns can be applied in practice, the above outlined methodology is applied to a, somewhat generic, streetscape...

In the illustration below four typical nodes of a street are defined:

A) Is the **main pedestrian spine** along which most of the streets users stroll...
B) Indicates the **entrance to a building**...
C) Indicates the **area flanking the curb**...
D) Defines the area of **a pedestrian crossing**...

generic street axio...



Locations of various perceptual impressions outlined on the following page...

Figure 6.17 A generic streetscape in which four key nodes are recognized...

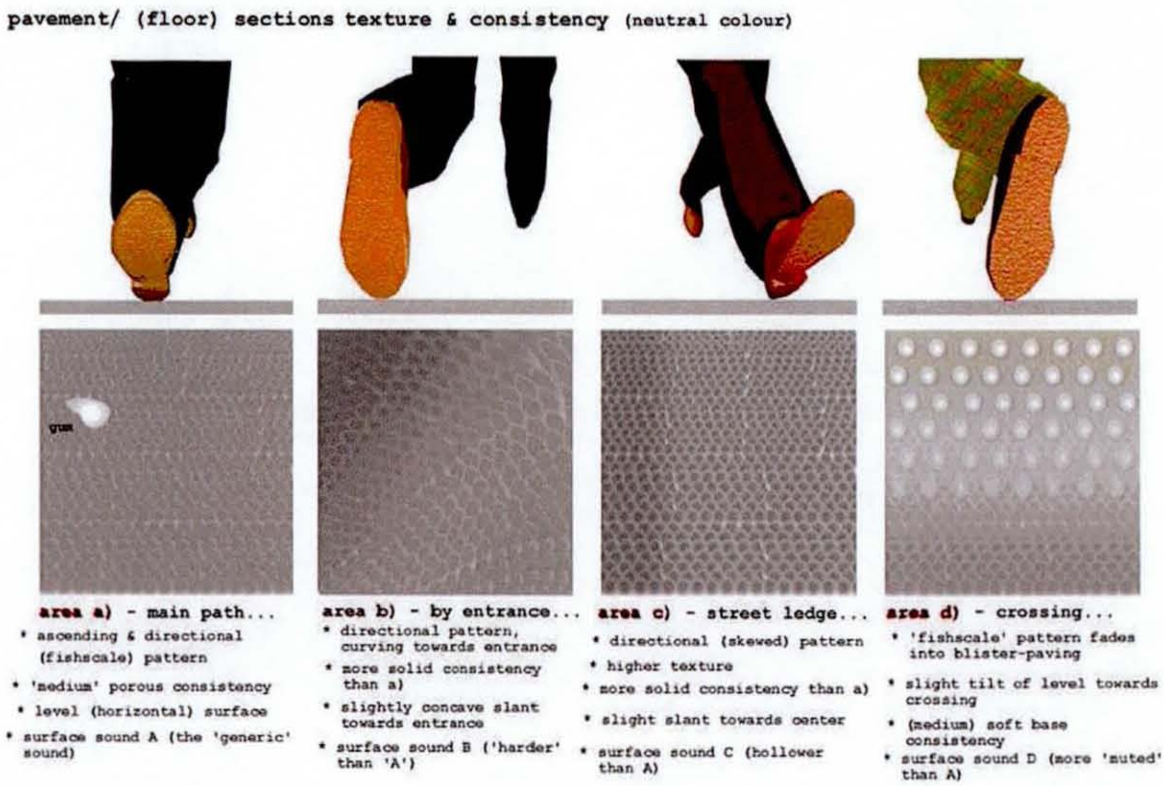


Figure 6.18 Breakdown of the variations in perceptual properties between the four key nodes of the generic streetscape…

- More solid surface consistency.
- Surface sound 'D' (more 'hollow' than surface sound 'A').

- The pedestrian crossing:
    - The fish-scale pattern fades into blister paving.
    - Slight, gradually increasing, concave surface tilt towards the crossing.
    - 'Softer' surface base consistency.
    - Surface sound 'D' (more 'muted' than surface sound 'A').

Even by the application of such a reduced taxonomy of iconic nodes an almost infinite variety of interpretative options and variations of patterning can be applied to the surface. The inherent flexibility of this parametric process also allows for the adjustment of the surface for a variety of different formats, be these for interiors, entailing a 'toning down' of the surfaces coarseness, or even more cold and tesing environments, where the surface is needed to be perceived through thick soled boots or gloves.

6.5.3 Results

Physical prototypes were fabricated, with a Selective Laser Sintering (SLS) machine (Fig. 6.19), and a Stereolithography (SLA), allowing for the testing both the tactile surfaces operational, wear & tear and function related, practicalities, as well as the surfaces ethereal characteristics, i.e. how it actually 'felt' and how easy or intelligible the surfaces intended expressive qualities actually were. The design did introduce a novel approach and vocabulary for how a more tactile method could be included into the general realm of design considerations. It also did provide a viable solution to a complex brief and consequently was considered a success.

Figure 6.19 A, 'Rhino' modelled, sectioned Selective Laser Sintering (SLS) model of the Tactile Paving, showing an early version of how, by varying the density and distribution of a set of small 'magents' under the scaled top surface, the feel (the buoyancy) of the surface could be varied.

7.0 Snakeskin – A Manuductory Interface

The Snakeskin (haptic manuductory[1] interface), located usually along transitional areas, provides a tactile mapping of key approaching elements along its route. The guiding principles of the Snakeskin design[2] was the same as in the floor based GroundDesign, described in the previous chapter, only now applied in a strip format to the wall. This adaptation of tactile medium and mode (from feet to hand) required a number of adjustments, for not only is the hand the main entity we use in sensing things through touch, but it also is much more 'exposed' that our feet, which are usually buffered by footwear. This increased degree of sensitivity inevitably complicated things, but also uncovered many additional possibilities. For not only is the hand in many ways a more dexterous machination than a foot, but, due both its location at the upper end of our torso and the unavoidable conditions that brings forth regarding various social and cultural factors and dynamics[3], how it is used includes many more limits and preconditions as well as necessarily learnt skills and avoidances that need to be mastered in comparison to the foot.

These considerations were prompted by the taxonomies and tactile semantics, discussed earlier. When applied into the context of the Snakeskin a more particular set of criteria necessary. These factors included the way we perceive touch whilst in motion, which includes not only our awareness of being in motion, a rendition of the stereognostic and kinaesthetic senses, but also the way our physiological extensions, our limbs and their digits, react and behave when interacting with a surface patterns (Fig. 7.1). We have a set of preferred fingers (the three central, indicator, long and ring fingers, see figure 7.2) through which we experience and explore things, but, conversely, the role of the main protagonist finger may change when used to sense [redacted]n[4] (Fig. 7.3 and 7.4). The medium through which this form of touch also shifts

1 The word 'manuductory' is a somewhat obscure term, however, as its meaning ' directing or guiding, leading by the hand', is such a close fit to the aims of the Snakeskin, it has been allowed to remain as a part of the title and text. See: http://www.tiscali.co.uk/reference/dictionaries/difficultwords/data/d0007969.html (accessed May, 2008).

2 The word 'manuductory' is a somewhat obscure term, however, as its meaning ' directing or guiding, leading by the hand', is such a close fit to the aims of the Snakeskin, it has been allowed to remain as a part of the title and text. See: http://www.tiscali.co.uk/reference/dictionaries/difficultwords/data/d0007969.html (accessed May, 2008).

3 For Example, what can be touched, or how one can/ should touch various things. Actions such as, say, whose hand to shake, how to shake it, how strong should the grip be, etc. These considerations vary depending on if you are in the UK or Abu Dhabi, they are also dependent on your gender, and the gender and position to whom you are talking to…

4 Even though we usually seem to have a preferred finger we use to explore, pick on, something, it seems that during extended 'touching' whilst in motion the main finger gets 'tired' and needs to take a back seat while one of its companions takes the lead role for a while. This oscillating substitution of the lead finger allows for the

Figure 7.1 The Snakeskin is perceived, through the hand, whilst in motion.

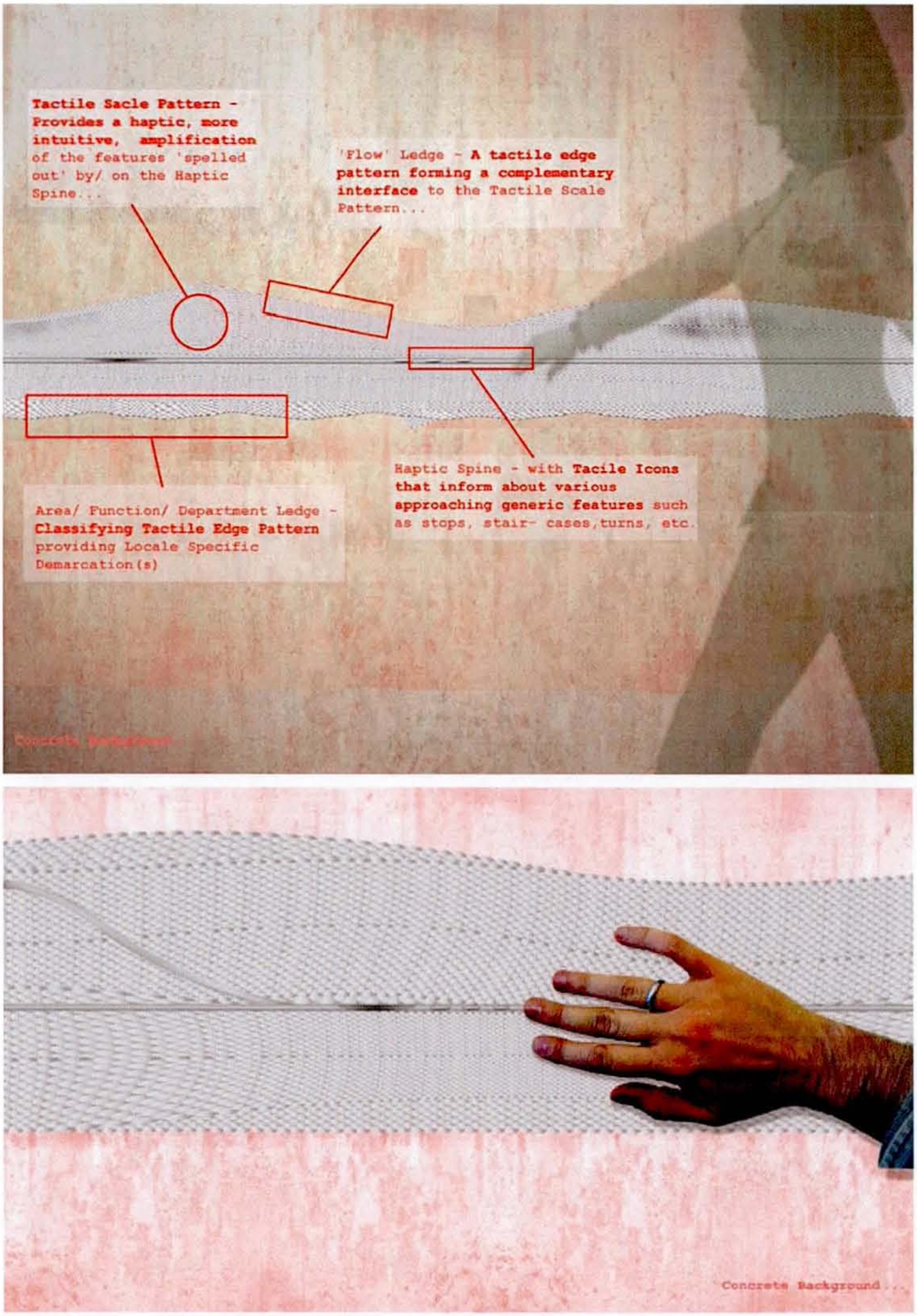


Figure 7.2 Early renditions of the Snakeskin design. Most of the terms in the image above has since been altered.

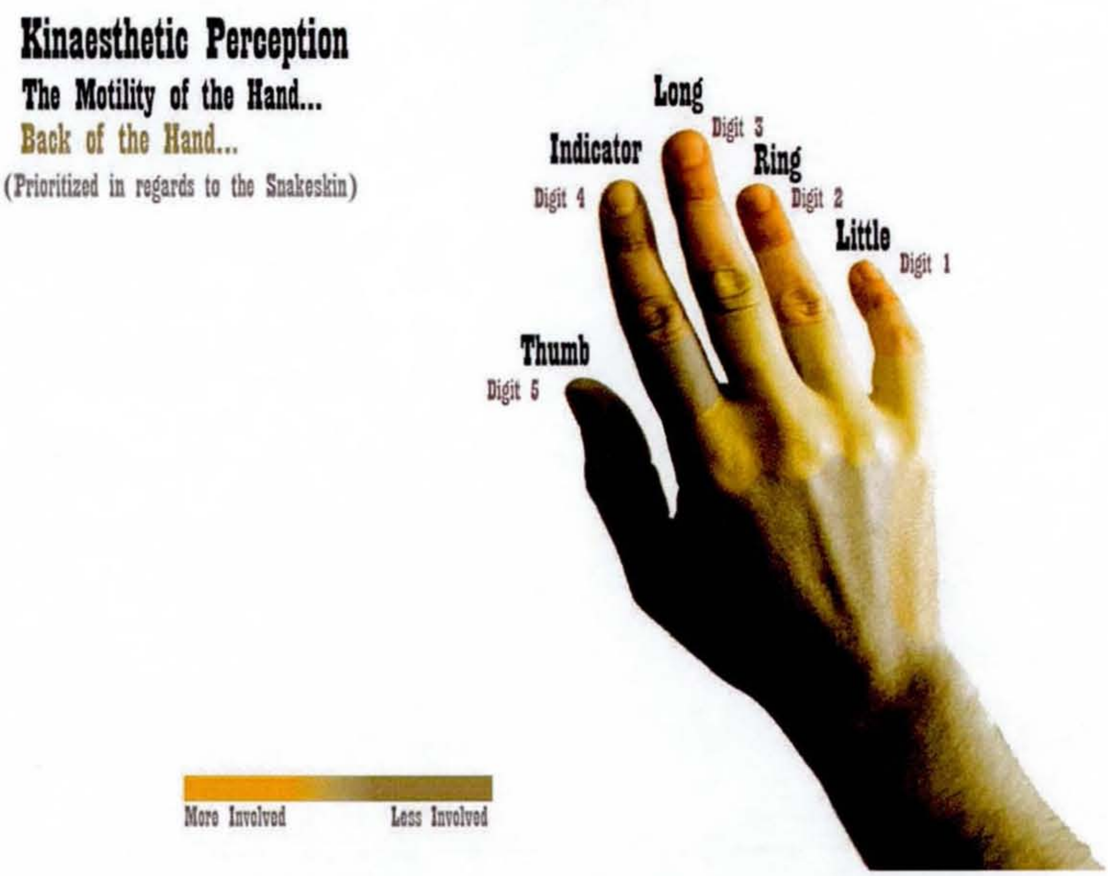
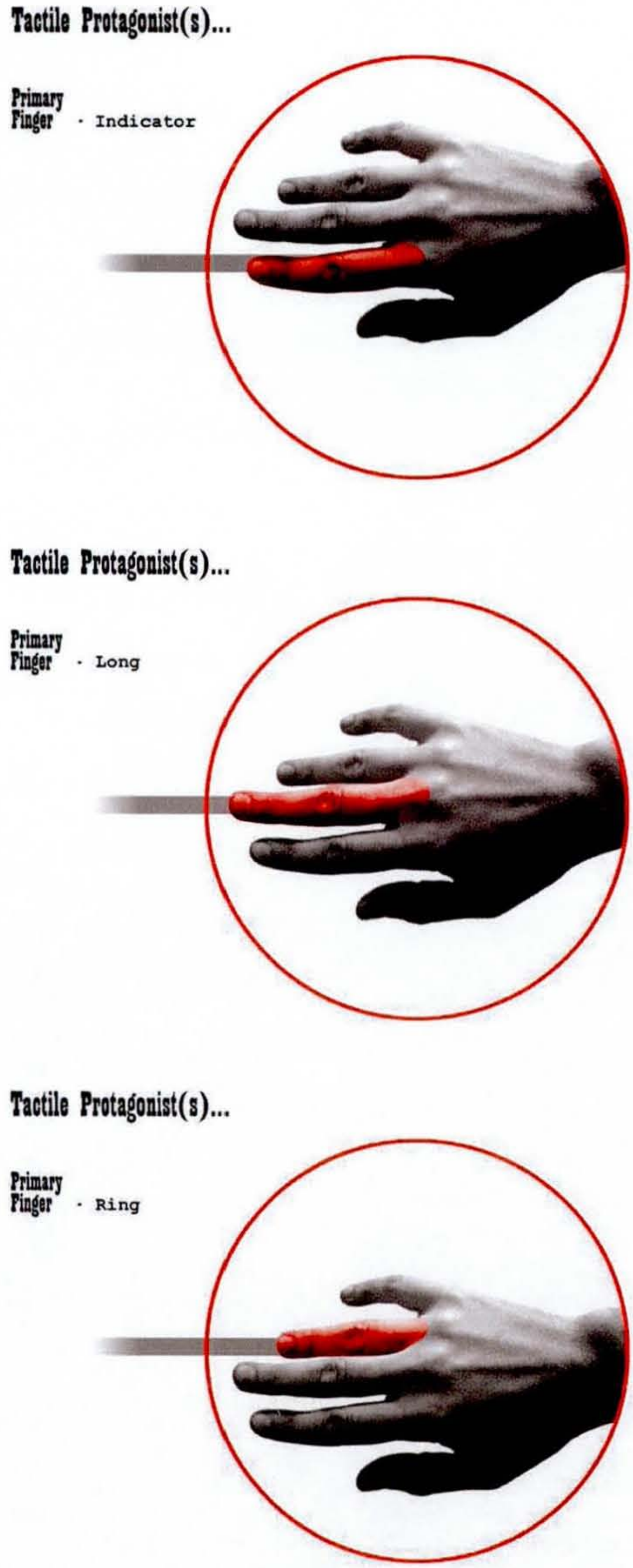


Figure 7.3 Two illustrations showing how the various fingers, and sides of the hand, seem to prioritize certain fingers or areas of the palm over other when ran across the Snakeskin relief patterns.



Figures 7.4 The three 'protagonist' fingers which seem to be the preferred fingers to use in conjunction with the Snakeskin.

during prolonged stretches of haptic contact, from the cushion side of the finger tips, to (by allowing the fingers to curl over) the finger nails, introducing a configuration of touch where the textural input is transmitted through a nerveless medium, the nail, rather than the epidermis itself (Fig. 7.5). The design aimed to consider these both forms of cutaneous sensing in its implementation. There is an alteration, a lateral skewing or shifting of sorts, in what the fingers explore, with the three central fingers changing which areas of a surface they're exploring, and how the hand, forearm, and arm respond to such affects (Fig. 7.6).

Along with directly tactile or sensory considerations, factors such as the placement of the texture on a vertical surface, and the body's positioning along it, as well as the way the body relates to a space/ place and other bodies in the vicinity, also matter. As the design is usually located by the periphery of a space or route (as people usually use the centre of a space or passage, making the access to the wall easier), be this a narrow corridor or a more volumetric space[5], the user based spatial concerns were included as significant elements in the design (Fig. 7.7). This included the sound when the fingers run across a patterned texture, or, in a auditory fashion, the 'hollowness' of the design was varied to produce a distinct type of sound when in use or even when consciously tapped (7.8). This involved making the design hollow around the central part of a Snakeskin stretch, and more dense towards the ends, providing it with an aural dimension to match that of the tactile.

7.1 Key Snakeskin Features

The Snakeskin is made up of five integrated components, which, even though perceived in unison, do each provide a distinct function. These are: the Tactile-Spine, The Handscape, the Clicks, the Quivers, and the Fire-Spine (Fig. 7.9). Each of these are explained in more detail below.

7.1.1 Tactile Spine

The Tactile Spine forms the central raised spine which runs all along the length of the Snake-

perception of the Snakeskin to remain 'fresh' and constant throughout.

5 Where, in the case of the latter space, some of the auxiliary senses might perhaps be compromised due to distracting noise, hindering one from perceiving the ambient features of a space; or because of other distractions usually affiliated with crowded places.

Figure 7.5 In prolonged use of the Snakeskin the fingers have a tendency, particularly when the pace increases, to 'curl over', necessitating for the design's features to be of a perceptible to both the cushion side of the fingertips (the usual means of perception), as well as their top-side, the nails...

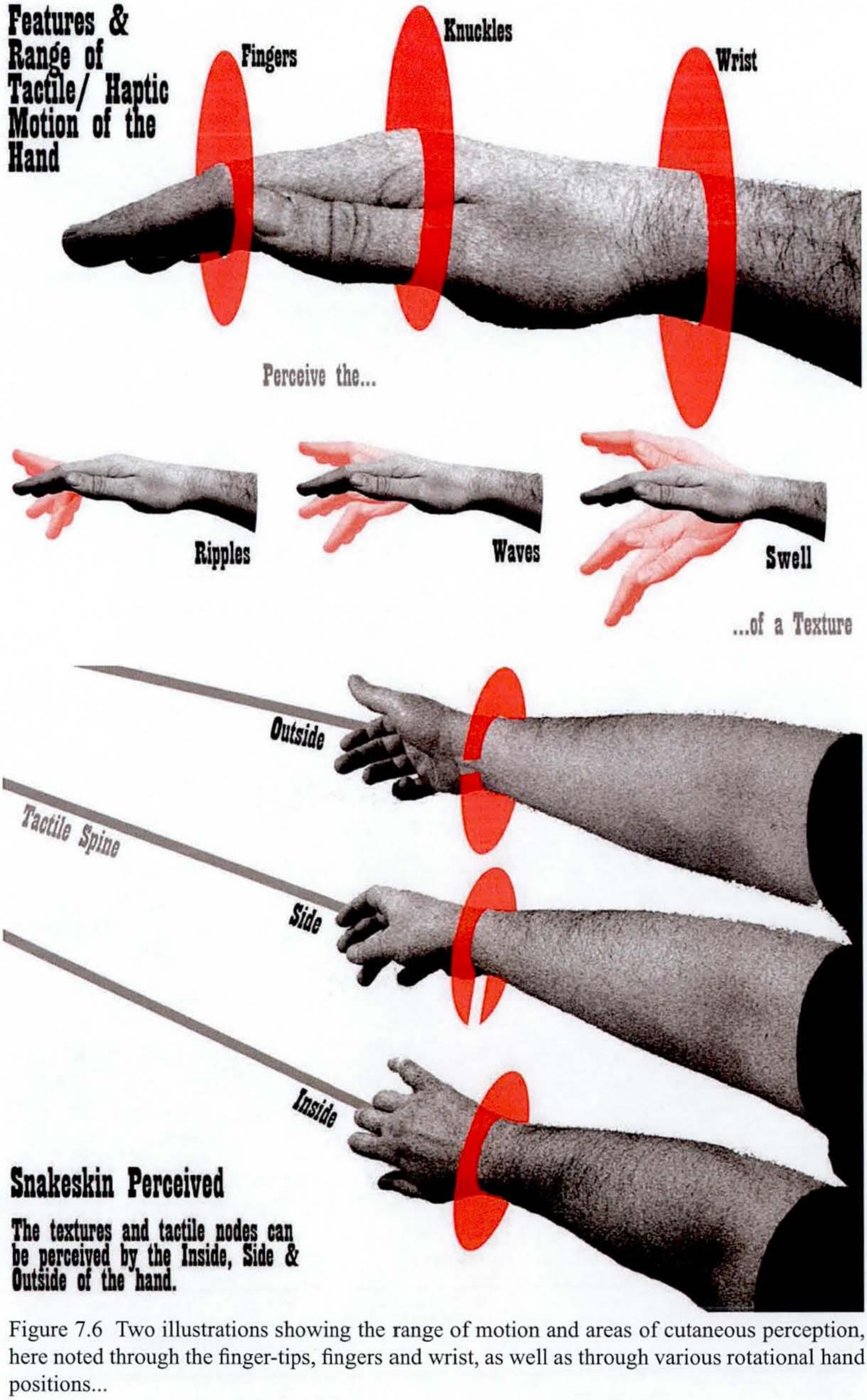


Figure 7.6 Two illustrations showing the range of motion and areas of cutaneous perception, here noted through the finger-tips, fingers and wrist, as well as through various rotational hand positions...

Snakeskin Reach

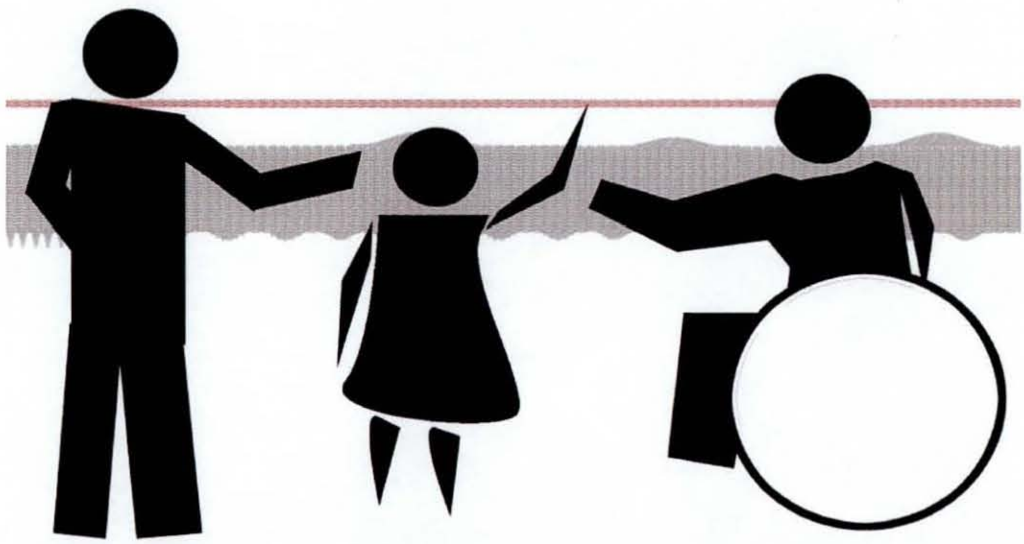


Figure 7.7 The Snakeskin design should be accessible to all, placed roughly at the height of a default handrail (1100 mm).

Figure 7.8 By altering the sound the Snakeskin makes whilst in use, the degree of hollowness of the design, can also be used to amplify the information the design is intended to transmit. It could, for example, be made to sounds gradually more 'solid' as the end of a stretch is approached.

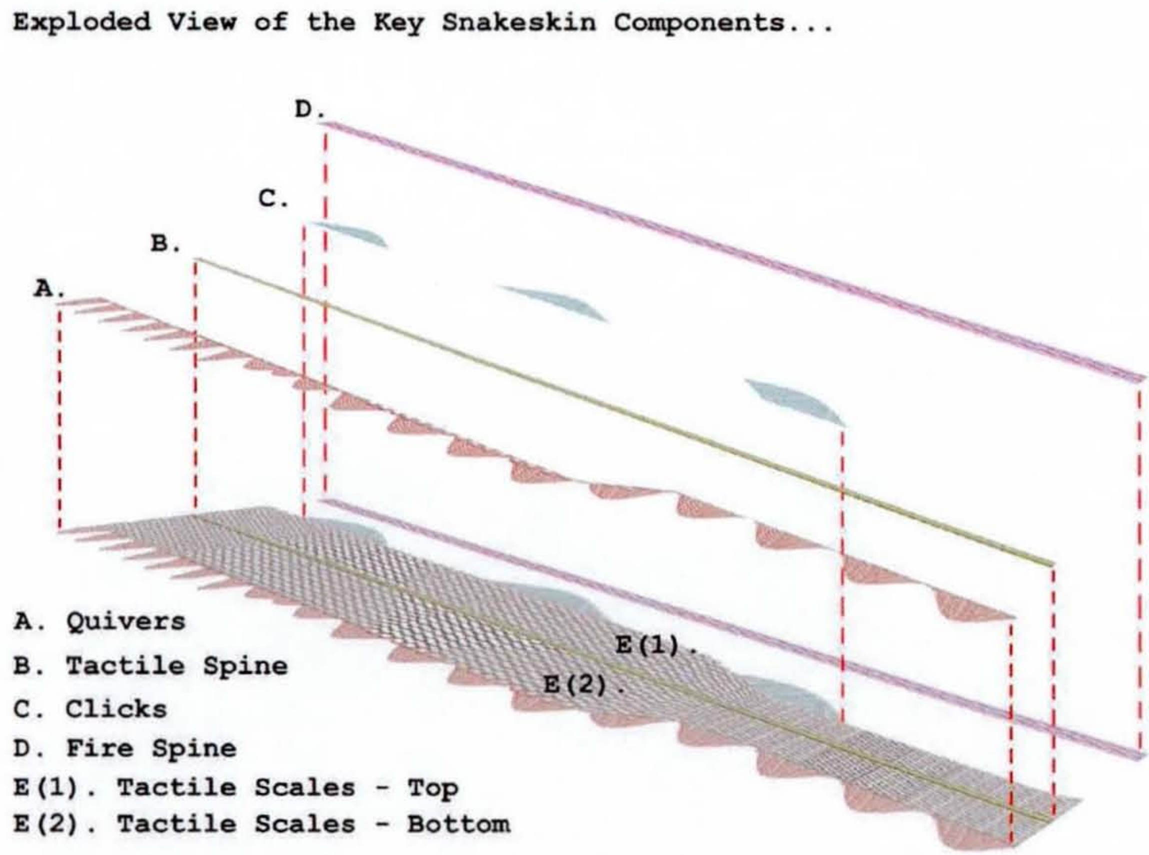
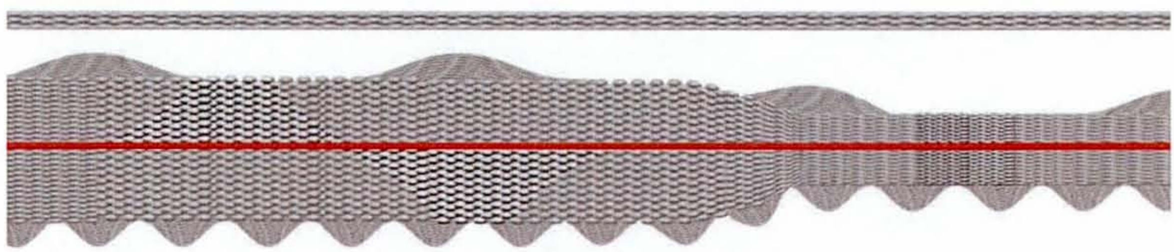


Figure 7.9 A breakdown of the Snakeskin's main elements...

Snakeskin Elements



Tactile spine - Main source of information. Expressed through a select number of 'Tactile Icons'...

Figure 7.10 The Tactile Spine, provides the most literal or graphical tactile means through which the Snakeskin communicates. It imparts its message through a set number of 'Tactile Icons' along its raised surface which each convey a particular bit of information, data such as 'speed-up', 'slow-down'. It can inform its user of an approaching route slit, or when the route will turn left...

skin (Fig. 7.10). Along this spine a set number of Tactile Icons communicate their message through various figurative patterned concavities and convexities. These tactile icons are divided into Tactile Nodes, which inform the Snakeskin's user about approaching features, and Tactile Coaxes, that provide suggestions for actions that its user might wish to follow. Examples of the tactile nodes, were, for example, a sign indicating an approaching left or right turn, or perhaps a route split/ intersection. The coaxes, inform us about, for example, an extended stretch during which nothing worthwhile takes place and we can speed-up. At the end of such a stretch an 'opposite' coax icon would infer one to slow down. The tactile nodes and coaxes are preceded by a 'Take-Note' icon (Fig. 7.11), which functions as a generic notification about an approaching (variable) tactile icon. The take-note icon works in combination with the other icons (nodes and coaxes), extending the stretch during which the gist of the icon, its message, is communicated (Fig. 7.12). The Tactile Spine takes the central role of an unvarying and settled touchstone against which the remaining, more 'animated', features of the Snakeskin can be compared.

7.1.2 Handscape

If the tactile spine acts as the design's backbone, the Handscape performs as its body or torso (Fig. 7.13). Made up of a 'scaled' friction surface, which has frictional resistance in one direction than the other, and thus provides an intuitive suggestion for in which direction one should move (the direction of least resistance). The Handscape amplifies the message conveyed by the tactile spine by providing an intuitive and suggestive interpretation of its expression. It does this by varying the pattern of the surface's scales – increase the friction of the scales to insinuate one should slow down, decrease the friction to indicate it is time to speed-up. Subtly angle the planes (as in a racetrack) before an approaching turn whilst gradually and lopsidedly increasing the degree of friction of the scale patterns on each side of the tactile spine (more on the side of the turn, slowing it down; less on the other side, speeding it up) , causing the hand to progressively twist in the direction of the turn (Fig. 7.14). The scale patterns were employed for other features – by routing the scales in various directions, or by sizing and scaling them, 'softening' them (through the use of Claytools and the SensAble Phantom), skewing them and angling them in different ways – the surface suggested a number of alternate indicative tex-

Figure 7.11 The 'take note' tactile icon, which proceeds all the other tactile icons...

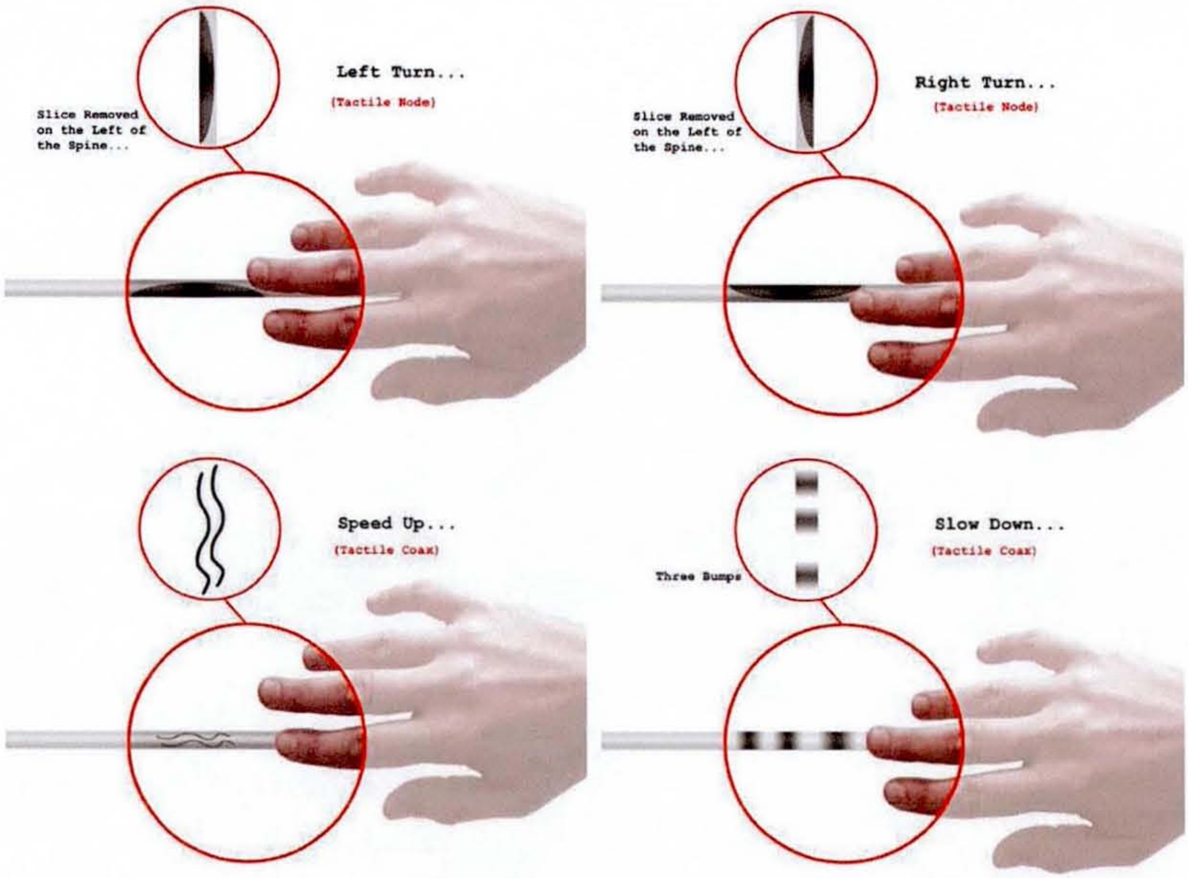
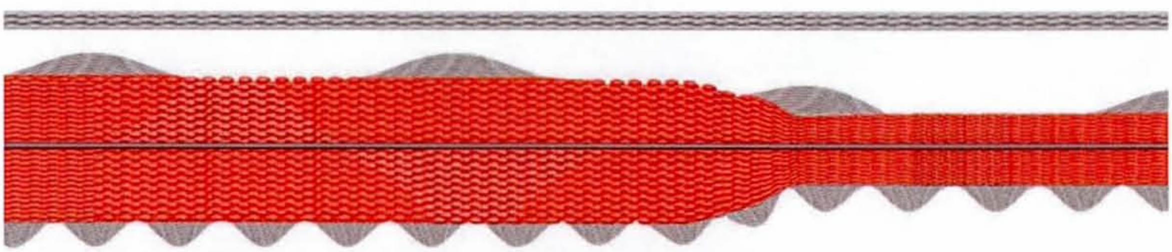


Figure 7.12 Tactile icons - the 'turn left' and 'turn right' nodes above, and the tactile coaxes 'speed-up' and 'slow-down' below...

Snakeskin Elements



Handscape - A directional tactile friction surface...

Figure 7.13 The Handscape forms the main, and most visible, component of the Snakeskin Tactile Relief Pattern. It forms a supporting envelope around the Tactile Spine, providing it with a supporting stratum of tacit information.

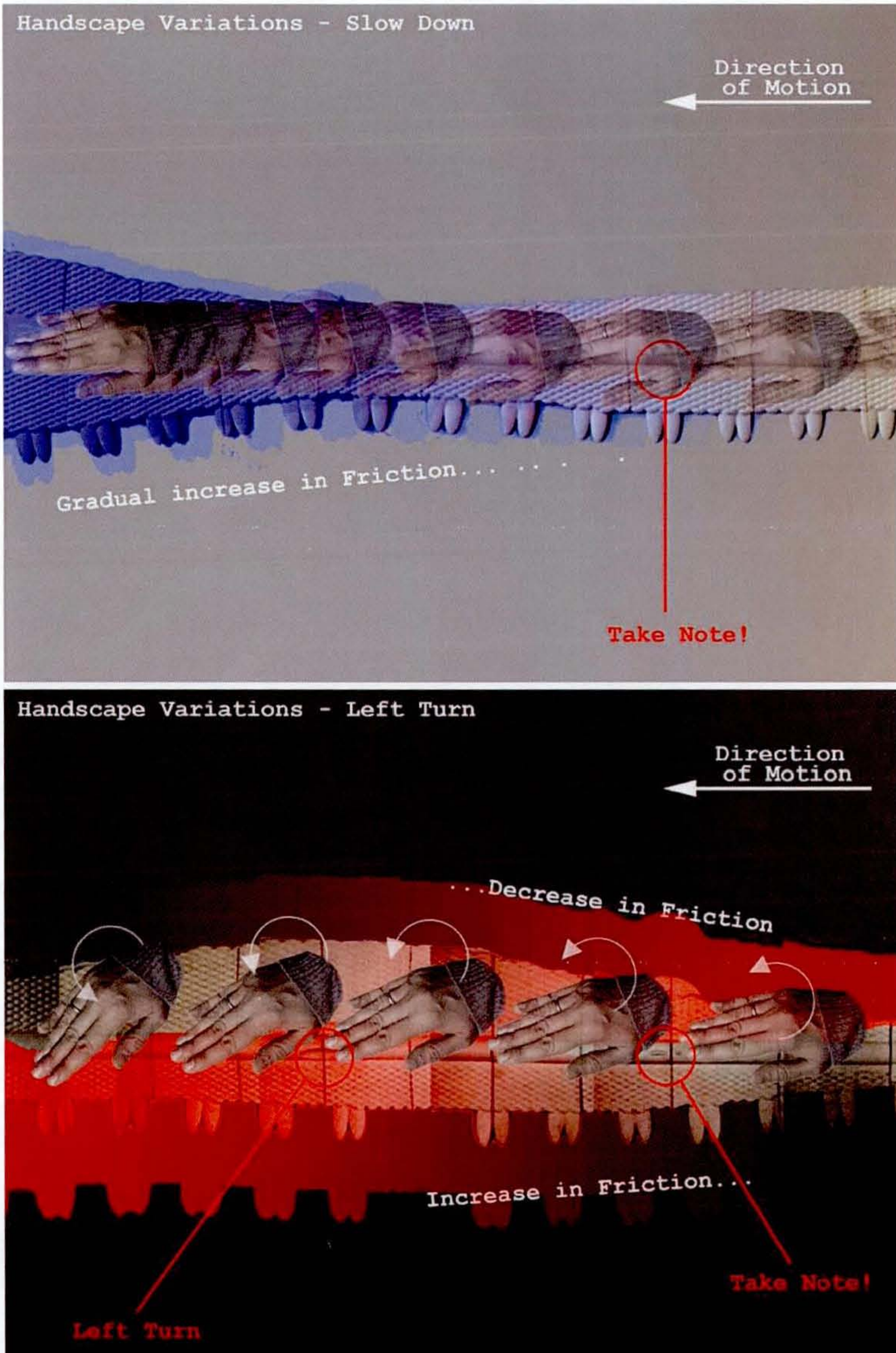


Figure 7.14 Two views of the Handscape, showing how the friction pattern of the surface scales can be manipulated to suggest various actions - gradually increase the degree of friction intuits one should slow down; increase it on one side whilst decreasing it on the other, resulting in the hand beginning to rotate (towards the direction of the more frictional side), to suggest a turn.

tures[6]. On a different but related note, the altering the visual appearance of the design was also considered, both from the perspective of graphical clarity (Fig. 7.15), as it turns out that approximately ninety-five percent of those classified as officially blind can see at least partially (Barker et al., 1995), and, as the hand is the main interface through which the design is perceived through, it inevitably will involve a degree of wear as well as accompanying staining, which in this instance can be used as a means for increasing the design's graphical or visual clarity (Fig. 7.16).

7.1.3 Clicks

The Clicks are an array of regular 'bumps' placed at every meter along the top ledge of the Snakeskin (Fig. 7.17). They provide a tactile cadence, which acts as a set and uniform (externalized) standard against which the remaining variable features of the Snakeskin can be compared, eg. the distance travelled.

7.1.4 Quivers

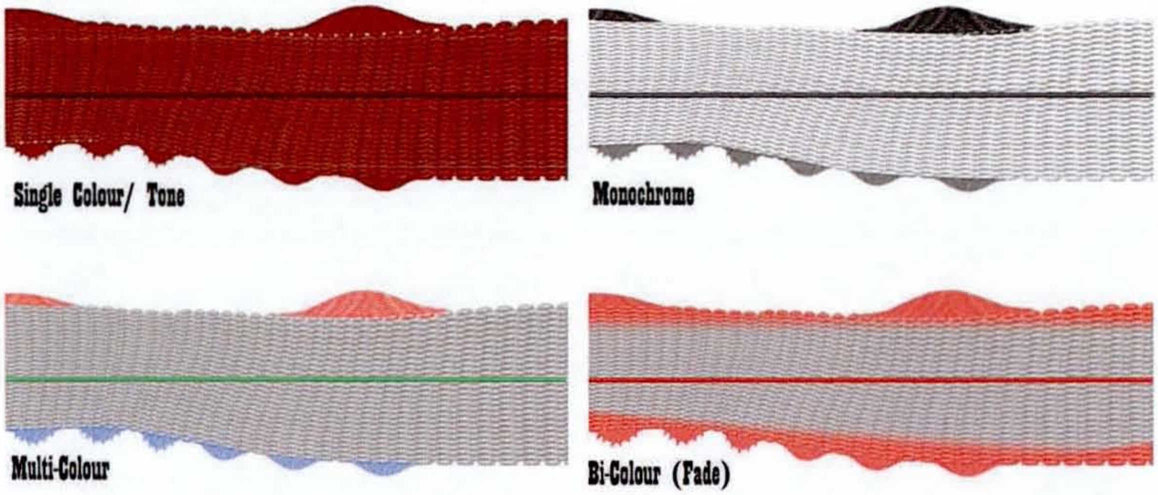
The Quivers occupy the bottom periphery of the Snakeskin, and provide a variable set of undulating patterns which are particular to a specific locale (Fig. 7.18). In other words the variously shaped profiles (with quasi-zoomorphic names such as rabbit-teeth or sharks-teeth) are used to distinguish one place/ department/ wing/ section/ division and even subdivision from another. Each such segment was provided with its own individual Quiver zone which acted as a tactile icon for the place. The Quivers were subdivided with various textures or sub-profiles on the Quivers themselves (smaller 'teeth' covering the rims of the larger Quiver contours).

7.1.5 Fire Spine

The Fire Spine's function is to guide its user to the nearest fire exit. The strip, a forty millimetre

6 Alternative friction patterns to the scales were considered, patterns such as 'breaking waves' (sequential strands of gradually varying 'ripples'), or finger-flutes which can be used to 'lead' ones fingers. However, the advantage with using the scales as a more or less default unit to manipulate is much easier to contour and manipulate – to direct, individually angle, skew, size, and eventually group at consecutive stages (groupings) of the scales, which were discussed and named according to the Avaterial classifications. Any of the alternate, nurb-based, control formats turned out to be much more difficult to actually realize….

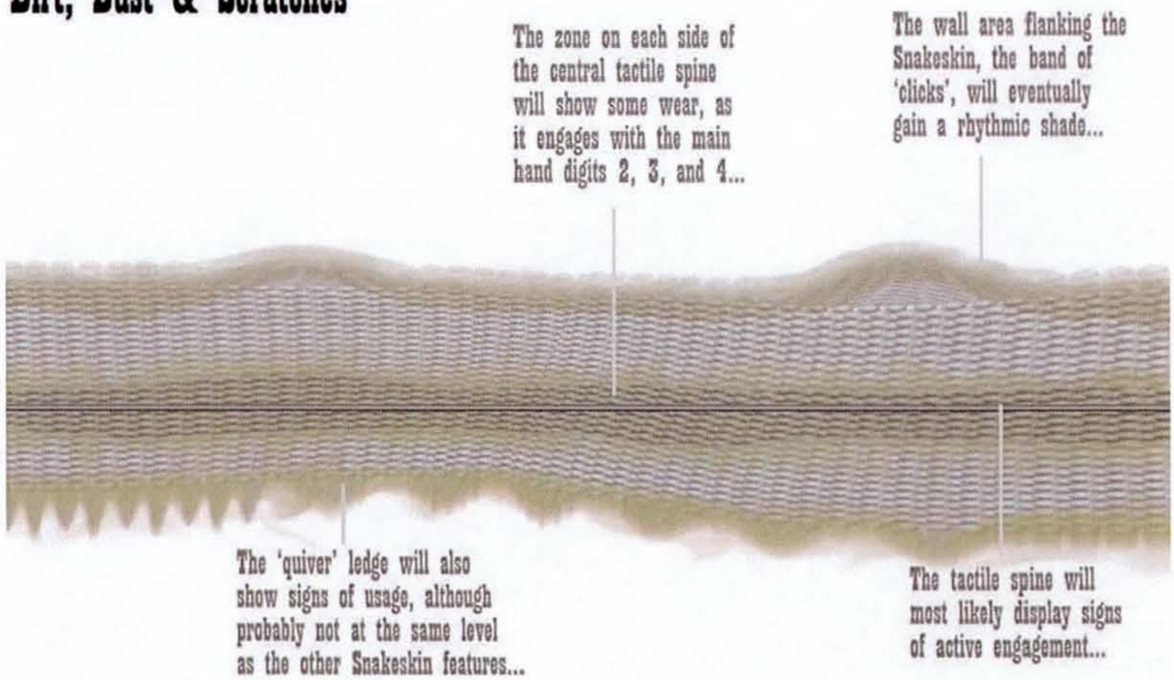
Snakeskin Colours



Ideally, the Snakeskin should remain a neutral colour (white), as this would allow it to be more adaptable from a design perspective. However, the use of colours has been considered, something that from a purely, call it, graphical, explanatory or clarityíng standpoint would make sense, particularily as only 5% of those classified as blind have no vision at all, the remaining 95% have partial, be it blurred or blocked vision...

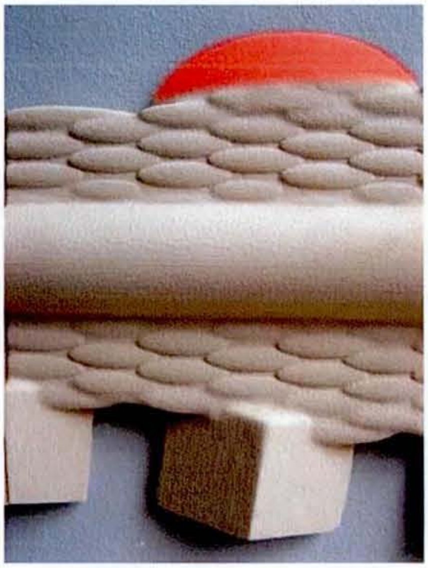
Figure 7.15 Examples of various more visual or graphical renditions of the Snakeskin.

Dirt, Dust & Scratches

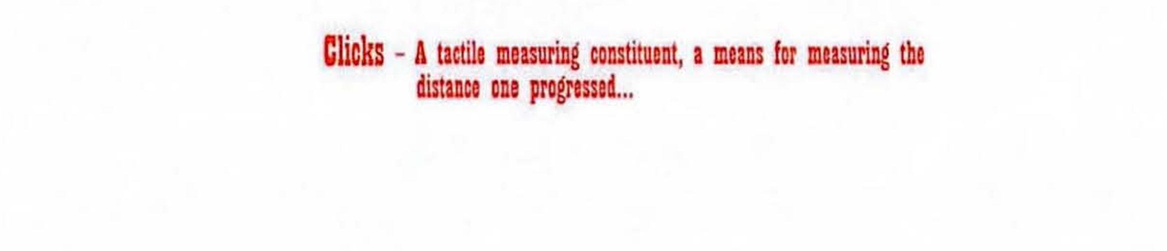


Inevitably the Snakeskin will show its age, particularily if used consistently - regardless of what material the relief is made of the signs of age, wear & tear - entrophy, will eventually become apparent. This, however, doesn't necessarily have to be a bad thing, as such signs of use can actually be included as featuers in the conception of the design.

Figure 7.16 An illustration exploring the assumed wear and staining patterns of the Snake-skin.

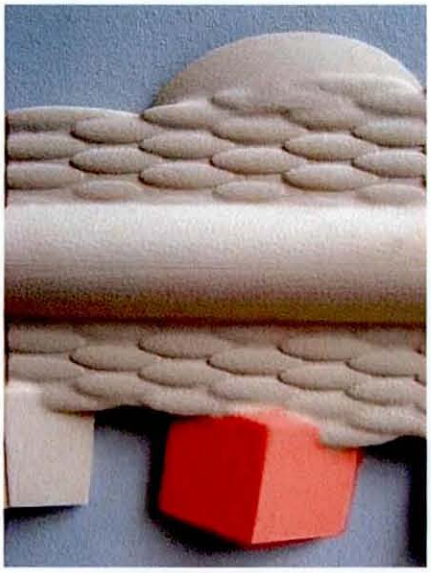


Snakeskin Elements

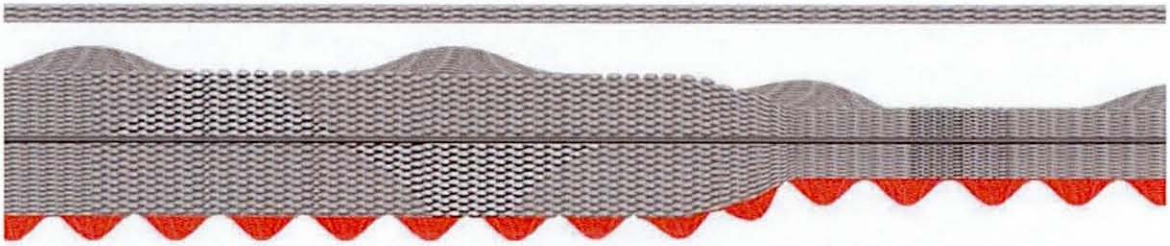


Clicks - A tactile measuring constituent, a means for measuring the distance one progressed...

Figure 7.17 The Clicks are a metric (regular) 'swell' pattern taking place along the top ledge of the Snakeskin. The clicks provide a default measuring pattern, with a 'swell' taking place at a one per meter sequence, which allows for a more generic point of comparison.



Snakeskin Elements



Quivers - Define through tactile means the area, department, section that the snakesin is progressing through...

7.18 The Quivers provide a bespoke pattern on the Snakeskin's lower ledge. These are used to indicate a particular general location, distinguishing, say, the Chemical Engineering Department from the Mechanical Engineering Department at an University; or Terminal One from Terminal Five at an Airport. The Quivers can also be customized with secondary patterns to allow for sub-divisions within the main patterns (smaller 'waves' covering the ledges of the larger 'dune' patterns)...

wide scaled surface, occupying an adjacent, but not directly linked, position above the main body of the Snakeskin. It was made to 'point' (lead) at most in two directions, regardless of at which location one stands, the Fire Spine will always guide you to the closest, or most easily reached, escape route (Fig. 7.19).

The Fire Spine can was applied in two different degrees of resolution. As a generic pattern, the friction surface is uniform throughout, the scales being homogeneous whatever the location, their only duty being to lead the user to his or her desired destination. In a bespoke application the scale-patterns would be customized to reflect their approximate distance to their destination by varying the friction surface's resistance. Elongating the scales of the surface, hence lessening their degree of friction without reducing their intelligibility, suggests that the user is still some distance from the target and needs to hurry up. Making the scales more pronounced closer to the exit (thus making them indicative of a tactile condition affiliated with slowing down and consequently an approaching exit) indicates that safety is near.

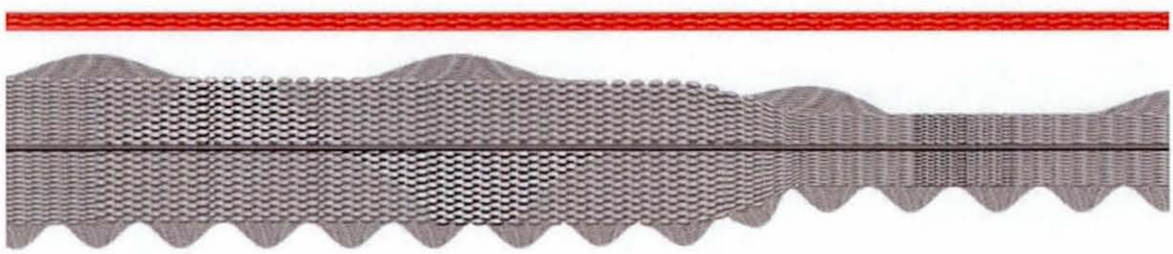
7.1.6 Alternate Features and Elements

The start of a strip, called the 'Intro Info', and the finish of a Snakeskin segment, named simply 'Strip End', both provided adaptations of the above features.

The Intro Info located at the start of a Snakeskin length, is an modified segment, a topography and feature map of sorts, of the design that operates as a brief summary of the upcoming section, listing key aspects of the upcoming route such as turns, doors (which is inclusive of information on what to expect behind the door), and action coaxes. It also includes a guide for directing or leading ones hand to the start of the Snakeskin (Fig. 7.20). The transition from the Intro Info to the actual Snakeskin is indicated by three consecutive smooth depressions in the tactile-spine.

The Strip End, in turn, is a means to indicate that a stretch of the Snakeskin is approaching its end (Fig. 7.21). It achieves this in similar tactile means to those found in an approaching turn – by using on the tactile spine the 'stop' icon, and by an initial gradual increase in the friction of the handscape, but which, different from the texture of a turn, begins here, to, step by step, smooth out both its guiding elements and textures to conclude in a smooth, finely textured, surface, which fades into the wall.

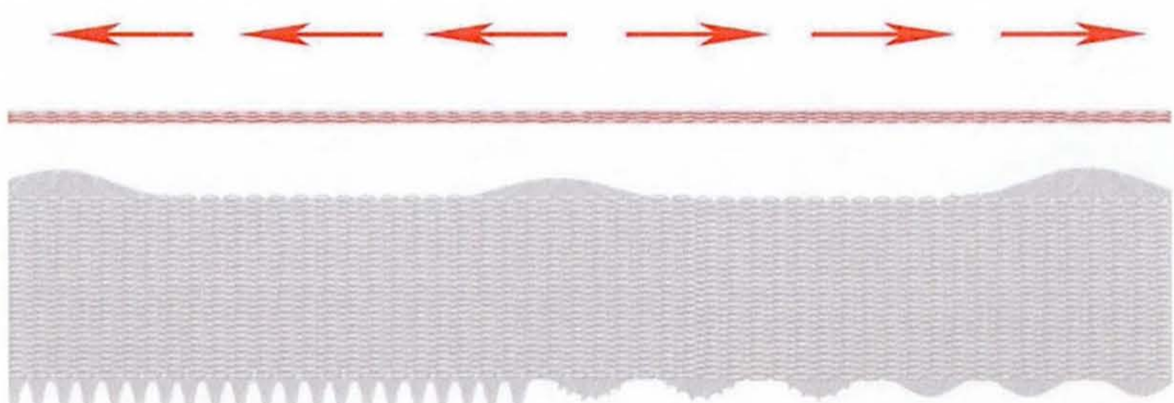
Snakeskin Elements



Fire Spine - A separate directional tactile spine which only purpose is to provide a route to the closest emergency exit...

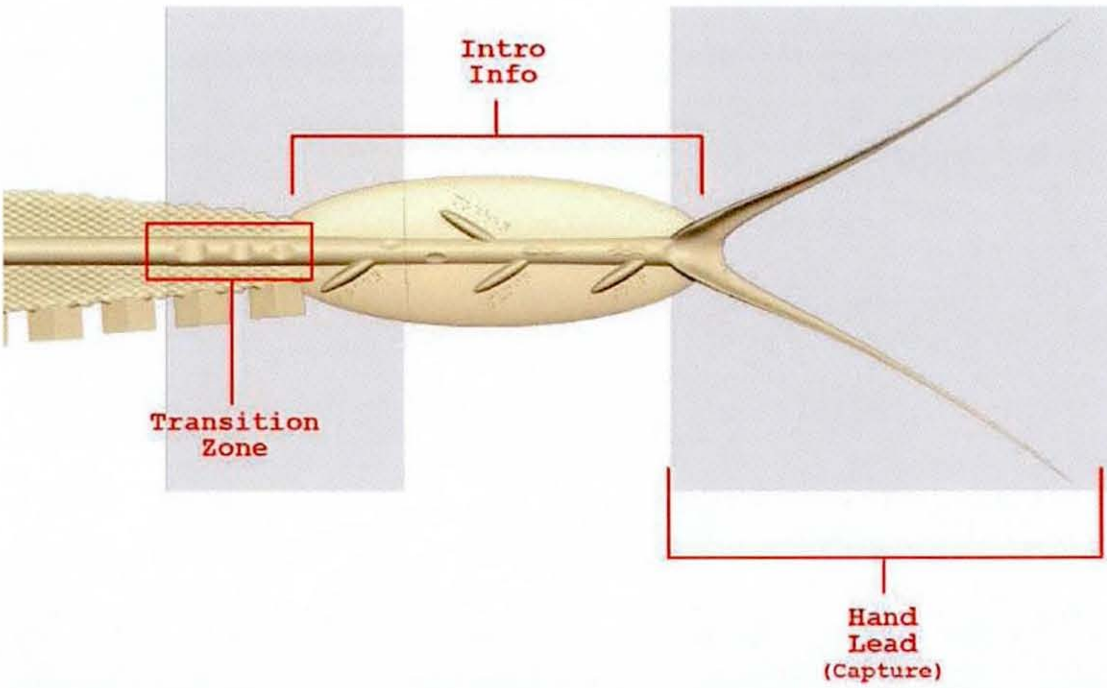
Fire Spine

Texture Direction - The arrows show the direction of less friction...



The Fire Spine is a smaller, separate, texture spine, flanking the main Snakeskin on top, which sole purpose is to indicate the direction of the closest emergency exit. Thus, for each uniterrupted run of the spine, it can only have a maximum of two different directions...

Figure 7.19 The Fire-spine is a separate tactile relief stip located above the Snakeskin. Its sole purpose is to provide a tactile route to the closest fire-escape.



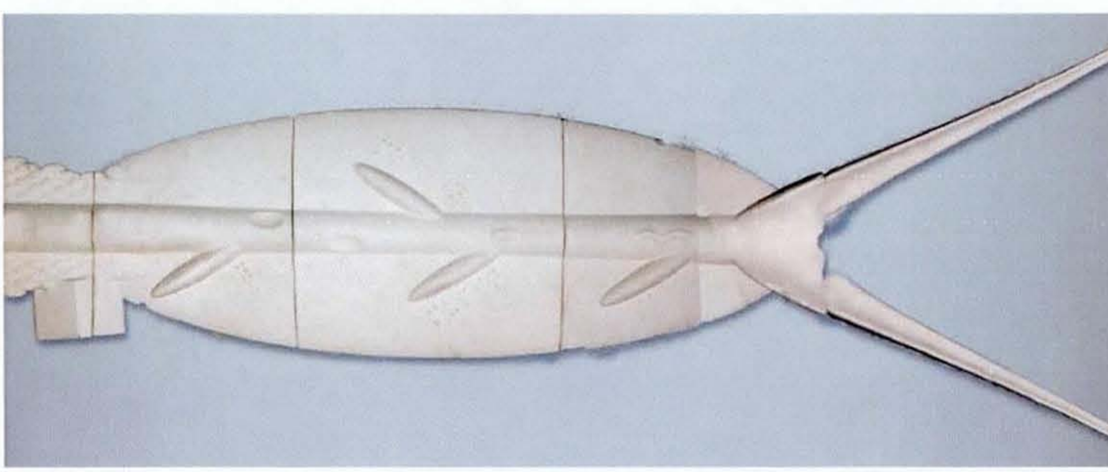
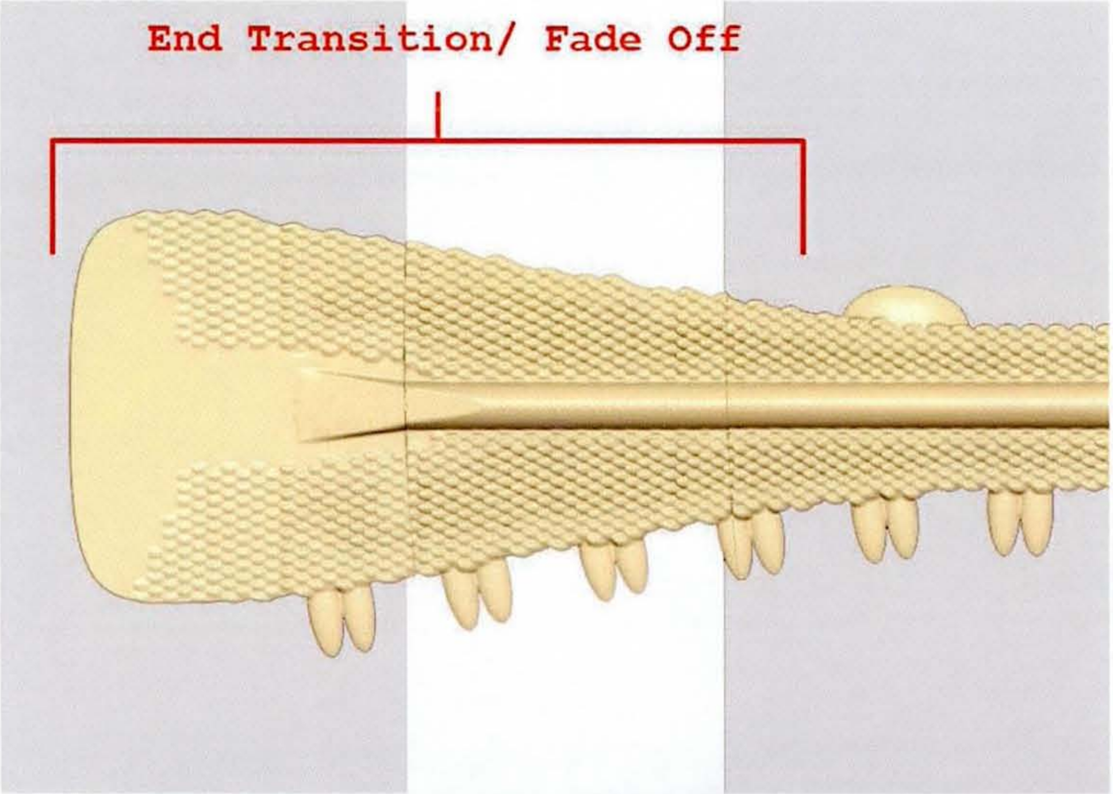


Figure 7.20 The Intro Info of the Snakeskin - 'Captures' and provides the Snakeskin's user with a summary of the upcoming segment of the Snakeskin.



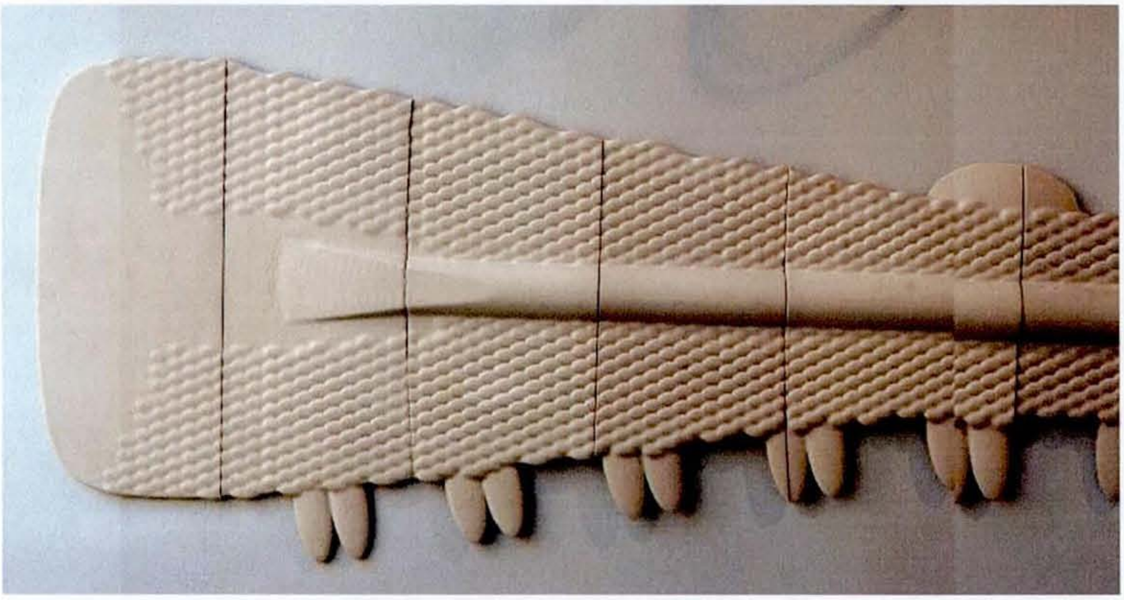


Figure 7.21 The Strip End of the Snakeskin - Concludes a particular stretch or segment of the Snakeskin. Here the texture gradually fades out and into the wall behind...

The concept could be extended to the floor where two lengths of Snakeskin are separated by a intersection or a perpendicular passageway. The links, which overlap with the main wall relief segments of the Snakeskin, provide and act again as an augmenting means to the principal hand-based transmission method, which provides its user with a corresponding 'pedestrian', foot based and transmitted, indication of an approaching junction to those supplied by the hand (Fig. 7.22).

The design was conceived so that the tactile spine and handscape were sensed together. Nevertheless, the categories provided a convenient means, and a set of encompassing terms that have been helpful in the elaboration of the project. A number of iterations for how the design was angled on the wall or raised off the surface (a railing, parapet, or other such partition) were considered (Fig. 7.23 and fig. 7.24). The one chosen was flush with the wall as this rendition was the least intrusive

7.2 Mapping the Snakeskin's Features

The planning of the Snakeskin, and its various variable features, became a logistic exercise in its own right, as, whilst the general guiding elements and principles of the design are limited, the variables according to which they are applied can fluctuate considerably. A system for mapping the design was needed. The suggestions for what this might entail was already suggested by the classifications that were used during the actual CAD design of the Snakeskin, which involved a set of made-up symbols and markers to distinguish its various patternings and function based locales (Fig. 7.25). These applications were experiential as a way for documenting the designs actions, a notation system inspired by both the London tube map (with its emphasis more on nodes rather than distances (Fig. 7.26) and Labanotation, a notation method used for documenting dance choreography (Fig. 7.27). This system of tactile notation has made the process of planning and documentation of the Snakeskin's assortment of variables much less cumbersome (Fig. 7.28).

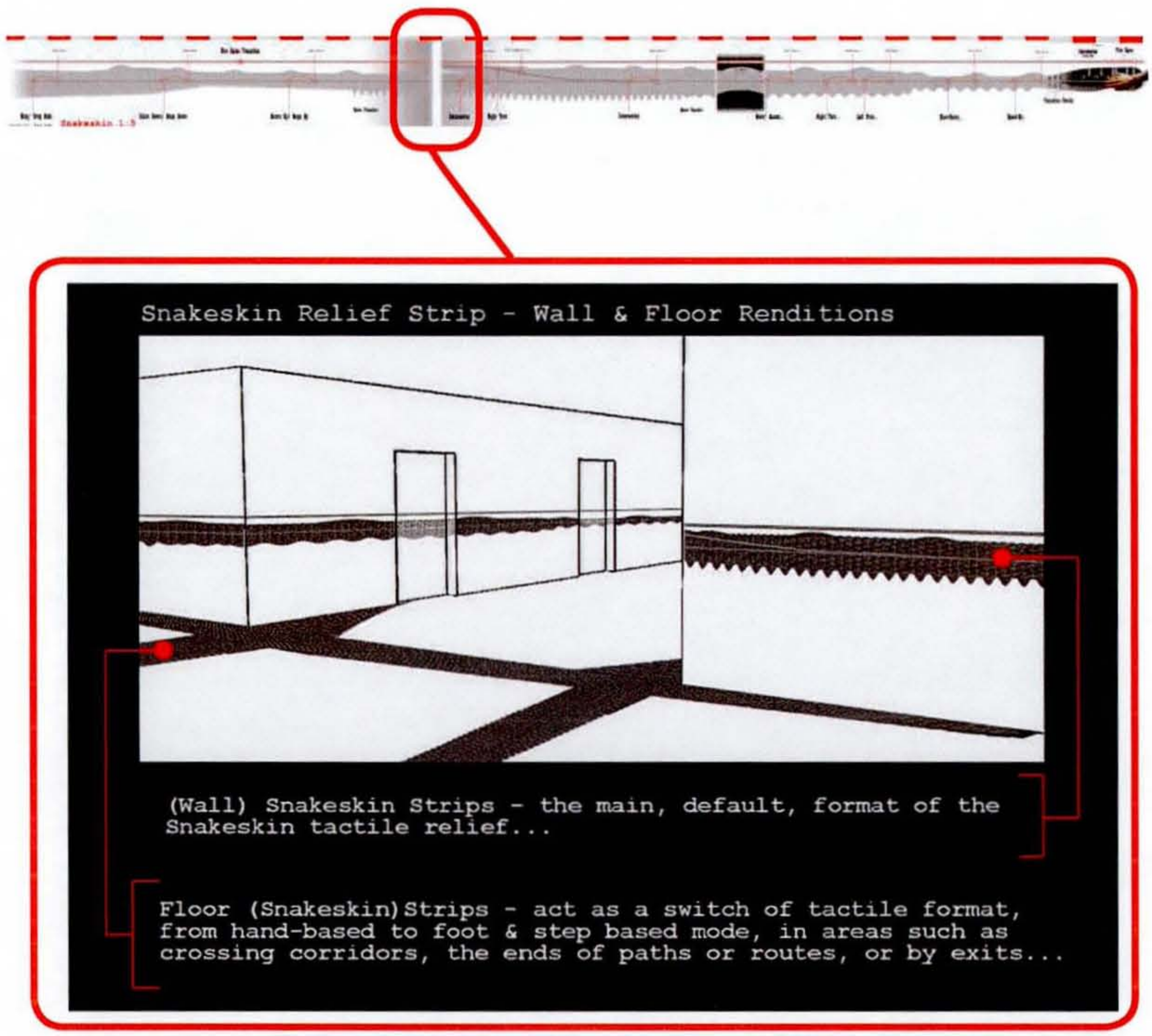


Figure 7.22 At locations where the Snakeskin relief cannot pass along a wall surface, the strip switches from a wall based to a floor based surface, so as to allow one to cross a path or intersection without losing touch (literarily) with the relief surface...

Snakeskin Profile & Setting Variations

A) Convex Wall Relief

B) 45 Degree Angle

C) Perpendicular

D) Concave Pocket Relief

Figure 7.23 Examples showing samples of the various angles considered for the Snake-skin relief.

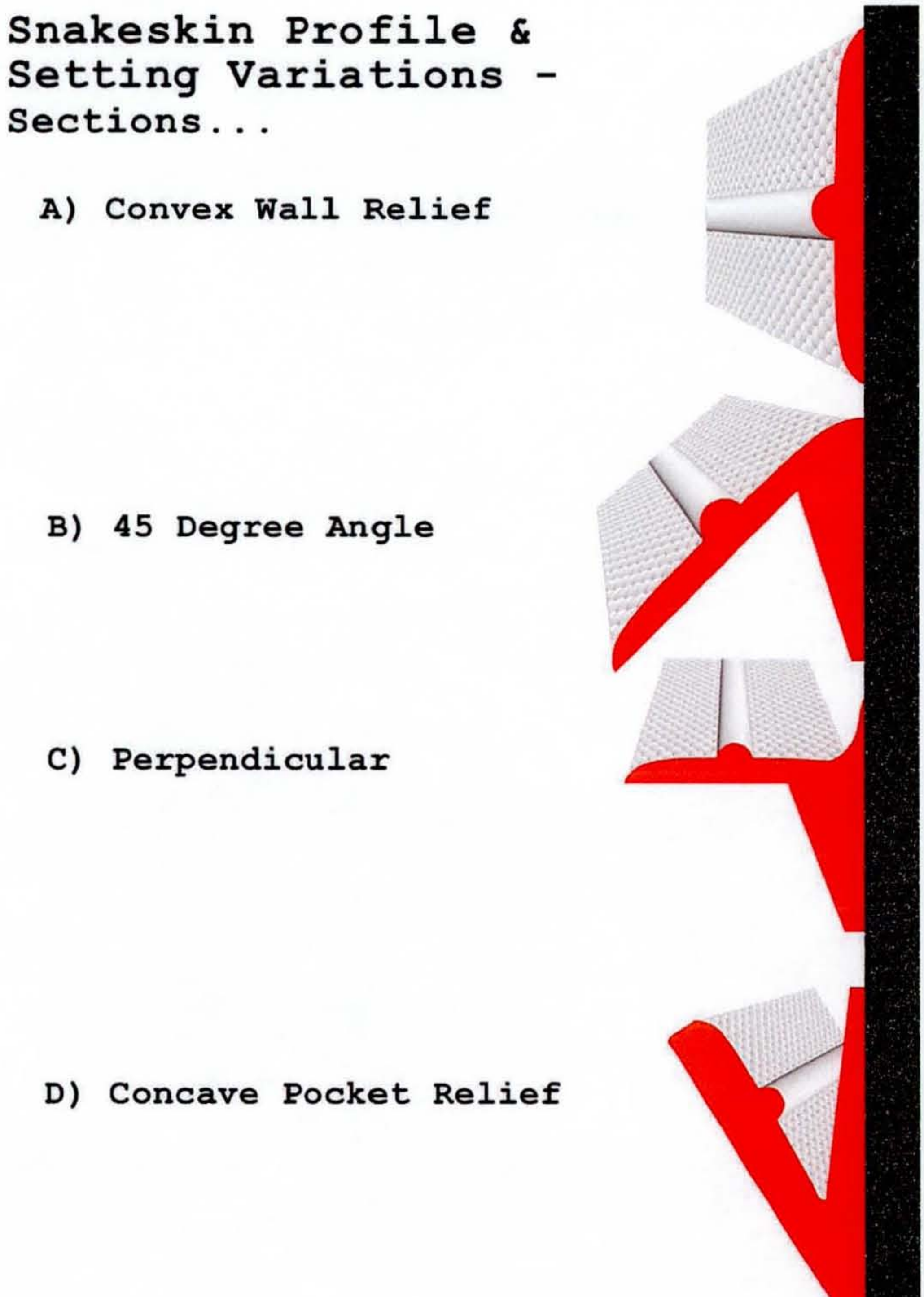
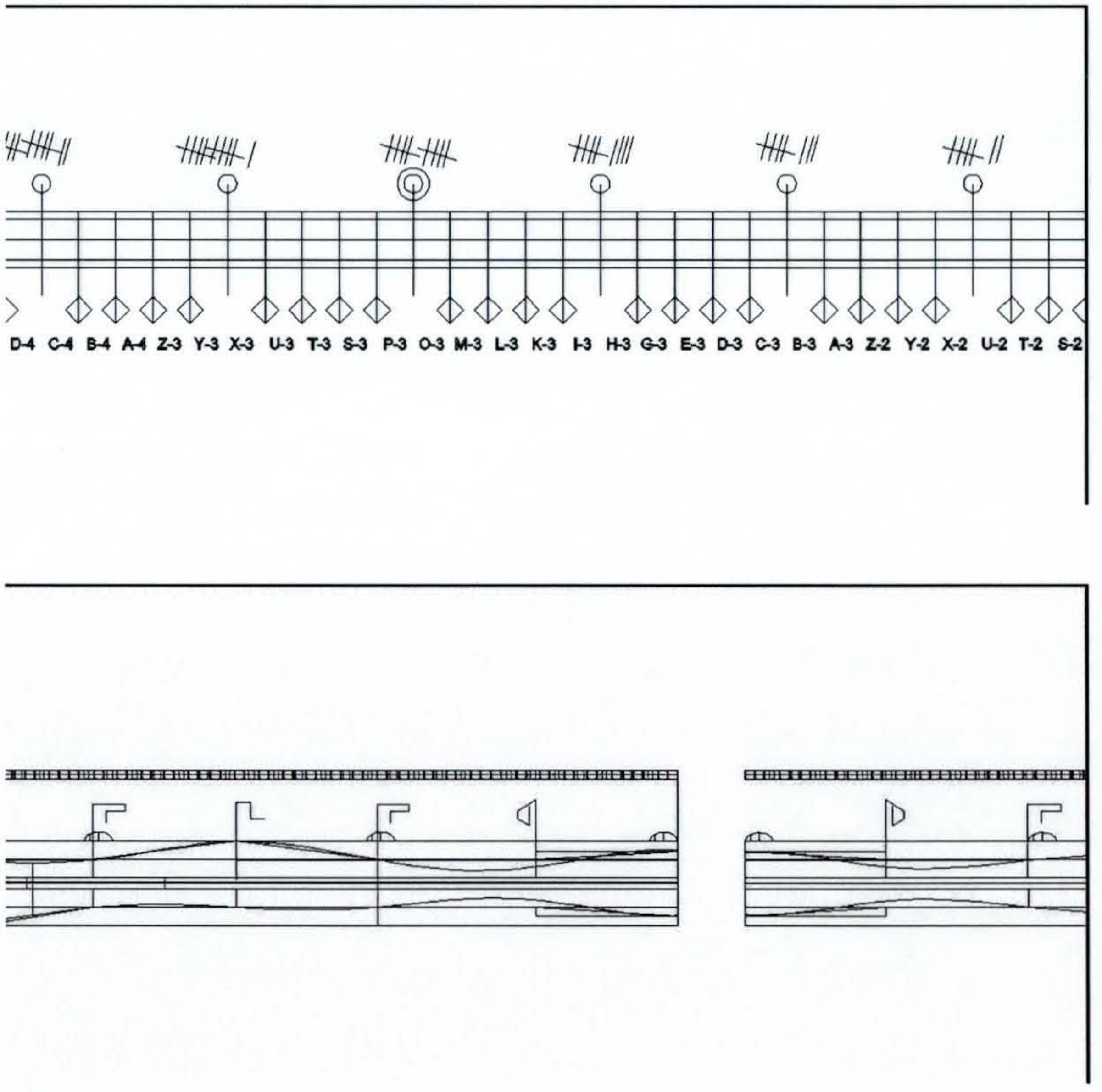


Figure 7.24 Sectional view of various angled positions for the Snakeskin relief strip.



Figures 7.25 Markings used in the placement of the Snakeskin design's various features, entailing a appropriated language of its own...

Figure 7.26 London tube map, an inspiration for the tactile mapping of the Snakeskin. (Source: www.london-tube-map.co.uk . Accessed January, 2007))

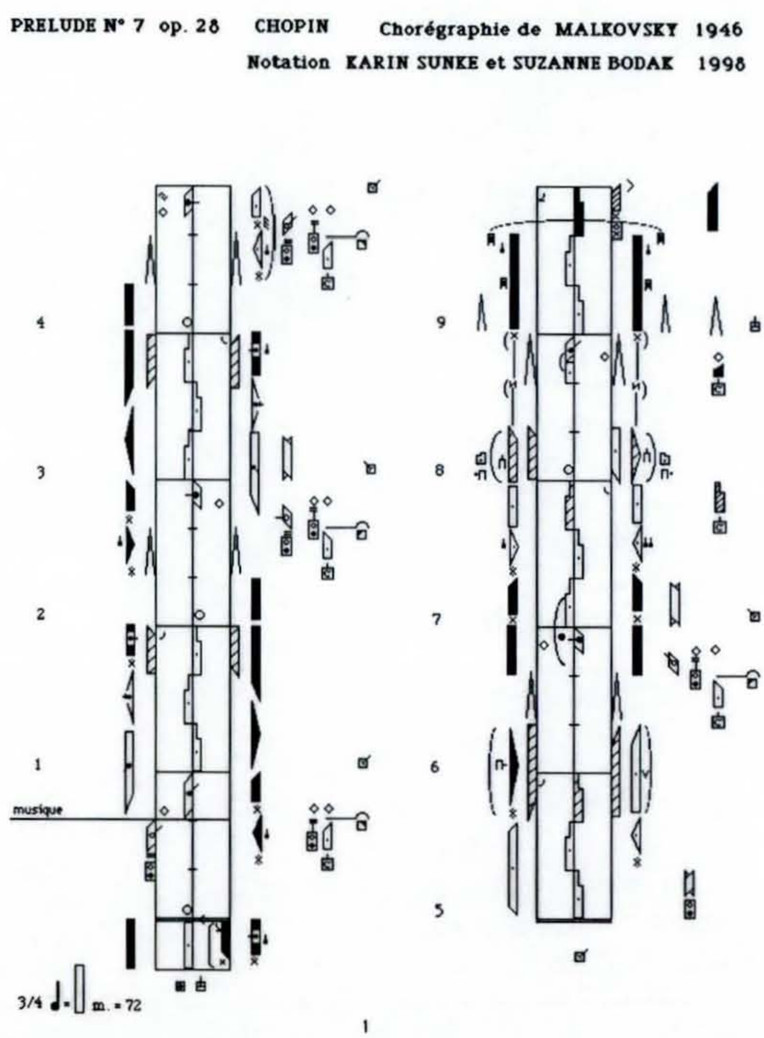
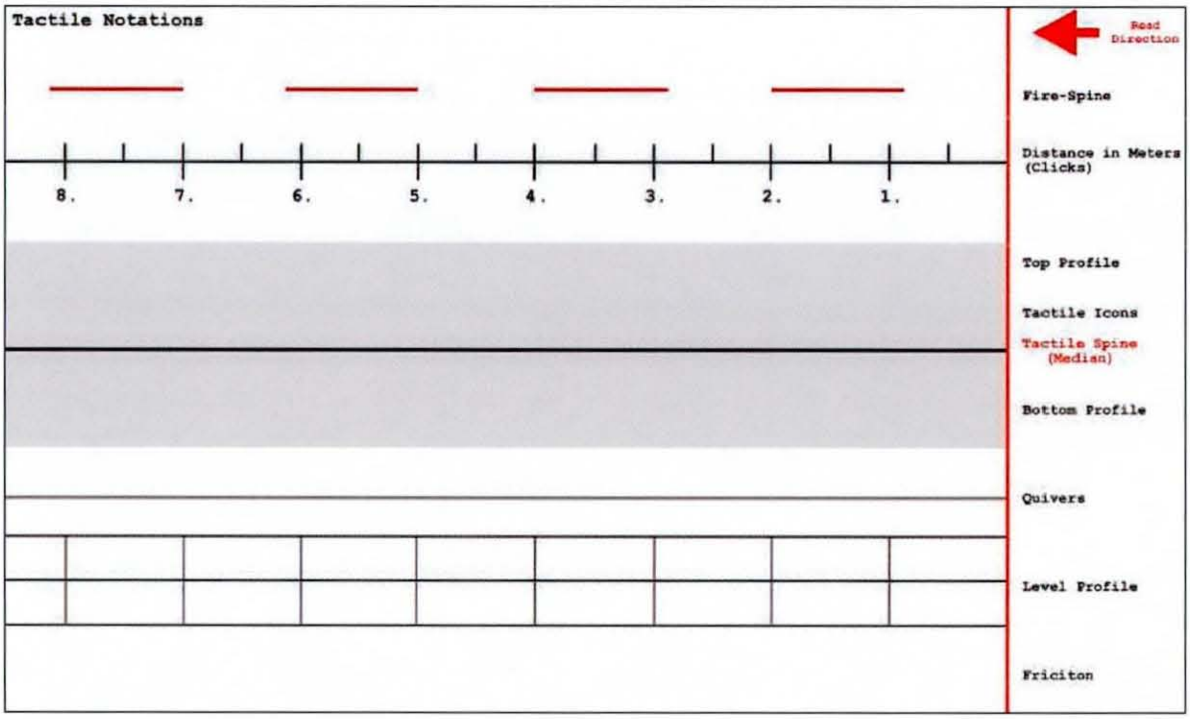
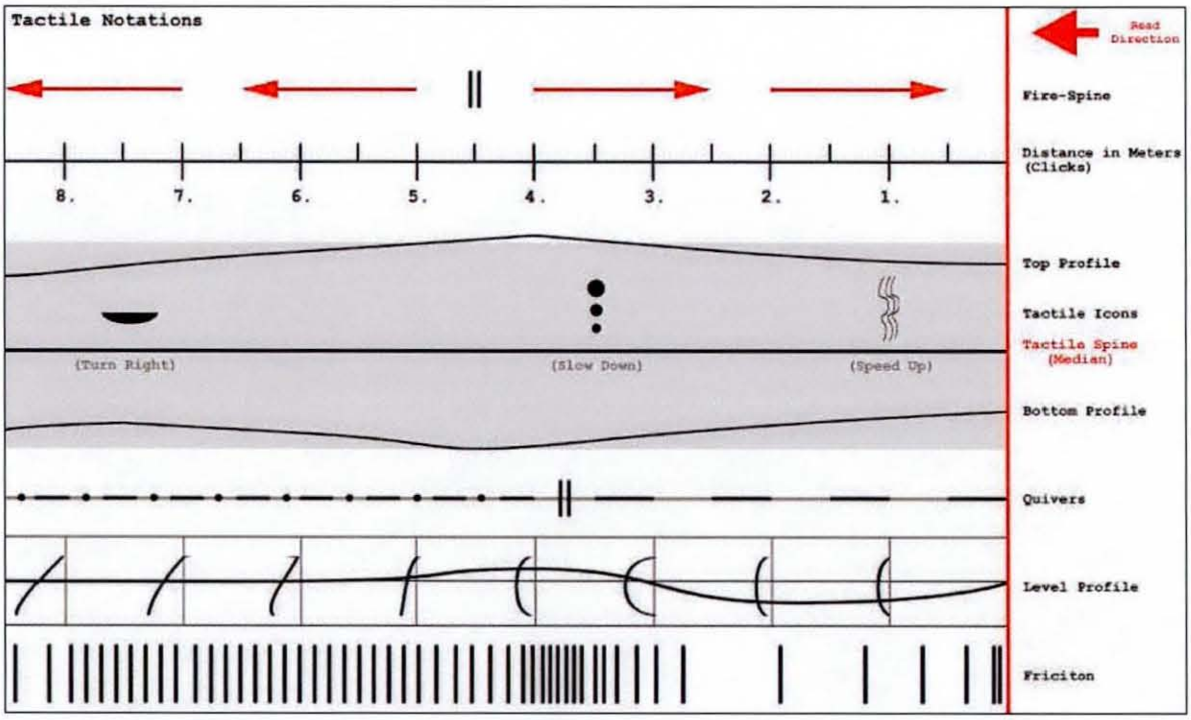


Figure 7.27 An example of Labanotation, the most established notation system for dance. (Source: www.ballet-dance.com . Accessed January 2007).





Figuers 7.28 Top image - a Tactile Notation sheet onto which a stretch of Snakeskin can be planned and documented.
Bottom image - shows how the Tactile Notation sheet can be used, here with various graphical notes relating to the various features of the Snakeskin - the friction direction of the Fire-spine, the metric measurements of the clicks, the profile of the Snakeskin, the various symbols of the Tactile Spine, the particular patterns of the Quivers, topographical sections of the Handscape, and its the degree of friction...

7.3 *Building the Snakeskin*

The Snakeskin design is a boundless design, as it lacks the need for a finiteness affiliated with most designs. It provides information and tactile stimulus about its environment, it remains indifferent regarding where, when and for how long it should do so. Thus it became, to some extent, quite tricky to define what to include, and how to contain, a physical rendition of the Snakeskin. Eventually its 'theme' and parameters were decided based on the number of tactile nodes that would be useful to include, as well as by an determination to build something sizeable, something unusually big even for these, RM related, means. The process proceeded from the bottom up and resulted in a physical Snakeskin prototype of 10.72 meters (Fig. 7.29). Parallel tests were conducted and modelled involving small, but full scale, tests built through various additive processes. A plasticine model was also used (Fig. 7.30), to test the guiding fundamentals of the design, such as the size and 'pronunciation' (roughness of smoothness) of the handscape's scale surface, or the appropriate width of the tactile spine, which needed to be central and wide enough to allow for the tactile icons to be easily noticed and 'read' (sensed), yet unobtrusive enough to not overwhelm the other features of the composition. The prototypes were subsequently developed further by building Stereolithography useable prototypes (Fig. 7.31), of over one meter long (110 centimetres each) strips named 'Sense Sticks' (7.32), which each summarized one particular icon-segment of the Snakeskin, i.e. a set of builds that allowed one to test how the tactile spine and the handscape performed in unison – the clarity of the tactile icons and the readability of the scale textures. The Sense Sticks provided a viable and realistic means to experience and test how a longer stretch of the design would be perceived. It was through this form of testing the appropriate height and width of the tactile spine, and the size of the scales of the handscape, were achieved.

7.3.1 *The Digital Phase*

Various linked CAD modelling methods were used to reach the rendition that was fabricated, with the initial version being built in Rhino (Fig. 7.33). This initial model was chopped during the CADing process due to its level of detail and file size (Fig. 7.34). The model existed as a set of thirty-seven consecutive matching pieces, which were saved as a set of separate STL files

The World's Longest RM Piece..?!

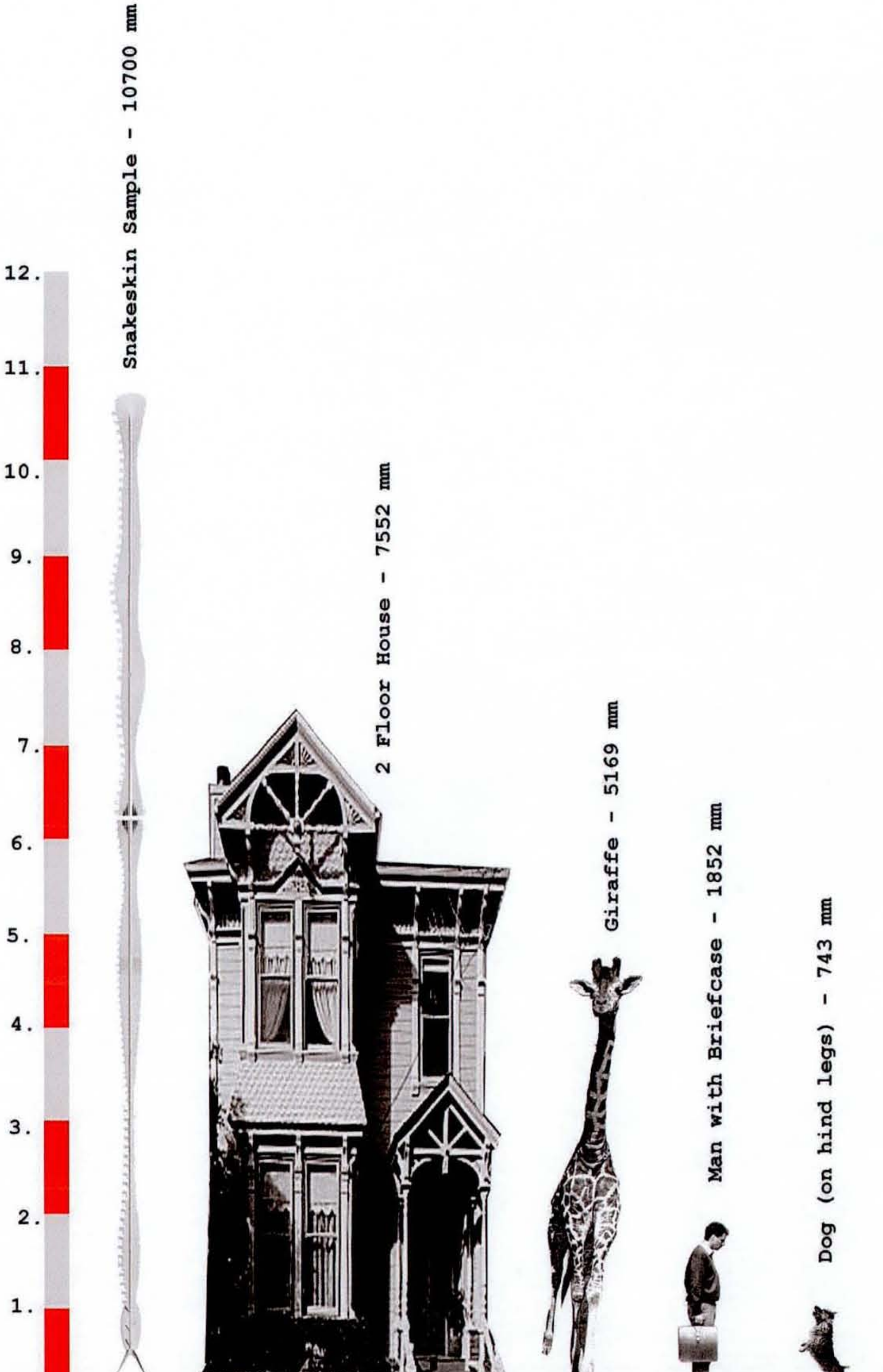
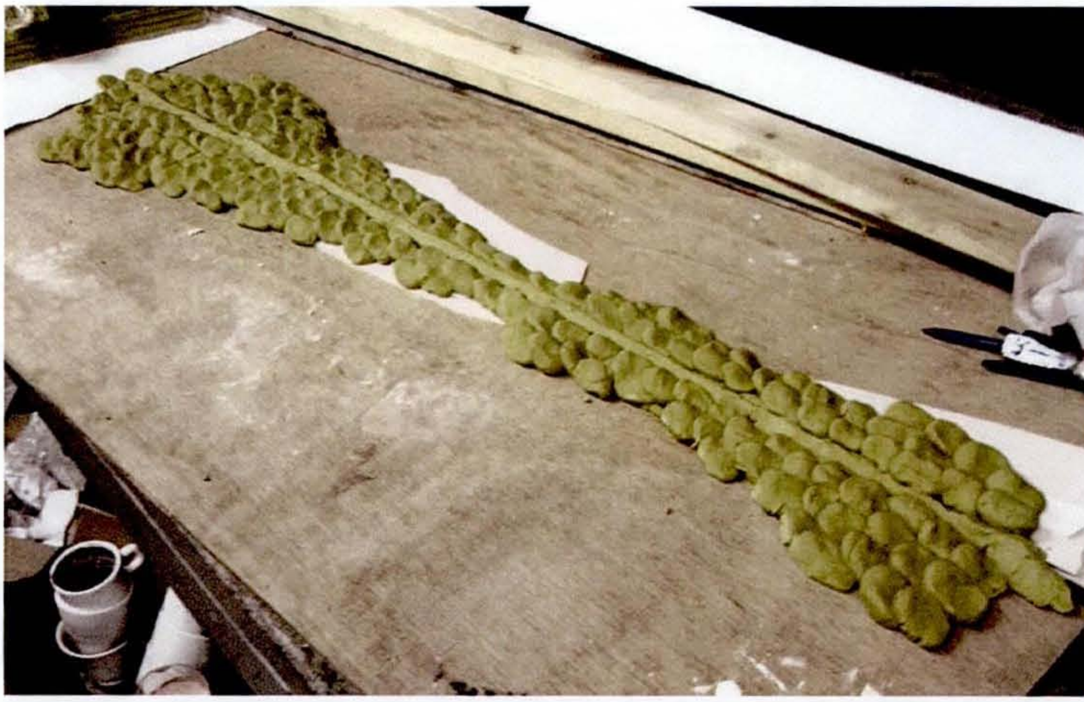


Figure 7.29 A comparative chart promoting the impressive size (length) of the LF (RM) fabricated Snakeskin relief strip...



Figures 7.30 Early plasticine model which allowed one to the opportunity to quickly test and 'feel' what rough proportions would be most suitable for the Snakeskin design...

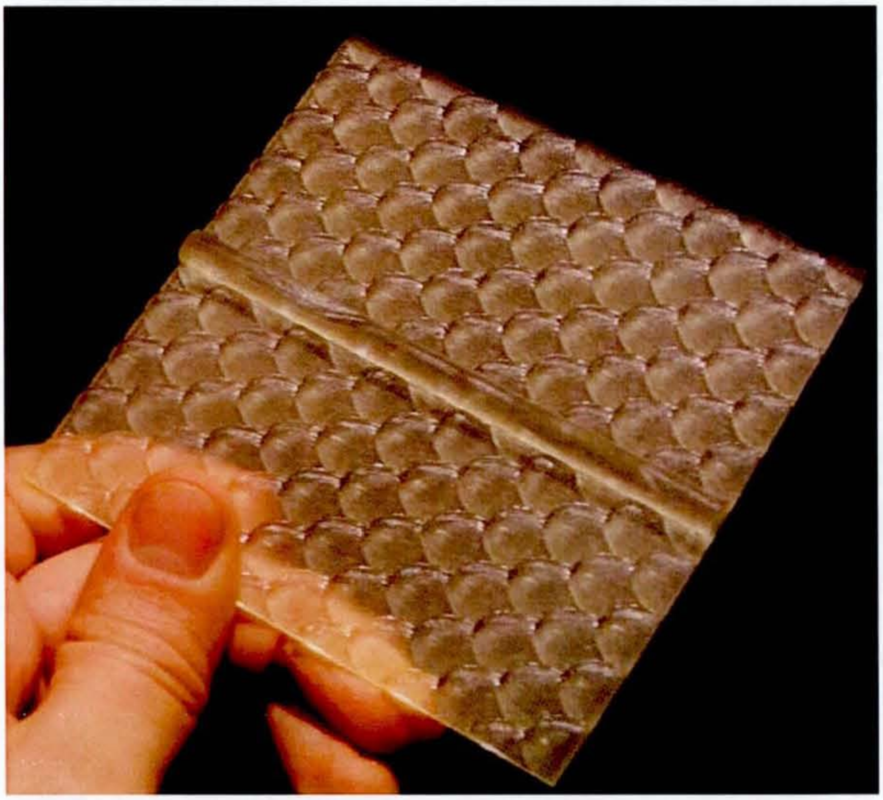


Figure 7.31 An early SLA rendition of the Snakeskin haptic interface.

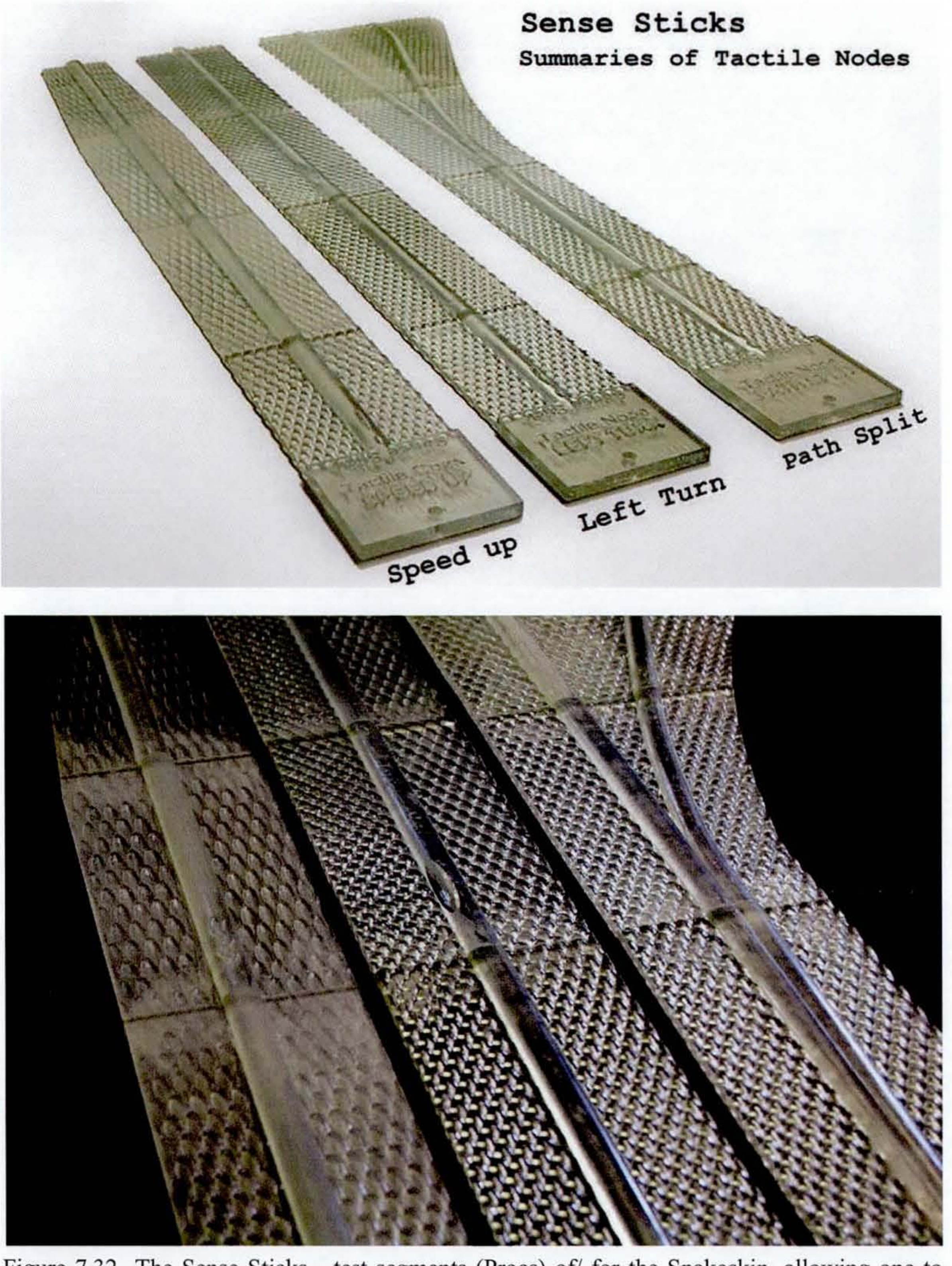


Figure 7.32 The Sense Sticks - test segments (Procs) of/ for the Snakeskin, allowing one to try out and assess how the various elements of the design work in unison. Each of the sticks is slightly over a meter long (roughly 110 cm) and were made through SLA.

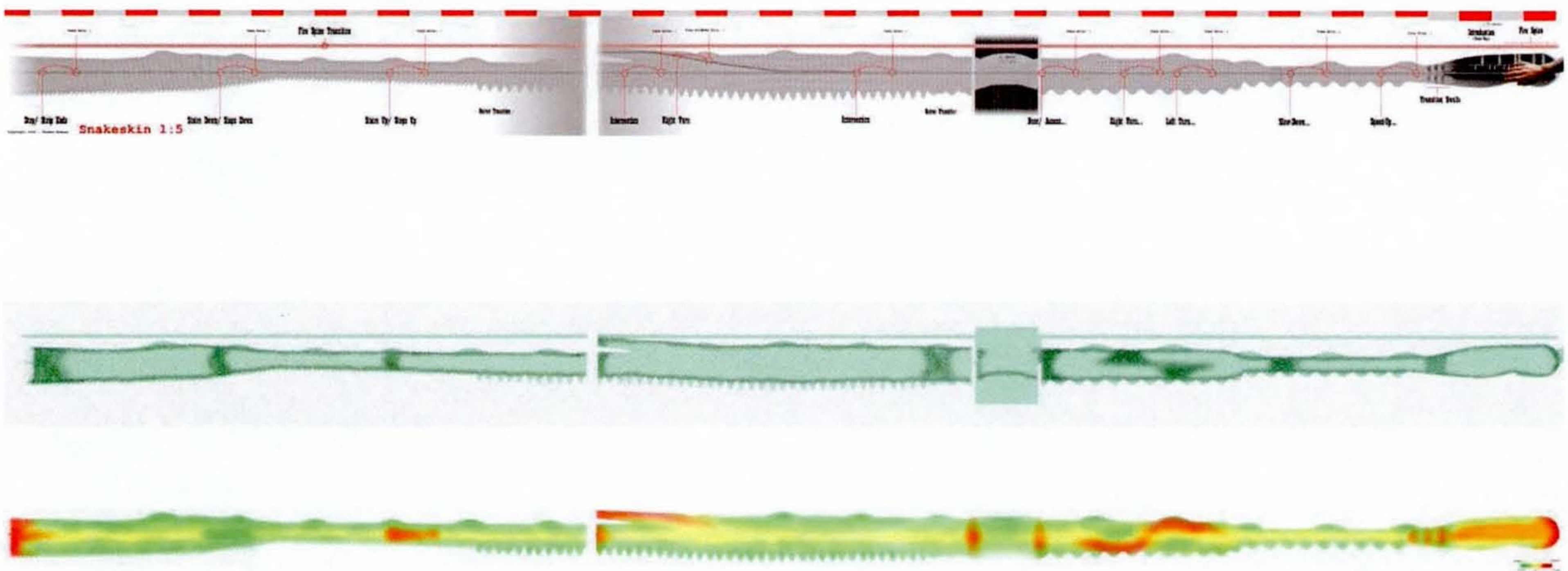
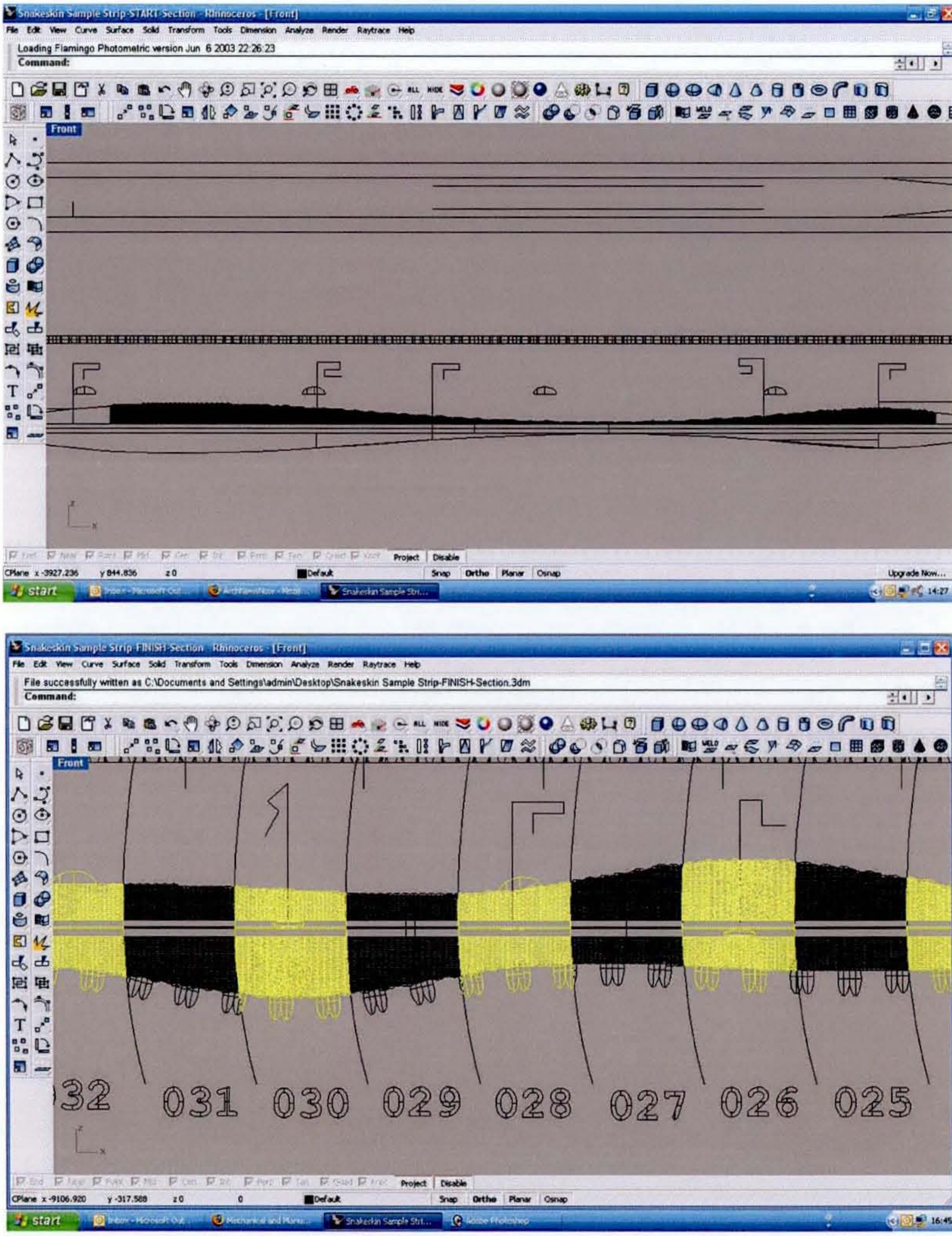
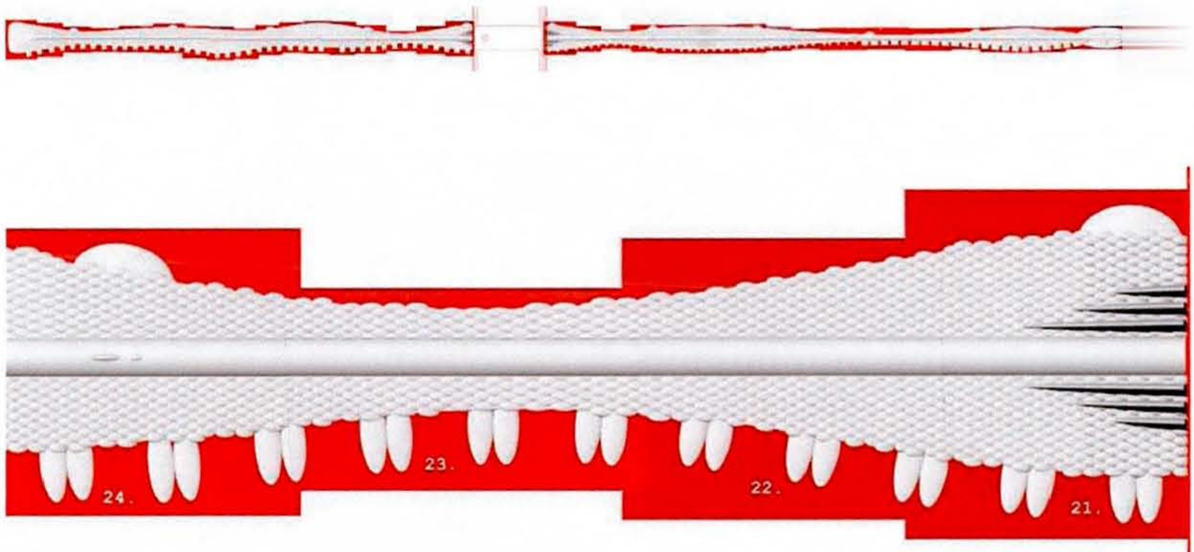


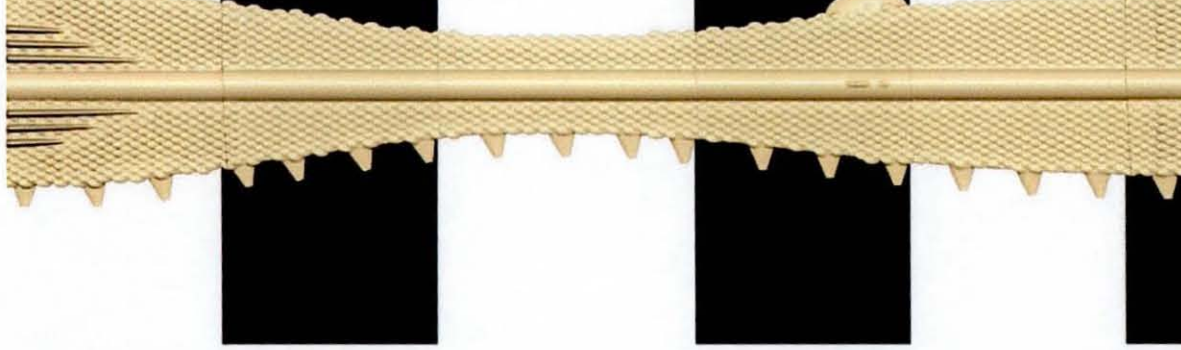
Figure 7.33 Top image: Initial illustrations of the Snakeskin sample strip showing the various icons and phases of the design. Middle image: A friction map of the above design. Bottom image: A level map of the design.



Figures 7.34 Snapshots of the screen, taken during the CAD (Rhino) design process.



Figures 7.35 Rendered versions, the whole strip and a close-up, of the initial Rhino model...



Figures 7.36 The final Claytools (Sensable) version (whole strip above, close-up below) of the Snakeskin Tactile Relief Strip, the 'zebra' striations are used to enhance the, slightly, in length, varying, segmenting of the design...

(Fig. 7.35). 'Cuts' were made between the segments which, by shaping and curving the cut-joint between two adjacent pieces one not only increased the bond surface between the pieces when they eventually would be (re) attached[7], but the groove between the bonded pieces also formed an additional regulated textural marking.

These files were imported into Claytools, the software that accommodates the SenAble haptic interface device, where they were modified according to a preset set of features that were systematically applied throughout the design (Fig. 7.36). Amendments included 'softening' the scale patterns around the handscape's edges and around the transition area between the handscape and the tactile spine (which allows one to 'feel' when one is approaching the edge of the Snakeskin, regardless of the direction, size or level of the handscape's scale-pattern), the removal of any sharp corners or features that might cause ones fingers to get caught, and the tactile testing and re-moulding of various other features that revealed themselves when surveyed through the medium of the SenAble device (Fig. 7.37).

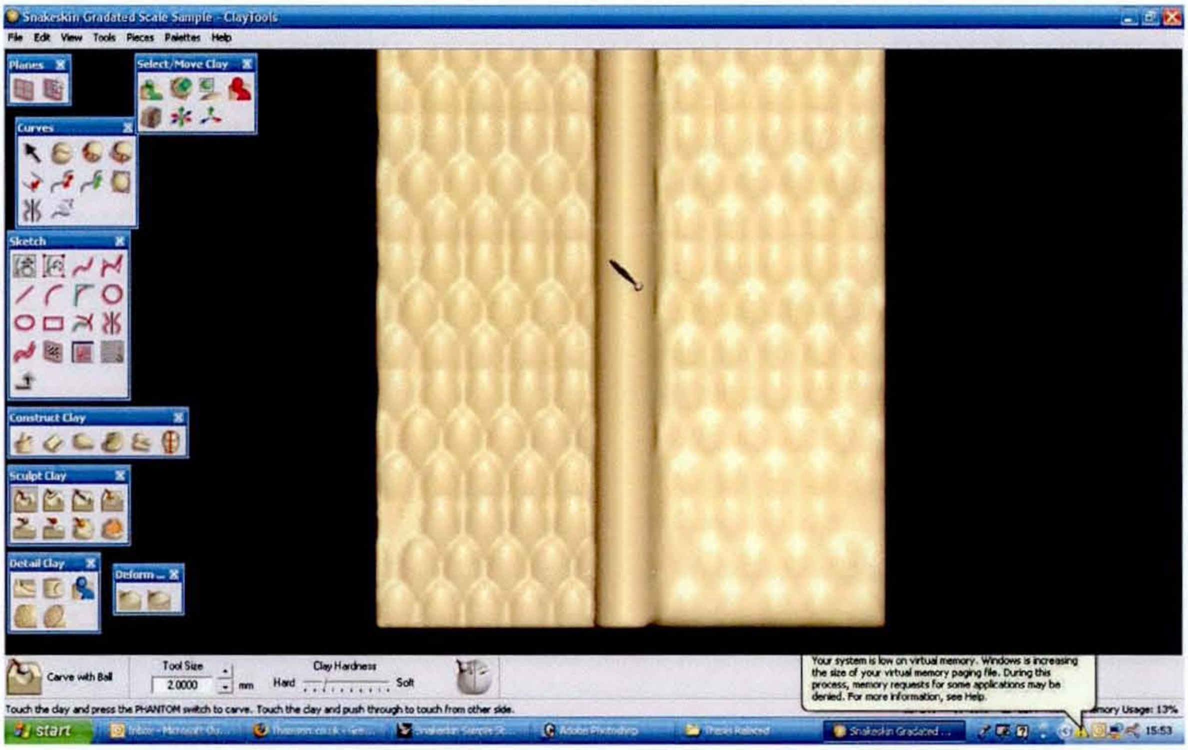
Once completed, the files were checked in Materialise Magics developed specifically for such undertakings. The pieces in seventy-two separate sections (Fig. 7.38) to provide more flexibility regarding arranging and optimizing the layout of the pieces within the fabricators build-chamber (Fig. 7.39), of the 3D printer.

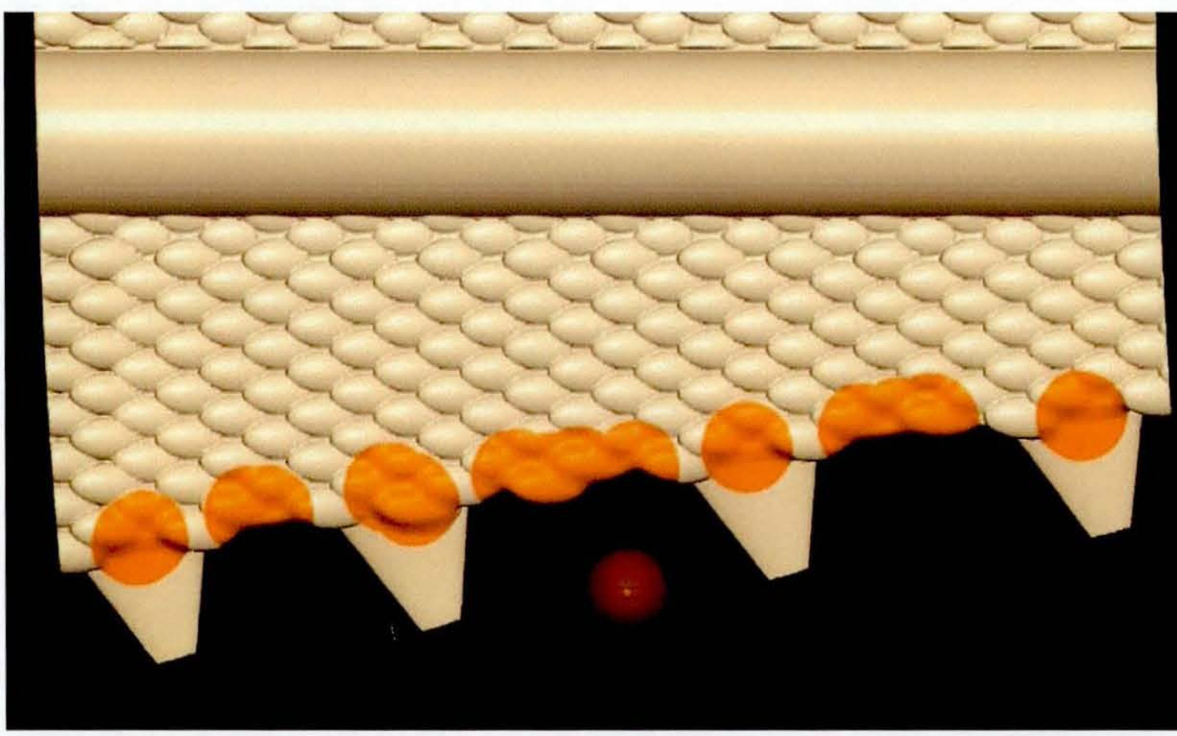
7.3.2 *The Build Phase*

The Z-Corp Spectrum Z510 3D Printer (Fig. 7.40), located at Loughborough University, was the means through which the design was built (Fig. 7.41).

The material used was a composite powder provided by Z-Corp, which is predominantly gypsum based. However, as the result of such 3D builds is a set of 'green' parts, which in themselves aren't as of yet, due to fragility, ready for use, a means, which was both economical as well as practical, needed to be found for infiltrating and hardening the design's numerous components. A number of options were discussed, including the printing company's own infiltration products, but which turned to be, due to the size of the build, comparatively too expensive and, within the set timeframe of the project, would have taken too long to acquire. Other options discussed included superglue (too expensive and difficult to get a hold and of and

7 Obviously this is the first time they would be physically attached as all previous links between the pieces have happened as avatars…





Figures 7.37 Screen-shots from the Claytools software, showing the 'softening' process applied to select areas of the Snakeskin design. The image above shows the 'before and after' image of the process; the image below shows how such selections can be 'painted' onto the surfaces.

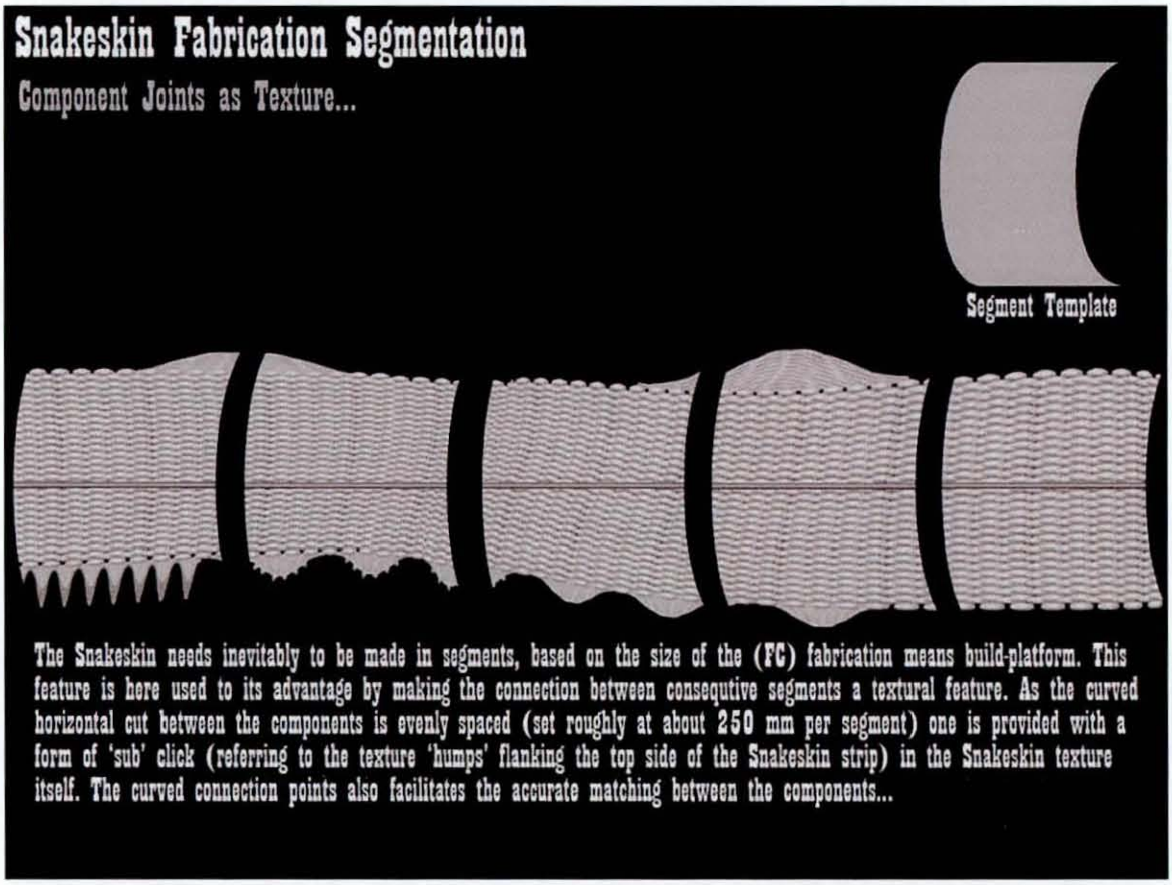
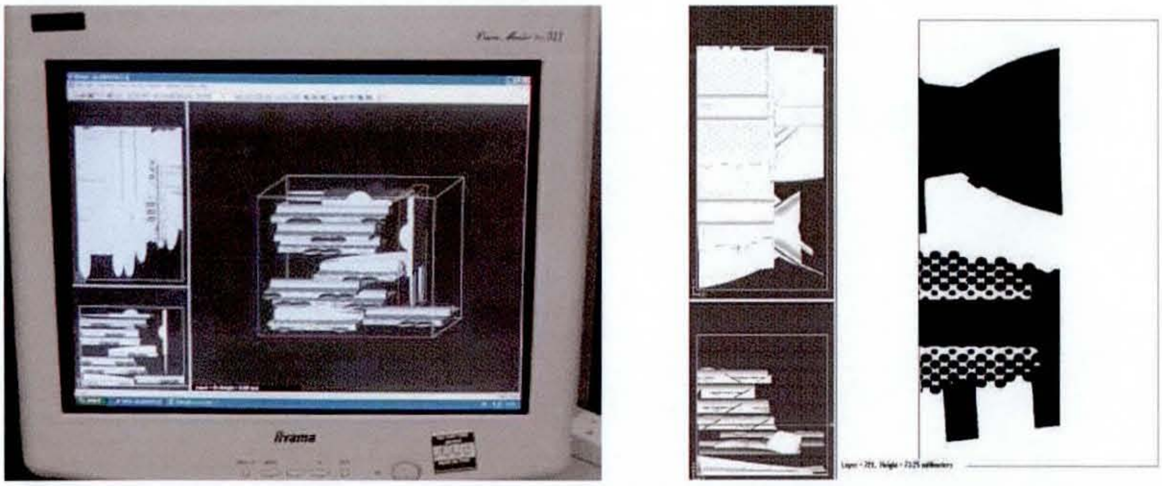
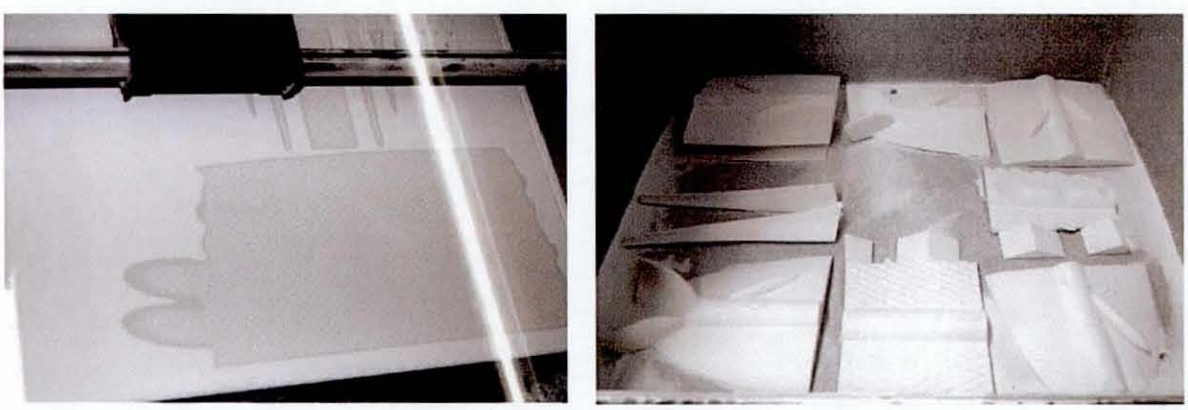


Figure 7.38 The illustration outlines how the inevitable segmenting of the design can be taken advantage of through using the transition gaps between the segments as a tactile node.



Figures 7.39 Two screen shots from the Snakeskin build. The image to the left showing a representation of the build-chamber and the stacking composition of the various pieces. The image on the right shows the application template for the binder at one particular slice (layer) of the build.



Figures 7.40 The image on the left shows a segment of the Snakeskin being built by the 3D printer. The image on the right shows some of the 'green' pieces in the process of being cleaned of any excess powder.

Figures 7.41 From top to bottom: The green parts, 'fresh' out of the 3D Printer; The individual pieces drying after being treated with wood-hardener; initial attempt to assemble and code the built pieces.

apply in the quantities needed), PVA (too viscous), various 'home-mixes' (too cumbersome), and even plain water (untested and result probably not strong enough). The product that was ultimately chosen was 'wood-hardener'[8], which is more commonly used to harden soft-wood window frames. This product, consists of epoxy in an acetone solution, was relatively cheap (approximately seven GB pounds per 500 millilitre container at retail prices), and, after tests, did provide a sufficient degree of strength to allow the design to be used and tested in a manner close enough to how it would be used upon implementation in an actual space and context. In total the build required between eight and nine litres of wood-hardener to solidify the whole design. It was applied onto the pieces manually, through brushing the hardener directly onto the segments. They were left to dry over a number of days in a well ventilated area. Once dry and completed, a set of industrial strength 'Velcro', hook and loop, attachments (which can hold up to five kilos per square centimetre) were attached to the backs of each piece. This was done so as to allow this sample rendition to be displayed at a number of locales rather than just one, as would be the case in any bespoke rendition of the design. Its first outing took place at the nous Gallery, an architectural gallery in London's Kings Cross area in April – May, 2008, where a larger community had a chance to try out and comment on the piece (Fig. 7.42, 7.43, 7.44).

7.4 Discussion

Regarding the adaptation of the icons or language of the Snakeskin it, even though intended to have a more intuitive or subconsciously suggestive side to it, was not self explanatory and did require one to initially learn the the shape or forms of the tactile icons as well as to recognize something through touch rather than through vision and/ or hearing[9]. This format requirement is analogous to the the difference between Apple's Newton message-pad and accompanying software Calligrapher, and Palm Inc.'s equivalent device, and its associated software Graffiti[10]. Wilst the former aimed to learn each users personal handwriting, with somewhat dire and unreliable consequences, mostly due to the extensive variability of even ones own shorthand.

8 A product suggested by architect Paul Brady.

9 This, in a similar fashion to Braille, requires some studious focus, as it actually takes a while (especially for someone used to rely on his or her eyes to preceive things of a similar scale) to even recognize the six dots (three stacked rows of two dots each) that make up the alphabet. It takews even longer if one is expected to recognize the variations between the signs solely through haptic/ cutaneous means...

10 Inspired by the 'Opinion' article titled *What We can Learn from Apple's Recipe*, by Saul Metzstein, in Building Design, issue 1827, July, 2008.

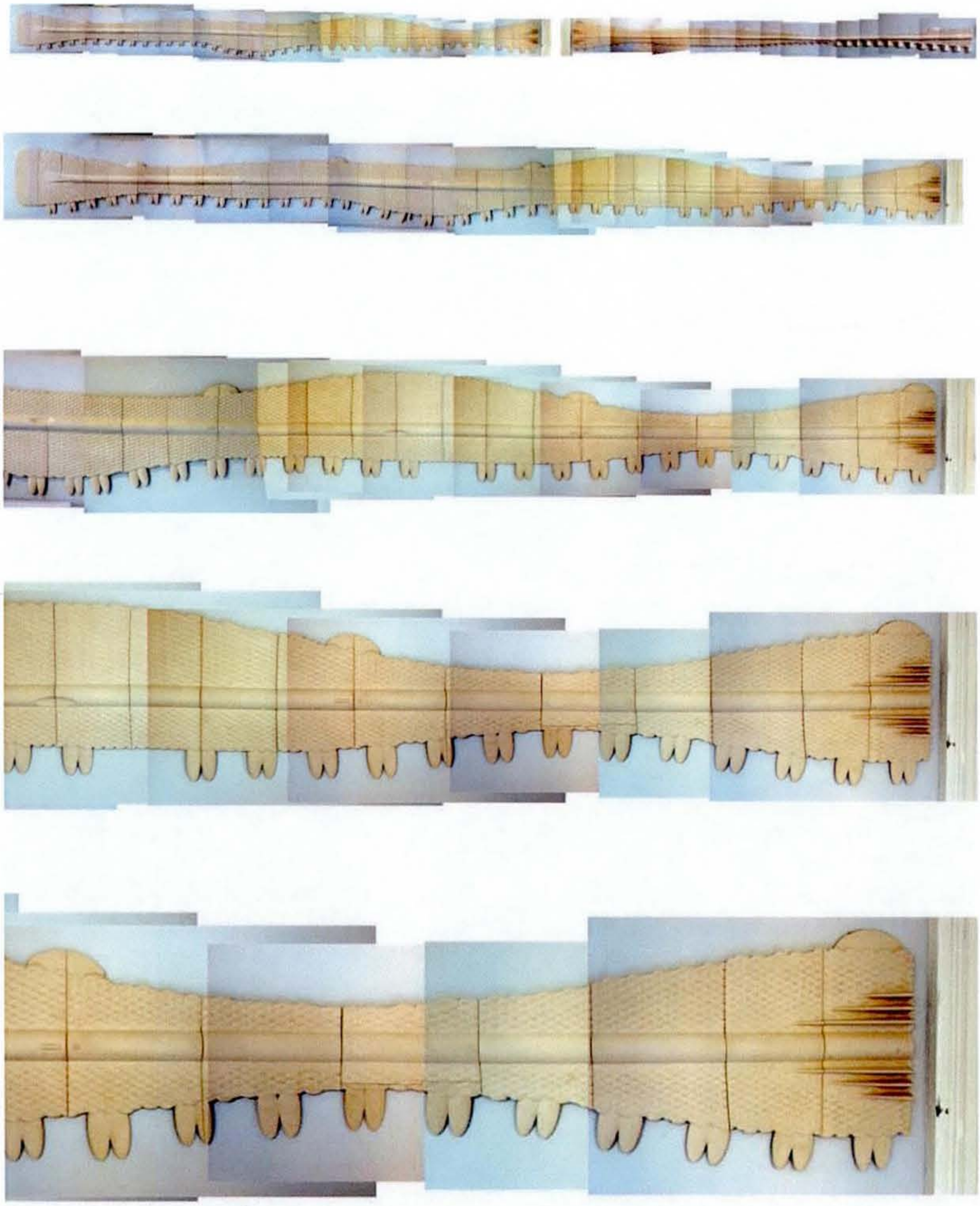
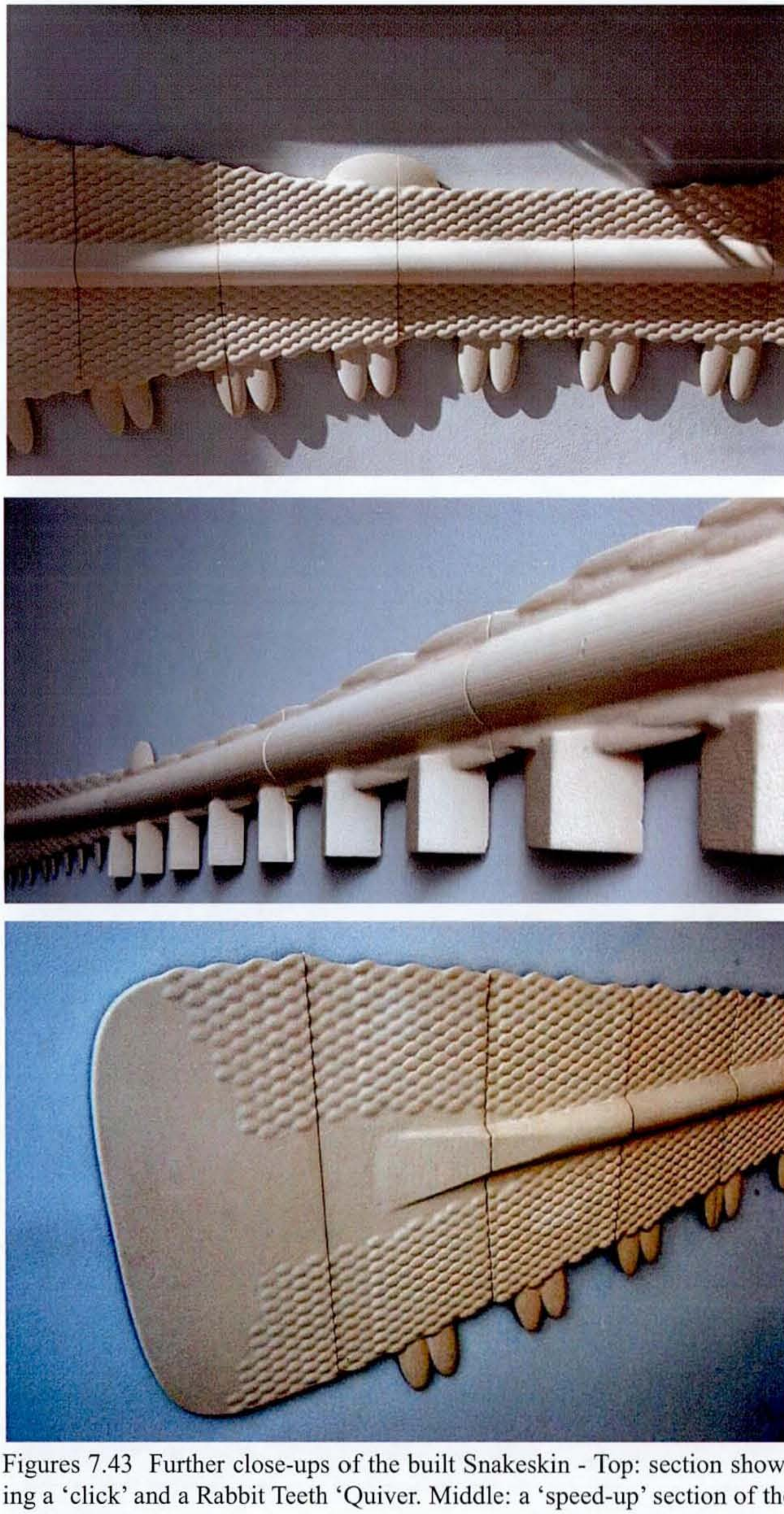
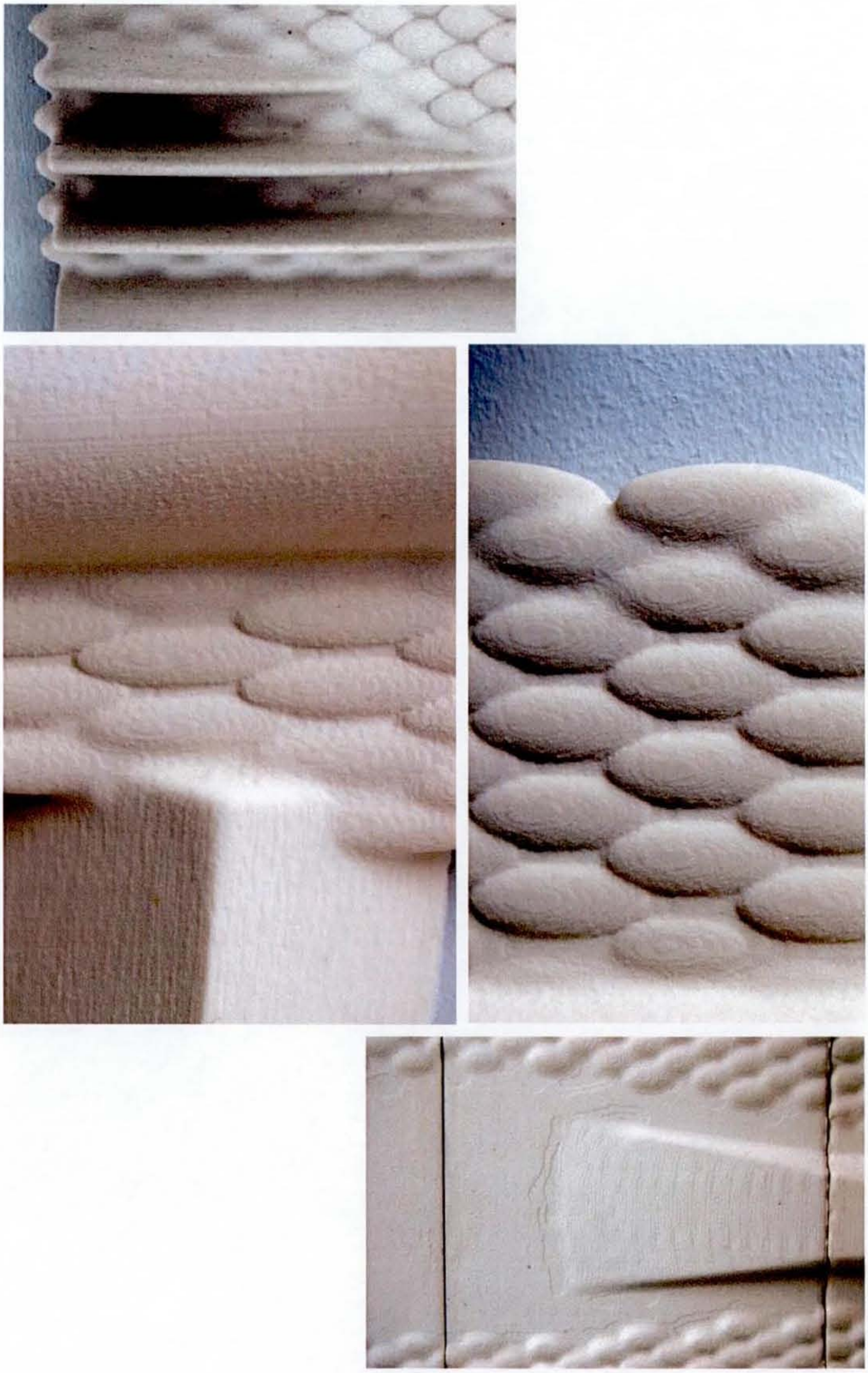


Figure 7.42 An assembled view and consecutive close-ups of (most of) the built, almost eleven meter long Snakeskin strip.



Figures 7.43 Further close-ups of the built Snakeskin - Top: section showing a 'click' and a Rabbit Teeth 'Quiver. Middle: a 'speed-up' section of the Snakeskin.

Bottom: the 'Door' icon, a grooved elevation that leads the fingers above (and across) the door-frame.



Figures 7.44 Textural close-ups of the Snakeskin 3DP build. Here both the 'stair-stepping' pattern of the fabrication process (3D Printing) as well as the edge 'softening', achieved in the Claytools software, can be observed...

The latter gadget required its user to learn a simplified script as defined by the device, which required its user to do the adapting. The Snakeskin is in its approach more like the Palm Inc, device, requiring one to master a small number of tactile signs (their number capped to only apply to more permanent features such as directional friction patterns, or features like stairwells, doorways, etc.) which, once adapted and absorbed on a more visceral level, will allow one to perceive the more subtle tactile variations of the design's grain and textural patterns.
It is also, however, important to state that the strength of the medium, and thus the design, isn't necessarily in the above, somewhat standardized, listings of the elements involved, but in the way they can be adapted and manipulated through both the CAD and the (additive) CAM methodologies. The levels of finesse and nuances that the surfaces can be provided with, and which can be customized according to any remit or context the design is used in, is where the design's forte is located. The eventual applications of the aforementioned elements could, and should, eventually be very different indeed from what the above might currently suggest as this ability is an inherent aspect in the LF process. The physical outcome, where the maxels can be sensed in the stair-stepping topographies and the fluency of the friction scales, analogous to a 'swarm' of nunods, all allow for a more fluent transition and expression of the united physical and computing based concepts and entities (Fig. 7.45).

7.5 Conclusion

The aim of the Snakeskin project was to establish a way of designing something that utilized and was instigated by digital (CAD) based means, through the use of Rapid Manufacturing, but did so without omitting the more innate sensory qualities of what usually makes one respond and appreciate a design (its physical presence, things such as its texture, apparent weight, or even the subtle 'sounds' it makes). By considering all the various tactile, auditory, in addition to the more obvious visual, aspects of the design already in the initial (digital) conception stage of the project, along with tying in with the process used for fabricating the design, an accomplished way for how one could achieve a more sensorially provoking end result is produced.
The design aimed to act as a non-intrusive, yet, for those actively seeking or are just generally more perceptually aware, source of informative stimuli that would provide an enriched strata of embedded information that reflected and interacted with its users and environment.

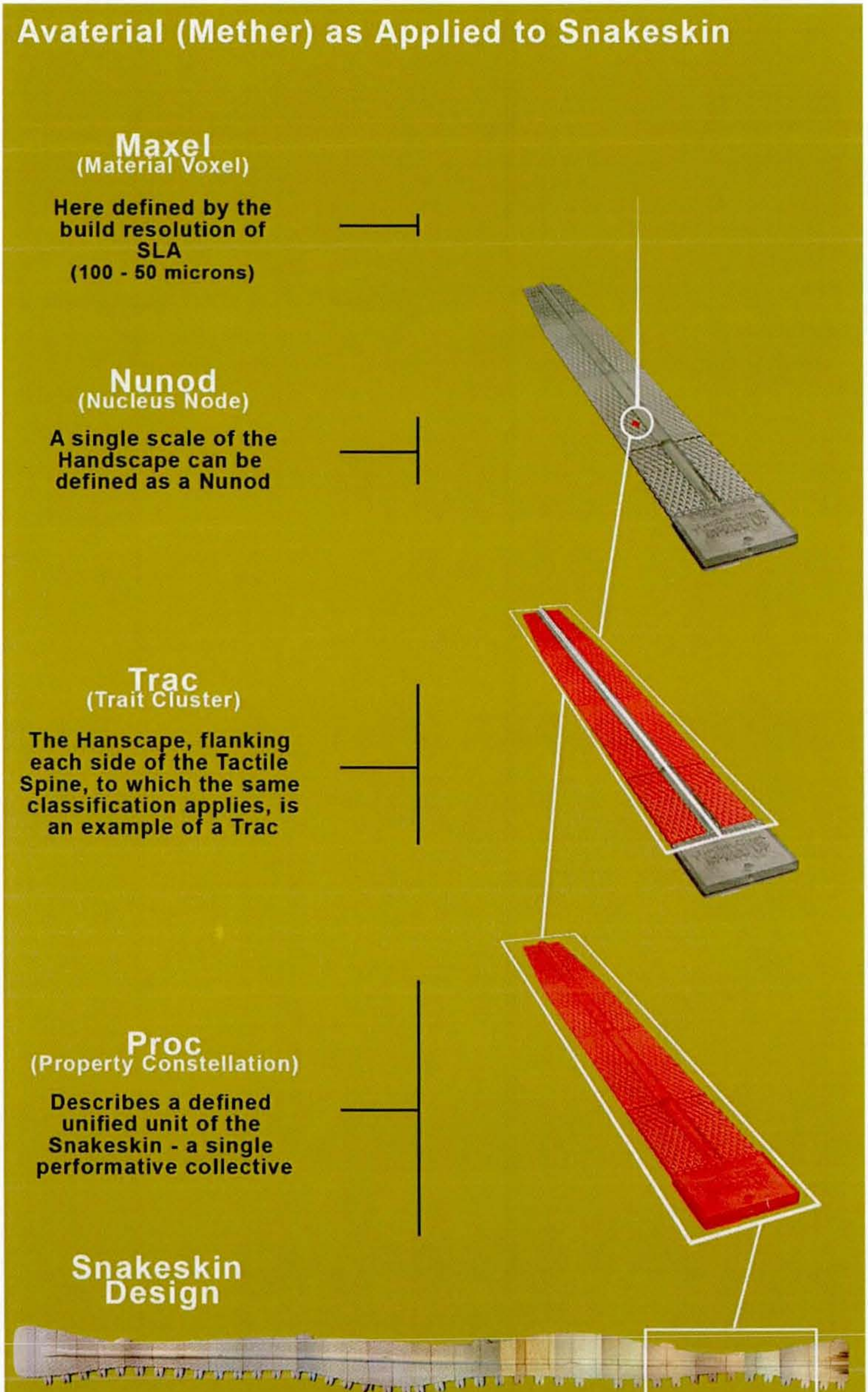


Figure 7.45 Avaterial taxonomy applied to the Snakeskin design.

The intent of this project is to suggest an approach to how architecture, here considered according to a more intrinsic tactile and sensorial paradigm, can be perceived and conceived. Its aim was not to exclude the other senses from the equation but to create a more comprehensive and attuned understanding of how, what we usually define as 'touch', could be included into the grammar and vocabulary according by which we read, define, design and build 'architecture' by[11]. By utilizing something as immediate as touch as a catalyst for the brief the hope was to form the foundations of a more personalized and distinctive approach for how to understand and define our built environment. An approach that transcends the purely pictorial (conceptual) and ocular drive that saturates what we today conceive of as architecture.

11 Chapter 9.2.4 introduces notions triggered by the Snakeskin design within a larger, more traditional, architectural remit.

8.0 Discussion

The thesis aims to deal with subjects beyond mere technology. It proceeds under the assumption that technology doesn't necessarily make life easier; it doesn't lessen the amount of choices or alternatives one has to take into account. It does provide alternatives to consider. It reformulates the questions at the beginning of a design, and it affects the way in which design structure is realized. In the LF-model, design moves away from an unquestionable faith in technology. With the LF-model the interpretation of technology is closer to the term *techne*, the act of rationally producing an object or objective and in which the process of making something is congenial with the end result (Hartoonian, 1997). Here making is thinking. Here material empathy is assimilated into a contemporary context, and into a form that recognizes cerebral and physical constraints, as well as norms of the past and today, which set the foundations for tomorrow.

These latter maxims also summarize the tone this thesis has been pursued in. Even though they hopefully manage to convey a true commitment and passion regarding its subject matter(s) – the accompanying technologies and associated ideas for how they can be utilized in the conception of things – it still contains an acknowledged and intentionally included morsel of doubt regarding their declared significance. This slight hesitation regarding their inevitable importance holds the key to furthering their development and creative evolution. This ambiguity of conviction will hopefully keep them from becoming set dogmas, and encourage their development as a continuous process rather than something with a set finiteness.

The core of the thesis lies in making things, and thinking about why they are the way they are. A simple, ascetic, statement. However, it is remarkable how often one comes across projects that have compromised on one of the two claims, i.e. designs that are conceived without any clear consideration or plan for how a design is to be made; or, vice versa, projects that are made without any apparent agenda for why they are fabricated the way they are, or why they need to be made in the first place. It is the symbiosis of the initial abovementioned aims this thesis is targeting. This doesn't necessarily mean that the project(s) have to be recognized as completed – on most projects the goal posts seem to grow and change as they progress – but that the processes used and intentions aimed for include such aim and process related aspirations from the beginning. This also inevitably entails that aspects such as material, procedural (CAD and CAM based), logistical (micro, meso, macro scale), social and cultural (generalized idiosyncrasies, perceptual), ergonomic (sensory and physiological), and emotional (personal, subjective and aesthetic) considerations need to be included in the equation that results in a 'design'. By appropriating the notion of *techne* these two core notions are combined, and a door is opened to new design capabilities which are inclusive of emotive expressions and intent - a move which brings us back to craft, a practice which encompasses simultaneously such cerebral and physical customs.

8.1 Outcomes

A synopsis of the thesis' outcomes are included below.

First Bullet - Foundation Polemic

Additive fabrication processes form the foundations of this thesis. First aim being to reassess CAD based methods used in the conception of a design – a process closer to a form of *transition* rather than the current, 'over the fence', *translational* process. This symbiotic response to fabrication means and methods of conception are closer in approach to methodologies outlined by the Italian philosopher Gianni Vattimo, whose ideas regarding weak or fragile thought, which the Finnish architect Juhani Pallasmaa appropriated into the context of architecture, than the more solitary and monocoque renditions put forth by proponents of modernism. Based on assumption - triggered by related literature, Layered Freeforming (LF) was defined as different from Rapid Manufacturing (RM) in that, unlike RM, LF does not compare itself against the manufacturing trade in general, but is selectively self-referential to the additive processes – taking its cues based on the discipline itself, rather than externalizing its pursuits. This should not be read as an exclusion, or preference, over other means of fabrication, but an acknowledgement that the additive fabrication methods have yet to reach a degree of conceptual maturity, a settling of its theoretical foundations, to allow it to be compared to traditional forms of manufacturing which have gained a certain gravitas, often by default, due to having been around longer. The thesis argues this is a position of strength, and will allow LF to develop further as a protean medium though which tasks and products can be conceived in responsive and flexible ways. As a consequence this also introduces a new model of production, the LF-model, through which designs, simultaneously of both a micro and a macro scale, can be achieved.

Second Bullet - A Particularised Method

The dissertation takes a material approach to digital design, something which, hand in hand with the development of the more theoretical components of the thesis, has allowed for a form of oscillating procedure to develop where a variety of designs and test-builds have fed the more theoretical supposition which, in turn, have again engendered additional material builds. This regular osmotic ebb and flow between the two realms has resulted in a gradual embedding of the foundations of an identifiable discipline and craft. An approach that was classified as pragmatism, which was formulated according to definitions by Sennett (2008), whose articulation of a more embodied and physical understanding of a process has provided the dissertation (here with a more relativistic frame of reference) with an inherently more hands-on and fluent medium through which its actions can be considered. At the same time as these were being cultivated, an accompaniment to the processes began to develop - a set discipline-specific taxonomies of interlinked words - neologies and process defining portmanteaus started to gradually materialize. These fairly idiosyncratic terms became, as the thesis progressed, a significant part in the daily parlance surrounding the projects and, even though a vast number of them fell by the wayside as the work pressed forward, a number of key terms did withstand. These survivors, which include terms such as *Avaterial*, *Mether*, and *Maxel*, to mention a few, have allowed for a LF specific jargon and accompanying model (the LF-model) to develop and can be considered evidence of a maturing discipline.

Third Bullet - Making them Real

A core standard for the builds that accompany the thesis has been to make them through the various additive fabrication affiliated methods and that - regardless of at which stage in the development the design, what size the build is, or through which fabrication method it is realized

- they are all fabricated at full, one to one, scale, and that the eventual completed pieces should retain the inherent qualities (textural, material) of the chosen fabrication processes and materials. Consequently any designs produced through these methods need to consider such textural and material qualities already during their conception stage, and allow the use of such features to not only benefit, but potentially even become defining attributes (USPs) in the eventual design. Thus the aim is not to make the projects simulate the 'look' or function of vacuum-forming or injection moulding, but to celebrate the inherent peculiarities of the additive fabrication methods themselves.

A set of case studies were developed to explore the LF-model. The SLA and FDM Bowl(s), and Alice Cups were projects that directly made use of the material and/ or procedural particulars of additive fabrication methods. From these first two studies the results suggested how design features exclusive to the fabrication means could be furthered. By combining the structural configurations of the former, with the parametric control factors of the latter, the Adaptive SLA Matrix resulted. The Ghost Tile explored how the opacity of an, initially clear, SLA build could be manipulated, and the PaperCuts investigated how aspects of a subtractive process could be taken advantage of when applied in an additive context. The Bead Pavillion design provided a template for how existing RM technologies could be utilized in the making of something of an architectural scale.

Accompanying the model explorations of physical builds, the 'Sliding Control Bar Principle', provided a suggestion for how an interface could be developed for parametric conception and fabrication as a variant of 'mass customization'.

The other notion, which expanded and took as its starting point the original more cutaneous interests presented, used a SensAble's Phantom haptic device to explore the link between the representation of something being made and the way it is actually physically and sensorially perceived and discerned. This tool, which allows for a more dimensional (at the same time both visual and tactile) approach to computing based design, lends itself more readily to the design of things which use the additive fabrication methods as it includes a tactile component as an inherent element in its interface. Here the medium of touch, even though still working through representational interface, was used to provide an empirical estimate of how the physical outcome will feel.

Fourth Bullet - Perceptual Designs

The Sensory Follies took the process based notions one step further by particularizing them into a perceptual context. These designs, are a reaction against the excessive ocularization of design in the context of ubiquitous computing and explore how digital processes can be utilized to make designs that are not predominantly based on vision or hearing, the two senses easies assimilated through computing based means. The the Architectural Tidbit, and the Fragrant Tower and Mobile, respectively provide a gustaory and olfactory renditions of what such designs can entail.

The thesis has three tactile design components, which explore various tactile impressions, sensations and formats of awareness regarding making and directly fabricating things through computational means. Their application was influenced by , and have been directly inspired by the taxonomies and haptic qualities that result from fabricating things through RM.
The Finger-Run, performs the role of a tactile folly, which, through its two adjacent panels, prompts one to explore its various patterns and textures, which have been designed to be felt, stroked, poked, rubbed, paddled and patted, surveyed and investigated with ones various cutaneous digits and appendages. The design, which was initially triggered by studies of various roundabouts and intersections found on Google Earth, and which was designed primarily with the SensAble device/ interface, has also provided an idiom of its own for creating designs through computing related means. Here these facilities have been utilized in a somewhat atypical fashion to the tool's original intentions in that its tactile abilities are actually used to explore the design's eventual touch-based impressions, rather than as a device for realizing various (as the promotional material accompanying the device explains) dental or surgical reconstructions or gaming figurines in a quicker and more conveniently way than through any more traditional, and manual, sculpting methods, but which, although made easier through the inclusion of a tactile dimension into the modeling process, are nevertheless not solely based or dependent upon it. In other words, the shaping and appropriateness of the resulting, say, dental or cranial prosthetics can be facilitated by the use of the device, but the processes and the resulting products inherent tactility isn't at the same degree of importance as their anatomical accuracy and physiological appropriateness, something which, compared how the device has been used

in the making of the Finger-Run panels, in which the tactile explorations are the main feature of the ensuing design, have introduced a novel set of semantic criteria to the making of things through this device. Here the tool's tactile abilities, the apparatus' 'there-there', instead of its time-saving or more visual faculties, are what matter. As a result how the device is utilized here as a medium allows for a distinctive paradigm in which a proposed surface treatment was conceived as 'pure texture', as what was felt and manipulated was pure representation and not an actual material.This 'avaterial' can be tweaked and adjusted, in regards to consistency (buoyancy), scale, size and degree of friction. Here the designer has the choice to decide how it should feel, instead on merely appropriating and manipulating an existing material to accommodate such qualities. Due to the ability to abstract the haptic, tangible sweeps and hand-sized gestures can result in as small and subtle a marking as to fit between the ridges of ones finger-prints, or can be as omnipotent, gigantic and fierce as to create furrows the size of Grand-Canyon. In this instance the tactile imagination is only guided (within the parameters determined by the tool) by the dexterity, spontaneity and skill of the users hand.

The Snakeskin expanded the Finger-Runs brief to include a wider remit of tactile sensibilities through the addition of more ambulatory and somatic perceptual experiences. This design, which not only informs its user about approaching features in his or her vernacular, but also aims to, as a continuation of the themes introduced by the Finger-Run design, expand on the tactile vocabulary as a more general and intuitive semiotic language. The design creates a form of 'touch-place' (an appropriation of Kenneth Frampton's notion of 'place-form' (Frampton, 1981), a tactile reading of space) which allows for a locale to be deciphered through a more haptic glossary of tangible sensations, some more apparent than others, that, in conjunction with the body's momentum and own inherent paces and patterns[1], encourages one to from a more comprehensive sensorium through which to perceive.

The design used a variety of methods, some more notable than others, to explore various haptic impressions and qualities. These explorations ranged from a plasticine model, which provided one with a more immediate proportional and sequential understanding of the design's various components, to a number of more developed versions, all made through a variety of RM methods, which allowed one to experience and test the design at a more developed level. All of

1 The way we breathe in and out, our heartbeat, the saccades of our eyes, the pace which we chew at, swallow at, scratch at, walk at...

these different methods played a crucial role in defining the eventual final design, which was presented as an almost eleven meter sample strip of the Snakeskin. This build, which weighted in total almost thirty kilos, can be classified amongst the most substantial single builds (when assembled) made through the additive fabrication methods.

8.2 Conclusion

Just as it is generally accepted today that our past is not made up of a single history, but a seemingly infinite number of more individual strands of histories (Vattimo, 1988), this thesis is not aiming to provide a comprehensible summary of what they are, or how the additive technologies should be used, but aims instead to provide a thread, a soft or fragile polemic, of thoughts and actions which form a reflection of the discipline.

The eventual aim is, whilst also developing more man-size artefacts, to do larger scale things through these means. To one day 'print' houses, and house sized things; buildings and building sized things; and ultimately even bigger entities. However, such goals need to be achieved one - if not cautious, at least considered - step at a time. Size does matter, but this reference should not exclude the minute, and needs to be simultaneously inclusive of entities and considerations of all sizes and scales. These concurrent size related factors, where the kindred technologies are being developed to accommodate both the nano as well as macro scales, are already well under way. Such somewhat 'non standard praxis'[2], where the simultaneously sizeless and all-sized are allowed to occupy the same semantic realm, is where the potential of Layered Freeforming nests. It is also probably from here form where the foundations of this developing craft will eventually emerge.

This thesis provided a few suggestions and glimpses of what to expect in terms of the additive fabrication technologies and their application in design and architecture, the latter (macro scale) discipline which inevitably here includes the former (micro and meso scale) practices within its confines, and, hopefully, inspiring further interest and exploration into this fascinating and groundbreaking discipline.

2 A term appropriated from the heading of a conference help at MIT in September 2004. See http://architecture.mit.edu/project/nsp/ (accessed June, 2008).

9.0 Conclusion and Recommendations

This chapter summarises the research work undertaken to develop and use RM as a defining component in design, and to develop a more sensorially inclusive conceptual process and framework for conceiving such designs. It presents the conclusion and contribution to knowledge. It also highlights the recommendations for further research.

9.1 Conclusion and Contribution to Original Knowledge

The research argues that the RM technologies, by being inherently linked to both the digital (CAD) and the physical (CAM) aspects of fabrication, provide a natural means to resolve the rupture currently dividing the way we conceive computing based designs from the way we construct them, a factor that has come about due to the present pervasiveness of computing and the inevitable ocular bias such means lead to in the conception of design and architecture. It contends that by applying a more inclusive sensory paradigm when conceiving designs through RM a more complete and congenial take on design, regardless of scale, can be achieved.
The thesis used the technologies affiliated with Rapid Manufacturing as defining components in the conception of its designs. Such aims were explored through the execution of a number of case-study designs which were conceived by utilizing particular qualities of the technologies which are unique to RM, and would be difficult or senseless to be made by alternate fabrication methods. This process, which acts as an inherent reflection of the fabrication means, became known as Layered Freeforming. It is within this framework the case-studies were formulated, fabricated and appraised.

The rationale and motivation for this research emerged from lack of engagement of the AF related disciplines with the inherent method based advantages this form of fabrication, a means which provided a natural bond between the digital processes and the material methods of realization. Nor is there a clear theoretical template according to which such endeavours could be advanced. The aim of the research was thus to use the additive fabrication methods as defining components in the conception of its designs, and to conceive such designs by applying a design approach which considers both the computing based as well as fabrication and material centred factors in their realization. These objectives were formulated through a more inclusive sensory and perceptual perspective. These aims were achieved through the accomplishment of the following objectives.

1) Build a clear understanding of comparable design based projects and research.
2) Review and define the scope of existing literature relating to the thesis aims.
3) Develop a methodology which is reflective of the particular processes and fabrication methods involved.
4) Develop a design taxonomy related to the methodology.
5) Develop a set of case-studies that reflect the unique qualities of the additive fabrication processes.
6) Develop design based case-studies which are founded on a particular sensory paradigm.
7) Chose a particular paradigm to develop further.

The methodology was formulated according to a qualitative method which used the exploratory and basic approaches in its fulfilment. The methods used for data collection were observation, literature review, unstructured interviews and case-studies. The methodology adapted a more bespoke take of the qualitative research approach by employing the notion of 'pragmatism' as a key element in its development. This approach, which considers LF a more craft-led approach to RM, allowed for a more hands-on and intuitive research approach to develop. As a parallel and ancillary act to this, the notion of a syncretic approach was advanced. This position, which blends together two or more different systems into an unified symbiotic unit, was also encouraged in the inception of the case-studies. The adopted methodology accomplished the research objectives and hence research aims. This research's contribution to original knowledge could be summarized as follows:

9.1.1 Layered Freeforming Concept

Rapid Manufacturing as a viable means of bespoke fabrication is gradually gaining recognition. However, the way the discipline is still viewed is as competition to more traditional methods of production (Park, 2008), rather than a complementary practice. The use of RM in the production of design and architecture is currently at most nominal, occupying the fringes of practice and academia. This is partly due to a lack of a framework according to which such pursuits could be structured. The thesis provides a way for using Layered Freeforming (an original definition of RM which was based and catalysed directly by RM technologies) in both the conceptualization and the actualization of designs and architecture. It conceived designs through exploiting the processes capabilities and to make designs that directly benefit (be it in something as subtle as in its texture or material consistency, or something as fundamental as its form), from making it through AF, and which would be difficult or pointless to realize by any other fabrication methods. The research provided a theoretical framework reflective and bespoke to the RM means of conception. It outlined a way for how RM could transcend into LF. Such intents were derived from precedents originating from a variety of disciplines, outlined in the literary review, which were unified through a form of syncretic merger. These approaches formulated along the lines of Vattimo's (1988) and Pallasmaa's (1996) 'fragile' thought and architecture; Porphyrio's (1982) ideas of structuring of ideas based on homotopic and heterotopic forms of though, and Leach et al. (2004) who made a distinction between classical and gothic means of conception, were all applied and contextualized to reflect the RM means of conception. By considering the practice of RM through the framework of LF, a more innate channel for formulating physical design through digital means was provided.

9.1.2 LF-Model and Related Terminology

The Layered Freeforming Model provides a 'open-source' (adaptable) taxonomy in tune with the AF affiliated methods of conception. The LF-Mode provided a foundation for how AF processes can be described. It refers to associative positioning and scaling where groupings are sequential but not necessarily linear, entailing that one link or node can have several (different) connections or continuations. The links of the various scales is proportional rather than metric. Adjacent categories are defined according to 'lesser than' and 'more than', or 'adjacent to' or 'controlled by', rather than as specific quantities, positions or sizes. The proportional distribution can also be asymmetrical, with certain volumes or proportions (aspects) of the design having a larger quantity of certain sub-categories than others Such conceptual groupings or arrangements are relevant because they provide means through which a number of adjacent and overlapping features, programs, elements can be described and defined. They provide a suggestive and generalized system for defining something that doesn't necessarily lend itself naturally to systemization. Their intent is to provide suggestive mind-maps without necessarily stifling subjective interpretation and usage of the terms. They provided a grain or resolution for a project conceived through these means that affords it with a set of interlinked reference points, a set of logistical buoys that act as anchors for any conversations (be these internalized, non-vocal, or externalized, amongst others) about related matters. Here the 'meaning' of a classification was not built around a core spine (a centralized approach), but is instead attached to the unit, the fragment or cell (the Mether related terms) which, in conjunction with other units, makes up the body of a notion (a clustered approach) - be this applied in the design of an idea of an artifact. The LF-model and accompanying terminology were generated along side the development of the case-studies and provide a integrated method for conceiving designs through AF related methods.

9.1.3 Applying the LF-Model in Design

The hypothetical proposition put forth were tested and amended according to the results of the case-studies. Six of the eleven case studies were designs that were generated by features and processes exclusive to RM. These case-studies were:

SLA & FDM Bowl(s)

The project explored how the default support structures of the two additive fabrication processes could be utilized as defining constituent in a design. It was also an example of 'what is designed (in CAD) is not what will be built (in CAM)', an factor unique to certain AF methods, which needed to be included as a founding consideration during the conception of the designs.

Adaptable SLA Material Matrix

The aim was to provide create a minute structural matrix with a performative purpose. It took the material properties of a SLA resin/ material as a starting point, and manipulated them into a variety of minute pre-determined patterns which allowed one to extend the 'intrinsic' properties of the material with a variety of additional ones based on how the micro-tessellations were arranged and distributed. Two samples were built as proof of concept which may be extended to produce more complex forms, in which the internal space frame varies its geometry across the object . Conceived in this manner the fine scale structure would be optimized at every point for the inherent forces at that specific point, creating an organically evolved and responsive fabrication.

Ghost Tile

The case-study explored how, by using select SLA photopolymers, markings can be 'burnished' into the fabricated resin units. The design provided a suggestion for how this particular application of the SLA process could be utilized to fulfill various opacity related design features.

Alice Cups

The case-study's applied the capacities, the manual parametric abilities, of CAD in the context of CAM, and explored how by simple acts of stretching, pulling, flattening and selectively combining a 'core' cup, a variety of alternate functions could be achieved. The resulting designs fulfilled and functioned according to initial intentions.

Bead Pavilion

The case-study attempted to design an architectural structure by using currently available RM technologies. A number of full scale beads were made through the SLS process, which allowed the viability of both the joints and the strength of the beads to be manually experienced and assessed. This particular application allowed, whilst still within their established remit, the technologies expand and be imagined beyond their usual scope, and provided a suggestion for how AF could be used in the implementation of larger scale builds.

PaperCuts

The case-study applied the subtractive fabrication processes to make an additive assembly, a technique where, usually to create a topographical representation, a number of cut-out profiles are combined and stacked to provide an analogue rendition of a mass or volume. However, here each 'layer' could also be altered and customized, allowing for the a different take of what 'layered' fabrication entails. The designs provided a suggestion for how the seemingly opposing CAD-CAM fabrication methods can be combined and how the advantages of each method could be united.

Collectively these case-studies provided a suggestive framework of techniques and features, unique to AF, which can be adapted and applied to fulfill a variety of different function and aesthetic based requirements.

9.1.4 A Sense Based Application of LF

The designs included here all aimed to realize designs that are directly reflective of the Rapid Manufacturing related fabrication methods, but do so by producing designs that are based on the three senses least affiliated with computing, i.e. taste, smell and touch. The designs are titled The Sensory Follies, and include the Gustatory Folly (taste/ digestion), Olfactory Folly (smell) and the Tactile Folly (touch). Each presented a distinct take of a perceptual sense by also applying particular AF features unique to Rapid Manufacturing.

Gustatory Folly

This case-study provided a novel application of AF. It endeavored to explore the gustatory qualities through the use of a specific additive fabrication process which allows for an edible piece to be built. It also examined the literal process of digestion of the design - how different flavours can be released, intermingled and sequenced.

Olfactory Follies

Two designs were made, which were as subtle and discrete, yet as expressive and catalytic, as a fragrance. Design that could be experienced without being seen, sensed before comprehended. Both designs were built through SLA, and used the support scaffolding for storing various fragrant oils, which were gradually released into the vernacular. The case-studies functioned as expected, distributing their subtle affect into their environments and did have a notable affect on the ambience of each space.

Finger Run

The case-study, a tactile folly, sought to, through the use of a 'pantom' haptic interface, make something to be experienced and explored through the sense of touch. It aim was to explore how the haptic device could be used to design things (through computing based means) which were designed through the sense of touch, to be perceived by the sense of touch. The design's two panels, which were fabricated through SLA, did provide a viable rendition and reflection of the design's original intentions. The scale and roughness of the textures were fabricated as anticipated, and the 'flow' of the hand and fingers across the panels was natural and lent itself to the aimed arch-like, elbow centered, motion. On more extended tactile exploration, done without the benefit of vision, the design's layers of different forms of textures and patterns became palpable, and did provide an emphatic refection of their conception and fabrication process.

Design Ground

The case-study was for a textured floor pattern used to provide understated cues to its ambulatory users. The design introduced a novel approach and vocabulary for how a more tactile method could be included into the general realm of design considerations. The design did provide a viable solution to a complex brief and was considered a success.

The Sensory Follies advanced and expanded the remit initiated by the initial set of case-studies by developing the brief to include alternate external considerations. By contextualizing their brief according to a particular set of conditions derived by selectively limiting sensory perception, the case-studies provided an alternate and original take on what computing based design entailed and thus did achieve their objectives.

9.1.5 Manuductory Tactile Mapping

Snakeskin, a manuductory interface – performs as an example of a design that has been directly catalyzed by, and inherently dependent upon, the technologies affiliated with Layered Free-forming. It became a culmination of all the aforementioned designs, and did utilize many of the

processes and material affects revealed during the preparations of the case-studies.
The Snakeskin is a wall based tactile relief mapping that informs its user about key approaching and surrounding vernacular elements and features. It is 'read' through cutaneous contact, which is communicated through a Braille-like vocabulary but which, instead of using a six-dot system like Braille, utilizes a set of 'tactile-icons' (sensed through the hand and arm whilst moving along the strip) to relay its message. A number of physical renditions were made through various RM methods of the design, which eventually resulted in the final version, an almost eleven meter long sample strip of the Snakeskin, made through 3D Printing, which consisted of seventy-two different pieces which were assembled into the final strip. The design, which weighted almost thirty kilos, is amongst the largest builds made through RM.

9.1.6 Publications and Exhibitions

Three papers have been completed, presented and the writings were included in the conference proceedings.

1. Modeen, Thomas; Pasquire, Christine; Soar, Rupert - *Ubiquitous Customization - Utilizing Rapid Manufacturing in the Production of Design and Architecture*. ARCOM 05, London, 2005.
2. Modeen, Thomas; Pasquire, Christine; Soar, Rupert - *Design Ground - An Iconic Tactile Surface*. ACADIA 05, Savannah, GA, 2005.
3. Modeen, Thomas; Pasquire, Christine; Soar, Rupert – *Exploring the Tactile Traits of Additive CAD-CAM Production – The Role of Touch in Contemporary Architectural Form Finding*. Sources of Architectural Form, Kuwait City, 2007.

Select pieces of the included work has also been exhibited at various venues. These include the 'Syn_athroisis' exhibition in Thessaloniki, Greece, in January 2008; Asia House, London, in March 2008; and the nous Gallery, London, in April - May, 2008 (Fig. 9.5).
Further exhibitions have been confirmed for the Fall of 2008 at the Dar Al-Funoon Gallery in Kuwait; and the La Fontaine Gallery in Manama, Bahrain.

9.2 *Research Recommendations*

The recommendations are the facts identified, ideas explored or new concepts developed based on academic endeavour that need to be advised, praised or commended by others (Othman, 2004). They can also be certain aspects of the subject being studied which are recognized as potential candidates for further work.

9.2.1 Adopting the Sliding Control Bar Approach in a Web-Based Application

The research proposed an application of a parametric control procedure, the sliding control-bar principle, according to which a core (genotype) RM based design could, through manual means, be sequentially altered to befit particular (phenotype) conditions. A case-study, the Alice Cups, was produced accordingly. These means, as a screen or even web-based application, have the potential to be applied as a way for RM to be utilized in a more direct and commercial context. It could allow a design to be manipulated, by sizing, stretching or extending it according to a x, y, z volume, to accommodate set circumstances, be these manipulating a intricate shelving-system to fit a particular niche; or adapt a lampshade's size and the size of its perforated pattern to suit specific lighting conditions.

9.2.2 Including the LF-Model in Ongoing Research

The approach to RM put forth in the thesis could also be applied in ongoing research projects. The '*Wonderwall*' project, currently run under the auspices of Buswell et al. (2005) explores using Freeform Construction related technologies in the realization of large scale builds. It endeavours to develop a more, in concept, mutable wall/ partition which, through the use of an evolved rendition of the additive processes (FC), can be made to accommodate a number of differing functions and conditions. By appropriating elements and features of LF, and the open-source hybrid practices is allows for, the research would benefit from an expanded set of resources and analogies according to which its objectives could be advanced (Fig. 9.1).

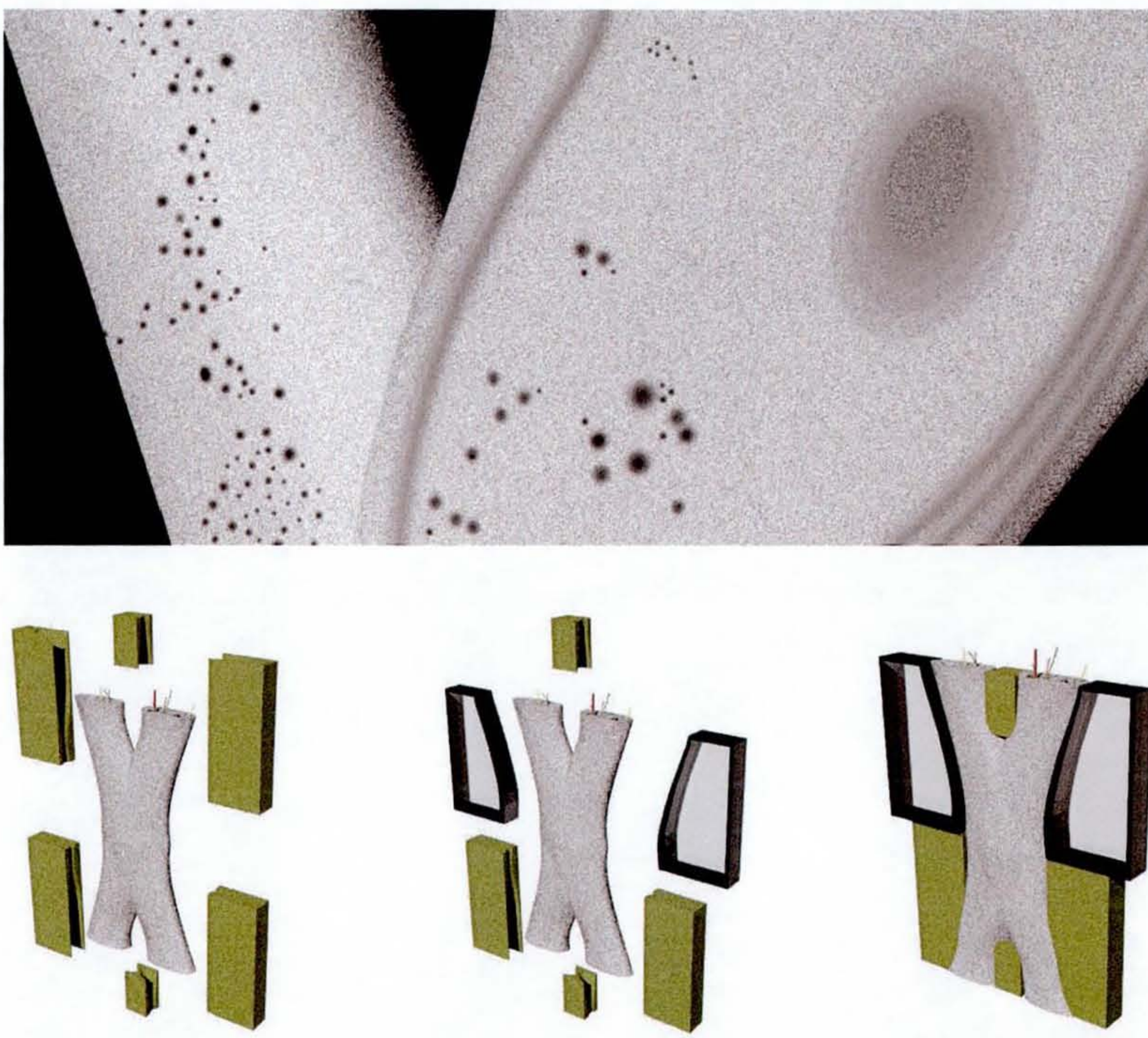


Figure 9.1 Features from the 'Wonderwall' project, exploring various hybrid systems that could be combined with the evolving additive (Freeform Construction) processes - a combination of fully bespoke (Layered Freeforming/ Freeform construction), semi-bespoke (transitional/ connective components), and generic (halbzeug/ mass produced) components and fabrication methods...

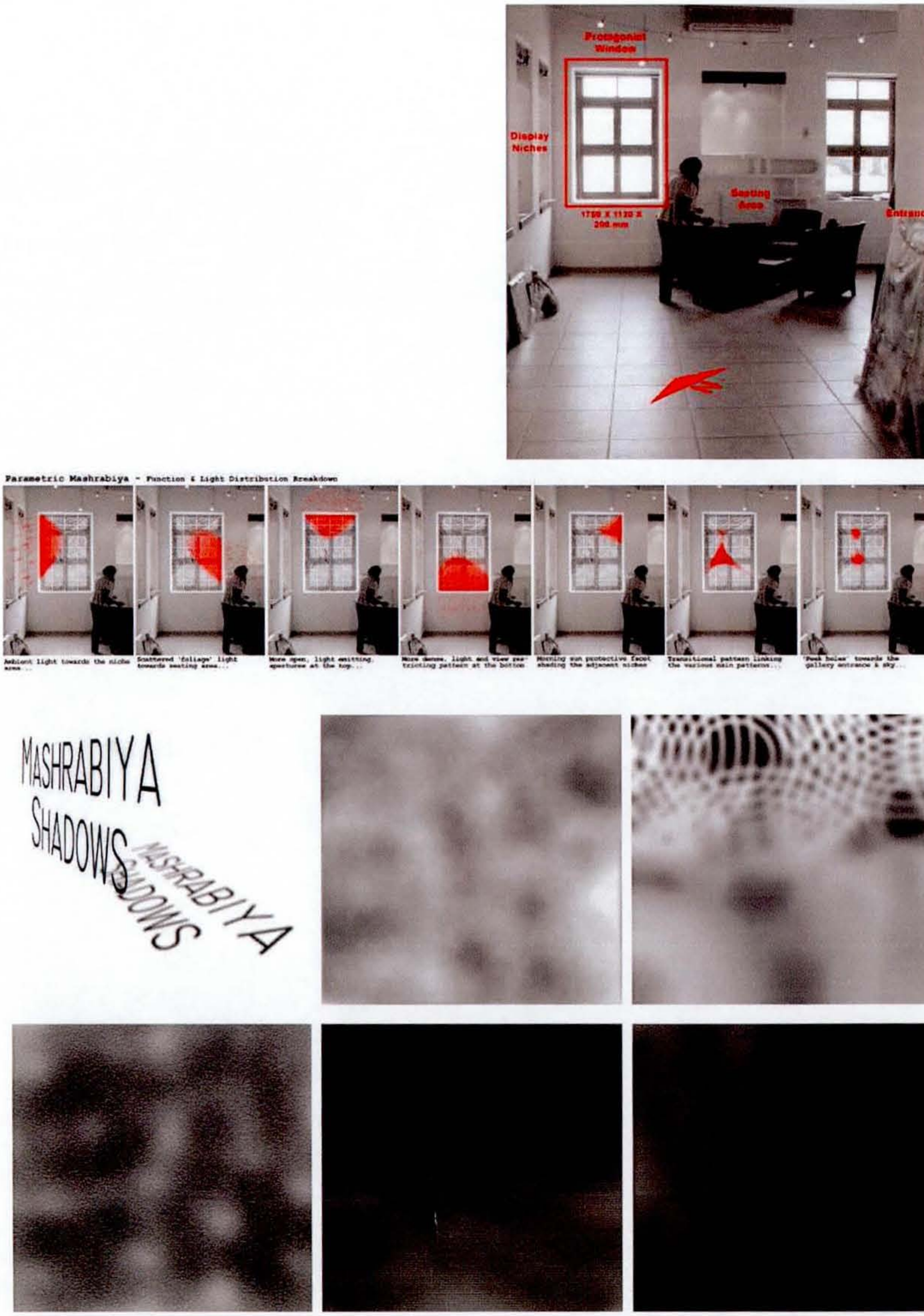


Figure 9.2 A bespoke Mashrabiya (a privacy screen and sun-shade - a type of middle-eastern oriel) made for a particular window (located at the Dar Al-Funoon Gallery) in Kuwait. The mashrabiya's shape and patterning was determined by the desired shadow patterns rather than by the material screen itself. The shadows came first - the screen design followed...

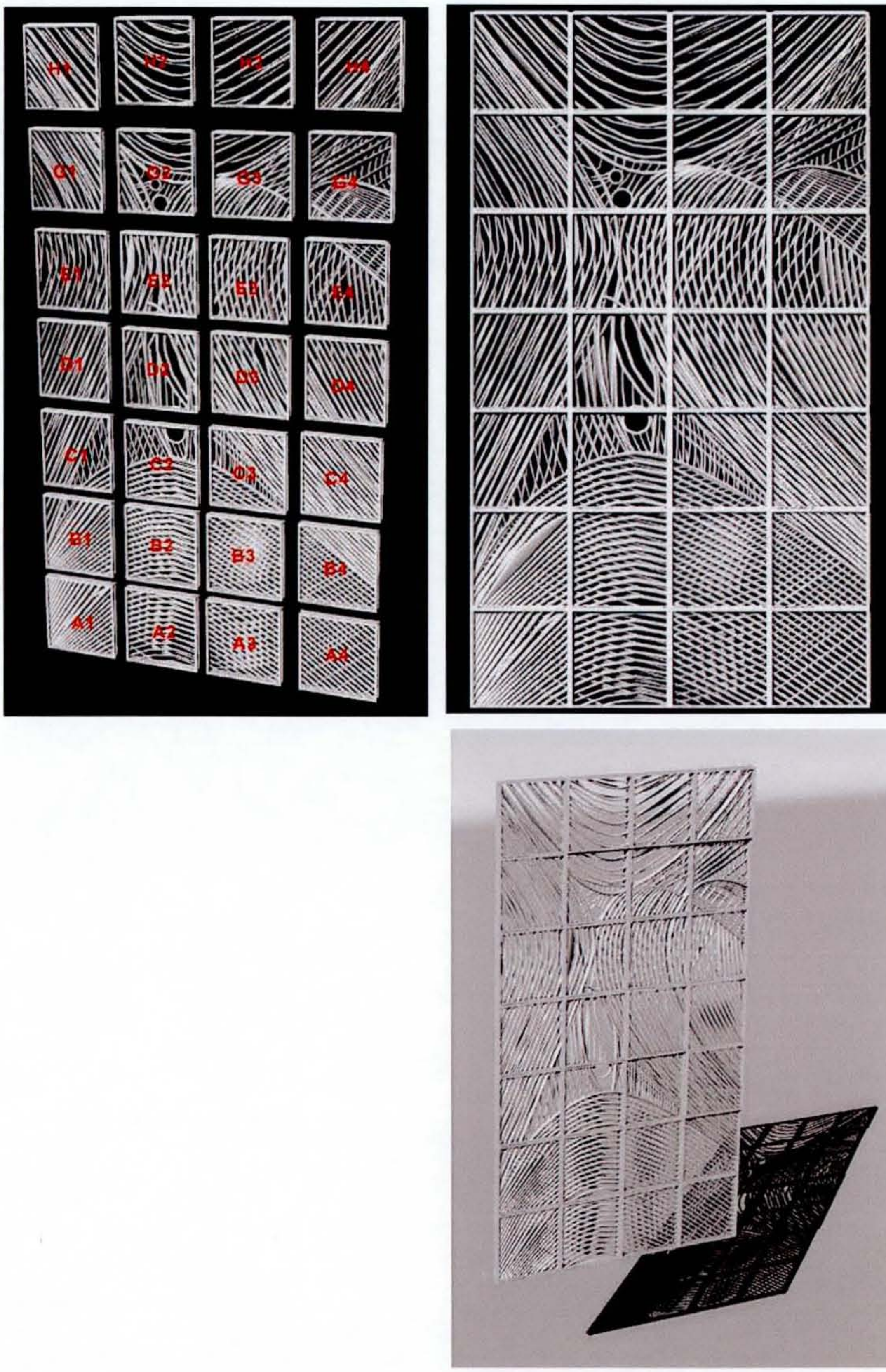


Figure 9.3 The mashrabiya is made up of twenty-eight bespoke coded tiles which slot together.

9.2.3 An Adapted Mashrabiya

The 'Parametric Mashrabiya', an updated rendition of the privacy-screen/ partition usually found in the middle-east (an 'oriel' is an occidental rendition of this). Based on designing the shadows rather than the screen (Fig. 9.2), which are simulated in CAD, the design reverses the means of design, and provides a bespoke response to a particular location and condition, where the distribution of light and views, as well as the shadow-patterns it forms, have been customized according to the specific needs of its user or proprietor. The design is made of twenty-eight separate and different framed components which all slot together to form a 175 cm by 100 cm frame (Fig. 9.3). The design is currently in process.

9.2.4 Expanding the Tactile Scope

Research is also ongoing regarding the expansion of the ideas explored during the initial stages of the Snakeskin design and during the making of the Design Ground and Finger-Run. These include making a whole wall plane into a haptic surface, and appropriating the lessons learnt during the making of the Snakeskin into a whole tactile (mostly horizontal) field of a tactile surface that introduces a whole new, more comprehensible, and less directional, domain within which related matters can be explored and expanded into (Fig. 9.4).

9.2.5 Expanding the Tactile Means

There are inherent advantages and potentials in using a haptic interface in designing physical artefacts. However, as a design tool, particularly in the context of design and architecture, this medium would benefit from further linkage and assimilation of various CAD and scripting based softwares and plug-ins. Allowing for a smoother and more error-free transition between these conception modes and integrating the means through which they are controlled, would hopefully allow the more material and qualities, textures and kinaesthetic attributes, of a design to be comprehended and appreciated.

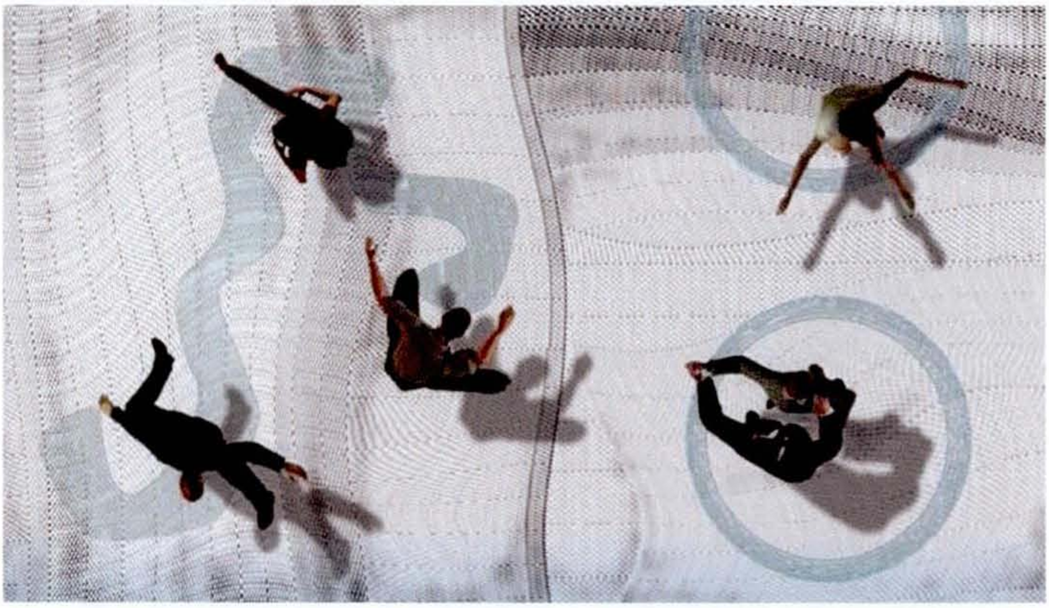


Figure 9.4 Plan view of a tactile field, where a larger area of the ground plane is treated as a tactile topographical surface. Here the vocabulary used in the Snakeskin is expanded and applied to a more comprehensive context, where the surfaces planes and textures aim to suggest, but not dictate, how the field should/ could be used. The image also shows examples of 'Designer Puddles' which, when dry, form subtle, almost un-noticeable identations in the plane. However, in the aftermath of a rain, these slight cavities retain a slight quantity of water, forming shallow reflective pools which are shaped into various images, forms, suggestive demarcations or even letterings that exist for a short while, until eventually even they dry up...

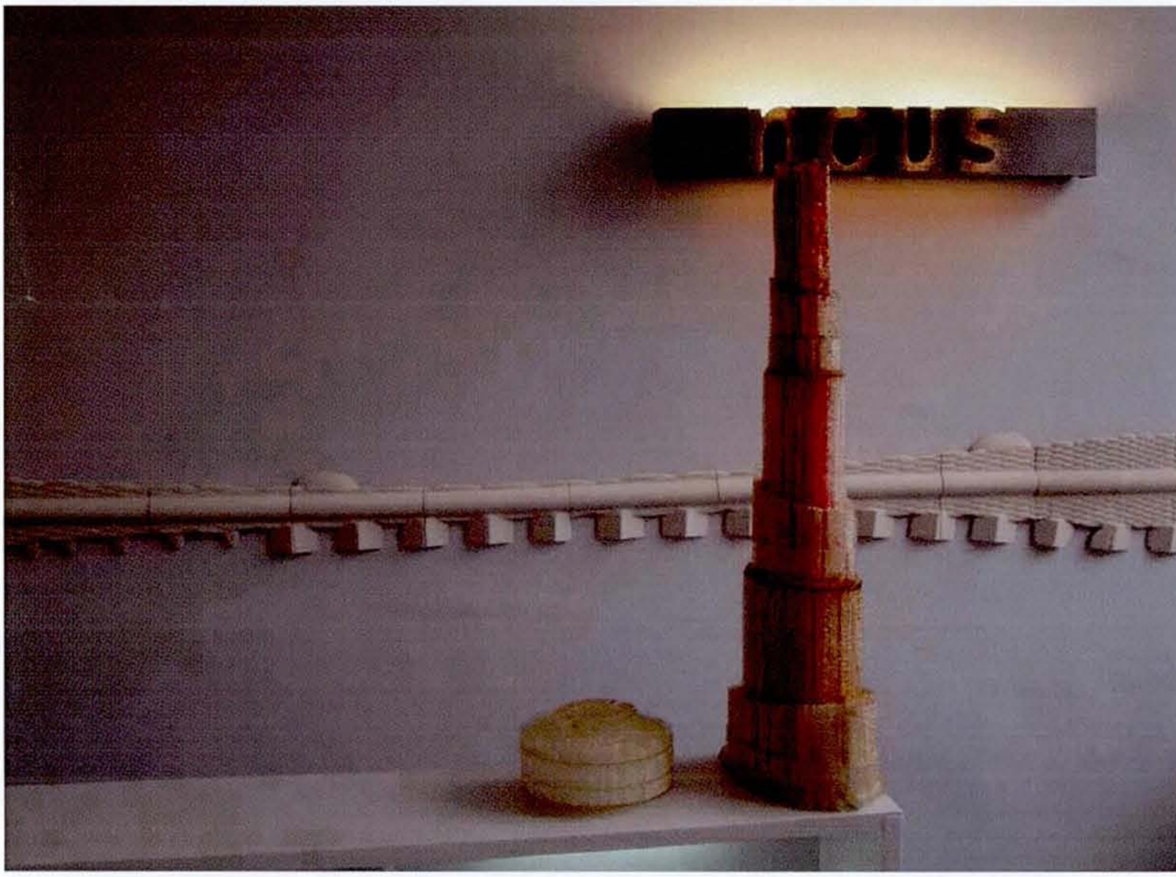


Figure 9.5 Image from the 'Residue' exhibition at the nous Gallery in London's Kings Cross, held in April - May, 2008. Both subtractive as well as additive (LF) processes were used in the making of the pieces on display. In the foreground one can observe the Fragrant Tower; in the background can a section of the Snakeskin be observed. The lit steel sign above, made bespoke for the gallery, spells out the gallery's name through over 3300 laser perforations...

References

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Appendix Contents

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Exploring Microstructure Optimization through the use of Stereolithography

By Jamie O'Brain, Sean Hanna, Siavash Haroun Mahdavi & Thomas Modeen

Jamie O'Brien, Sean Hanna, Siavash Haroun Mahdavi, Thomas Modeen

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CHECK THIS! C A Dobson, et al. Simulation of cancellous bone remodelling, structure and biomechanical stresses associated with osteoporosis: A review.

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Abstract

Our aim is to demonstrate that a strong yet lightweight material, with an optimized internal structure, can be designed through a heuristically selective process and produced with rapid prototyping. The heuristic we have used is a genetic algorithm which allows us to produce structures with a level of internal complexity that would otherwise render the material all but undesignable. We acknowledge that other heuristic algorithms may be used in this process but we have employed GAs because of their proven reliability, flexibility and robustness (Bentley, 1999, p8).

Rapid prototyping (RP) is a computer-aided manufacturing (CAM) procedure whereby an object or material can be generated by creating a build file in a computer-aided design (CAD) package and exporting the data to the RP equipment. The RP machine then interprets the data as a series of miniscule deposits, built up in layers until the object is fully formed. Our interest in this CAD-CAM process extends from the possibility of employing a heuristic algorithm at the CAD level to establish optimal struts in a CAM-generated material, thereby enabling us to produce intricate yet strong materials. For the purposes of the project we used Matlab for running the GAs, 3Ds Max for devising and exporting CAD files and a XXXXX stereolithography machine. The algorithm we devise will, we intend, be available for use in a variety of engineering or architectural projects.

This paper will cover the design and implementation of the algorithm and the material and discuss the broader issues of creating optimal materials with heuristic procedures. We have taken an interest in the use of RP in biomechanical procedures and how this medical application has assisted researchers understand the properties of bone - itself a complex yet optimized organic material. This observation provides, we believe, a useful analogy to draw upon when designing inorganic materials. The analogy will be outlined below.

1.0 Background

1.1 Artificial and natural structures and materials

Materials for building any structure need to be strong enough to support the stresses and strains exerted on the structure under a variety of circumstances. In previous generations, folk knowledge of the properties of materials, whether wood, stone or otherwise, was the preserve of the craftsman and sufficed for building simple structures and machines intended for specific tasks. The increased use of iron in the nineteenth century however necessitated an understanding of materials and structures based more on mathematics than folk knowledge. Thus the development of large-scale bridges, ships, railways and heavy machinery, etc., accelerated the pace of change in materials science. In recent decades the ever increasing use of computing in design and engineering has further pushed the possibilities of materials science and today the field may involve many disciplines from the physical and natural sciences, engineering and design.

In this way the very sophisticated performance of modern structures are effected by the behaviours of their materials. As non-designed structures in the natural world depend on the minutiae of their chemical components to avoid decay, so in the human sphere, our endeavors to surmount the obstacles of nature or the limitations of our own biology necessitate the development of strong, light and flexible materials; hence the aeroplane wing: a structure which is strong yet flexible enough to withstand the immense physical forces exerted against it and light so as not to hinder the plane's flight.

It is only relatively recently that we have begun to understand the physics of stress against a material, as well as the strain resulting from that stress, and the physical roles of springiness and stiffness in a material. The discoveries have however revolutionized the design of materials and therefore of structures.

Developments in the science of structures also allowed for the design of beams and trusses. Beams, like girders and train tracks, are solid materials and are able to take the strain of cantilevers by accommodating different types of stress within their fabric. Trusses are usually a collection of such beams and were employed initially, in modern times at least, to build railway bridges: a truss system is able to support the weight of the train as it shifts along the structure. Such bridges today are often constructed from strong and rigid Pratt trusses or Howe trusses.

It has often been noted that there are similarities between artificial structures and natural structures. D'Arcy Thompson's classic work On Growth and Form outlines this theme and provides many such examples of natural phenomena such as bone, wood and shell that are structurally strengthened by a process of evolutionary modification. Our interest in this intriguing observation is not so much the way in which things can be made strong at the material or organic level, but how such materials and organs can be designed for strength at a more fundamental stage: in organs this stage may be the genetic or cellular level, in materials this stage may be computational or micro-mechanical. The means by which such fundamental modification may be achieved artificially will be outlined in section 1.2 below.

1.2 Rapid prototyping and Biomechanics

In their paper 'Simulation of cancellous bone remodelling, structure and biomechanical stresses associated with osteoporosis' (2000), Morgan, Langton and Fagan outline the use and benefits of computer-aided design and manufacturing (henceforth CADCAM), in a biomechanical procedure. In short, they aim to understand the effects of this bone disease by artificially modelling bone-like structures with rapid prototyping equipment.

1.2.1

Rapid prototyping (RP) is a range of techniques for fabricating a part or an assembly using CAD data. The technique was first developed in the mid-1980s by 3D Systems, California, as Stereolithography (SLA) and has since been developed into a range of RP systems: Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), and Solid Ground Curing (SGC). A lathing process, Computer Numerical Processing (CNC), is also used in conjunction with FDM.

Stereolithography is currently the most widely used RP technique. In brief, it is able to fabricate a model by shining a laser into a vat of photosensitive resin which hardens, or 'cures', on contact with the beam. The model is made on a platform which moves vertically in a continuous action and downwardly in incremental steps, each step selected to a desired measure of thickness, typically about 0.1 mm. The model is eventually built from successive layers added in these thin 'slices' of cured resin and then sanded to smooth of the traces of steps on the surface.
Selective Laser Sintering was developed in the late 1980s. An SLS machine consists of two pow-

der magazines on either side of the work area. A levelling roller moves polymer-coated powder over from one magazine, crossing over the work area to the other magazine. The laser then traces out the layer. The work platform moves down by the thickness of one layer and the roller then moves in the opposite direction. The process repeats until the part is complete and the excess powder brushed off. SLS' advantage over SLA is in the property of the materials which are far less brittle, less prone to stress and approximate the modifiable properties of thermoplastics.

The Fused Deposition Modelling process was also developed in the late 1980s. The fundamental process involves heating a filament of thermoplastic polymer and channelling it through a small tube to form into the RP layers as it cools. This technique is of particular relevance to this paper as it is a commonly used technique in biomechanical modelling (Callicott, 2001, p151), and allows two separate polymers to be used in conjunction (the latter point will be addressed in more detail below).

1.2.2

We noted above that load-bearing natural phenomena such as skeletons are often similar in structure to artificial structures. To illustrate this point we can draw further on the example of human bone. 'Bone' is two things, an organ and a tissue, and each responds to the stresses and strains exerted on our bodies in childbirth, occupation, disease or aging, and so on (Bagge, 2000, p 1349). In this way, the biology of bone is intimately linked to the ways in which we live (hence the relationship between humans and nature). The very shape and density of our bones often reflects our occupation or our diets or lifestyles, (Roberts and Manchester, 1983, p105).

As bones change form at the organ level so they are also responding to our lifestyles at the structural level, the tissue level and the cellular level. This relationship between the over all structure and the internal composition of bone is of particular relevance to the CADCAM process, in that a synthetic structure can be optimised by engineering its internal form. In this respect it is worth noting the complexity and dynamic behaviour of bone growth, the process of which is outlined below.

Bone can be treated as a material, and in this respect it has unique properties. The purpose describing bone in this way is to demonstrate how it behaves as a dynamic system of compounds working together to improve its over all performance in a whole range of situations – both simultaneous demands, such as in a leap or fall, and in the changing types of demands over the span of a lifetime.

Bone has the ability to remodel biomechanically: the properties of its tissue and the design of its structure allows it to respond to this extraordinary range of demands. These demands are physical stresses and strains: tension, compression and torsion (the results of pulling, pushing and twisting respectively).

As with any type of material, the stress (the pushing forces of compression or tension), on a bone is measured either in kilograms per square centimetre (kg/cm^2) or meganewtons per square meter (mn/m^2); strain (the pulling forces upon atoms and molecules during stress), is measured as the percentage increase in length after stress (in bone as fractions of a millimetre). Elasticity is measured in Young's modulus (measurement E correlating to kg/cm^2) of stress/strain (that is, the force per unit divided by the change in length as the result of that force). Strength is measured as the amount of tensile force required to break the material.

Bone is stronger than the sum of its compound parts, unusually so for a mineralised material, with a tensile strength parallel to the axis of the whole bone of about 1128 kg/cm^2, and perpendicular to the axis of about 705 kg/cm^2. Its tensile strength is about 1008 kg/cm^2 and compressive strength about 1509 kg/cm^2. It's Young's modulus is about 210,930 (figures taken from Shipman et al, 1985, pp53-54). The hollowness of a bone also contributes to its strength in that it allows for a more complex internal mechanism to deal with a range of stresses and strains. However, changes between the compounds of bone over a lifetime (for example, the increases in molecular bonding and decreases in collagen and hydroxyapatite bonding), result in increased brittleness and weakening.

The compounds from which younger bone is made contribute to its resistance to breakage. They come in two forms of matrix, the organic (or osteoid) and the inorganic. The organic matrix (primarily made up of collagen), gives bone its elasticity, whereas the inorganic matrix, (primarily the calcium salt hydroxyapatite), gives bone its hardness and strength in compression. The compounds respond to the supply of blood throughout the bone and serve different functions: forming either cancellous bone (bony tissue surrounded by blood vessels), compact bone (blood vessels surrounded by bony tissue) or subchondral (less vascular than compact bone, more vascular than cancellous bone). The deposition of these types of bone varies according to the maturity of the bone, resulting in different forms of new bone (woven, laminar and fine cancellous), performing different functions and each contributing to the development of mature or adult bone, known as lamellar.

The cellular make up of bone allows this complex behaviour at the tissue level. Bone cells come in three forms – osteoblasts, osteoctyes and osteoclasts – and have the functions of producing new bone and reabsorbing old bone by way of their internal organelles (chiefly the Golgi apparatus). These three types of cells work together to constantly grow and remodel bone. Osteoblasts are the cells which produce bone by secreting osteoid; osteoctyes have the effect of responding to the body's need for a balance of minerals in bone and soft organs; osteoclasts reabsorb bone for use in other bone production.

It is not necessary to describe the function of every bone in the body but, needless to say, the particular pressures placed on each bone are responded to at the tissue level and therefore the cellular level in a process of selection. These minute responses in nature are localised responses to selective pressures (whether molecular or ecological pressures, or both) and are triggered at the genetic level. In understanding and harnessing this process we can begin to design more responsive and more economical materials and structures.

1.2.3

The feature common to biomechanical modelling to CAMCAD is a simulation process, finite element (FE) analysis. This is a computational method that subdivides an object into a system of very small (but finite) elements to create a finite element model. Each element is assigned a set of equations, describing mechanical properties, boundary conditions, imposed forces and so on. These equations are then solved as a set of simultaneous equations to predict the emergent behaviour of the object; the greater the number of finite elements, the more accurate the analysis.

The use of this in biomechanics is extensive. It is used, for example, in modelling bone stress and adaptation, reconstructive surgery and implant design. Ultrasound scanning can also be used to model internal organs, bullets from gun shot wounds or embryos, the data of which can all be fed into CAD programme and then used for Fused Deposition Modelling to aid surgeons.

The proximity of this medical procedure to the CADCAM process outlined in this paper provides an intriguing opportunity to also apply search algorithms to the design process. In a paper on the microstructural adaptation of a femur after fracturing, Bagge (2000), seeks to demonstrate how the spicules of bone achieve an optimal path to seal the breakage. This process of biomechanical optimisation may provide the model for applying search algorithms to a synthetic modelling process. Our research has attempted to realise this possibility and the process we have employed is outlined in section 3, below.

2.0 Search algorithms and evolutionary systems – a brief introduction

2.1 A few examples

GAs are one type of method among many in the field of generative systems. Other algorithms include simulated annealing and tabu search. Generative systems, such as expert systems, cellular automata and genetic programming, are able to produce streams of data, select the best data, or paths of data, and store those 'decisions' for future use. Although generative systems rely on a user to input 'rewards' or 'punishments' for good or bad decisions, their value is in their ability to produce highly complex systems over many generations that the user is incapable of conceiving unaided. The field of generative systems will now be described very briefly by way of a few examples.

Stephen Wolfram in his book A New Kind of Science (Wolfram, 2002) devises thousands of examples of cellular automata – simple elements processed through simple rules that, after thousands or tens of thousands of generations, produce extraordinarily rich and intricate patterns, suggesting something of the way in which nature also produces such complexities.

Karl Sims (Sims, 1999) developed artificial creatures, made out of computer-generated shapes (usually squares and rectangles), which at the design stage moved to specified rules (for example, a twist-bend rule, a revolute rule, spherical movement rule and so on), and were rewarded when they achieved their fitness function of advancing forward in a simulation of swimming or walking, leaping or following another creature. Over successive generations Sims built up a sequence of successful movements that resulted in the creatures appearing to move in a remarkably life-like way.

In genetic programming the elements of the test case are initialised, so that the 'genome' of the specimen can itself be altered. Gruau (see Banzahf et al, 1998), for example devised a six-legged insect based upon cellular code and the 'legs' as trees of these cells, establishing a neural network of joint neurons and sensor neurons in each leg. 'Walking' values were included in the algorithm so that the movements could be encoded at the programming level.

2.1.2 Search algorithms and the evolutionary approach to design

Designs in both engineering and more creative fields can benefit from a randomised algorithmic search for an optimum factor, similar to the evolutionary process in nature outlined in the preceding section. The following section will serve to outline the principles of search algorithms useful to the design process, focussing only on the two algorithms most relevant to the focus of this paper, (a practicable explanation of this process is beyond the scope of this paper).

Genetic Algorithms

Of all evolutionary design techniques GAs are the most widely used (Reeves, 2003, p2). This may be due to their reflecting the 'innovative flair of human search' and their reliable flexibility, their robustness (Bentley, 1999, p8). Importantly, and despite the randomness of its search mechanism, the process of designing with GAs is controlled by the user.

For a GA to work, its search space and solution space must be defined. The search space is a population of coded solutions – analogous to the genotype – and the solution species the actual form desired by the designer, onto which the search space must be mapped – the analogous phenotype. The code of the search space is a series of 1s and 0s, (the 'alleles', to draw another analogy from genetics), and are formed in a string as a binary chromosome.

In a 'simple' or 'canonical' GA the genotypes of the elements in a population are given random chromosomes and the evaluation of their fitness begins. The more fit the chromosome according to the phenotype specification, the higher the score it is given. Those chromosomes achieving the highest fitness scores are channelled back into the next algorithm to produce a successive 'mating pool'. Parent chromosomes within this pool are then selected randomly, and offspring are generated from their mating (or 'crossover operator'). And so the process continues until either all the fitness functions have been fulfilled or the algorithm has completed the desired number of generations. More advanced GAs can detect greater detail within its own search – such as when evolution stops occurring or the development of 'elite' chromosomes passing through more than one generation.

Simulated annealing

In brief, annealing is the physical process of heating a solid and then cooling it slowly in order to strengthen it. The strength is brought about by the atoms realigning during the high temperature phase and then settling into a crystalline pattern as the temperature gradually reduces. During this gradual cooling, the various states at which the solid arrives can serve as models for possible ways to achieve optimisation, such models can be simulated by an algorithm and iterated through a computer programme.

The simulated annealing algorithm makes a random selection from the alignment of atoms, changes the alignment (in a simulation of temperature change), and then compares these two atomic solutions to establish a cost function. If the cost function is negative then the new solution is taken to be the current solution, if not then the former solution remains; in either case the algorithm repeats (that is, the 'temperature' changes), until optimisation is achieved.

3.0 Experiment outline

3.1 The programme

The data for this experiment was sourced from the physics of structures and from a Matlab programme which computationally fixed random points in space, and shown in the software's visualisation package. The GA then searched through various combinations of these points, with possible paths drawn between them (shown as read lines in the visuals), which represented the trusses or, one might say, the 'spicules' of the bone-like resin that we intended the stereolithography machine to produce. A series of forces was computationally exerted against these trusses and the truss under the greatest stress was demarcated in purple in the Matlab visualisation.

The GA gave either reward and penalty scores for structures that accommodated stress well or poorly respectively, and also for the weight of the trusses with penalty scores imposed for heaviness. Other penalties were given for trusses with an angle less than 30 degrees as the stereolithography resin would loose strength and resolution.

The GA also proved highly effective in searching for optimal structures as, with around 3 billion possible combinations of trusses, it would otherwise take several years to search through every possible structure. None of the thousand generations was discarded however as it was not possible to select optimal structures until the entire programme was complete.

3.2 The physical structures

Given the wide use of the technique, and its established reliability, we elected to use the stereolithography (STL) equipment at the Royal College of Art. This STL machine (a 3i Systems Viper), is technically able to produce resinous nodules to a standard resolution of 0.05mm (although a resolution of 0.025mm is possible), yet despite the broad acknowledgement of the equipment's mechanical prowess (REF CALLICOT??), it was nevertheless essential for us to establish the physical properties, benefits and limitations of the resin in a variety of forms and under different types and levels of stress. Test structures were computer modeled in 3Ds Max, which is able to export STL files, involving a sequence of columns varying from 2mm – 0.1mm in diameter and 90 – 30 degrees in angle, and a series of holes, in a sheet 2mm thick, with widths varying from 2mm to 0.1mm.

The lasers in the STL machine can be set at different orientations to produce arrange of textures and qualities. The variability in the angles of the columns was intended to test whether the shape of the structure would be effected by the orientation of the lasers.

Firstly, however, we noted that the rigorous cleaning process meant that all of the finest columns (0.1mm) had snapped off the model. Also, as the resin is cured by exposure to ultraviolet light (usually for around four hours in a curing oven), exposure to any unfiltered light would cause it to harden and become less flexible and more brittle, (for the purposes of our test we cured it for eight hours to increase the hardness). The tensile strength of the columns therefore depends on the age of the unprotected material and a minimum diameter of 0.2mm is recommended.

The columns were then tested by exerting a constant force against them, the flexibility of the resin meant that they bend to a certain angle before snapping. We took the maximum angle to which they can be bent as a measure of their strength. These results were tabulated, below.

3.3 Producing and testing the trusses

Once the GA had produced a certain number of solutions, the points in space could be plotted in an AutoCad file as 3D spheres, the paths between them that the GA had established could then be established as members in a structure by drawing them with CAD cylinders. Once one element had been created in AutoCad we were able to produce an array of them, joining the members together along rows and columns until a mesh-like structure was formed. This AutoCad file was then exported to 3Ds Max for rendering, and an STL file created.

Three models of different scales were made, 2.5 x 2.5 x 5cm.

Appendix 02

An Evolutionary Approach to Microstructure Optimization of Stereolithographic Models

By Siavash Haroun Mahdavi & Sean Hanna[1]

A paper summarizing some of the key programing related components described in chapter 5.2.

[redacted]

1 1 The author provided the founding concept which was explored in the paper an is acknowledged in its 'Acknowledgements' section.

An Evolutionary approach to microstructure optimisation of stereolithographic models.

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Abstract- The aim of this work is to utilize an evolutationary algorithm to evolve the microstructure of an object created by a stereolithography machine. This should be optimised to be able to withstand loads applied to it while at the same time minimizing its overall weight. A two part algorithm is proposed which evolves the topology of the structure with a genetic algorithm, while calculating the details of the shape with a separate, deterministic, iterative process derived from standard principles of structural engineering. The division of the method into two separate processes allows both flexibility to changed design parameters without the need for re-evolution, and scalability of the microstructure to manufacture objects of increasing size. The results show that a structure was evolved that was both light and stable. The overall shape of the evolved lattice resembled a honeycomb structure that also satisfied the restrictions imposed by the stereolithography machine.

1 Introduction

In his influential 1917 treatise *On Growth and Form*, D'Arcy Thompson describes the processes determining the shape of living organisms as consisting only partly of Darwinian evolution and partly of the external forces imposed on the organism as it grows in its environment. In the case of bone, for instance, he states:

> 'Here, for once, it is safe to say that 'heredity' need not and cannot be invoked to account for the configuration and arrangement of the trebeculae: for we can see them at any time of life in the making under the direct action and control of the forces to which the system is exposed.'
> (Thomson 1917)

While initially intended as an explanation of biology, his work has had a great following among engineers, and it is in the tradition of his proposal that we propose an algorithmic method of deriving an object's internal structure based partly on evolution, and partly on deterministic structural engineering principles. This structure is analogous to the fibrous interior of bone, both lightweight and strong, to be manufactured by stereolithography, a computer controlled manufacturing process which uses a laser to set a form in a tank of resin. A series of linear structural members acting in either tension or compression traverse the volume of the object to be made and meet at node points, much like a 3D space frame, only rather than consisting of identical members at fixed angles from one another, their position and orientation are dependent on the forces that the object is to carry.

Stereolithography builds the entire structure as a unit, so complexity costs nothing. With a resolution of 0.05mm, the process can currently build the structural members under a millimetre in length resulting in a material similar in texture to sponge. This material could be formed to any shape required, and be organized at the smallest scale to carry external forces most efficiently.

In a very basic example of an evenly loaded rectangular beam for instance, points above the central axis are in horizontal compression, and points below are in horizontal tension, and these forces increase vertically from this axis, and decrease horizontally from the centre of the beam, see Fig.1. Rather than adding and removing large areas of material from the beam's cross section as in the case of a typical 'I' cross section, the small scale structure at each point of the beam can be optimised for its structural capacity and least weight see Fig.2.

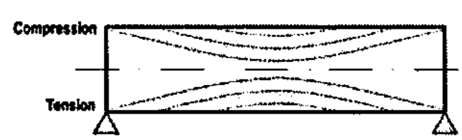

Fig.1 A simply loaded beam.

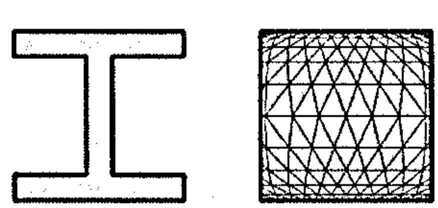

Fig.2 The mass of a typical 'I' beam is concentrated at its extreme edges. A similar effect can be achieved by altering the microstructure.

Typically structural optimisation methods seek to minimize the weight of a structure capable of withstanding a given set of forces. The work presented here is the first step in forming more complex structures than the simple beam; at this stage we present a method which is scalable in terms of both size and complexity, and produces a generic internal structure which is not under specific loading conditions. External forces are assumed to be in equilibrium and therefore the structure has a regularity at the intermediate scale, but the method is set out for increased complexity in the future.

2 Background

2.1 Stereolithography: The Process

Stereolithography is a method of creating solid 3D models of CAD drawings, see (Brain 2002) for a fuller explanation. It is one of the many types of machines collectively called 'rapid prototyping machines'. As the name suggests, their primary usage is with the rapid building of prototypes for testing by engineers and designers. However as the technology has been dramatically improving over the past several years, it has become evident that this process can be used for more than building prototypes and can be itself a method for constructing parts.

The stereolithography machine consists of a tank filled with liquid photopolymer which is sensitive to ultraviolet light. An ultraviolet laser 'paints' one of the layers, exposing the liquid in the tank and hardening it, a platform then drops down into the tank a fraction of a millimetre and the laser paints the next layer. This process repeats until the model is complete.

Once completed, the object is rinsed with a solvent and then baked in an ultraviolet oven that thoroughly cures the plastic.

2.2 Structural Optimisation: Previous Work

Several techniques have been devised for generating the topology of continuous solids analysed by the Finite Element Method (FEM). Both GA and non-random iterative methods have been used. Marc Schoenhauer reviews a number of GA methods for generating topology in 2D or 3D space to optimise structural problems involving continuous shapes. The genetic representation in these cases can determine a configuration of holes and solid using Voronoï diagrams or a list of hole shapes (Schoenhauer 1996). Yu-Ming Chen uses a non-random iterative process of shifting node points in the FEM representation toward high stress zones to examine similar problems (Chen 2002). These methods can determine the number and position of holes in a cantilevered plate, for instance, but do not deal with truss-like structures.

The majority of research into the optimisation of discrete element structures (trusses, space-frames) has been in the refining of the shape or member sizes, rather than the topology (in terms of members connecting the node points of the structure). Adeli and Cheng use a GA to optimise the weight of space trusses by determining the width of each member in a given structure. The shape and load points are fixed in advanced, and the cross sectional areas of groups of members are encoded in the genome, then selected to minimize the total weight (Adeli and Cheng 1993). Yang Jia Ping has developed a GA which determines both shape and topology, however the algorithm must begin with an acceptable unoptimised solution and refine the topology by removing connections (Ping 1996).

2.3 Stereolithography: Previous Work

Stereolithography and other rapid prototyping techniques are now beginning to be investigated as an alternative method of construction for objects of high complexity, particularly with intricate internal structures. This has not yet become commercially viable for mass production, but several researchers are preparing for the increasing accuracy and decreasing cost of the technology in the future. Molecular Geodesisics, Inc. is investigating structures based on a regular tensegrity space frame which would, at a microscopic size, be useful as biological or industrial filters (Molecular Geodesics 1999).

3 Method

3.1 Overview

The volume of the overall object is divided into a three dimensional grid of cubes, each forming a modular unit to which will be referred to as 'unit cubes'. As the work presented here is concerned with relative performance rather than a specific complex loading condition with real world units of force and size, no real world units are used throughout. This unit cube defines the basic unit of measurement used in the algorithm and has a volume of one. The actual size of these is dependant on the machine and material used but is in the range of one to several millimetres. In a loaded object the stresses at all points can be calculated using the element analysis equations (see sec. 4.1) and can be seen to vary continuously from point to adjacent point. Each one of these cubes contains a group of struts oriented to optimise its efficiency for the stresses incurred at that particular point, and its adjacent units contain a very slightly different structure for a slightly different stress condition. In the object as a whole the arrangement of each cube varies considerably, but does so gradually and continuously over its volume in response to the external forces, see Fig. 3.

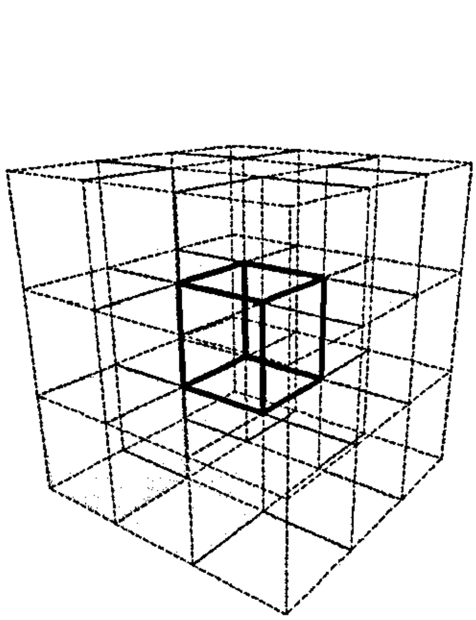

Fig. 3. An array of 26 outer cubes surrounding the central cube.

Two separate processes are used to determine the structure: the connections between nodes evolved by a genetic algorithm (GA) and their positions by a deterministic analysis of the forces. Given n points in space, a graph of connections (the 'connection graph') can be formed between them that does not vary topologically as the locations of any of the points change. The number of possible graphs is 'n factorial', and it is this connection graph between the nodes that the GA evolves. This process takes some time and by its nature involves randomness. The actual position of the nodes however, is determined by a separate, iterative process of moving points in space to achieve structural equilibrium. This standard analysis of structural equations is deterministic and efficient.

The placement of the node points in 3d space varies from point to point, but their connections to one another do not. This accomplishes two things that we find necessary for scalability. First, it avoids breaks in the continuity of the structure by allowing a difference between one unit cube of structure and the next which can be scaled to arbitrary units of precision. These break points would literally be break points if the connection graph were to change, as adjacent units of incompatible structures would be zones of weakness in the overall object. Second, it allows one single graph of connections to be evolved which can be applicable to all points. This allows an object of any size and any number of units to be evolved once, rather than running the GA many times to generate structures for large objects or complex load conditions.

Analysis of an overall complex shape or complex loading is a standard procedure usually performed by the finite element method (FEM) and by many existing software applications, as such it is not considered in this paper. Instead, the work presented here is the creation of a structure at the simple end of this range, designed to test the method. Evolution is performed to optimise the connection graph under a range of differing tensile conditions but the overall object is not subjected to complex loads at varying points, and as such, the final position of nodes in each unit cube does not vary.

3.2 Geometrical Representation

Associated with each unit cube are n points that define the nodes at which two or more linear structural members meet. The structural members forming connections between these points are determined by the connection graph evolved by the GA and their size and the location of node points determined by the iterative process described below. Each node point may be connected to any number of other points in either its own unit or any adjacent unit to form a basic structural unit of the design, repeated in each unit cube of the structure. Although the unit cube defines a volume of space, the node points are not constrained by it and are free to extend this structural unit beyond any of the boundaries, thereby overlapping the adjacent structural unit.

There are n points in each unit cube, therefore each point may be connected to any of the (n − 1) points in its own unit, or any of the same n points in the 26 (including corner adjacencies) adjacent cubes. This results in a total of (27n −1) possible connections to each node point, see Fig. 3.

4 Iterative Structural Analysis

4.1 Methods of Analysis

Standard vector methods were used in the analysis of the structures. Given a tensile or compressive force **F** acting in the direction of the structural element this can be decomposed into its (x,y,z) components along each of our axes. For each node point to be in a state of equilibrium, all of its connecting members are considered using the element analysis equations, such that:

$$\sum \mathbf{F}_x = 0 \qquad \sum \mathbf{F}_y = 0 \qquad \sum \mathbf{F}_z = 0$$

The simultaneous analysis of multiple elements is performed using the direct stiffness method (DSM). (See (McGuire 2000) or other structural analysis textbook for a full explanation of this technique.) As mentioned in Section 3.1, at this stage the optimisation process is designed to achieve relative performance, rather than meet a specific load condition, so all calculations are simplified by being performed without units. The modular unit cube serves as the measure of length, and elastic moduli and cross sectional areas are considered equal in all members so are set to one in the DSM equations.

The structure is analysed as a pin jointed system rather than a frame in bending, so no moments need be considered in the equations.

4.2 Iterative Determination of Node Positions

While the GA generates the pattern of connections, the actual position of node points in space is determined by a deterministic process involving no randomness. These are based purely on the connection graph and the given direction and size of forces acting on each point in the structure. Given a connection graph indicating which nodes are to be connected to one another, the location of each node in space is determined by an iterative process which moves each node from an initial start point in the direction required to bring the forces in each connected member into equilibrium. To begin the process, all nodes are placed at the origin (0,0,0) point in 3d space. For each iteration the list of node points is traversed, and the (x,y,z) coordinates of each point updated to the weighted average of the coordinates of all points to which it is connected. Thus the node points are pulled from the centre of the unit cube in the directions of the adjacent cubes to which they are connected. The process is stopped when the maximum movement of any point is within a given tolerance (0.1 units) or after a set number (500) of iterations.

All points are moved at each iteration, therefore the structure tends to oscillate around a solution. Often the ideal points are converged upon quite quickly but sometimes the process continues for more than the maximum number of allowed iterations. If this occurs the given points are considered to have been oscillating around a state of equilibrium, and have therefore not yet found a solution. Thus the points are less fit and the solution is penalized in the fitness function of the GA. Also, because there are no fixed points in the structure, the entire set of points could move in space as equilibrium is established between the members. At each iteration therefore, the mean coordinates of the entire set of points is reset to the origin.

As mentioned above, the evolved connection graph is meant to be viable (with some translation of node positions) under a range of tensile or compressive forces in any direction. Weighting the above calculation in the direction of the forces to be applied simulates different loading conditions for each unit cube. The stereolithography resin is able to act in both tension and compression so one set of tensile calculations was used for both. To weight the calculation of the node position, applied forces are broken into their respective (x,y,z) component vectors as are each of the members in the calculation, and the node point with its connecting members treated as an isolated structural unit under those forces, to be solved by the element analysis equations. The different component vectors of the applied tensions are divided between the unit vectors of the members, and the resulting tension solved by the element analysis equations used to weight the averaging calculation. Thus under different loading conditions the shape of the structure is seen to shift to accommodate the change in forces, see Fig. 4.

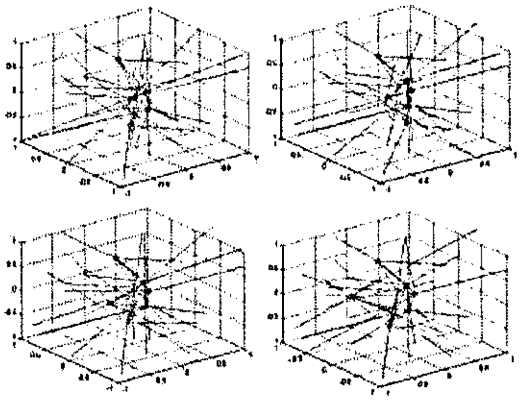

Fig. 4. A unit cube that has been orientated to remain in equilibrium when exposed to forces coming from different directions. (Equal tension in all axes, then 5:1 in the x, y and z axes respectively.)

The efficiency of the calculation is improved by taking advantage of the fact that there is a greater difference in the position of the points found under each load condition and their starting point at the origin than between either of the different solutions found. The point locations are first found for an equally tensioned condition, that is a tension of one unit along each axis, and this result is then used as the starting position for each of the other conditions. A tension of five units was used for each of the (x,y,z) axes in sequence.

4.3 Analysis of the Solution by DSM

The resulting solution is a list of fixed points in space connected by members of known length and orientation is then evaluated for deflection using the direct stiffness method. The set of all nodes in the unit, with their internal connections and those to adjacent unit cubes, are considered as an isolated structure placed under the applied external forces. The deflection of each member is calculated, and these used in the fitness function to assess the solution.

5 Material considerations

In construction, the structure is formed in a liquid stereolithography resin as a series of horizontal layers. This results in an inherent horizontal 'grain' in every part of the model and an inability to construct the underside of any portion at an angle of less than 30° from horizontal. Members constructed at differing angles to this 'grain' therefore have differing strengths and their calculated deflections were modified accordingly in assessing the fitness of the solution.

A series of tests were made of small sample members varying from 0.5mm to 1.5mm, and constructed at angles ranging from 30° to 90° from horizontal. Each sample was tested for strength and it was found that the vertical struts were roughly twice as strong as those near 30°. A function determining strength from angle was determined based on this data with all angles below 30° at a strength of zero, see Fig. 5. Then, in determining deflection for the fitness function, the calculated deflection of all members was divided by the value of this function. The method for calculating the strength of the struts was one used for testing the strength of fibres. This method, bend strength testing, is a standard method of evaluating the strength of a fibre or a thin rod that cannot be compressed without it bending. An equation then relates this bend strength to the compressive strength of the strut.

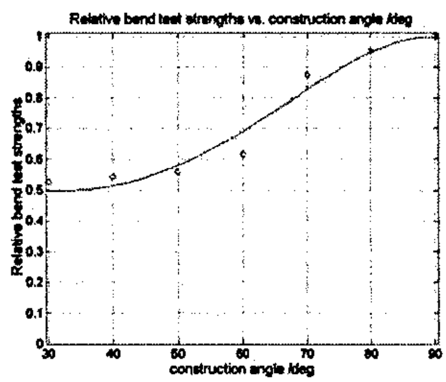

Fig. 5. Plot of the angle vs. relative strength.

The stereolithography machine used has the ability to manufacture geometry to a resolution of 0.05mm. However because the liquid resin has to drain from anything built in the machine, and the designed structure is full of holes, an experiment was done to investigate the minimum size hole from which the resin could drain.

A plate was constructed with holes ranging in radius from 5mm to 0.05mm. It was observed that the smallest hole from which resin could drain was 0.6mm. This was taken into consideration when deciding on a scale to construct the structure.

6 The Genetic Algorithm

6.1 Chromosome Structure

The genetic algorithm is used to evolve the connection graphs, which describe the connections between the nodes. The structure of the chromosome is a series of upper triangular matrices (UTM) that describe the connections of these nodes to one another. The first UTM describes the internal connections of the n nodes within the cube. The other 26 UTMs describe connections between the nodes within the original centre cube and the copies of themselves in the surrounding cubes. Below is an example of the 27 UTMs when just four nodes are used, see Fig. 6.

	1	2	3	4	1a	2a	3a	4a	1b	2b	3b	4b		1z	2z	3z	4z
1	0	1	1	0	0	0	1	1	0	0	0	0	...	0	0	0	0
2		0	0	1		0	0	0		0	1	0	...		0	0	1
3			0	1			0	0			0	0	...			0	0
4				0				0				0	...				0

Fig 6. An example of the 27 UTMs using 4 nodes.

If any point row contains entirely zeros this indicates a lack of connections and the point is effectively eliminated from the structure. The chromosome is constructed to allow this to occur as an implicit method of simplifying the overall structure. If such a simplification occurs under crossover and mutation and is found to increase the fitness by reducing weight and still maintaining a stable structure this will be likely to influence future generations, gradually reducing the effective number of points over time.

6.2 Initial Population

For the initial population, each bit is created randomly. The probability of having a 1 in the first UTM (connection between two internal nodes) is 0.5. By intuition, the probability of having a 1 in any of the other UTMs is set to around 0.03 (connection between internal nodes and the copies of themselves in the surrounding cubes). This low value was selected as an equal number of each bit would result in far too high a number of connections, and as evolution would bring this number down over time. Thus a head start was given. This assumption was verified as the number of cross cube connections decreased from 0.03 to 0.0016 during evolution in the longest run of the algorithm, presented in Section 7.

6.3 Crossover

The point numbers have no effect on the topology of the connection graph, so the numbering of the points is arbitrary. The crossover function is therefore not performed by taking a whole length along the chromosome, instead x randomly chosen points from all the 27 UTMs are taken from each parent and the two corresponding values are swapped. The final crossover rate used was 30%.

6.4 Mutation

The mutation mechanism is separated into two types: one for the central cube and another for all of the other surrounding cubes. For the central cube, a number of mutation points are chosen, depending on the mutation rate, and these bits are then flipped (0 replaced with 1 or vice versa).

As each mutation is intended to forge or break connections with similar probability, the sparseness of the connection graph for the surrounding cubes requires the mechanism for the rest of the cubes to be a little different. Because of the very large number of 0s in these outer cubes, if a standard mutation was carried out on random bits, then the number of external connections would dramatically increase in the following generations. To overcome this, the program decides on whether to flip a 0 or 1 with a probability of 0.5. If a 0 is chosen, one of the 0s in the outer UTM is found randomly and flipped. If a 1 is chosen, one of the 1s in the outer UTM is found randomly and flipped. This has the effect of mutation and can over time vary the proportion of 0s and 1s.

6.5 Fitness Function

The factors taken into consideration when determining the fitness of each individual in the population are as follows:

- The number of angles below 30°
- The overall weight of the individual
- The maximum deflection within the system
- Whether the iterative node placement had found a solution that settled down

The effect of each one of these factors was weighted as follows:

A = 2.0
W = 0.4
D = 3.0
C = 2.0

The values of A and C have to simply be high enough to ensure that individuals with angles below 30° (a material constraint) and those that are not in equilibrium have a significantly lower fitness.

The values of W and D were chosen so that the weight of the structure and its strength have a roughly equal importance. These four variables were then put into the following equation for each test under a different stress condition (T):

$$T = \frac{1}{(1 + A \times lowAngles + W \times weight + D \times maxDeflection + C \times count)}$$

The fitness of each individual was then the sum of the Ts for each of the four test.

6.6 Selection

The individuals in the population were selected using roulette wheel selection. The genetic algorithm was elitist in that the top two individuals of each generation were placed directly into the next generation. This meant that the fitness of the best member of the population at each generation never decreased.

7 Results

All initial test runs of the algorithm showed similar rates of increase in fitness. For the longest run, the population size was set at 50 and the program was run for 10,000 generations. The time taken for each individual was about half a second (all four test conditions) making the total time taken to run the whole experiment around three days.

The following plot displays the fitnesses over time for this longest of several test runs of the combined algorithm. This resulted in the structure with the highest fitness found. The plot shows the maximum and average fitness of the individuals at each generation, see Fig. 7. These values start, in the first generation, at a maximum value of 0.0575 and an average value of 0.0322. By the end of the final generation, these values increase to 0.3766 and 0.1580 respectively.

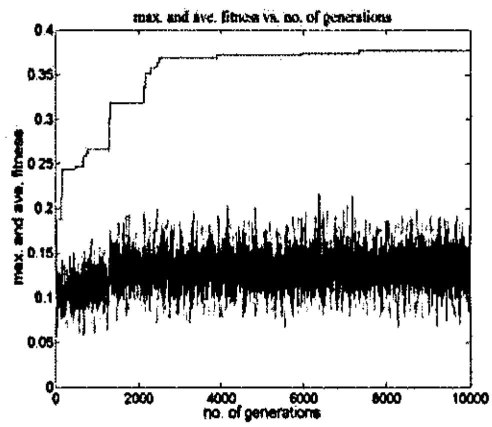

Fig. 7. A plot of the maximum and average fitness at each generation.

8 Analysis

In the course of several test runs, the following were observed:

- The number of connections to adjacent cubes always decreased.
- The number of internal connections always decreased.
- The angles of the members always increased beyond 30° with a preference for steeper angles.
- Point reduction over time was observed.

The diagram of a single unit of the best individual found from the plot shown in Fig. 7 is depicted below, see Fig. 8. It is worth examining this structure in more detail. This solution is noticeably simpler than an average solution found in the early stages of evolution, see Fig. 9. The number of outer cube connections has also dropped considerably to only three.

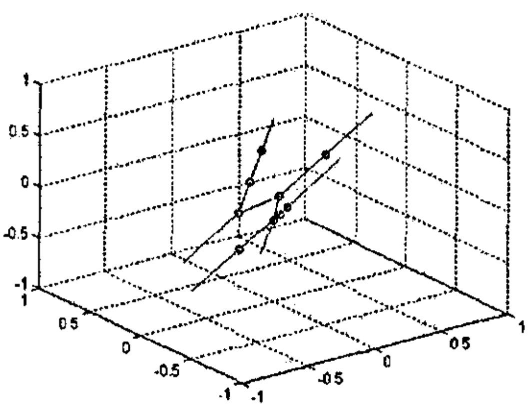

Fig. 8. A unit cube of the best individual evolved.

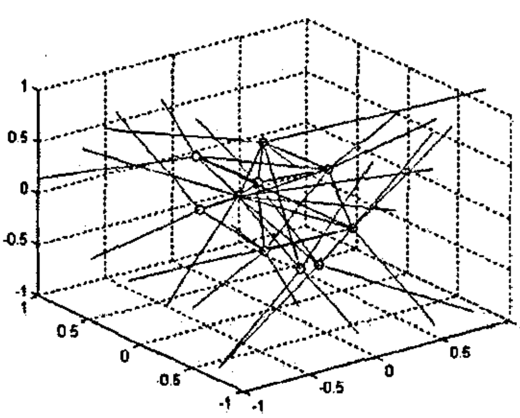

Fig. 9. A unit cube of an average individual evolved.

As mentioned in Section 6.1, the simplification of structure by point elimination is possible over time. This has occurred here. Of the twelve initial points in the connection graph, two have been effectively eliminated from the solution by removal of all their connections to other points.

As can be observed in the unit cube diagram, the solution is not an obvious one. However once the individual unit is arrayed, one can see that a very interesting solution has been evolved. The shape of the repeating pattern very much resembles that of a honeycomb structure. Seen from above, the structural members are aligned to the edges of a tiled pattern of almost regular hexagons with approximately equal angles. When viewed from the side however, near vertical elements predominate due to the material constraints mentioned previously: because the hardened photopolymer has a greater structural strength at steeper angles, the structure appears elongated in this direction. Also, no members at an angle of less than 30° are found. Both the satisfaction of these constraints, and the shape of the honeycomb structure can be seen in Fig. 10 below.

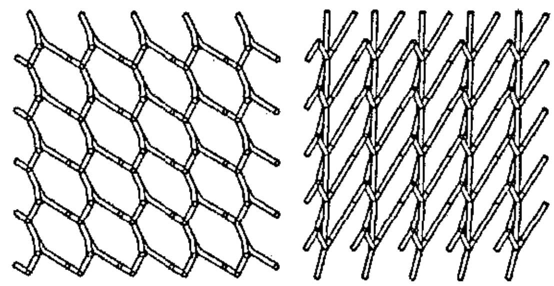

Fig. 10. The top and side views of the final structure evolved.

The module can be repeated as a unit cube to manufacture the final object of any size. The resulting structure is self-supporting and optimized for the material properties of the liquid photopolymer, the stereolithography process and an identical stress condition throughout, see Fig. 11.

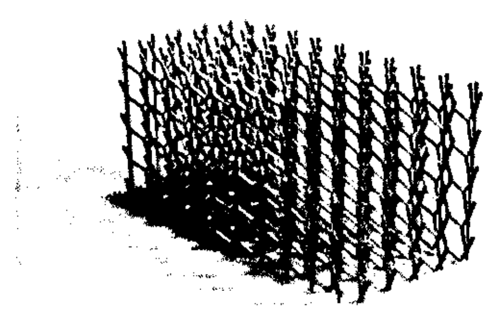

Fig. 11. A 10 x 5 x 5 example of the evolved structure.

9 Conclusion

The aims were to generate a repeatable structure which minimised weight and maximised strength, while considering the specific properties of the material in which it is built. This was to have the ability to transform continuously to accommodate the range of forces which may be present in the object without the necessity of re-evolving the structure.

The method of representing the connection graph in a genome comprised of UTMs is a straightforward method which yields good results under the mutation and crossover operators. The number and size of structural members was seen to decrease over the course of the run while maintaining a stable and viable structure within the constraints provided.

While most previous methods for evolving shape or topology of structures have focused on a single solution optimised for a particular load condition, the two stage process presented here is flexible and scalable to objects of greater complexity. The evolutionary process takes time, but the node positions of a fit solution can be recalculated deterministically and quickly to changes in load. A solution generated for the particular properties of the material and a given range of forces can therefore be quickly modified to the redesign of the object or a new stress distribution without rerunning the algorithm.

10 Future Work

As previously discussed, throughout this work, the values of force, displacement, weight etc. were not selected for a specific problem, but were chosen in arbitrary units to test the algorithm. Of primary importance was that the final evolved product had reduced its overall weight to strength ratio. Future work would involve simulating a specific task with very specific weight and strength requirements, and subjecting the evolved structures to rigorous laboratory testing.

The algorithm presented evolves a generic unit of connections which can be made to accommodate the specific forces presented in given real world problems. Future work would involve constructing objects which, while under these specific loading conditions, have a variety of differing node placements in each unit cube. These nodes will vary continuously throughout the object to accommodate the change in direction of the applied forces on that point, and member widths will vary to accommodate changes in magnitude. These local effects are seen as the tools for a larger scale optimisation as described in the example of the 'I' cross section beam in Fig. 2. As such these tools will be applied to problems of greater complexity.

Acknowledgments

We would like to thank Thomas Modeen for his continuing investigation into novel applications for rapid prototyping techniques, and Chris Williams for his knowledgeable advice and inspiring structural engineering methods.

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Appendix 3

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Ubiquitous Customization - Utilizing Rapid Manufacturing in the Production of Design and Architecture

UBIQUITOUS CUSTOMIZATION – UTILIZING RAPID MANUFACTURING IN THE PRODUCTION OF DESIGN AND ARCHITECTURE

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Over the past few years the term and notion of ubiquitous customization has entered the parlance and discourse of the design and architecture related research disciplines. However, whatever its guise, much of what this has entailed is usually explored and formulated through a language that still seems to persist with production processes that aren't much different than those utilized over the last half century - the 'tools of the trade', when it comes to actually implementing a building, are more or less the same, resulting in the modus operandi becoming a question of logistics rather than something more original and reflective of the digital processes we nowadays use to conceive our designs. Over the last few years, however, a number of potentially fundamentally pioneering fabrication techniques have entered the picture. One of these, Rapid Manufacturing (RM), has a number of factors that innately lend themselves for such parametrically variable production suggested by the title. This rapidly evolving branch of fabrication and means of conception, that has one foot firmly rooted in the digital realm, the other one in the analog world, is already in the process of instituting a paradigmatic shift in the way we envision and construct our built environment. The defining taxonomies and semantic patterns that allow for such pervasive variability of making and thinking about our built environment, and all that that entails, are still in the process of evolvement, however, preliminary suggestions of how such methods might operate and appear can already be observed. The projects included reflect and partake in the evolution of this still developing manufacturing discipline.

Keywords: Architecture, Design, Rapid Manufacturing, Ubiquitous Customization

INTRODUCTION

For many the term 'ubiquitous customization' is somewhat of an oxymoron, for how can something pervasive also be, as the term suggests, almost infinitely varied? The expression, in which the initial word seems to suggest a latent trait of uniformity and large scale repetition (a form of omnipresence), is seemingly capriciously combined with a term that alludes to something bespoke, subjective and one-off. The rapport between the two flanking words seems at best to be an affiliation of hovering, but tolerable, compliance, at worst a case of something disruptively discordant and nonsensical. The notion of something ubiquitously customized is potentially fraught with controversy.

Also, what exactly would the advantages be of such a process? Why would someone wish to have a product that can be seemingly infinitely diversified? In fact, isn't it exactly the consistency of a product, be this a type of Linguini or a pre-fab building component, which in this context is its valued quality? Isn't it precisely this evenness, its non-variability, and thus predictability, which is appreciated? Indeed, aren't our shops and warehouses stacked with countless quantities of such replicas, rows upon rows of indistinguishable products lining their identical shelves? Why would one wish to change or adjust such over centuries evolved principles and logistical systems of taxonomies?

However, when the aforementioned issues are scrutinized in a bit more detail it becomes apparent that variation is inevitable. The more complex and involved the process of conception and fabrication, the more opportunities there are for differentiation to occur. Such slippage can of course be reduced by rigorous planning and supervision, however, some level of discrepancy will always be present.

Also, if considered from a slightly different angle, as objective, uniform and effective as we would like to claim our universal products to be, the notion of what its 'function' entails can be surprisingly varied. In other words, the object might be identical, however, how we use it varies. The 'genotype' of the concept is inescapably varied in its 'phenotype' implementation. Such diversity in use can range from, say, the simple variations in mannerism regarding how, and in which hand, we hold our fork, to more complex reflections of both cultural and social peculiarities in how we perceive and occupy space, the different ways we, for instance, sleep, dine or even socialize in and around different both private and public environments and occasions. The cultural anthropologist Edward T. Hall has written extensively on the subject (Hall 1966, Hall 1983).

Such subtle, yet still premeditated, societal diversification usually appears in the details of a product that can manifest themselves in the application of a design (as in the way in some parts of the world it is the custom to leave the protective plastics on the seats of a recently bought car for considerable periods of time so as it will appear 'new' for longer) as well as in variations in the form of the design (left and right handed scissors, variations in public toilet design between the genders and cultures).

PERVASIVE TECHNOLOGY

"Recently we have witnessed a paradigm shift from cyberspace to pervasive computing. Instead of pulling us through the looking glass into some sterile, luminous world, digital technology now pours out beyond the screen, into our messy places, under our laws of physics; it is built into our rooms, embedded in our props and devices – everywhere." (McCullough 2004: 9)

The notion of ubiquity is particularly prevalent in the realm of technology (which in this context will includes building technology) in which each of us on a daily basis seem to engage with variously pervasive, yet somehow customized, interfaces and devices, be these personal computers (with customized PC shells and desktop patterns), mobile phones (with individualized ring-tones), or even Apple's iPods (with their personalized play-lists). We desire the recognizable brand (the value object), whilst simultaneously aspiring to differentiate and individualize such, still by default generic, artefacts as our own. However, such individualization is inevitably a retroactive manipulation of a standardized product. Only in the most exclusive (and thus often dear) designs is there the potential to tailor the design to befit its intended user perfectly from the beginning. This is in particular true in regards to how we conceive and build our houses. The notion of custom-built buildings is usually reserved to only the most exclusive or high-spec or prestige construction projects. Very seldom does one come across such bespoke building in more 'ordinary' developments such as schools or social housing. Such lack of customization is usually justified by the apparent cost such construction typically entails. Alas, at some level this type of rationalization and pseudo-validation has to be classified as a type of misinterpreted apathy, as anyone directly involved with any type of more involved building project must realize is that there seldom is such a thing as a 'generic' application, that the recognition, consideration and appropriation of a project's specific nuances do matter, and if these are not recognized early enough, they will inexorably raise their ugly heads later in the lifespan of a building, usually when correcting them will require exponentially increased quantities of time, effort and finance.

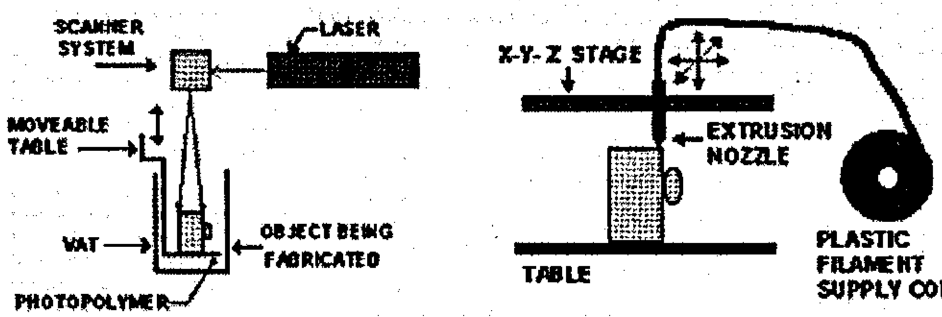
In the context of the aforementioned 'technology' (here interpreted in its more suggestive, utopian sense) has often been touted as the solution to the various, usually somewhat unspecified, social ills and implementation related shortcomings. However, on a directly implementational level this 'technology', be it the various takes of CAD (Computer Aided Design) or any of the more logistics based applications, has had only a marginal impact on the way we actually conceive, erect and realize our buildings. We're still predominantly dependent on similar, if not the same, tools and construction mediums (cranes, scaffolding, and manual skills) that we did four decades ago, long before the 'digital-age' took root (http://www.freeformconstruction.co.uk/environmental_fc.htm). We still seem to be dependent on realising our three-dimensional and physical constructions based on two-dimensional technical drawing, saturated with iconic representations (abstractions) of anything from insulation to fire-hydrants; drawings through which we interpret the building to be through various standardised notion of plans, elevations and sections. At some level 'technology' has allowed us to up the pace of how we mechanically actualise things, be these construction drawings or even buildings, however, the means by which we do so remain more or less the same.

Alas, for those with a 'nose' for related matters, there's been a distinguishable whiff of something new in the air emanating from the fringes of the associated professions over the last few years. There seems to be an evolving sense that many of the currently somewhat peripheral activities that have been taking place in the various related branches of academia and, usually more small scale, architectural practice are approaching some form of a nexus. One such node is at present known as Rapid Manufacturing.

RAPID MANUFACTURING

Raid Manufacturing (RM) is an evolved derivative of Rapid Prototyping (RP), which itself is still a relatively recent phenomenon within the design related disciplines. This process, that is a form of three-dimensional printing, is a procedure in which a virtual three-dimensional CAD model can be physically reproduced by gradually assembling the design by stacking layer onto thin, almost microscopic, layer of material (that can range from various photo-polymers, to ABS plastic, gypsum, nylon, starch, to even diverse metals) to eventually build an accurate physical replica of the initial computer based model. This technology is still predominantly used within certain sections of engineering, medicine and, within architecture, for the production of usually quite complex and detailed scale models of buildings. Similar results could potentially be achieved by other means, but it has proven to be comparatively both quicker and more precise to fabricate them through RP.

The main difference between Rapid Prototyping and Rapid Manufacturing is that whereas RP is used for predominantly conceiving a mere three dimensional representation of a design concept (that is usually used in the context of a presentation), RM aims to conceive things that are the actual, bona fide, final utilitarian thing. The technological means are still essentially the same in both RP and RM (the materials used in RM are usually more robust) only in RM the aim is to use the intrinsic pros of the processes to their advantage in the implementation of a design instead of merely creating an initial conceptual simile of a design that is to be produced by other, usually more traditional, means at a later date. The designs realized through RM use the process as a catalytic factor in the realization of the design and would be very difficult, if not impossible, to be made by any other means.



Illustrations outlining the SLA and the FDM processes

The Cons and Pros of the Rapid Manufacturing Process

Some of the current disadvantages of the RM process are:

In real time the build speed is quite slow. Depending on the required level of accuracy and the size of the design the process can take from a few hours to a number of days.

Currently there are some limits to the size of objects one is able to produce. Most commercially available machines can still only fabricate items within a roughly five-hundred millimetre cubed volume. There are, however, already a number of exceptions to this rule.

The number of materials available for additive RM is still somewhat limited, particularly in comparison to those appropriate to CNC-milling (a routing based subtractive process). Again, however, the number of suitable materials specifically designed for the various RM processes is increasing rapidly.

The final surface quality usually needs some secondary finishing, this applies in particular to smaller, tangible, objects in which finishing is of more importance.

The completed piece is usually structurally less sound compared to a cast component (Kwon 2002). Although, yet again, there are already some exceptions to this generality.

Some of the advantages of this procedure are:

Direct generation based on digital data, without the errors arising from a tradesman's interpretation of the designer's drawings (http://www.Ennex.com/~fabbers/intro.asp).

Ease of iteration. Part of a design can be changed and the object re-fabricated without the need to redo the design of the entire object (http://www.Ennex.com/~fabbers/intro.asp).

Accuracy and repeatability of dimensions on the order of 25 to 250 microns (http://www.Ennex.com/~fabbers/intro.asp).

The ability to produce complex and detailed three-dimensional forms. The additive process allows for deep undercuts as well as features such as building pieces within (even enclosed) other pieces ('Ship in a Bottle' structures), properties that would be very difficult, if not impossible, to produce directly by any other means.

Reduce lead times for unique parts Unlike in many machining operations, no jigs, moulds, or other external support devices are needed to fabricate the object (Callicott 2001: 144).

As most RM processes are completely enclosed, thus producing very little noise and waste, a clean production environment is produced that allows for the installation of the machines into non-industrial environments (Callicott 2001: 144).

TOWARDS PROTEAN TENDENCIES

There is also a financial argument for why the above notions are of importance. As our own desires are gradually progressing towards more and more personalised realm, our means for realising and accommodating such cravings need to keep pace. Or as the two Swedish economists below argue:

"Those who lack the capacity and willingness to make sense of fragmentation – to operate in an institutional vacuum of increased individualism – will have a tough time. They simply will not possess the adaptive capacity so vital for success in a fast-changing world. Both attitude and adaptability are central.

People lacking such 'protean' capabilities, as sociologist Robert Jay Lifton calls them (referring to the Greek sea god Proteus who could take any shape at any time) will be at a huge disadvantage. [...] Power is being transferred from the rule-takers to the rule-breakers and the rule-makers." (Ridderstråle and Nordström: 46-47)

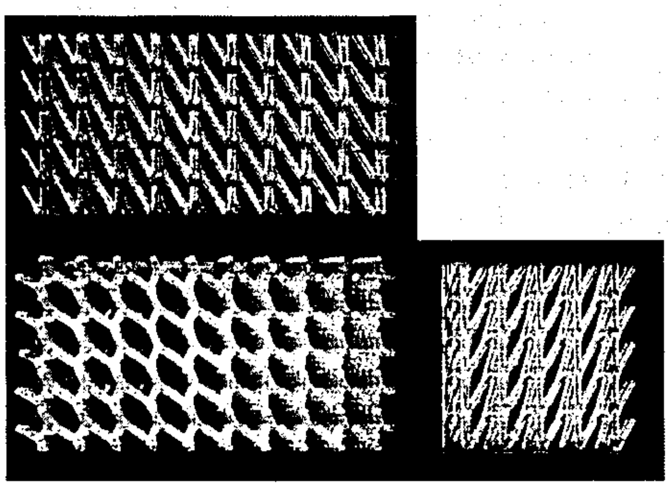
It is here, in the context of the aforesaid (quoted from a book dealing with current emerging socio-economic conditions), that Rapid Manufacturing enters the picture and gains significance. Assuming the suggestive quote above is even partly accurate, RM could provide a proposition by which such 'protean capabilities' can be achieved. With enough forethought, RM has the processes and tools by which such preordained variableness of individualistic fragmentation could be understood and realized. If our built (designed) environments are a manifestation of us as a collective of individuals, RM could provide a venue for how the things we make can become reflective of such individualism. RM already has the structures available to accommodate such parametric variability.

PARAMETRIC DEXTERITY

Some of the distinguishing qualities innate to Rapid Manufacturing are pivotal in the aforesaid assumptions:

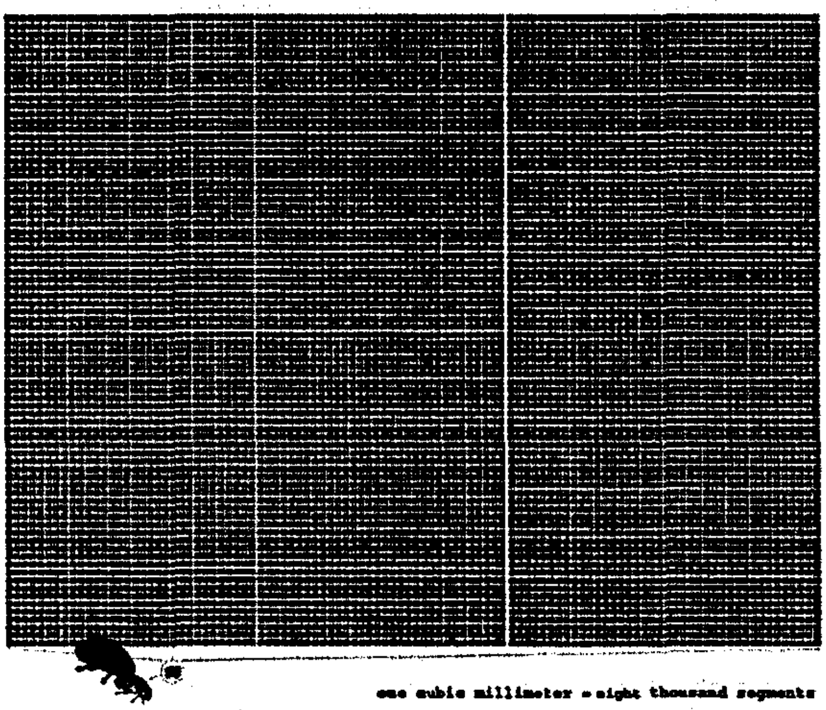
Firstly, through the RM mode of fabrication one can manipulate a (RM) material at a remarkably minute and accurate level. For example, in stereolithography, a process in which a photo-sensitive resin is cured by a laser, the machine's default resolution is a twentieth of a millimeter. This entails that if one was to make a millimeter cube (smaller than a pin-head) it could potentially be consistent of up to eight-thousand variable components. This fact introduces a whole new setting for how a design can be formulated and actualized. At this scale, which mostly surpasses beyond our somatic sensory perception, one can actually begin, not only to apply, but to design, a texture. Also, by being able to control elements at this minute scale one can actually begin to design the qualitative material properties of the design instead of having to 'collage', connect and shape different materials to fulfill the same function.

This means, for example, that if one, say, defines one of the core building components of a design as a minuscule 'rod', and by allowing such minute rods in a tessellated RM matrix to be thicker in one direction and a bit thinner and longer in another, or by angling the fibers into or away from the expected direction of impact, one can allow the physical model to have more strength in the one direction and more flex in the another (Assuming the innate properties of the used (RM) material allow for this). Or, by adjusting the 'density' of the tessellated matrix (the size of, and distance between, the nodes), one can control the 'solidity or how 'porous' this particular locale of the design would be. Also, by, say, connecting and shaping the fibers of this 'digital-shrubbery' to follow a weaved, spiraling, spring-like, pattern, one can provide the design with a controllable 'bounce' (or a degree of 'softness'). An early sample of such a responsive and variable structure can be seen below. Initial attempts at such minute manipulations have already been attempted and partly attained by a project done in conjunction with relevant strands of research pursued at the University College London(Hanna, S and Haroun-Mahdavi: 2004).



A tessellated variable cube, built and reflective of, the particulars of the stereolithography process and a set of simulated external constraints. The project was developed in conjunction with Siavash Haroun Mahdavi and Sean Hanna of University College London who where responsible of the programming that guided the process. The sample was built by Rapidform, London.

Now, the logistics and taxonomies guiding such metadata (data about data) is, suffice to say, a separate subject in itself (dragging an vast number of subtopics in its wake), however, the means by which one would control the arrangement of such immense amounts of data that realizing this type of design would involve would be managed by various linked networks of algorithms (Genetic Algorithms, Cellular Automata) (http://www.uel.ac.uk/ceca, as well as various simulation and optimization programs (Finite Element Analysis, Computational Fluid dynamics).



Eight-thousand manipulative components in an area smaller than a ladybug

Secondly, there is no need for templates or formwork in the Rapid Manufacturing mode of fabrication. For the RM machines it is irrelevant if two consecutively produced designs or components of a design are the same or different – if the variable design's volume and resolution remains roughly the same the technology can handle each with equal ease. Here, when considered within the context of RM, time and cost related restraints aren't an issue. This means that realizing a design is mainly limited by our own ingenuity.

Thirdly, even though the RM means of conceiving a design have a foot in both the digital as well as the analog world (a distinct advantage to most other digital, purely CAD, based modes used today for conceiving things), entailing that a number of degrees are removed between the conception of an idea and its realization, the fact remains that the resulting product, in its completeness, is also going to manifest itself as a purely digital data file. This means that the design can be, either wholly or partially, reproduced without any excessive interventions from secondary parties.

Also, as the technology is already somewhat generic (the RM machines can already be bought through relevant retail outlets) the production, or reproduction, of designs through the RM means aren't necessarily locale specific. A file can be produced in

London, swiftly sent through broadband to Madagascar where it can be immediately fabricated without the involvement of intermediaries. This factor also means that no, say, spare parts would be needed in hard to reach places as only having a RM machine and some of the pertaining material would allow one to 'print' out any needed components directly. All one would need is a hard drive with all the various potentially needed spares saved as three dimensional digital files that could then be fabricated according to need.

By conceiving a design through the modus of RM a whole new realm of conception and fabrication related 'nuances' are introduced.

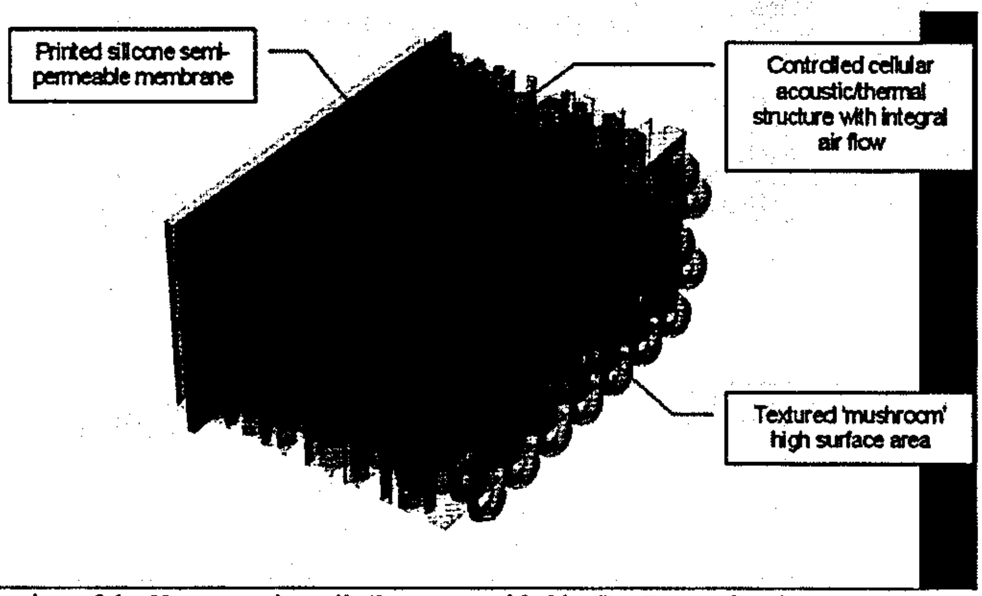
RAPID MANUFACTURINGED DESIGNS

How such matters can be formulated and implemented is provided, in brief, by the two included examples below. The initial one, devised at the Rapid Manufacturing Unit at Loughborough University, is a homeostatic wall unit that in one comprehensive go would provide all the required services and various material properties required through a singular monocoque build. The second example included is of an epidermal surface design titled 'Design Ground'. This design allows one to, through the use of a simple predetermined and intuitive 'tactile-iconography', create a customized surface that can be 'read' solely by the means of touch. Both of the included examples would not be practical to produce, due to the needed parametric variability, through any other means than Rapid Manufacturing.

HOMEOSTATIC WALL

The notion of a Homeostatic wall is one constituent of the more encompassing notion titled an 'Optimised Structure', a term used to describe a means through which a design can be realised, through the use of a single or limited amount of materials, that fulfils all the requirements of a structure - its tectonic considerations, its various services – that would all be fabricated in one go. This means that the various types of piping and ducting, even the integrated wiring and optical distribution systems, could be 'printed' simultaneously into epidermis like walls. How such various, potentially conflicting, chores would be distributed and synchronised would be determined by Computer Aided Optimisation or Metamorphic Development techniques with solid CAD (UG/ProE) software (http://www.freeformconstruction.co.uk/integration.htm).

The project is also partially inspired and derived, as the heading suggests, by various biomimetic factors, diverse dynamic systems found in nature. In this instance the workings of various termite mounds have been of particular relevance. The structure they build, within the mound, is so innately autonomous that it is able to regulate and control their environment even beyond the levels we currently expect from our own heating and cooling systems, and they achieve this without the use of any external power sources. In effect, these termites have evolved a construction method so advanced that it can control its internal environment to within fractions of a degree, regardless of how much the external environment is fluctuating (http://www.freeformconstruction.co.uk/fc_structural_homeostasis.htm). The aim is to appropriate such quite remarkable accommodating and responsive abilities in the structures we conceive for ourselves.



Section of the Homeostatic wall. (Image provided by Dr. Rupert Soar)

DESIGN-GROUND

Initially constructed around a design competition brief for a Swedish flooring company, this project was construed around two fundamental catalysts, firstly, it should try to conceive a digital design that does not solely rely or result in something purely visual; and secondly, to use Rapid Manufacturing as the means through which the design is realised.

The resulting creation, inspired by the various patterns formed by the multitudes of discarded chewing-gum found on the pavements on London's Exhibition Road, formed a tactile epidermis, a surface into which various haptic (cutaneous) relief-like signs could be embedded (somewhat similar to Braille), that could be used to both inform and insinuate various features or qualities found in the environment. For example, if the surface was shaped in a scale-like manner (as in the scales of a fish or snake) one is immediately provided with a texture that is smooth in one direction, rougher, or more resistant, in the other. Such a binary differentiation can immediately be used to fulfil a number of functions. It could be applied in, say, hospitals, hotels or airports to function as a tactile tool to inform people where the closest fire exits would be. In limited visibility, if the air is full of smoke, all one would have to do is pull ones foot (or hand) over the surface, and follow the least resistant texture to the nearest fire escape. This texture could also easily be inlaid with additional, more subtle, clues for how to proceed as well as with other environmental information - tactile dots to measure distances; make the surface texture more or less coarse to suggest how fast or slow someone should, or can, move, etc.

Even though the principals guiding the design are simple, the parametric applications of the various textural and information based layers make it almost infinitely variable. It would be close to impossible to realise this design by any other means than Rapid Manufacturing. The design is currently in its initial testing phase.

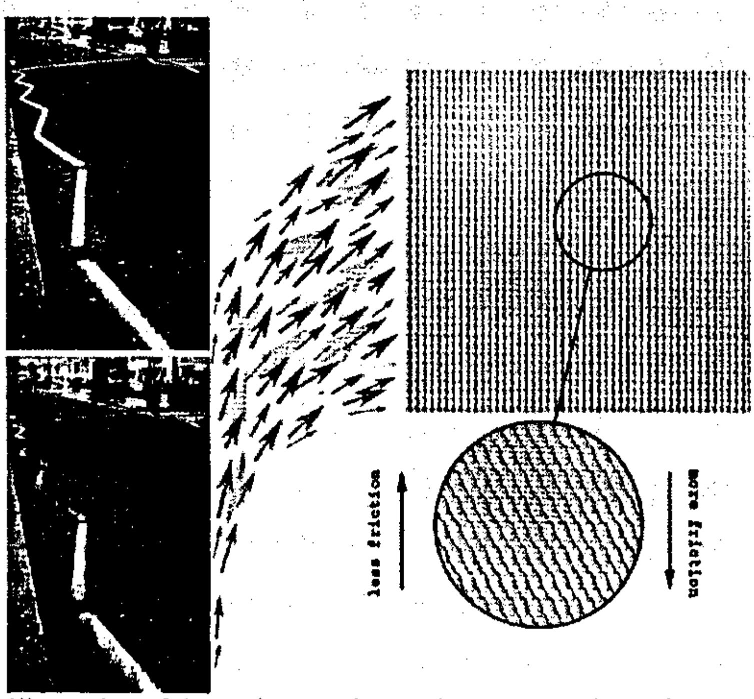


Illustration of the project catalysts - the patterns of chewing-gum on London's Exhibition Road.

CONCLUSION

As laudable as the aims suggested by the combination of such seemingly contradictory terms as 'ubiquitous' with 'customization' are, the implementation of any more involved bespoke a design inevitably entails the need for a modicum of control, usually manifesting itself through a limitation of dissimilarity, that, nevertheless, often has a habit of superseding the end aim of producing a successful customized product. Alas, idiosyncrasy always seems to hide in the corners of even the most generically applicable, researched and market tested creations.

Rapid Manufacturing as a means for both conceiving as well as fabricating something designed (for inescapably everything we do, for better or worse, is designed) introduces a paradigmatic shift in the way one can approach the whole process of actualizing a design. By streamlining and enmeshing the phases between initial tentative conception of an idea, and its final conclusive actualisation, that includes intrinsically all logistical, financial, hierarchical considerations, the process becomes more comprehensive in its formulation. The allowance for variability is an innate factor in this means of creation. By being a digital process that is intrinsically linked to (a or its) physical outcome, a number of intermediate manufacturing stages separating the idea from the final end result are removed Here there is no call for any type of batch production as the RM means allows each individual design produced becomes, in a way, its own 'batch'.

The (not too distant) future prevalence of Rapid Manufacturing, regardless of how convoluted or altered it might appear, in whatever composite hybrid form, is guaranteed. The question is, are we going to be prime movers or vassals in the process? Originating and idea, the foundations and means for doing something in a certain way, is always difficult, and requires copious and ceaseless quantities of faith in notions that usually, at least initially, are not much more than intuitive suggestions.

How receptive we are to this and similar branches of still evolving technologies will ultimately determine our position and role in a more and more knowledge based world. To embrace something that is still being defined on a fundamental level is simultaneously a risk and an opportunity. Alas, the (still somewhat dormant) potentials of Rapid Manufacturing are too tempting to resist, and partaking in the creation of something of significance is a rewarding process in itself. One must only hope that such opportunities have a chance to bloom and that the fertile grounds for related memes (idea viruses) to germinate will continue.

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Appendix 4

ACADIA 05 Smart Architecture - Savannah

Design Ground - An Iconic Tactile Surface

Design Ground - An Iconic Tactile Surface

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Abstract

This paper forms an intermediary summary of a project which aim is to suggest an alternate methodology for utilizing additive Rapid Manufacturing (an evolved rendition of Rapid Prototyping), for the conceptualization and fabrication of design and architecture. It plans to do so by establishing a methodology that is innate and a direct reflection of the additive RM production process. The project also aims to address the seemingly divisive discrepancy between the process of digitally conceiving a design and the intrinsically somatic way we perceive it.
Such aims are explored through a surface design that is not predominantly guided by visually derived nodes but instead relies on a form of 'tactile iconography' as a means for expressing and amplifying various qualities and elements found in its vernacular. The resulting design would be very difficult, if not impossible, to make by any other means.

Introduction

"The entire body may 'know' a dance. In such cases, knowledge is all the more likely to be physically inscribed, without an overtly intellectual component."

Quote from Malcom McCullough's book, 'Abstracting Craft: The Practiced Digital Hand.'

The project was instigated based on two defining parameters.

Firstly, *to produce a sensorially inclusive design.* To produce a design that 'looks' beyond visual, or visually derived, stimuli. To allow the haptic (touch), auditory (sound), kinesthetic (motion), and all the substrata of such perceptual formulations (temperature, vibration, pitch, treble, rhythm, obliqueness, texture, friction, etc.) to play a more involved role in the conception of a design. To produce a design framework within which such aims can be achieved...

Secondly, to use Rapid Manufacturing (RM) in the formulation of the designs conceptual foundation as well as for final physical fabrication. To, through the conception of a design, suggest a way in which this quite remarkable, and still evolving, technology could be formulated in a way that reflects and utilizes its intrinsic qualities instead of merely mimicking alternate fabrication methods...

Project Catalyst

"Wittgenstein liked to say that the most difficult problems are the ones right in front of our eyes, the ones we don't see *as* problems. Those are the ones we have to struggle to perceive."
Quote from James Elkins' book, 'The Object Stares Back - On the Nature of Seeing.'

The project was initially constructed around a competition brief provided by the Swedish flooring company 'Pergo'. The brief was left somewhat undefined, requesting its participants simply to design something 'innovative', and that such novelty should happen in/ on the plane below ones feet.

How such an open brief was developed for this particular project was initially prompted by the, to some extent peripheral, qualities of the paved surface around the neighborhood of London's Exhibition Road in South Kensington, an area occupied by number of the city's main museums and galleries. However, it wasn't necessarily the more, call it, 'highbrow' aspects of this locale that were of interest, but the more peripheral marks of human/ urban occupation – the blots of discarded chewing gum that seemed to saturate the streetscape. There must have been thousands, tens of thousands, hundreds of thousands of these, predominantly off white, specks carpeting the main segments of the road and flanking sidewalks.

Observing these blots closer it was interesting to note how one could decipher their approximate location on the road simply by their shapes and the patterns they formed. Very dense around and just outside the sidewalk curb. Dense, but more pronounced, by pedestrian crossings; less dense and elongated by the main or central footpaths; and sparse by the inside (building side) of the sidewalk.

These patterns, somewhat suggestive of Braille (the tactile reading and writing method used by the visually disabled), provided the initial clue for how to proceed.

What if, instead of merely passively interpreting these aforementioned patterns, one would provide them with meaning, immerse them with performative attributes that could inform one of their immediate vernacular on a more planned and specific level? Could one, by manipulating such patterns' surface and consistency, create an additional strata of, non-intrusive, sensory stimuli that, ideally, would not only enrich the streetscape on a purely perceptual and affective level, but craft something that could also act as a functional tool for conveying empirical information to those with, and without, a sensory disability? Could the surface be made to perform an amplifying role in clarifying the features of its immediate environs?

Design Implementation

"As the most ancient and largest sense organ of the body, the skin enables the organism to learn about its environment. It is the medium, in all its differentiated parts, by which the external world is perceived."

Quote from Ashley Montagu's book, 'Touching - The Human Significance of Skin.'

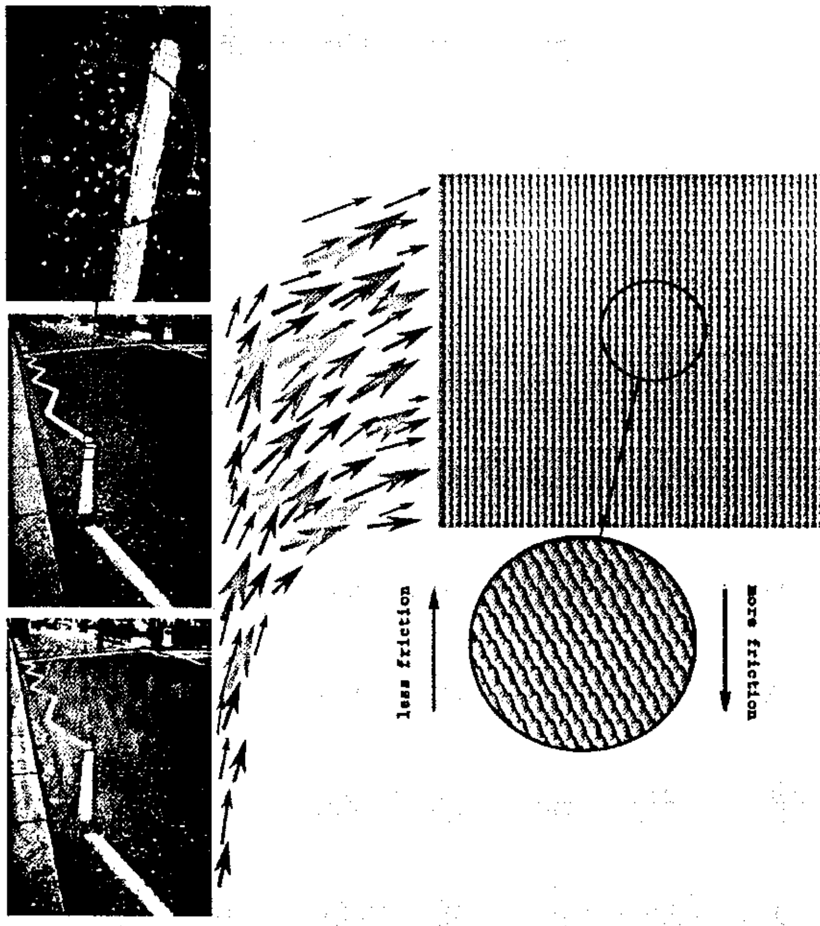

Figure 1. The project was catalyzed by the 'field' of discarded chewing-gums on London's Exhibition Road. These patterns were used to suggest how the consequent patterns of the surface should be implemented

How such concerns were put into practice required that the aforementioned gum-patterns be conceived within a more regimented framework. This entailed that the initially more randomly distributed gum-blotches were conceived as a fish-scale like array of small tactile components that allow for a surface with a binary and directional pattern (the surface is smoother in one direction, and 'rougher' in the other).

This surface could consequently be 'enriched' by applying simple binary 'deformations' to the core pattern. The scales of the surface could be made (gradually, as on a sliding scale) smaller or larger, thinner or wider, more or less pronounced, etc., according to various predetermined and intuitive haptic iconographies. This fish-scale pattern could also be curved towards, and obliquely angled, to show and insinuate various surrounding features (as, say, the entrance of a building or an approaching pedestrian crossing).

One could even, by manipulating the consistency of the fabrication material (something that is possible thanks to the minuteness and accuracy at which one can control the composition of a material through this technology), change its tactile and even auditory qualities. I.e. by making the surface more or less dense, and by patterning such consistencies according to various utility and performance based configurations, one can make the surface 'feel' and even sound different (when walked upon) at various locations.

How such features are actually applied is explained further in the following chapter, however here it is worth noting that the paradigms within which the aforesaid notions have been conceived in have

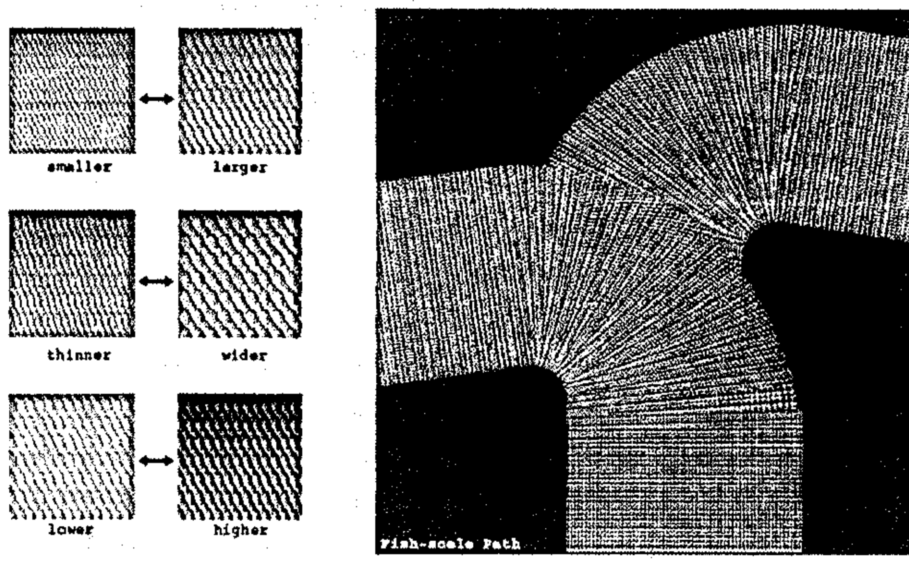

Figure 2. *Illustrations of how one can amplify the affective qualities of the surface by simple binary means – making it more or less pronounced, wider or narrower, smaller or larger, etc. The scale pattern can also be made to curve or/ and angle towards various relevant nodes in its vernacular*

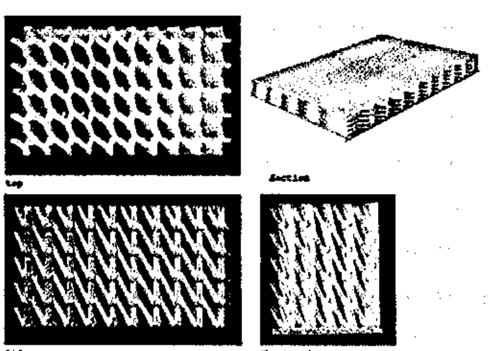

Figure 3. *An example of how the surface properties could be affected – here by setting up a truss matrix which constraints were determined by the properties of both the fabrication process and its accompanying material. Here this entails that the make-up of the designs truss based structure can be adjusted according to a responsive algorithm that can be attuned to reflect particular tactile traits, such as softness, elasticity, or a variety of different textures... This aspect of the project was developed in conjunction with Sean Hanna and Siavash Haroun Mahdavi from University College London, the Bartlett (school of architecture) and Department of Computer Science*

all been guided by a framework set by what the relevant technologies (both software and Hardware based) allow for. This entails that the size, patterning and modulation of the designs become somewhat arbitrary – for to fabricate the design(s) it is its mass and volume, not its complexity or the repetition of a set formulae, that matters. Here there is no need for a fabrication template (entailing a set of identical pieces) as for the RM machines it is equally laborious to produce two (or more) alike pieces as it is to produce a number of, roughly equal in mass and volume, but still drastically different components. This is both the processes advantage and its crux, as the seemingly almost infinite freedom this means of production seemingly entails, it still needs to be defined and thus confined, according to some form of predetermined parameters – a protocol that is still in need of further revisions before a set, almost innately settled, modus operandi has been established.

Design Application

"Smooth surfaces invite close contact, while rough materials such as hammered concrete generate movement in wide radii around corners and more careful, tentative movement through corridors. Changes of texture often signal special events and can trigger a slowing or quickening of pace. It would be possible to generate a whole choreography of movement through the composition of textural changes alone."

Quote from Kent Bloomer's & Charles Moore's book, 'Body, Memory and Architecture.'

How such aforementioned interests could be applied in a design is illustrated in the example below.

In a generic streetscape four key nodes of a pedestrian sidewalk are recognized: the main (or 'spine') path of the sidewalk, the entrance to a building, the curb, and the area of a pedestrian crossing.

Applying the aforesaid principals to each of these four key locales the various surface properties could differ as follows:

- *The main path of the sidewalk:*
    - Directional (fish-scale) pattern applied along the main spine of the pedestrian passage.
    - 'Medium' porous consistency.(1)
    - Level, horizontal, surface.
    - Surface sound 'A' (generic surface sound).
- *The entrance to a building:*
    - Directional fish-scale pattern towards the entrance of the building.
    - More solid surface consistency than along the main path.
    - Slightly convex slant (surface obliqueness) towards the building entrance.
    - Surface sound 'B' (a 'harder' sound than sound 'A').
- *The curb:*
    - Directional, skewed, fish-scale pattern.
    - Higher, more pronounced, texture.
    - Surface level slightly higher than along the main path (the surface is oblique down towards the main spine of the sidewalk).
    - More solid surface consistency.
    - Surface sound 'D' (more 'hollow' than surface sound 'A').
- *The pedestrian crossing:*
    - The fish-scale pattern fades into blister paving.
    - Slight, gradually increasing, concave surface tilt towards the crossing.
    - 'Softer' surface base consistency.
    - Surface sound 'D' (more 'muted' than surface sound 'A').

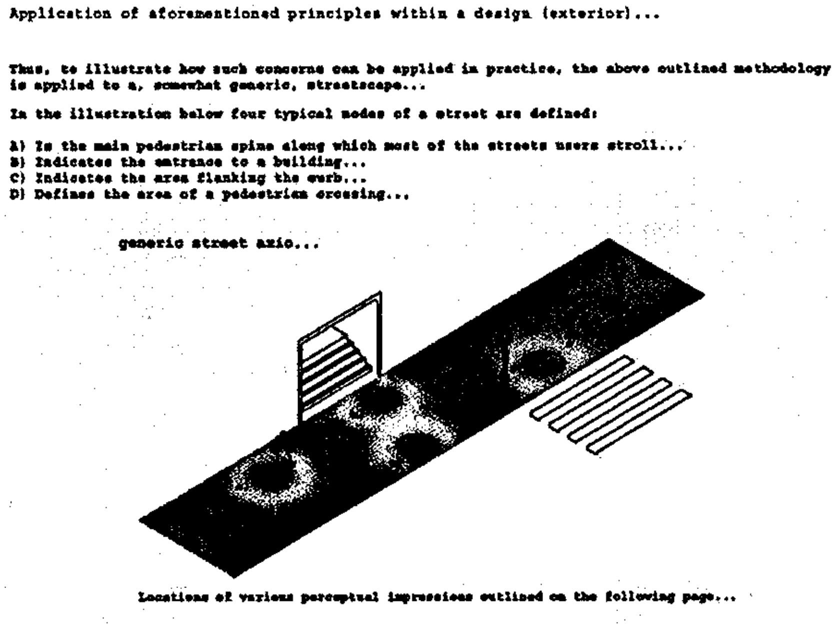

***Figure 4.** A generic streetscape in which four key nodes are recognized*

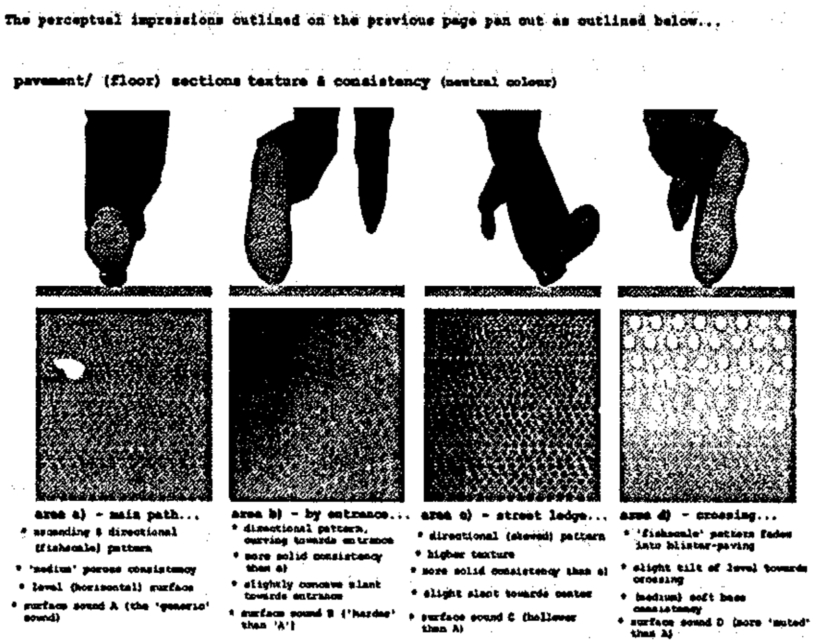

Figure 5. *Breakdown of the variations in perceptual properties between the four key nodes of the generic streetscape*

Even by the application of such a reduced taxonomy of iconic nodes an almost infinite variety of interpretative options and variations of patterning cold be applied to the surface. The inherent flexibility of this parametric process also allows for the adjustment of the surface for a variety of different formats, be these for interiors (entailing a 'toning down' of the surfaces coarseness), to even applying these principals to a wall surface (as briefly outlined below).

A number of physical prototypes have also been fabricated, both through the use of a Selective Laser Sintering (SLS) machine, and a Stereolithography (SLA) machine, allowing for the testing both the tactile surfaces operational, wear & tear and function related, practicalities, as well as the surfaces more ethereal characteristics, how it actually 'feels' and how easy or intelligible the surfaces intended expressive qualities actually are.

Additional Adaptations of the Design

"The hands of the sculptor are independent organisms of recognition and thought; the hands are the sculptor's eyes."

Quote from Juhani Pallasmaa's book, 'Polemics - The Eyes of the Skin.'

As insinuated above the project has also explored additional means for how the principals examined could be adapted to serve a variety of other purposes. These include developing the Ground Design in more, call it, 'expressive' ways to, say, change its color when the surface get dangerously hot (which would be useful when in the vicinity of a stove), or, by making subtle indentations in the surface, make it form, when it rains, 'Designer-Puddles' in the shape of images letters or paths. It could also be conceived in the format of a wall surface, a continuous organic relief of sorts, that would allow one to perceive or read things through the use of ones palms and fingers. Even further applications are being explored – the potentials for such parametric conceptions seem to be almost limitless...

Conclusion

In conclusion, the aim of the project is to establish a way of designing something that utilizes and is instigated by digital (CAD) based means, here

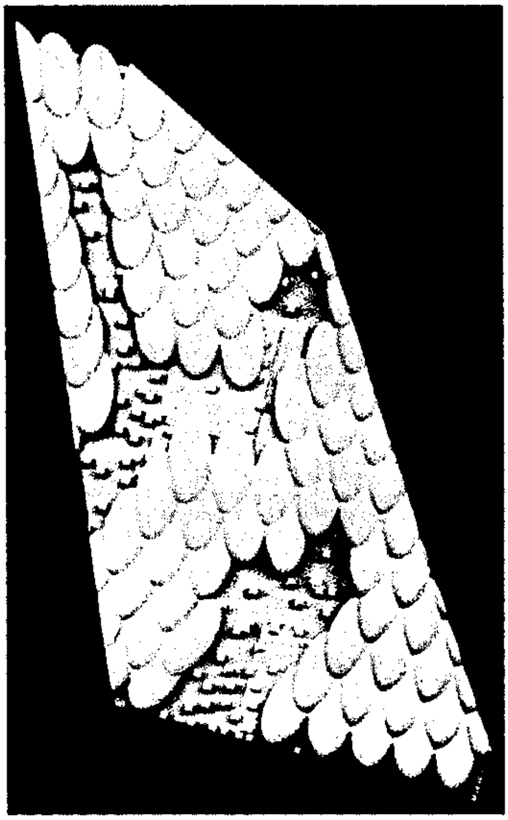

***Figure 6.A** 'Rhino' modeled, sectioned Selective Laser Sintering (SLS) model of the Tactile Paving*

***Figure 6 B.** segment of the Tactile Wall-Scale Surface prototype, made through Stereolithography*

through the use of Rapid Manufacturing, but does so without omitting the more innate sensory qualities of what usually makes one respond and appreciate a design (its physical presence, things such as its texture, apparent weight, or even the subtle 'sounds' it makes). By considering all the various tactile, auditory, in addition to the more obvious visual, aspects of the design already in the initial (digital) conception stage of the project, along with attempting to tie such considerations in with the process used for actually fabricating the design, hopefully a more accomplished way for how one could achieve a more sensorially provoking and invigorating end result is implied.

The design is still in the process of being implemented. Currently we're in the process of scaling-up, testing and fine-tuning further the aforementioned assumptions. But hopefully the final realization of the design will act as a non-intrusive, yet, for those actively seeking or are just generally more perceptually aware, subtly inciting additional source of either empirically informative or just purely pleasurable stimuli that would provide an additional enriched strata of embedded data that could reflect and interact with its users and environment without adding further to the already saturated clutter of the urban fabric.

The intent of the project is to suggest a somewhat deviant approach to how architecture can be perceived and conceived. Its aim would not be to exclude the other senses from the equation but to create a more comprehensive and attuned understanding of how, what we usually define as 'touch', could be included more inseparably into the grammar and vocabulary according by which we read, define, design and build our 'architecture' by. By utilizing something as immediate as touch as a catalyst for the brief the hope was to form the foundations of a more personalized and distinctive approach for how to understand and define our built environment. An approach that transcends beyond the purely pictorial (conceptual) and ocular drive that seems to saturate so much of what we today conceive of as architecture into a realm more in tune with how we actually sense things, both within and outside ourselves.

Notes

(1) Here terms such as 'medium', or 'sound 'A', are used as purely, hermetically comparative, expressions that are only referential to each other instead of some more generic (haptic or tone based) standard.

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Appendix 5

Sources of Architectural Form 07 - Kuwait City

Exploring the Tactile Traits of Additive CAD-CAM Production - The Role of Touch in Contemporary Architectural From Finding

EXPLORING THE TACIT TRAITS OF ADDITIVE CAD-CAM PRODUCTION – THE ROLE OF TOUCH IN CONTEMPORARY ARCHITECTURAL FORM FINDING

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Introduction

The use of Rapid Prototyping (RP), the technology by which a physical replica can be produced directly out of a virtual model, is still a relatively recent phenomenon within the architectural community. Particularly the use of the additive processes, such as stereolithography (SLA) or Selective Laser Sintering (SLS), have predominantly only been used within certain sections of engineering, medicine, and, within architecture, for the production of CAD based scale models of buildings.

Freeforming ('F2-ing'), a more evolved adaptation of RP, utilizes predominantly the same technological means as RP but differs from it in that instead of creating a mere physical representation of a project, it aims to use the technology to make the final completed design. This it does in a manner that reflects the more innate aspects of the fabrication process, its more tactile and material presence, already during the conception phase. The intention is to design things, environments and conditions that could not be realized through any other means than those related to Freeforming and to do so in a manner that utilizes some of the particulars and idiosyncrasies of the process of executing a design.

Forming

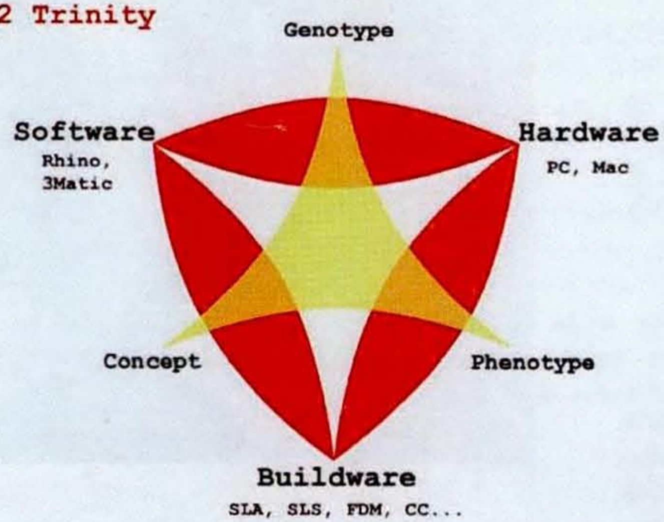
"We do not imagine the production of form to be the end point of design. We look for something more difficult and tenuous: to engage as directly as possible the environment within which design occurs. Adopting provisional strategies, then, is a technique for providing the designer with space within which to work, one outside of the relentless demands for form or novelty. At certain moments it is the search for freedom"[i].

These words by the Canadian designer Bruce Mau aptly summarize a fitting, and sufficiently generic, starting point and foundation for some of the pursued interests outlined below. Here the various constituents of the process are used to guide the development of the design without the burden of having any preconceived ideas about what the resulting 'form' of the design should be – a more evolutionary and symbiotic process in which subjective preferences and, call them, more 'objective' requirements are amalgamated into a more organic conclusion. In this case such polemics are built around two core premises:

- That the use of digital tools are used, even embraced, wholeheartedly in the conception and realization of a design, regardless of its scale or purpose (this does not entail the exclusion of alternate or more 'conventional' or time-honoured methods of design conception and fabrication).
- That a design is conceived, defined and judged according to a more comprehensive sensory spectrum, one that transcends beyond the merely visual realm.

The chart below provides a framework for how such aims are formulated.

F2 Trinity



Here the usual Siamese affinity, or orthodox duality, between software and hardware has been expanded into a trinity by the assimilation of 'buildware', denoting all CAD dependent fabrication (CAM) processes which build a physical object directly from a digital file - adjusting the paradigm into a more volumetric realm in which both the conception and fabrication (the digital and analog formation) of a design are more intrinsically united.

By re-conceiving the physical, CAM phase, of a (digitally ideated) design as a defining aspect of designing already from the more foundation stage will inevitably result in a design in which the corporeal and sensorial qualities are richer and more concluded. This applies particularly to the more tacit and haptic attributes of the design.

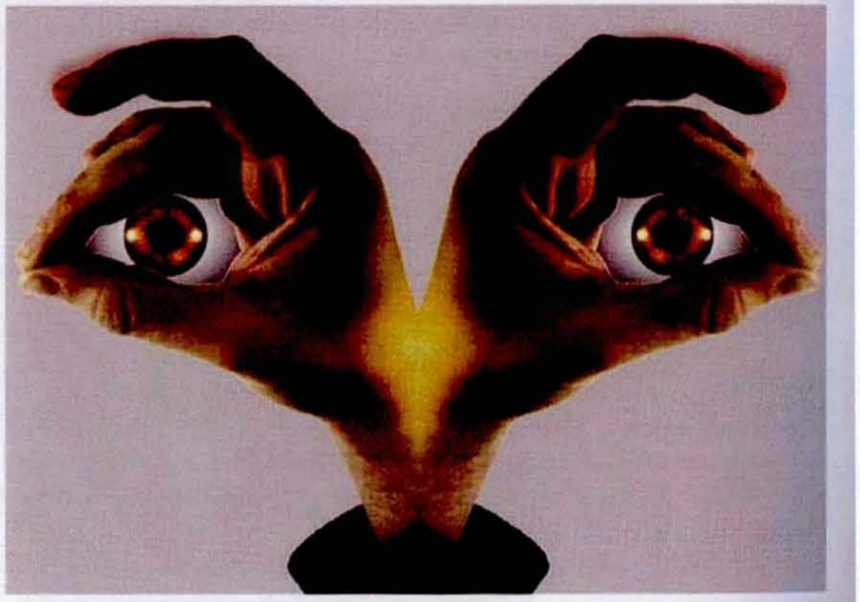
Allegorical Touch

"The sense of reality is also strengthened by the wide range of sensations a phantom limb can have. Pressure, warmth, cold, and many different kinds of pain are common. A phantom can feel wet (as when an artificial foot is seen stepping into a puddle). Or it can itch, which can be extremely distressing, although scratching the apparent site of discomfort can sometimes actually relieve the annoyance. The person may also feel as if the limb is being tickled or sweaty or prickly."[ii]

It seems like, at least to a degree, how we perceive, the format according to how our senses provide us with impressions and how such impressions are digested and manifested, is both a subjective and empirical process. Without excessively debating the more phenomenological, epistemological or ontological implications of such a statement it is clear that we can learn to see, hear, smell, taste and touch in ways that weren't immediately apparent before. One can learn to see patterns, or variations from such, in a starry sky. One can be taught to hear even a subtly discordant note. You can be taught to smell the olfactory particulars of a poisonous substance. And with tuition and practice you can learn to recognize the tactile, six dotted, configurations of Braille.

In addition, the separations between the various sensory modes seem not to be clear-cut. Taste and smell are intimately connected, as anyone who's tried, usually in vain, to enjoy a meal whilst suffering from a cold can attest to. There also seems to be an evolved empathy between vision and touch, with our haptic sense often validating what we see. In fact the division between the senses appear to be much more blurred or diverse than generally acknowledged, with most of our five senses at least partially overlapping and possessing a subtly synesthetic quality.

Touch by itself can be sub-divided into a number of sub-divisions such as pressure, pleasurable and painful sensations, and the ability to sense warmth and cold. It is also strongly coupled with the kinaesthetic and proprioceptive sense - our feeling and understanding of motion and the relative positioning of our body parts to each other. Touch also seems to have an allegorical quality, a 'tactile gestalt' of sorts, in which various figurative and suggestive symbols usually related with vision can also be applied to our tactile sense. Curved lines imply directional motion; lines converging lines denote perspective; the profile (outline) of an object is suggestive of the item it represents, even to the visually disabled.[iii] There are also various means through which our sense of touch can be directed or 'fooled' to sense particular shapes or textures.[iv]



The recognition of such dynamics provide a conduit for how the notion of touch can be appropriated into a more digital mode without necessarily having to rely on haptic interfaces such as the 'Sensable'[v] devices or any of the various formats of 3D scanning and reverse engineering. It involves the appreciation of an expanded sensory parameters and the acknowledgement of a, call it, 'tactile imagination' through which one can imagine or 'think' directly through more somatic modes of conception. This format of imagination needs to become more linked to how we design our things and environments through the various computational means.

Digitized Tactile Fabrication

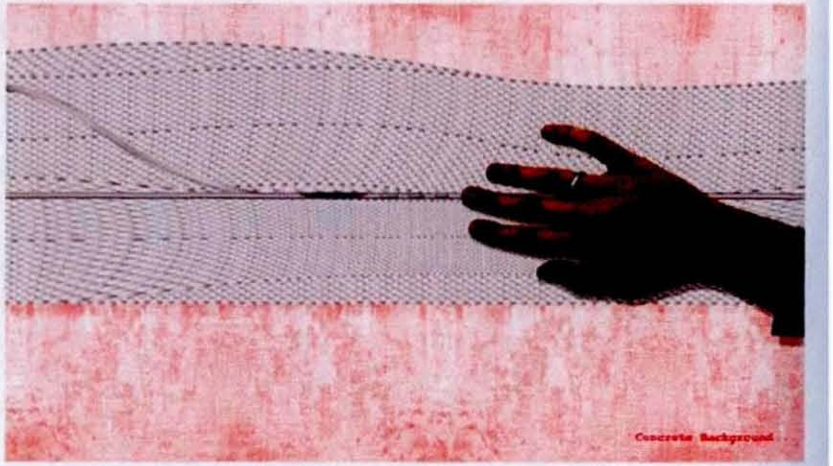
"...The core of such an approach is an understanding of material systems as generative drivers in the design process – rather than derivatives of standardized building systems and elements facilitating the construction of predetermined design schemes. A design can thus be pursued through the material system's intrinsic performative capacities if the notion of material system is extended to include its material characteristics, geometric behaviour, manufacturing constraints and assembly logics. This promotes an understanding of form, materials and structure not as separate elements, but as complex interrelations in polymorphic systems resulting from the response to varied input and feedback relations"[vi]

The various additive CAD-CAM processes, of which stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), and 3D Printing (3DP) are the most common, are still in their infancy in regards to producing usable end products. Many of the aforementioned technologies, particularly when including some of the more recent material and technological developments, already allow for more robust and sizeable builds, however, such means are still mostly used to produce replicas of future designs rather than the actual final designs.

In fact, even though the role of both subtractive and additive CAD-CAM processes is usually acknowledged as an enabling factor in the realization of more recent, more ambitious, architectural and design projects, with its role usually defined in type as almost a generic, as a means as something that should enable one to realize even the most thorny and complex designs, how such technologies are put into practice is usually not considered in detail during the design phase. The implementational logistics used by the various CAD-CAM technologies involved are seldom included as a central and key factor in the design process, let alone utilizing any of the particulars and idiosyncrasies (playing with the milling routes of g-code as a design element; using the 'stair-stepping' textures of the additive processes in a more utilitarian manner) of the various CAD-dependent fabrication processes as catalytic attributes aiding in defining a design. To recognize this omission, the fact that there still exists a substantial schism separating the conception and fabrication of a design when using digital tools, is vital if it is to be mended. This clearly also applies to ameliorating the still somewhat disregarded or even forgotten affinity between conceiving things (through CAD means), making them (by using CAM), and experiencing and using them.

As examples of such fabrication-means-specific idiosyncrasies which could aid in the more inclusive implementation of a scheme could be listed, for example, the default voxel (maxel[vii]) resolution of a stereolithography machine, which allows one to fabricate something at even 50 micron accuracy. This is a level of material finesse that extends almost beyond our sense of touch. The ability to manipulate elements at this level provides one with the opportunity to not only use, but to actually design and customize textures, something not usually considered or allowed for when implementing a design. The various additive CAM technologies also allow for components to be built around and within other components directly (to build a perforated ball within a ball within a ball…) which suggests that a new tack needs to be considered regarding component assembly strategies and construction logistics in general.

The image above is an illustration of a project that aims to use the abovementioned principles. Titled 'Snakeskin' (due to its appearance which comes across as a flattened out hide of a large boa constrictor) it functions as a tactile surface and wall relief which provides information of its immediate environments through the sense of touch. This is achieved through varying the surface consistency, texture, shape, level and friction according to defined tactile taxonomies ('tactile icons') which in unison allow for a more subtle and intuitive form of tangible expression. The design can be as short or as long as required. It can be customized to reflect aspects from it surrounding regardless of locale. It can be as pronounced or as discrete as necessary. Due to the variety of amalgamated tactile factors involved in the project, which results in an exponential number of variations for how the different tactile symbols can be appropriated, this design would be very difficult to implement through any other means than the additive CAM processes.



Conclusion

In conclusion, the aim of this ongoing research is to establish a bespoke set of taxonomies for this still evolving procedure, and to institute a paradigm of practice in which the two divorced realms separating CAD from (the predominantly additive) CAM process, might be symbiotically reunited – allowing for a more direct and inherent link to evolve between how we (and the tools we use to) conceive a design, and the processes we use to fabricate them today, could be more directly integrated. This entails a reversal, of sorts, of how we actualize a design through digital means, in that its physical presence should play a more substantial role already in the founding phases of any digitally conceived design. This involves that the various material, technological, structural, logistical, as well as any cultural, functional, even financial aspects need to be fused into a more aggregate synthesis consistent of a more dynamic non-hierarchical template for implementing designs. Current digital CAD-CAM means, due to the unavoidable link the practice has simultaneously to both the digital and the analog side of the design process, is in the process of routing out a more appropriate, comprehensive and inclusive mode for achieving this.

i. Mau, Bruce. 12 Strategies, Notes, found in: Weiber, Peter (Ed.) Olafur Eliasson – Surrounding Surrounded – Essays on Space and Science. MIT Press, 2001. p. 389.

ii. Melzack, Ronald. Phantom Limbs, found in: Scientific American Special Edition – Secrets of the Senses, 2006. p. 54.

iii. http://www.utsc.utoronto.ca/~kennedy/Kennedy-Juricevic.pdf. http://www.utsc.utoronto.ca/~kennedy/SciAmerican-JMK.pdf

iv. http://www.technologyreview.com/BioTech/17363/page1/

v. http://www.sensable.com/

vi. Hesnsel, Michael (Ed.), Menges, Achim (Ed.). Morpho-Ecologies. AA Publications, 2006. p.21.

vii. A 'Maxel' is a physical, or the physical equivalent, of a (virtual) voxel