Digital sculpture: conceptually motivated sculptural models through the application of three-dimensional computer-aided design and additive fabrication technologies

Dissertation submitted in fulfilment of the requirements for the awarding of the degree
Magister Technologiae (Design Technology)
Faculty of Engineering, Information and Communication Technology
School of Design Technology and Visual Art

Central University of Technology, Free State
South Africa

August 2009

By

Carol Kühn

Supervisor: Dr. R.W. de Lange
Co-supervisor: Prof. D. de Beer

DECLARATION

I, the undersigned, hereby declare that this dissertation is my own independent work and that the dissertation, or parts thereof, has not previously been submitted by myself to any other institution in order to obtain a qualification.

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Date Signature

SUMMARY

This research examines the interdisciplinary interface between engineering-based, additive fabrication (AF), rapid prototyping (RP) technology and 3-D computer-aided design (CAD) digital sculpting. The study was guided by the following objectives:

- The review of applicable literature sources that outline technical and aesthetic developments revealing the status surrounding the interface between 3-D CAD, AF and RP technologies.
- To introduce the simulating haptic sculpting device as input mode that addresses the sculptor's need for human-connectedness. Further to develop a schematic model that outlines user "construction" systems as means of navigating an interactive design approach to haptic sculpting. These user "construction" systems are applied to case studies that reveal technical and sensory modes surrounding the generation and realisation of digital form.
- Three digital sculptures are conceptualised and designed to support the various research components. Concepts for the three sculptures have evolved from ideas that have either deviated or emerged in their aesthetic and technical development. The conceptual development of each sculpture is guided by the researcher's ideology, perception and way in which these are influenced by various worldviews.
- Further case study extends the language of sculpture beyond the current domain by way of examining technical and aesthetic geometries inherent within 3-D CAD input design software, AF and RP output modes.

Technological and aesthetic characteristics reflect that as medium digital sculpting has surpassed traditional manufacturing boundaries allowing for the design and build of sculptural form that facilitates aesthetic uniqueness. The interdisciplinary application of these technologies throughout the design and manufacture of sculptures displays distinct aesthetic uniqueness towards the use of surface, substance and tools, unlike the notion that 3-D CAD design is rooted in geometric, industry-related form alone. The outcomes of the various research objectives above reveal the need for an expanded "synthesis", "construction" and "production" systemic structure as a way forward for engaging in digital sculpting.

ACKNOWLEDGEMENTS

I sincerely thank my supervisor Rudi de Lange for his continual motivation throughout this research and for realising his vision to instil a research culture within the School of Design Technology and Visual art of the Central University of Technology, Free State (CUT). Furthermore, I thank my co-supervisor Deon De Beer for introducing Free Form Fabrication as a visionary technology, thereby aligning the CUT as an international role player. The CRPM, the P.A. Alize Malan Trust, and CUT's Research & Innovation Fund likewise deserve special recognition for their technical and financial support, which has facilitated this research. I thank colleagues and students for their support and patience as well as CUT for granting academic relief in times of need. Last but not least, I thank family and friends for their continuous support and encouragement throughout this research process.

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DEFINITION OF TERMS

Definitions not referenced have been formulated by the author in order to clarify concepts.

Digital sculpture

Digital Sculpture involves the following three complimentary activities:

i. Creation and visualisation by computer of forms or constructions in three-dimensions;

ii. Digitising real objects and their eventual modification made possible by computer calculations, and

iii. The production of physical objects by numerically controlled machines that are used to materialise synthetic images (Lavigne, 1998).

Rapid Prototyping and Manufacturing

Rapid Prototyping and Manufacturing (RPM) is a digitally-driven, automatic additive manufacturing process that begins with the designing of a model from CAD data to the eventual building of a 3-D prototype.

Additive Fabrication

Additive Fabrication (AF) refers to a group of technologies used for building physical models, prototypes, tooling components and finished series production parts from 3-D CAD data. Unlike machining processes, which are subtractive in nature, additive systems join liquid powder.

Haptic Modality

"Haptic" is derived from a Greek word meaning "able to lay hold of" and encompasses the tactile action on which a haptic feedback system relies in order to stimulate haptic perception. The modality thereof would then refer to an overall grammar of the idea or concept that this expresses.

Haptic Interface

A Haptic Interface activates when a device composed of mechanical components physically encounters the human body for the purpose of exchanging information with the human nervous system (Srinivasan, 2007).

Haptic Modelling

Haptic Modelling refers to the 3-D construction of computational models.

Haptic-Loop

A Haptic-Loop encompasses the cyclic action activated by the force feedback experienced by the user through the haptic device (Hayward *et al*., 2004).

ACRONYMS

.3dm	Rhinoceros® file
.cly	FreeForm® Modeling™ virtual clay file
.stl	Standard Triangulated Language
ABS	Acrylonitrile Butadiene Styrene
AF	Additive Fabrication
CAD	Computer-Aided Design
CRPM	Centre for Rapid Prototyping and Manufacturing
CUT	Central University of Technology, Free State
DLP	Direct Light Processing
DMLS	Direct Metal laser Sintering
DOF	Degrees of Freedom
EOM	Edge of Memory
FabLab	Fabrication Laboratory
FDM	Fused Deposition Modelling
FM	Free Form
FMM	FreeForm® Modeling™
LS	Laser Sintering
NURBS	Non-Uniform Rational B-Splines
RP	Rapid Prototyping
RPM	Rapid Prototyping and Manufacturing
SLA	Stereoliography
SLM	Selective Laser Melting

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STRUCTURE OF THE DISSERTATION

This dissertation is submitted via publication output route in the form of two submitted journal articles (addendum 1 and 2) and three case studies (chapter 4). The results from two of the articles (chapters 2 & 3) were also presented at the 2007 and 2008 Rapid Product Development Association of South Africa's (RAPDASA) annual international conference. Sculptures evolving from the study were exhibited to form part of a Free State artists' group national exhibition displaying additive fabrication built digital sculpture on a platform of this nature for the first time in South Africa (addendum 4).

The first article (chapter 2) outlines a review of technical and aesthetic considerations applicable to current input and output modes of additive fabricated sculpture. The second (chapter 3) schematically outlines systemic haptic user "construction" modes of 3-D digital form generation, culminating in the application of various technological and sensory modalities to a single case study. Chapter 4 explores the conceptual motivation for each of the three case studies as well as the technical procedural documentation thereof. The research concludes with an overall discussion and recommendations surrounding the various components. The addendum consists of the final drafts of the two journal articles (chapters 2 and 3) and a third collaborative-authored article examining digital sculpture as extended sculptural language, three authors contributed to the article of which the researcher is the primary author (addendum 3).

CHAPTER I

Introduction and background to the study

1.1 Introduction

A brief introductory reference to applicable events and theories surrounding early explorations between art and technology outlines the milieu from which digital sculpting evolved. Initial collaborative projects between artist and engineering industries surfaced during the 1966 New York exhibition "Experiments in Art and Technology" (E.A.T.). Continuances of such collaborations during the 1968 "Cybernetic Serendipity" exhibition at the London Institute of Contemporary Art demonstrated a predominance of the thematically-centred relationship between computers and creativity. American theorist Jack Burnham, curator of the significant exhibition "Software, Information Technology: Its New Meaning for Art", draws significant parallels between the transient nature of computer software and the emerging dematerialised art object prevalent at the time of experimental art. In his visionary publication *"The Aesthetics of Intelligent Systems"*, Burnham (1970) claims that with the intervention of the computer, artists found themselves forced to dismiss classical views of art and reality, as at that point they were dealing with an art mode where the aesthetic dimensions thereof were difficult to comprehend. In this publication, Burnham suggests how a dialogue between the computer program and the human subject evolves allowing both participants to move beyond their original state, therefore creating a two-way interactive communication system in art. Digital sculpting as medium emulates this concept, as it manifests in a communication system of receiving, applying and sending data between artist and computer.

Prior to the development of advanced interactive communication systems such as three-dimensional (3-D) computer-aided design (CAD) sculpting and haptic modelling devices, the development of an innovative collaborative project addressing the individual aesthetic concerns of the sculptor was undertaken by Michael Rees and Christopher Burnett. Rees and Burnett, both sculptors by profession, developed the software operating system called "Sculpture User Interface®" (Rees, 1998). This development formed part of the exhibition “Artificial Sculpture”, funded by the National Endowment for the Arts (USA) during November 1999. “Sculpture User Interface®” aimed at investigating collective data input issues of image, text and object within the computer. The software input system simultaneously employs language, image and object embedded in the digital formation of sculptural objects. The structure of this system entails a library of objects activated by typing letters and words via keyboard to produce objects or interchangeable combinations thereof (Rees, 1999). Although this endeavour failed to fulfil the sculptor’s human-connectedness need, it, however, revealed the future call for the development of an operating system that supports the tactile and aesthetic needs of the sculptor. Recent years have seen the development of several haptic modelling devices (www.SenseAble.com) operating as interactive input systems that address the concern of human-connectedness as well as deal with sculptors’ aesthetic and technical requirements of surface, substance and tool.

Digital sculpting involves the simultaneous interaction between synthesis, construction and production modes of representation. Defining digital representation encompasses the interactive exploration of both medium and tools. Erik Koed (2005) characterises digital sculpture as “sculptural” medium determined by the way in which representation is attained and interpreted, rejecting previous notions of an isolated use of 3-D material or the mere representation of space. Mandelbrojt, Frémiot and Malina (1999) previously defined “aesthetics of interactivity” as an intellectual process where the idea is activated by the representation of things. Margot Lovejoy (2004) repositions this definition to form part of a larger frame of reference by claiming that representation rests on an intersection between the “way” and “means” it is achieved. Digital sculpting acts on representations that have no material reality, therefore dissimilarly altering the “way” and “means” by which representation is created. This dematerialisation requires an inclusive understanding of aesthetics and technologies surrounding this immersive virtual environment as medium. The symbiotic, interactive nature of digital sculpting therefore challenges the conventional idea of representation as the artist’s role broadens to active, passive, curator and consumer, participant and spectator, artist and critic.

Currently the medium of digital sculpture and 3-D builds produced via rapid prototyping (RP) present varied technical limitations that still need bridging when measured against traditional sculpting characteristics. However, an aspect of this technology exceeding traditional sculpting limitations is the 3-D CAD free form design capabilities which allow the sculptor to manipulate intertwined, convoluted form beyond real world sculpting expectations as RP build processes are unimpeded by complexity of form. The distinct build nature of various 3-D RP machines and range of additive fabricated (AF) printout materials position the sculptor to explore “sculptural” within a “new paradigm” irrespective of technical and/or aesthetic limitations such as software, colour, surface finish, durability, scale and cost. An advantage for the sculptor engaging in this technology is the reduced size of studio space needed as well as low start-up capital, as AF build technologies can be accessed through various external RP stations. As new technology, 3-D CAD and haptic modelling are slowly adopted because artistic users are generally resistant to change and learning the program is a time-consuming process. Future users mostly tend to wait until current technologies are redundant or outdated (Sequin, 2005).

Design fields where 3-D CAD applications are increasingly facilitating production are industrial, product design and film animation. Designers are realistically able to generate 3-D CAD files for the manufacture of tooling prototypes or product testing. Emerging artists and designers are able to access these advanced technologies via the newly developed Fabrication Laboratory (FabLab) technology station concept that has currently emerged throughout South Africa as well as other international locations. During 2006, South Africa saw the first role-out of this unique facility. The FabLab concept was founded by Neil Gershenfeld, the director at the Centre for Bits and Atoms, Massachusetts Institute of Technology. The objective of this South African part government funded initiative is to bring prototyping requirements to under-serviced communities that have been beyond the reach of conventional technology development and deployment and in doing so provide a bridge that will link informal traders into the mainstream economy (Engineering News, 2006). The available digital fabrication technologies and open source software programs available at these labs are specifically suited to assist crafters, artists and innovative designers to transcend traditional manufacturing processes. At present most of these facilities are located within or near educational training institutions with part of the aim being to drive technology skills transfer.

Burnham (1970) stated that in time there would be a need to shift conventional art training to suit the need of industry and speculated that through product demand, computers would be capable of surpassing “handcrafted” products. At present, this shift is largely evident with many artists expanding the field of sculpture by blurring traditional disciplinary boundaries to include Engineering-based technologies such as CAM (computer-assisted milling), CNC (computer numerical control) milling, and RPM (rapid prototyping and manufacturing) under which AF technologies assemble. Over the past decade, several established organisations/programmes supporting artists engaging in digital and RP technologies have emerged. Fine Art Sculptors and Technology in the United Kingdom (FasT-UK) is a prolific example of such an organisation. Digital sculptor Keith Brown, founder member of FasT-UK at Manchester Metropolitan University, Faculty of Art & Design, established a Research Unit for sculpture and technology to include RP facilities within the Fine Art Department, this venture therefore enforcing Burnham’s early 1970 prediction. Globally at present, there are several tertiary educational institutions equipped with RP units or individual AF machines, offering a range of build materials. Collaborative Engineering and Art & Design ventures like these progressively stimulate the concept of an interdisciplinary approach towards 3-D design and build technologies that support the needs of industry.

William Ganis (2004) forecast that the digital sculptor would remain confronted with ongoing challenges until such time that developments in technology fulfil artistic needs. At present relying on medium for content or presence poses the most significant challenge due to a general geometric semblance of form, resulting from mathematical data translations built into most CAD software programs. The appealing properties of infinite dissemination, multiple reproducibility and new material remain convincing; however, it is the application of this technology to artistic form and content that raises challenging questions. This research explores the above by developing conceptually motivated sculptures that challenge aesthetic and technical input and output boundaries inherent within 3-D CAD design, haptic “construction” and engineering-based AF technologies. As new artistic form, these input and output modes have contributed to redefining the function and reception of sculpture on both aesthetic and technical levels.

1.2 The Problem

The design and manufacture of 3-D digital sculpture reliant on an interdisciplinary approach between artist and engineer present varied aesthetic and technical options. This research as a whole proposes to research the interface between sculpture, AF engineering- based technologies, haptic device and 3-D CAD applications as a developing sculptural medium that aids a “sculptural paradigm shift” in the evolution of technology.

1.3 Hypothesis

During the incubation stages of both art and conceptual design, a piece of work is usually a refinement of a previous one. This refinement process, referred to as the act of creative recursion, is where innovation and concept manifest (Hon, 2001). The effectiveness of the creative process therefore depends on a speedy and unhindered recursion. This research hypothesises that the engineering-based AF technologies and free form 3-D CAD design programs Rhinoceros® and FreeForm® Modeling™ (FM) driven by haptic device - applied as sculpting “construction” tools - adequately facilitate a speedy object-creator recursive interaction as opposed to the notion that these technologies are limited to being industry design-related tools alone. Therefore, 3-D CAD, haptic modelling and AF technologies successfully relate to the CAD design and AF build of conceptually motivated sculptures without compromising form or content.

1.4 The aim of the study

The collective aim of this study is to examine the interface between digital sculpture and current AF engineering technologies. A perspective on the status of aesthetic and technical developments surrounding the interface between 3-D CAD and AF modes applicable to sculpture is presented. Secondly, to identify and schematically outline various haptic user “construction” systems as a way of navigating an interactive design approach to haptic virtual sculpting. Thirdly, the design and construction of three conceptually motivated digital sculptures to support the various research components. Additional case studies extend the language of sculpture as new artistic form through the 3-D CAD and AF exploration of varying sculptural geometries.

1.5 Methodology

Digital sculpting is examined as a paradigm shift, by reviewing surrounding technical and aesthetic 3-D CAD and AF technology practices applicable to sculpture (chapter 2). The FreeForm® Modeling™ software program driven by manipulating the PHANToM® haptic device is used to explore interactive 3-D data input manipulation in order to present a schematic outlining 3-D haptic design “construction” systems, which are then applied to case studies (chapter 3). Three-polyamide nylon AF digital sculptures were built in collaboration with the Central University of Technology’s Centre for Rapid Prototyping and Manufacturing (CRPM). The procedural conceptual, 3-D design and “construction” stages were documented as a culmination of the aesthetic and technical results (chapter 4). An additional co-authored article (addendum 3) outlines several case studies that examine digital sculpture as extended language and new artistic form by adopting an interdisciplinary artistic and engineering approach to technical and aesthetic 3-D design principals.

CHAPTER 2

Digital sculpture: technical and aesthetic considerations applicable to current input and output modes of additive fabricated sculpture

2.1 Overview

This chapter examines various viewpoints surrounding digital sculpture and its position as an emerging sculpting medium. The complete article has been forwarded to the *Journal for New Generation Sciences* (JNGS) and is scheduled to be published during November 2009 vol 7, no 2. (addendum 1) The researcher has also presented the outcomes of this research at the Rapid Product Development Association of South Africa (RAPDASA) 2007 Conference.

2.2 Introduction

Overall, technological developments increasingly reflect that as medium digital sculpting has surpassed traditional manufacturing boundaries allowing for the design and build of sculptural form that facilitates aesthetic uniqueness. The design and manufacture thereof is, however, reliant on an interdisciplinary approach between artist and engineer, where technical and creative problem solving merge from the onset of an idea. Although recent years have witnessed several technological advances in the 3-D design and build of digital sculptures, most of these 3-D build technologies are engineering-based in their RPM (Rapid Prototyping and Manufacturing) mechanical applications. More accommodating to the artists needs are developments in 3-D free-form computer-aided design (CAD) software applications that progressively allow for innovative artistic intervention during the design input and conceptual planning stages of digital works. The challenge for most 3-D CAD product developers is therefore to facilitate maximum artistic intervention and therein address the ongoing need for human-connectedness during the creative process. Maintaining human-connectedness for the sculptor forms a fundamental creative element from incubation of idea through to the development phase of a conceptually motivated artwork.

Michael Century's (1999) publication titled *Pathways to Innovation in Digital Culture* examines the generation of technological innovation as hybridised cultural research in which he cautions against too much exposure to digital technology as it could lead to a loss of criticality in the arts because of technologies automating as opposed to acting as creative partners. Irrespective of this caution, artists are located in a time where technologies and new media accelerate through using; it is therefore the artists' responsibility to maintain a balance between form, content, technique and idea in order to establish the said creative partnership. With similar cautionary intensity, Lovejoy (2004) claims that artists wishing to stay entrenched within a traditional fine art discourse will remain confronted with challenging high/low artistic boundaries arising from the merging of fine art with commercial design production. Therefore, to engage in the technology, the sculptor is required to free him or herself from a "medium specific" process to explore this elusive dematerialised artistic medium in order to forge creative partnerships within art and technology paradigms.

For the sculptor, the layered manufacturing additive fabrication (AF) technology application is regarded as new artistic form. AF technology has therefore contributed to redefining the function and reception of sculpture on both technical and aesthetic levels. Digital sculptor Keith Brown, founder member of FasT-UK (Fine Art Sculptors and Technology in the United Kingdom), states that digital sculpture has led to a "new order" of sculptural object, a paradigm shift, and the emergence of a new digital aesthetic (Duffield, 2001). In this article, the current technical status and the impact of aesthetic issues surrounding digital sculpting is explored as a technology based creative partnership, towards defining a perspective on this "new order" of sculptural object.

2.3 Digital sculpture as medium

Digital sculpting encompasses the creative development of an idea in virtual space, with the work being realised in physical space i.e. AF technologies. Author and digital sculptor Christian Lavigne (1998) defines digital sculpture as a linkage of the following three complimentary activities:

- Creation and visualisation by computer of forms or constructions in three-dimensions;

- Digitising real objects and their eventual modification made possible by computer calculations; and
- The production of physical objects by numerically controlled machines that are used to materialise synthetic images.

Digital media often lacks narrative content as a result of it being a technological vehicle. In an attempt to categorise this phenomenon, the medium has been compared to the minimalist sculptures produced during the 1960's, where the modalities of technology become the substance of the work which is modelled, manipulated and juxtaposed with the viewer, to create meaning (Penny, 1999). Edward Shanken (2002) expands on this form of sculpture by stating that computer technologies have played a unique role in the aesthetic value of sculpture delivery, due to advances in technology providing tools that enable artists to cross-examine the conventional materiality and semiotic complexity of art objects that were previously unavailable.

However, William Ganis (2004) questions the conceptual facility of digital sculpture as an output medium and states that it could not be relied on for content or quality artistic forms until such time that technology develops. As mentioned above, this line of thought can be challenged with the knowledge that when producing digital sculptures using CAD design and AF processes in many cases, as with the minimalist sculptures produced in the 1960's, the technological combination becomes the content of the work and the conveying of narrative content possibly becomes a secondary issue.

Digital sculptors work in a medium of repetition without an original object and have the option of unlimited duplication. It can therefore be argued that such sculptures deny the sculpted materials "aura" of authenticity, the loss thereof first sited by Walter Benjamin (1969), since the electronic data used to develop digital works are easily transported via the internet and can be accurately reproduced by any RP station. The ubiquitous nature of this medium constantly stimulates debate around issues of authorship, originality and copyright, addressed as aesthetic concerns further on in this article.

Several established digital sculptors have emerged producing works that stand on their own as "masterpieces" within both the conceptual and technical boundaries of digital sculpture. After reviewing the working methods of several distinct sculptors i.e. Carlo

Sequin, Michael Rees, Christian Lavigne, Mary Visser, Lionel Dean and Bathsheba Grossman, findings revealed that in their works all employed CAD as a fundamental tool in their procedural shape generation, thus indicating a high value for CAD as input mode. The same high value was displayed with all making use of various standard output AF build technologies. Shortcomings in their technological applications indicated a restricted use of varied input devices (i.e. haptic devices, 3-D scanning, data gloves, virtual headsets), reasons which could possibly be linked to cost or accessibility. Each artist has however explored the advanced technology of 3-D colour building as an output mode at some stage or other but none approaching it as a specialist medium, possibly due to current inadequate data translations from CAD to RP machines. The majority of the reviewed artists make limited use of narrative concepts as aesthetic element. Comparatively this displays a lesser overall representational modality with regard to conceptual meaning. For most, a strong focus remains on the intersection between abstract form and mathematics as a conceptual departure point, therefore indicating a high non-representational conceptual modality. One could therefore deduce that there is a growing need for all aspects of the technology to accommodate a representational as well as an abstract non-representational approach to this “new form” of sculpture. Although at present, abstract non-representational sculpted form remains a more predominant mode of 3-D digital aesthetic delivery, therefore questioning digital technologies role as narrative conceptual creative partner.

2.4 Current 3-D input and output modes

2.4.1 Three-dimensional design input modes

There are several 3-D CAD programs available on the market, e.g. Maya, Form Z, Solid Works, 3-D Studio Max, ArtCam and Rhinoceros. The latter is an inexpensive, easy and popular software program applicable to the sculptors’ free form design needs. Most 3-D CAD programmes support the .stl (Standard Triangulated Language) suffix needed for RP builds. CAD programmes based on Non-Uniform Rational B-Splines (NURBS) geometry are suitable for 3-D designers who work with free-flowing form. NURBS-based software programs are therefore ideally suited to the design and build of complex sculptural models that explore the synergy of form and content. For the sculptor a benefit of 3-D CAD is that it allows for the pre-examination of form and structure, complex macro and micro viewpoints in a weightless environment prior to the realisation in physical space.

The 3-D scanning of an object by way of reverse engineering is an input mode of generating virtualised object models by measuring data such as the shape and texture of 3-D form. The type of scanner (probe or laser) and its current technological advancement normally determines restrictions. The recent launch of Z Corporations 24 bit colour mobile ZScanner® 700 CX presents potential for the virtual recording of 3-D artworks destined for digital database development and similar recording applications. However, at present this scanner offers a low texture resolution of 250 dpi, which presents difficulty when scanning detailed colour texture resolutions.

The loss of human-connectedness through automation will remain a limitation within this new artistic form until computer technology input modes successfully evolve to replicate the physiology of human sensory touch. In an attempt to break free from the mouse-driven CAD input approach, the development of a less constrained, more naturalistic input mode is the innovative “haptic design interface” device developed by SensAble Technologies (figure 2.1).

Figure 2. 1. Omni PHANToM haptic device, SensAble Technologies, 2007.

The designer’s hand is able to move around the illusional object, virtually feeling its shape while viewing and manipulating it on the computer screen. The system is able to mimic the sculptor’s pushing and pulling of the modelling surface and offers a range of multi-resolution modelling tools, which enhance the modelling of form and 3-D texture.

Irrespective of the significant developments of this system, it still operates on a single "patch" area manipulation, which demonstrates a limitation when compared to the physiological sensory application of the human hand. Developments surrounding the "multi-patch" manipulation of the NURBS surface and the addition of more complex modelling tools present research potential that will aid sculptural applications and inturn facilitate the conceptual design process.

Carlo Sequin (2005), computer science professor at Berkeley, University of California, proposes that as technological and mechanical aspects of design improve, 3-D CAD tools need the most development with the speed of real-time interactivity during the early conceptual design phase to ensure that the designer's creative thinking process is not hindered. Therefore, the CAD input environment will be at its most effective once the artist can process conceptual ideas at the real-time speed with which they are generated in the creative mind.
Renewed developments of design input modes facilitate a more fluid and flexible human-centred digital design environment. In turn, this enhances the overall interactive conceptual design process and therefore shortens the development cycle of producing aesthetically distinct 3-D models.

2.4.2 Three-dimensional additive fabrication output modes

At present engineering-based AF technologies have prominently infiltrated the 3-D build of complex computer-designed functional form. The accelerated impact of this technology is evident in the unique functional organic sculptural forms produced by UK product designer Lionel Dean (www.futurefactories.com). AF technologies allow Dean to explore the adaptation and personalisation of complex creative form for an emerging Rapid Manufacturing (RM) market. Michael Rees (1999), a USA sculptor working with AF, has termed this accelerated technology "Desktop manufacturing", which clearly depicts the accessible potential that this technology represents. The current developments of less expensive desktop 3-D RP modellers (uPrint) developed by Stratasys Inc. are able to provide quick feedback during the conceptual design process, a uniqueness that transcends present artistic manufacturing boundaries.

AF technologies vary in cost, process and material and constantly face technological advances. Implementing rapid changes in technology mostly presents financial limitations for the sculptor. However in time, the direct Laser Sintering (LS) of metals (titanium, bronze, bronze-nickel blend, steel) proves to be the way forward for the metal-working sculptor as this system can be used for a broad range of applications: investment casting, direct model building, hard and soft tooling. Stereolithography (SLA), a finer build process best suited to detailed form, wherein liquid resin cures by exposure to ultraviolet light. An alternative to laser sintered materials (LS) is the slower build Fused Deposition Modelling (FDM) process, which feeds Acrylonitrile Butadiene Styrene (ABS) thermoplastics and an investment casting wax through a narrow, heated nozzle, which then fuses over the base plate. At present, the post-processing of the irregular layered surface finish (evident in cheaper builds) and option to post-apply colour presents inexpensive and accessible aesthetic solutions for reintroducing the sought-after creative element of maintaining human-connectedness.

Most RP bureaus are more or less equipped with the above machine types with their various print options. Nonetheless, with the accelerated rate with which the technology is advancing, some of these machines have already been updated with faster build speeds, larger build platforms, reduced pricing and ground-breaking material builds such as the recent Digital Light Processing (DLP) of photopolymer material as an alternative to the widely used LS powders. At this stage, the larger interest is RM and whether build material properties are able to adequately develop in order to meet RM industry expectations (Wohlers, 2006b).

2.4.3 Hybridisation of new technology and traditional art processes

Through a collaborative effort since 1995 computer professor, Carlo Sequin and abstract geometric wood sculptor Brent Collins have been exploring the hybridisation of computer technology and the traditional art process by generating various 3-D CAD visualisations of complex structures. The carved, twisted, seven-story, ring, wooden sculpture "Hyperbolic Heptagon" (figure 2a) initially built by Collins and later a combined digital exploration thereof by Collins and Sequin (figure 2b) further stimulated the design of sculptures with much higher complexity, i.e. "Heptoroid" (figure 3). This was made possible by Sequin, who developed a specific computer program (Sculpture Generator) that calculated each complex sculptural configuration as commercial 3-D CAD tools lacked the convenient procedural capabilities. The developed computer program transcended the initial expectation of achieving a means to a speedy template design for the complex geometric wooden sculptures, but instead facilitated the development of a design structure that would not have been possible without the aid of the computer. Sequin (2005) refers to these programs as his, "[…] virtual constructivist ''sculpting tools" and concludes, "[…] the computer thus becomes an active partner in the creative process of discovering and inventing novel aesthetic shapes".

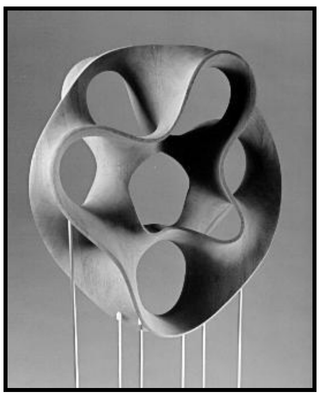


Figure 2.2a. *Hyperbolic Heptagon,*
B. Collins, 1995.

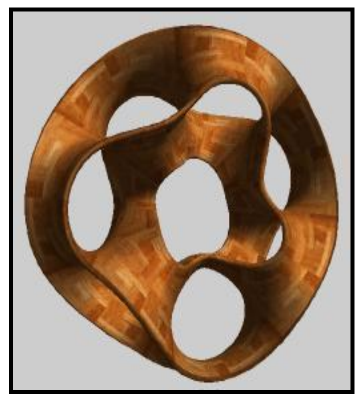


Figure 2.2b. *Hyperbolic Heptagon*,
C. Sequin & B.Collins, 1995.

Figure 2.3. *Heptoroid*,
C. Sequin & B. Collins, 1996.

The hybridisation of new and traditional technology is evident in the direct FDM build of ABS plastics, wax expendable models, LS powder builds and SLA Accura® Amethyst® resin, which can be burnt out during the traditional investment casting process with limited mould defects. The ceramic shell investment of RP master built models is particularly suited to complex forms where it would be difficult to make a traditional flexible rubber mould from an existing master pattern for the casting of a secondary wax. However, the ceramic shell moulding and burnout technique of these RP built models for the investment casting of metals remains a delicate process and an area in need of additional research. Problems occur as a result of the following: residues left within the mould cavity, mould damage due to the expansion of the various material builds during burnout, pattern distortion as a result of warm weather, incomplete bonding of shell layers and surface defects due to pattern porosity (Dickens, Stangroom, Greul and Holmer, 1995). Direct RP methods of arriving at a model are still regarded as more costly than traditional moulding and wax pouring of secondary models currently used by most foundries. However, the disadvantage of traditional indirect model reproduction via flexible rubber mould is that it is restricted to less complex form.

The above indicates how the hybridisation of new technology and traditional art processes remain technical research areas of varied potential that currently not only facilitate the artistic manufacturing process, but also predict that in time the cost-effectiveness of RP technology will allow this technology to become accessible to many.

2.5 Sculpture: Technical limitations and developments in 3-D CAD and additive fabrication technologies

The medium of digital sculpture and the RP build thereof when measured against traditional "sculptural" characteristics presents varied technical limitations that still need to be overcome. As mentioned a key development is the ability to design intertwined convoluted 3-D form beyond "sculptural" expectations as the RP build process is unimpeded by complexity of form. The sculptor is therefore presented with a weightless platform to explore "sculptural" within a "new paradigm" irrespective of the technical limitations encountered with CAD software programs, colour, surface finish, durability, scale or cost.

Software developer and product analyst Suchit Jain (2006), at Solid Works Corporation, claims that introducing conceptual design tools into the software system of automated 3-D CAD technology is the answer to reducing the current time spent on design analysis, as 60%-70% of product development is spent on the concept design cycle. Currently most CAD designers still prefer to pre-sketch their conceptual designs by hand or to a lesser extent utilise digital conceptual analysis tools. These however are not able to integrate with the 3-D CAD design environment and create real-time delays therefore restricting creative innovation. For the artist this presents a concern as during the conceptual design phase, an unhindered cycle of creative recursion remains a key element in producing innovative concepts and therefore innovative RP builds.

Three-dimensional colour building and AF remain areas of research that have yet to develop to their full potential. The most recent commercial colour RP system introduced by Z Corporation is the ZPrinter® 650, which can build parts in monochrome, multicolour and true black modes at 600 x 540 dpi resolutions. Z Corporation has in addition recently developed the ZPR binary file format that supports colour and texture maps unlike the common .stl file format used to move CAD data to RP machines which do not read colour data (Wohlers, 2006a). The application of colour for an artist generally creates meaning, content and nuance, which, unlike for an engineer, the inclusion thereof is often essential to the work (Rees, 1999). Therefore, the constraints surrounding the development of accessible high-resolution 3-D colour building can be regarded as a limitation, seeking solutions for the long-term development of digital sculpture.

The mineral or geological quality detected on most inexpensive RP builds is a surface property of the layer building technology. To overcome this surface finish problem, most minimal detailed RP builds undergo either tumbling or sandblasting to smooth out the surface. A limitation linked to post-processing the build is the risk of damaging the model, particularly the starch-based powders, as they are brittle. Research opportunities therefore exist in areas to improve model quality and factors that would influence these improvements (Dimitrov, Wijck, Schreve and De Beer, 2003). Surface finish as a build limitation too impacts on the CAD NURBS-based user; since on-screen 3-D objects are digitally created using smooth surfaces, which then due to the lack of an adequate translator from NURBS to .stl, the smoothness during the RP build is compromised (Wohlers, 1992). Various RP software translators are used for the pre-build repairing of unstable or defective file parts. These translators also assist with loading and manipulating the position of the model on the build platform. The correct model positioning in relation to the RP machines' laser beam is able to improve a rough surface finish or prevent the form from "curling".

Presently metallic materials are regarded as the stronger and more durable prototyped material. High strength and durability tests forming part of a comparative analysis between various metal RPM systems using DMLS (Direct Metal Laser Sintering), LS (Laser Sintering) and SLM (Selective Laser Melting) processes overall revealed that high strength is determined by low porosity and high density of material builds. These properties in turn affect the dimensional precision and overall surface finish of the product. Results showed that although the LS metal processes proved rather slow and costly, it was found to be more durable, accurate and a reliable future technology to develop (Ghany and Moustafa, 2006).

The RP build of a maquette assists in eliminating many unforeseen aesthetic and structural problems that may arise, and therefore presents the sculptor with a more accurate preview of the final product. A sculptor needing to produce a larger work would be confronted with having to build a model in sections due to size limitation of the various RP machine build platforms. For a large sculpture this limitation would possibly increase the number of builds, which in turn increases the build and post-processing time and therefore cost. Dimitrov, Schreve, Taylor and Vincent's (2007) concluding test results on a series of large plastic and metal built components found that the build accuracy and surface finish of components did not measure up to conventional methods; however, they were not too far off the mark either. Increased scale of the plastic builds was restricted to a polyurethane material; however, large metal builds proved unrestricted in metal type. From a design perspective, metal builds seemed to have greater capacity for handling complex form. Ultimately, a significant 65-80% timesaving was reflected in the production of metal components. However, the issue of high cost was set off against non-monetary advantages such as quality and reduced risk management. Therefore, producing large components via RP showed that the process was competitive with traditional manufacturing routes and therefore a viable option for the established sculptor to consider.

An advantage of RP technology is that complex entwined forms are built at the same speed as a solid block of the same size; however, finer resolution machines do build slower. Current material and machine running costs remain to be an element of this technology that renders its status exclusive. However, as the industry grows and technology develops, costs will align with traditional manufacturing processes. Generally, for sculptors, CAD tools and RP processes are slow in being adopted as new technology because users are generally resistant to change, learning the program is a time-consuming process and most future users will wait until the current technology becomes outdated before changing over (Sequin, 2005). For the medium of digital sculpture, these factors play a role in impeding the accelerated development of this “new form” of sculpture delivery.

2.6 Sculpture: Aesthetic concerns surrounding 3-D CAD and additive fabrication technologies

The aesthetic focus of this article outlines issues such as authorship, authenticity and originality, which are concerns that encompass the use of the medium in a way that differs from what has sculpturally gone before. The 3-D build of digitally designed sculpture is a practice where technologically advanced “new form” and medium bring with it alternate aesthetic considerations regarding authenticity. One such aesthetic consideration would be to investigate the medium as a “new form” of production as opposed to a reproduction process alone. Koed (2005) expands on this aesthetic shift in his prediction that “[…] the diverse characteristics of the contemporary art world might undermine theories of the nature of sculpture that appeal to particular physical properties of materials, or the involvement of specific perceptual modes, phenomena, or sensibilities, as criteria.”

At present the RP build of sculpture is met with much of the same scepticism as was the onset of photography (Lovejoy, 1990), because of a similar loss of human-connectedness and the question of originality. Fifield (1999) comments on originality and the copy by stating “[…] when 3-D photographic reproduction achieves the economic level of print reproductions, sculptors will face much of the same issues as printmakers did when the copy machine first appeared.” He also remarks that with this change of concept, issues about meaning and multiplicity in sculpture will grow. Wai (2001) postulates on the issue of multiplicity by claiming that if RP continues to being limited to the production of presentation models alone, it will continue to be regarded as a limitation when compared to traditional modelling techniques. Presently, this concern is at the forefront of technological development and, as previously noted, the RP industry has significantly shifted its interest to RM, thereby encompassing future issues surrounding multiplicity.

Currently the 3-D reverse engineering scanning process is one of the most commercially utilised tools for capturing 3-D form to a digital format, from which multiple reproductions of varying size can be reproduced via RP technologies. Ellen Thornton (2001), a legal specialist, claims that an aspect of digital copying to consider is that once the form has been scanned, the "copy" now consists of binary data bearing no resemblance to the original. With current legislation protecting artistic feeling and the original material character of an artwork, it could be difficult to defend this claim in the case of a digital artwork. However, as the concept of copying forms the bases for any infringement, for the moment it also includes the mode with which it is stored. This therefore potentially weakens the argument that binary data as a transformed character of the original would not be deemed a copy (South African Copyright Act No.98 of 1978).

As postmodern perspectives blurred distinctions between original artworks and copies at the onset of "appropriation art", copyright and authorship issues have ever since continued to be at the forefront of artistic debate. The 3-D RP build of sculptures via AF too push the boundaries of authenticity and originality within existing definitions of sculpture. This is displayed in the current unlimited RP build and virtual display capabilities of digital sculpture, which are encased with extended meaning by way of its ubiquitous nature.

When the envisaged display moves beyond the 3-D virtual environment to a fixed RP 3-D build, one would assume that the sculpture displayed as a tangible, fixed object requires less debate than a virtual object as laws are easier to apply. However, this "new form" of sculpture delivery has copyright protection issues of its own to consider. The most significant would be the ubiquitous nature of the file data of a digitally designed sculpture, which is easily transported via electronic network to any RP station for the envisaged 3-D build thereof. An aesthetic viewpoint surrounding the concern of ubiquity introduced by

Mandelbrojt, Frémiot and Malina (1999) draws an interesting analogy of technological art by viewing it "[…] equivalent to the traditional concept of durability and lastingness, with the infinity of space replacing the infinity of time […]". This thought can be considered as a fulfilling aesthetic prospect; however, within a legal situation one is still left with the nature of the file data presenting an object with no fixed original and unlimited reproducibility.

When analysing the vast abilities of digital sculpture, Rees (1999) speculates on authorship and the possible outcome of future software programs specifically designed to facilitate the creative process by stating that "[…] if sculpture became the agent of ubiquitous computing, then it also becomes the originator of the content and the controller of the context in which it gets interpreted." With all these concerns in mind, a possible hurdle that most mainstream critics and practising artists encounter when confronted with this technology is that it challenges their imbedded consciousness about whether it is sculpture.

2.7 Concluding comments

Indications illustrate that irrespective of current strengths and weaknesses, for the evolving sculptor, an interactive creative partnership between art and engineering technologies equally positions this "new form" of sculpture delivery as a leading role player towards defining a new digital aesthetic. Appealing properties such as infinite dissemination, multiple reproducibility and new material redefine the function and reception of digital sculpture on both aesthetic and technical levels. When applying these properties to artistic form and content, challenging unresolved aesthetic debate surrounding authenticity, copyright and authorship surface.

The establishing of an interactive creative partnership between the two disciplines determines the "way" and "means" digital sculpting intersect as a medium of artistic representation. It is therefore evident that a sculptor's user requirements prior to engaging in these technologies need to include a sound understanding of available AF output material builds, their technological parameters, skill of an appropriate input mode(s), structural elements associated with 3-D form as well as an understanding of the aesthetics of conceptual design. This expanded set of 3-D design requirements clearly indicates that conventional 3-D art and design training collectively is in need of a shift to accommodate developing technical and aesthetic requirements.

2.8 The Way Forward

The technical manipulation of 3-D form increasingly occurs through applications such as virtual reality headsets and electronic data gloves. Compared to the familiar "haptic device" sculpting mode, these too rely on sensory and technological elements. Therefore, the aesthetic exploration of "user" interactivity as an advancing sensory mode of technology necessitates critical aesthetic research in order to define 3-D digital artistic interactivity.

An engaging approach towards forging a creative partnership through multivalent artistic activity within a "polycentric" world characterises the current activities surrounding digital sculpting. This approach has the potential of addressing telematic networking as the organisational framework for a transdisciplinary knowledge production of future digital design tasks. Simultaneously such interaction could present an institutional forum for developing a virtual faculty with student-teacher interaction over long distances as these technologies are at present largely based within educational institutions.

CHAPTER 3

Haptic modality: an inscribed systemic user “construction” approach to sculpture

3.1 Overview

This chapter presents the haptic modelling device as an alternative to mouse-driven 3-D sculpting. A reduced article of approximately 4200 words outlining the collated results has been forwarded to the *Journal for New Generation Sciences* (JNGS) for publication review (addendum 2). The researcher has in addition presented the outcomes of this research at the 2008 Rapid Product Development Association of South Africa (RAPDASA) Conference.

3.2 Introduction

This article explores “construction” systems of haptic sculpture design as a way of navigating an interactive design approach to sculpture. A review of sculpture from a critical perspective, as was carried out by theorist Alex Potts (2000, 2004), indicates that sculpture as medium has transformed over time, yet remaining a convenient label for several artistic processes. Within each process termed sculpture there remains a physiological interaction with substances involving tactile and supplementary material properties. By focusing on haptic sculpting as a virtual material substance with interactive surface properties, and the occupancy of space as separate from what it might represent as image, a mode of viewing is activated that suspends the recognition of sculpture as merely a static object or an arrangement of objects. The interactive haptic modality of digitally designed sculpture calls for an inclusive understanding of this new medium to enable an exploration of user “construction” systems influencing 3-D haptic sculpture. Rosalind Krauss (1999) outlines an expansive understanding of the medium of sculpture as not only inclusive of the literal material support of an image or the substance of an object, but also the arena of display and modalities that viewing invites.

In this haptic instance, these aspects translate as interactive medium, “construction” of form and the virtual display environment.

The machine controlled 3-D haptic CAD environment used to generate digital sculpture presents a renewed perspective on the display arena when applying real world modalities of sculpture. Mandayam Srinivasan (2007), director of the Laboratory for Human and Machine Haptics at the Massachusetts Institute of Technology, defines haptics as:

> “[…] the design, construction, and use of machines to replace or augment human touch.” Furthermore the “haptic interface” is defined as “a device composed of mechanical components in physical contact with the human body for purpose of exchanging information with the human nervous system.”

This article explores systemic user elements applicable to human and machine haptics where the PHANTOM® (Personal Haptic iNTerface Mechanism) Desktop™ haptic device and FreeForm® Modeling™ version 9.2 CAD software developed by SensAble Technologies are used to generate, manipulate and render the touch and feel of a virtual designed sculpture.

Presented is a user-based, systemic approach to “construction” modalities of haptic generated form, sought after by way of exploring a signifying system of “inscription”, defined by Gunter Kress and Theo Van Leeuwen (1996) as a 3-D modality comprised of interrelated existing classifications of visual semiotic resources such as surface, substance and tools. Contrastingly, 3-D haptic sculpting collectively presents a synthetic-based mode of the latter, termed “construction” in their haptic interaction. Therefore, when systemically categorised, haptic sculpting emerges as a synthesised inscription system of technology whereby the human hand is reintroduced via a technological “interface”. This results in existing classifications of sculptural modalities assigned to representation deconstructing as a form of synthetic inscription. According to Kress and Van Leeuwen (1996), the systemic focus of technologically produced sculpture should then shift to “synthesis”, “construction” and “production” of representation. This chapter presents an interrelated user “construction” sign-system inscribed with technological and sensory modalities (Table 3.1). Outlining these modalities presents a hypothesis toward a 3-D, user interactive haptic sculpture design system as a way forward for an “inscription” system of haptic technology. Such “construction” modes embedded within an inscribed user system assemble various renewed effects of the meaning of “surface”, “substance” and “tools” in their haptic user interaction.

Michael O’Toole’s (1994) theory on a semiotics of sculpture makes provision for functions and systems of representational, modal and compositional elements associated with existing classifications of sculpture, which collectively guide our interaction and perception of a 3-D artwork. Although postmodern art practices generally reject such a systemic approach preferring a separate analysis of object, subject and context, the interactivity of haptic user “construction” lends towards applying a systemic approach as departure point in defining this elusive 3-D medium. In support of such an approach is author Simone Gumtau (2006) from the School of Art, Design and Media of the University of Portsmouth in the United Kingdom, who claims that identifying semiotic relationships for haptic variables are the most distinctive design parameters and a step towards determining a possible 3-D haptic design palette. This chapter therefore presents a schematic representation outlining potential sensory and technological “construction” parameters such as spatial orientation, volume, temporality, form manipulation and tool options towards defining a systemic user “construction” design palette for interactive haptic sculpting.

TABLE 3.1 SYSTEMIC USER CONSTRUCTION MODALITIES OF HAPTIC SCULPTURE

<table>
<tr><td colspan="3" rowspan="2">MODALITY
INSCRIPTION SYSTEMS</td><td colspan="2">CONSTRUCTION</td></tr>
<tr><td>TECHNOLOGICAL</td><td>SENSORY</td></tr>
<tr><td rowspan="3">SPATIAL ORIENTATION</td><td colspan="2" rowspan="2">PLIABILITY</td><td colspan="2">HUMAN SENSORY LOOP
(Data: receives/applies/sends)</td></tr>
<tr><td colspan="2">KINAESTHETIC/TACTILE
(Bodily: sense/state/position)</td></tr>
<tr><td colspan="2">SPATIAL COORDINATES</td><td>ERGONOMICS</td><td>MAPPING X, Y, Z
(Anisotropic, Isotropic, Oblique)</td></tr>
<tr><td colspan="3">VOLUME</td><td>WEIGHTLESSNESS</td><td>SOLIDITY/PENETRABILITY/PLASTICITY</td></tr>
<tr><td rowspan="2">TEMPORALITY (Substance)</td><td>TEMPORAL PRESENCE</td><td rowspan="2">Tactile communicative agents</td><td></td><td>RECURSIVE SUBSTANCE
(Endless/Duration/Repetition)</td></tr>
<tr><td>REAL-TIME INTERACTIVITY</td><td>MECHANICAL AUTOMATISM</td><td>RECURSIVE AUTOMATISM
(Link: time/medium)</td></tr>
<tr><td colspan="3">FORM MANIPULATION</td><td>HAPTIC-LOOP
COLLISION DETECTION/RESPONSE
FILE IMPORT/EXPORT
VOXEL SOLIDS</td><td>VOLUMETRIC MODELLING
HAPTIC TEXTURING</td></tr>
<tr><td colspan="3">TOOL OPTIONS</td><td>SYSTEM ARCHITECTURE</td><td>MODELLING/CARVING/CONSTRUCTION
RENDERING</td></tr>
</table>

3.3 Haptic modality

Western ethics remains dominated by applying a utilitarian approach to humankind with the interaction thereof suggesting a twofold view of body and mind. French rationalist René Descartes (1596-1650) moral theory is firmly based in “utilitarianism” and refers to an inner self that is separate from bodily sensations resulting in human reason created from within humankind (Descartes, 1960). This twofold view implies that the physical sense of touch as pure contact to be less significant. Consequently, this implies that touch in a creative environment is therefore open to sensory substitution. With this ethical perspective in mind, the sensory substitution of the haptic user ‘construction’ environment for the sculptor introduces the device as a contact interface, which functions cognitively comparable to sight or hearing.

Srinivasan (2007) outlines that to perform a task using a haptic interface, the human user conveys motor actions by physically manipulating the interface, which in turn displays tactual sensory information to the user by stimulation of human tactile and kinaesthetic sensory systems. The haptic device controlled by the user results in an immediate engagement with substance and process within the computer as a weightless, ubiquitous environment. This engagement by the sculptor risks being compared to 1950’s and 1960’s artistic production of artworks where the process of production, distribution and consumption in society deemed the artistic media casual and experimental (Potts, 2004). Current haptic sculpting echoes similar doubt due to its defiance of existing classifications of representation, replaced by virtual materiality and weightless spatial orientation amongst others. However, as mentioned, the interactive medium, “construction” of form and virtual display environment present renewed effects of meaning applicable to this transformed sculptural paradigm.

In this chapter, haptic modelling refers to the 3-D “construction” of computational models. The CAD interface shift from keyboard, mouse and joystick operation to the haptic device as “construction” tool is no longer revolutionary, as its use has become familiar in simulators for medical training as well as film animation design; however, it has not yet impacted as a widespread sculpting medium. The adjective “haptic” is derived from a Greek word meaning “able to lay hold of” and encompasses the tactile action on which a haptic feedback system relies in order to stimulate haptic perception. A haptic feedback system activated through touch imposes forces on the skin; these, together with posture and hand-arm coordination, transmit to the brain as kinaesthetic information. The haptic user is able to determine properties of coarse texture and large scale in this kinaesthetic way. Contrastingly, surface contact with an object activates tactile sensors embed in the skin, which conveys spatial and temporal variations of force distributions on the skin such as subtle movement, fine texture, small shapes and softness as opposed to kinaesthetic force transmission (Salisbury and Srinivasan, 1997). Haptic force feedback is therefore determined by collision detection and response reliant on kinematic and sensory system architectures. The force feedback to the user through the device is termed the haptic-loop. The bidirectionality of this haptic-loop is the most distinguishing feature of the haptic interface, which explains why a strong sensation of immediacy exists during the actual manipulation in pursuit of realism (Hayward, Astley, Hernandez, Grant and Robles-De-La-Torre, 2004). This sensory haptic-loop continues to occur during both exploration and manipulation of virtual objects classifying the device as a force feedback interface as well as an input apparatus appropriate to the sculptor's tactile needs.

3.4 Inscribed systems of construction

3.4.1 Spatial orientation

Spatial properties of a haptic designed object involve hand-arm displacement in order to explore the stimulus. According to Lederman and Klatzky (1993), the limited portion of the hand as well as the length of the arm that is in contact with the external stimulus refer to the "tactile perceptual field". This "tactile perceptual field" primarily activates various aspects relating to the overall spatial orientation within a virtual and physiological user design environment. Defining "construction" aspects encompass technological device parameters and interactive sensory user factors, dependent on tactile and kinaesthetic pliability as well as activated spatial coordinates of the haptic perceptual field.

3.4.1.1 Pliability

Digital design has both temporal and spatial qualities. With 2-D digital design, much of the meaning permeates on the surface of the virtual object whereas the interactive 3-D virtual design environment facilitates meaning to emerge from a sustained human-machine interaction, termed pliability. Pliability is a characteristic of this sustained interaction determined by the degree to which the user's experience-based interaction feels and facilitates the malleability of temporal and visual-tactile qualities. Conditions for maintaining pliability as an aesthetic experience within an interactive digital design environment are based on prior experiential qualities and procedural knowledge determined by the user to a lesser or greater degree. Within the realm of aesthetics and creativity, Richard Wollheim (1984) initially defined this concept "cognitive stock". Pliability therefore emerges during interactive haptic design influencing the aesthetics of spatial properties (Löwgren, 2007). Digitally designed sculpture that displays a close connected haptic-loop between tactile and kinaesthetic senses can be characterised as having a strong pliable interaction. The understanding of the tactile and kinaesthetic digital interaction is therefore reliant on the strength of this aesthetic quality termed "pliability". "Pliability" within the haptic environment requires these senses to operate simultaneously to provide the user with means to perceive and act on both technological and sensory interactive modalities within a digital "construction" environment.

Tactile and Kinaesthetic senses

Tactile and kinaesthetic senses simultaneously form key operational principles for the duration of the haptic interaction. Both senses are reliant on the stimulation of varied physiological sensory receptors. The skin is classified as the largest sensory organ in the human body, a tactile system attributed with various types of receptors depending on which part of the body it covers. Hand-arm tactile sensations include pressure, texture, puncture and softness as well as local features of an object such as shape, edges, embossing and recesses (Hayward *et al*., 2004). Kinaesthetic senses refer to the bodily sense of state, position and the motion of limbs activated by associated forces; these too transmit through sensory receptors in the skin positioned around the joints, tendons, muscles, etc. The PHANToM® haptic device, reliant on hand-arm operation, stimulates cutaneous mechanoreceptors transmitted through the skin enabling the user to experience tactile and kinaesthetic sensations through haptic force reflecting technology.

When reviewing a sculptural haptic interface as tactile medium, its sculptural introduction is reminiscent of Alex Potts's (2004) claim with regard to the first appearance of Joseph Beuys's formless block-like, disposable material sensory sculptures. In these the emphasis placed on the tactile values causes a perceptual relocation of any uncertainty towards structural qualities associated with sculpture as a traditional art form. As a result, the viewer is engaged in a sense of "immersion" with regard to material, texture and substance. A similar "immersion" exists during the interactivity experienced throughout the human-machine haptic "construction' process. The haptic user confronts a relocation of existing classifications of sculpture due to an expanded technological, sensory, kinaesthetic and tactile interaction.

3.4.1.2 Spatial coordinates

Ergonomics

The ergonomics surrounding haptic design viewed as an essential technological positioning coordinate determines the user's interaction and work place flexibility with the device as well as the model within the virtual display area. The direct, point-based PHANToM® stylus used for interacting with the digital clay operates freely on an articulated armature offering six degrees of freedom (6 DOF) output capability. The range of motion is, however, ergonomically reliant on the user's hand-arm movement pivoting at the wrist for adequate haptic simulation. Indirect ergonomic options available in the software program facilitate manipulating the virtual clay surface through a range of multi-resolution modelling tools with the user able to manipulate the model from the inside out; this assists with the deforming of the surface without the tool tip obstructing the modelling area. Further settings such as hardness and surface smoothness as well as clay coarseness are adjustable in the dynabar tool options menu. These ergonomic aspects directly or indirectly maintain the necessary tactile relationship between user, device and model.

Mapping x, y, z

Gentaz, Baud-Bovy and Luyat (2008) claim that sensory spatial coordinates of haptic perception "[...] differ from the proximal simulation experienced through manual exploration, and depend on spacio-temporal integration of kinaesthetic and tactile inputs to build a representation of the stimulus." The stimulus in this article takes into account the haptic design of sculptural models that too are reliant on kinaesthetic and tactile inputs linked to the device user to form the previously-mentioned haptic-loop. However, the sensory nature of this immersive spatial design experience relies on fundamental orientation coordinate mapping (x, y, z) properties of the design arena within which form is explored. Familiarisation with the defined orientation processing of form and spatial user haptic properties allows the user to engage in an enhanced tactile-field.

According to Gentaz, Baud-Bovy, and Luyat (2008), spatial properties of haptic perception such as orientation coordinates (x, y, z) and length distort when compared to physical reality manipulation. In conclusion these authors suggest that, as a result of observed irregular biases in spatial perception, the properties of a virtual object be processed independently from each other and do not necessarily refer to a single primary representation of space. This conclusion was determined as an outcome of several case studies in which haptic properties of perception of a virtual object influence the tactile field-manipulation of spatial orientations. Therefore, when exploring haptic space, the following properties should be considered:

- Orientation processing: anisotropic (stretching properties), isotropic (same physical properties in all directions) and oblique (slanting from the horizontal or vertical) affect the modality of motor command responses by the user.
- The role of prior knowledge, verbal or visual surrounding standard orientations of form influence both informed and uninformed orientation parameters.
- The hand–shoulder gravitational constraints are influenced by the haptic effect through antigravity forces being produced as a result of the haptic exploration of form, in return producing “gravitational cues” which are dependant on muscular forces needed to maintain or displace the shoulder-hand system against gravity.

The spatial modality of haptic user “construction” is therefore reliant on exploratory conditions (degree coordinates) relating to the various directional planes/stimuli (horizontal, vertical, oblique) which prove crucial to the production or reduction of gravitational forces. In this instance, the user is therefore required to consider the role of gravity and the coding of an orientation in space to ensure an accurate manipulation of the desired form. Simultaneously the user needs to rely on the “working memory” of prior knowledge. This is termed a “cognitive stock” resource within each individual on which the haptic user relies to achieve the mental synthesis that is necessary to construct a representational object within the tactile perceptual field.

3.5 Volume

Michael 0'Toole (1994) refers to mass as one of the key characteristics of sculpture. Mass is regarded as a system embedded with features such as an object's centre of gravity, its relation to the horizontal, solidity, impenetrability and the way in which it interplays with its surrounding space. The "construction" of haptic sculpture engaging with the body of the user in relation to various spatial properties of volume becomes characteristic of virtual mass.

Weightlessness

To consider phenomenologist Merleau-Ponty's (1962, 1968) view of artistic making as a perfect symbiosis of eye, mind and hand, works to the disadvantage of the medium specific sculpture due to weight and substance. The confrontation of spontaneous handling of material as substance allows a split in symbiosis to intrude between inner visual awareness (mental conception) and the act of fabrication (physical substance). In rethinking the medium of haptic-modelled sculpture within its virtual environment, Merleau-Ponty's approach to artmaking should be reconsidered in this weightless unrestrained "construction" environment as well as the intangible substance of virtual clay, thereby facilitating a symbiotic sculpting process.

Plasticity/solidity/penetrability

To explore plasticity properties of virtual clay as simulated haptic sensory volume element, characteristics pertaining to real clay need consideration. Three main characteristics are prevalent: 1) moist properties of the calculated clay body through water saturation aid its plastic deformation; 2) volume preservation during deformation because of its irreducible saturated material character; 3) increased surface tension due to saturation prohibits material disintegration. Guillaume Dewaele and Marie-Paule Cani (2004) performed comparative plasticity tests on interactive global and local deformations for virtual clay. The aim of this research was to collectively simulate virtual clay characteristics via computational models to maintain the substance effects of a real clay body. Plasticity, solidity and penetrable deformations applied to simple clay formations explored actions such as bending, digging holes, fold formation and tool imprinting. Although inspired by the physical properties of clay, the proposed model is not physically based as it relies on fluid mechanics and mathematical computations to push, pull, twist and bend the virtual objects. An example of such a computational procedure is the haptic simulation of material disintegration through virtual modelling which leaves “orphaned clay” fragments floating in space that cannot be felt by the user. The safe removal of unwanted “orphaned clay” merely requires a computation procedure of inverted lump selection and removal as opposed to removal through haptic manipulation. Overall findings in the above plasticity case studies reveal that the main characteristics of real clay can be simulated in real time at a low computational cost providing the user with a realistic interaction with clay as modelling substance.

3.6 Temporality

Late twentieth century, process-orientated artworks shifted beyond the confines of a commitment to medium specificity or a concern with the materiality of things and their substances (Potts, 2004). The term medium within existing classifications of sculpture mostly refers to the physical material of the sculpture. Pamela Lee (2004) proposes a more primary understanding of medium that emphasises its influential value as a communicative agent between two points and in doing so, a dialogue establishes between artwork and beholder. Within a haptic user “construction” interface, temporal presence and real-time interactivity encapsulate such a dialogue as communicative agents.

3.6.1 Temporal presence

A digital medium as material property explored via haptic input device and 3-D CAD software manipulation unavoidably shifts the focus to the physiological, tactile manipulation as well as device and software architecture, which cancel out an immediate response to the qualities normally associated with producing sculpture. The overall temporality of the recursive sensory tactility experienced by 3-D haptic sculpting generates a renewed perspective on how existing classifications of sculpting modalities apply to this medium.

Michael Fried's (1998) significant theory on sculpture, as expounded in *Art and Objecthood* refrains from directly addressing technology and its temporal presence; however, it does refer to the temporal dimensions of minimalism as cited by Lee (2004) as "[…] an experience of endlessness, duration and repetition […]". Lee (2004) continues "[…] when examining these temporal characteristics against 1960's minimalist art, one is presented with work based on non-linear paradigms of seriality, systems-based as opposed to medium specific, with production entailing recursion and autopoeisis […]". Simon Penny (1999) also directly addresses temporality as a category of technology within a digital medium by comparing it to the 1960's minimalist sculptures, where the modalities of digital technology become the substance of the work that is modelled, manipulated and juxtaposed with the viewer to create meaning. Fried's (1998) definition of temporality as recursive experience and Penny's (1999) reference to digital technology as substance implicit of meaning entwine as sensory "construction" modalities inducing a temporal presence within a haptic system of "inscription". The haptic user's recursive experience of endlessness, duration and repetition applicable to manipulating virtual technology assign as substance of meaning therefore uniting to form "temporal presence".

3.6.2 Real-time interactivity

In filmmaking, Stanley Carvell (1976) explores the relationship between time and medium as an "automatic" quality between the camera and human interaction, also defined as the mediums "manufacturing mechanism" where the medium reproduces within its own mechanism, consequently referred to as "recursion". Comparatively it represents that which Fried (1998) claims about existing classifications of sculpture: an experience persisting in time, an indefinite duration which surfaces as an engaging characteristic termed "presentness", collectively referring to a certainty of our ability to establish a connection with reality. Fried (1998) further claims that "time" as a temporal element is inseparable from any form of art, as the object demands a connective link to the viewer's relation of time and circumstance. Lee (2004) concurs with Fried (1998) in stating that "time" mistakenly is regarded as secondary to the spatial considerations of minimalist sculpture. As a result, the dialogue between new media and medium during the 1960's is not a matter of reducing medium to its material essence, but considered as a dialogue mediated by "time" taking on a circular recursive force, organised by the structure of “time”. A similar recursive temporal force occurs during the maintenance of a haptic sensory loop determined by tactile and kinaesthetic spatial orientations, which are regulated by time.

Due to the mechanical user interface of the PHANToM® haptic device and its association with sculpture, it would be more suitable to assign Krauss’s (2000) aligned interpretation of “automatism” as a mode of production of a present (reality-based), complete interactive character wherein a beholder’s presence is suspended through mechanical manipulation, i.e. film. In this systemic instance, “real-time interactivity” driven by “automatism” inscribes as an inseparable system consisting of the user’s physiological circumstance and the parameters built into the haptic device system architecture. For that reason, “automatism” - with its sensory and technological user interaction (haptic-loop) applied as a “time”-based system embedded in temporality-suitably equates a haptic “construction” interface activated during user interaction with the medium.

3.7 Form manipulation

Haptic-loop

Technologically, the force feedback of the haptic-loop operates at a frequency range of 10 Hz as a delayed frequency designed to compute geometric data via a collision detection/response module. Without the built-in delay of force feedback generated via a slower frequency, the user’s immediate simulated experience would not be realistic due to the rapid changes of real-time forces. Therefore the haptic-loop, in its delayed design structure, performs the following functions (Bordegoni, Colombo and Formentini, 2006):

- it asynchronously receives intersecting data from the geometric model;
- it applies the data to a time delay compensation allowing the system to reconstruct; and
- it sends to the haptic system the appropriate data parameters to exert the computed forces.

The efficient functioning of the haptic-loop can, however, be interrupted by system architecture failure encountered by edge of memory (EOM) issues that force modelling to exit and most often results in data being lost. The two primary variables that contribute to EOM problems are: 1) high clay resolution and 2) large model file size. Additionally, several other operations can also lead to EOM issues, particularly when combining models of finer clay coarseness or large file size. These memory intensive operations include:

- reduce for export (decimation) of large/high-resolution models;
- setting relatively fine values for clay and tools size for certain operations (i.e. convert to clay, smooth);
- shelling hi-resolution models;
- emboss with curve or wrapped image on high-resolution model;
- deforming clay; and
- shaping clay with large files.

Collision detection/response

During user operation, collision detection and response occur when the PHANToM® stylus touches the virtual surface during contact positioning and/or surface manipulation. At this point, a computational mechanistic model calculating the reaction force during every servo-loop alters the surface of the probe point. Basis-Spline or curved surfaces mathematically transfer as a continuous computational model into a layer of uniformly distributed sampling points. The inside/outside property of the function enables a slight collision between the sampling points and surface of the probe. Each point's coordinates input into the computational function, and are then evaluated according to an in-or outside positioning of the probe surface. Once a collision point is detected inside the probe surface area, it mathematically responds via modified force vectors, which feed back to the user through the haptic device (Gao and Gibson, 2006).

File import/export

To facilitate user "construction", FM can import a variety of file formats, which allow conversion to virtual clay for further manipulation. However, in some instances due to the lack of standardisation among other software applications, some geometry does not import as expected, requiring extensive form manipulation prior to continued "construction". Models can be imported as a native .cly file or file types such as .stl, Wavefront OBJ, Z Corporation ZCP, PLY, STEP, Parasolid Binary and Text as well as IGES curves files. The overall file import/export exchange facility enhances the program software interoperability allowing the user a range of pre- and post "construction" options.

Voxel solids

The mechanical file structure of haptic designed FM models are comprised of voxels. Voxel, an abbreviation of "volume element", can be defined as a 3-D pixel. It is a numerical volume unit that is represented by its specific position in x, y, and z coordinates; these units of information make up digital clay. Due to its three-dimensionality, a voxel is different from the building structures used in typical 2-D CAD packages, and surface-orientated facets or triangles used in 3-D design programs. Voxel's however, do limit the surface quality for downstream product development requiring that the model be exported as a compatible file conversion format for further program interoperability or the RP thereof. Once the digital clay model has adequately been reduced, voids filled and the successful translation from a .cly to a specified file format for export has occurred then limited post-file surface repair is required. Interoperable specifics such as these not only facilitate user "construction", but also encourage haptic modelling with FFM as operational design system of choice in an expanding 3-D modelling market.

Volumetric modelling

FM via haptic device enables a point-based sensory interaction with digital clay for the "construction" of volumetric objects made up of voxels as defined above. Mandayam Srinivasan and Cagatay Basdogan (1997) explain the computational operation encased in a voxel as haptic interaction properties consisting of bytes of information such as material density, density gradient, colour, stiffness and viscosity assigned to each voxel that computes at the haptic interface point. A further intricacy for simulating volumetric modelling is to achieve a balance between the complex computation of interaction properties and real-time haptic display. Although deformation can easily be altered, volumetric PHANToM® FreeForm® Modeling™ with its point-surface interaction creates difficulty in depicting the exact deformation results as opposed to surface physics-based sculpting processes. However, a 3-D modelling feature that far surpasses surface-based, mouse-driven 3-D design is that the haptic device provides both force and torque feedback. Force feedback, as previously discussed, is a haptic-loop operation; torque feedback enhances realism by stimulating a general tool-object interaction as the user's sculpting tool passes over the implicit surface as a rotating force (Gao and Gibson, 2006). The realism experienced with tool-object user "construction" facilitates a fluid modelling interaction better suited to the sculptor's needs.

Haptic texturing

The haptic texturing of a surface is determined by frequency and height as main indicators of form, irrespective of the modelling approach. Two approaches define haptic texturing. The first approach entails an image–based texturing, allowing the user to access a range of software specific pre-loaded synthetic textures that are wrapped around the surfaces of constructed 3-D objects and then manipulated accordingly. Procedural haptic texturing, a second approach to haptic texturing, generates synthetic texture fields using mathematical functions for determining the height field of the required texture from which the gradient vector at the contact point is calculated in order to agitate or transform the surface geometry of the object (Srinivasan and Basdogan, 1997). Prior knowledge and an understanding of natural textures and how they interact with the human tactile sensory system are required irrespective of which approach the user follows to create texture.

3.8 Tool options

System architecture

The haptic interface as a "construction" tool has two basic functions: 1) to measure the position and contact forces of the user's hand or other body parts, and 2) to display contact forces and positions and/or their spatial and temporal distributions to the user. The following advantageous features of a force-reflecting haptic interface support effective haptic performance (Srinivasan and Basdogan, 1997):

- low back-drive inertia and friction allowing no constraints on motion imposed by the device kinaematics;
- range resolution, and bandwidth of position sensing and force reflection should compare to the human tactile system measuring (~1 KHz); and

- ergonomics and comfort are essential features in creating an environment conducive to maximum haptic sensation.

Defining the kinaematic (technological) and contact (sensory) force variables are dependent on the hardware and software, as well as the tasks the interface architecture engages in. Current hardware specifications for the optimal running of the device and compatible FFM software requires an Intel-based workstation with a minimum processor running at 2.4 GHz, 2 Gb of RAM, 150 MB of free disk space and a high-end video graphics card. The PHANToM® Desktop™ device integrated with 6 DOF (x, y, z, roll, pitch, yaw) position input, and 3 DOF (x, y, z) force output operation within the virtual spatial coordinates operates comparatively less than the 22 DOF activated through numerous tendons within the physiological structure of the human hand, nevertheless at present a significant technological development.

The haptic system consists of both visual and haptic processes. The visual process facilitate by an adequate system architecture involves sculpting and rendering the model, processing user input, transforming values for haptic and image-based texturing and editing surface properties of the volumetric representation. The haptic process includes updating the force feedback displayed by the PHANToM® collision and response detection feature, finding the contact point, simulating surface properties such as friction and stiffness, and executing the optimal ~1 KHz vibration force computation within the haptic-loop. The high-end haptic system architecture as tool provides a 1000 Hz interpolated fixed force-torque servo-loop rate in FFM supplying the continuous real-time force-torque applicable to user “construction”.

Modelling/ Carving/Construction

Virtual clay deforms according to the user’s intended manipulation through simulated pushing and pulling of the virtual surface. For this, there are three main groupings of “construction” tools: curves, planes and virtual clay. The model formation is, however, not only dependent on the tool paths but also the size and shape of each tool. Editing options in each of these tools assist to generate form; these include control points, direct manipulation, free form deformation and variation modelling. The selection of each tool shape should therefore suit the envisaged “construction” to enable swift and optimal deformation of virtual clay. Within FFM version 9.2, the user is able to design tool shapes based on the sculptor's customised needs; this function voids any concerns regarding limited modelling and carving tool types. However, according to Diana Mahoney (2000), the vast range of tool options available within CAD programs is regarded as a limitation as often more time is spent considering tool options as opposed to focusing on the making. This limitation has since continued as software designers strive to offer multiple tool options within each new development.

The modelling, carving and construction of form too rely on the surface properties of clay during simultaneous interaction. Therefore, overall possibilities of editing form and varied tool selections contribute to the users' dependence on a dynamic interaction between model properties and tool options within the haptic "construction" system.

Rendering

FFM rendering functions applied to constructed virtual clay models, surfaces and solids are most often used to replicate the envisaged 3-D virtual display or to explore material build properties, surface colour and textures. Options within the rendering tool properties such as colour, surface finish, reflection, transparency, cast shadows, light refraction index, display scene, textures, material types and environment placement are manipulated to enhance the overall 3-D virtual display. However, when considering these varied material rendering possibilities, it is recommended that the user consider haptic perception from a virtual display perspective as "construction" modality.

A case study highlighting the relevance of this in a series of tests relating to the influence of colour on haptic textured surfaces revealed that the colour yellow displays the most optimal rough surface texture and colourless portraying smoother surfaces. This shows that colour does influence the haptic perception of texture and therefore acts as a significant means of visual engagement (Luo and Imamiya, 2003). With this in mind, it is then interesting to note that the default display colour of virtual clay within FFM is a tone of yellow. In addition, the FFM application is able to create individual QuickTime virtual renderings of valid views running 360° around the model, a rendering tool that the user is able to apply to enhance overall haptic perception.

3.9 Case study

Artistic intent and content, according to Gumtau (2006), are defined as the most characteristic parameters of haptic design, therefore a shift towards a holistic integrated, synthesised and embodied approach to person, sensory apparatus, social and cultural context is proposed. This case study transcribes user “construction” parameters applicable to the haptic modelling of sculpture, which encompasses the above premise as collective outcome. “Construction”- related aspects such as generation of form, editing and manufacturing, and realisation of form are outlined. From conception to fabrication, these modalities align this artistic medium within the paradigm of sculpture.

The sculpture (figure 3.4) was designed using Windows XP Professional SP2 (32 bit edition) operating system to run FreeForm® Modeling™ v9.2 software and haptic device. Onboard system-architecture included an Intel Dual Core processor running at 2.13 GHz with 4 Gb memory. The processor running slightly below the suggested minimum proved satisfactory in its operation, possibly due to the more than optimal installed memory requirement. The entry-level, onboard NIVIDIA Quadro FX 560 SensAble compatible graphics card operating with 128 MB memory demonstrated adequate display results throughout the design process. The PHANToM® Desktop™ device operating on 6 DOF position input and 3 DOF force output operation demonstrates optimal resolution, flexibility, back-drive friction and exertable force results as outlined in the device specifications (www.sensable.com). With the necessary system-architecture in place, the user was able to remain focused on various interactive “construction” properties resulting in limited obstructions during the “construction” process.

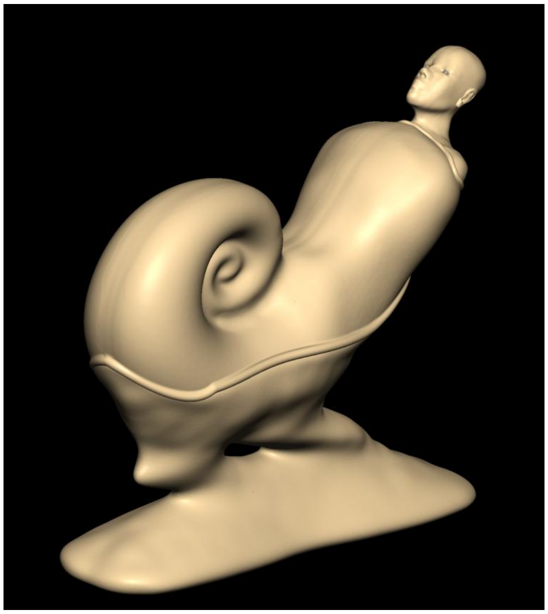


Figure 3.4. “Helix Rest”

3.9.1 Generation of form

Profile construction

The general approach to starting a haptic virtual clay modelling process begins with the generation of a basic sketch outline similar to a traditional woodcarving process in which contour outlines are drawn using closed curves or pre-drawn imported sketches as reference guides (figures 3.5a and 3.6a). Sketch files such as IGES files, Adobe® Illustrator® or previously saved FreeForm® Modeling™ sketch (.skh) files are projected onto a clay surface determining the required form from various x, y, z profiles. This process allows for extensive editing options of the profile curve facilitating a more controlled user interaction. At this stage, the curve can either be inflated as clay piece or cut away from a pre-constructed geometric shape prior to further manipulation (figure 3.5b). Either approach requires a reasonable amount of accuracy to ensure adequate control during volumetric modelling.

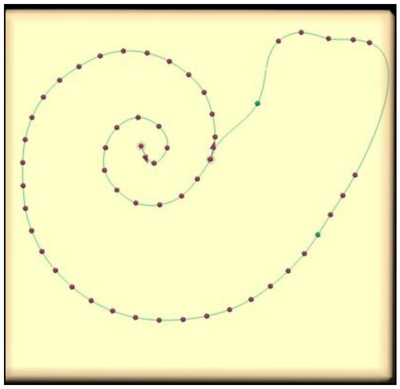


Figure 3.5a. Closed curve profile

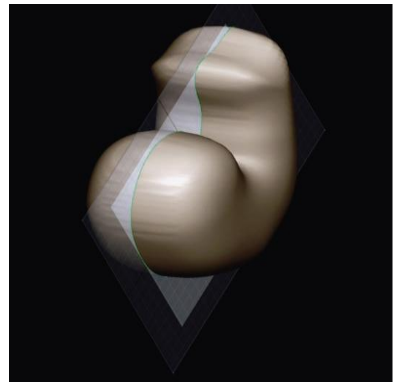


Figure 3.5b. Inflated curve profile

At various stages of this case study, a disruption in surface finish or sketch profile deviation was freely explored allowing the user to deviate from the initial design. Mark Evans (2005) expresses a similar deviation explored through a procedural industrial design case study, which determined that haptic feedback and RP strategies align to artistic activities where disruptions to surface finish may be required as opposed to rigid industrial design practice. Edmonds and Soufi (1996) refer to this practice as "emergence" where ambiguous mark making develops through concept sketching. At an early stage of this sculpting process a similar "emergence" filters through the initial "construction" during which profiles and constructed forms are dragged, pushed and pulled via control point or box deformation editing options. As a result, user modifications to sketch profiles and initial form "construction" develop into an expansion of idea in which deviation through "emergence" via sketching and modelling are purposefully manipulated. Represented in figures 3.6a, 3.6b and 3.6c are sequential screen renderings from sketch to interactive sculpting depicting the results of such form deformation.

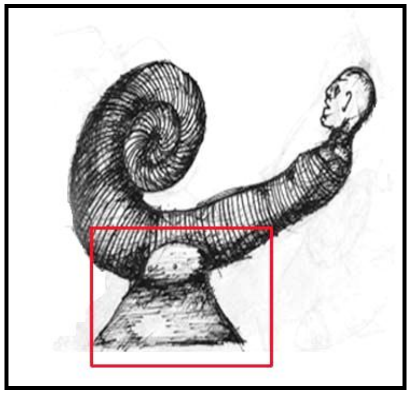


Figure 3.6a. Initial sketch

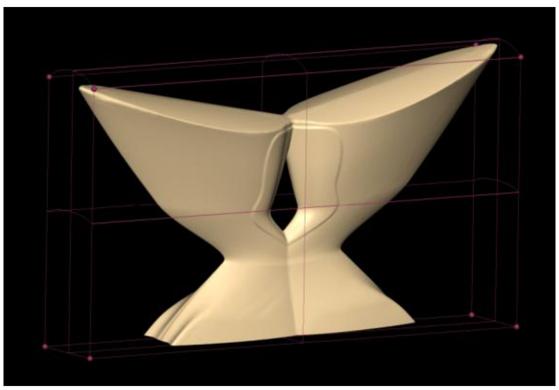


Figure 3.6b. Initial clay construction deviation

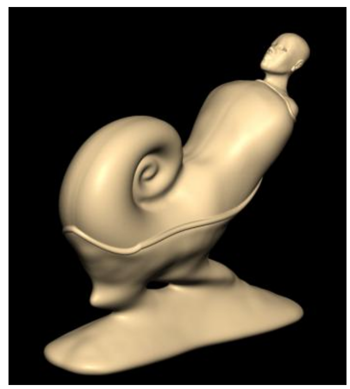


Figure 3.6c. Further deviation

Approximation of form

During the "construction" of the sculpture, form was largely achieved through a volumetric approach in which cones, cylinders, spheres, cubes and profile contours were manipulated. Due to the level of detail required for the RP of the form, the clay coarseness was set to a fine resolution from the beginning, thereby increasing the voxel density and file size. As a result, the haptic interaction (haptic-loop) between sculptor, device and virtual display at times exceeded its virtual memory limit resulting in the user more than often waiting several minutes for data translation feedback to take effect. This EOM system failure at times resulted in the abrupt exit of the application. In this case, the cause being the premature focus on detail (fine clay selection) during the initial "construction" process, which resulted in lost data and wasted production time due to EOM system failure. It is proposed that form "construction" be approached from a coarse clay selection and from there gradually refining the density as more detail is required, thereby avoiding EOM failure. Alternatively, the user could approach "construction" as separate objects, thereby facilitating a speedy data translation of reduced voxel density or file size prior to the merging of objects. Due to the intensity of the facial detail, a separate object "construction" approach was applied to the sculpture titled "Helix Rest" with the intention of combining the pieces at the final stage (figure 3.7a and 3.7b). Separate objects are indicated by different clay colourings, which also indicate which clay parts are active (yellow) or inactive (grey).

Figure 3.7a. Separate active/inactive clay objects

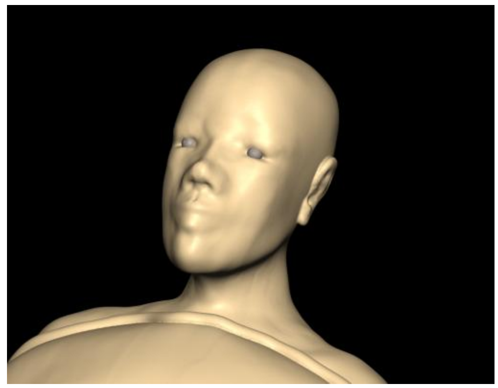


Figure 3.7b. Head detail

The global or local deformations of clay within the weightless 3-D CAD environment present significant technological and sensory spatial considerations for the user. The mapping of the x, y, z triad coordinates allows the user to locate the object within the global axes which is found at the centre of the model's workspace or the corner of the user's view port. Local coordinates are, however, tied to individual models which allow for independent articulation. This spatial frame of reference becomes an essential tool when importing objects from different file locations. More than often the spatial coordinates of an imported file do not correlate and require either local or global origin import translations. The same coordinate translation is required when repositioning two objects to align within an existing weightless environment; at this point the exact collision data of the two objects needs recording within the object information list for alignment to occur. Alternatively the object can be manually orientated using the "grab" tool option. Applying the coordinate translation is, however, a fast and accurate option when two objects are weightlessly floating in infinity. Spatial orientation of this technical nature presents to the sculptor an adjustment in coordination dynamics that influences the mechanical automatism experienced as an engaging characteristic of real-time interactivity.

Surface deformation

Once an approximate form has been achieved, the user is confronted with issues surrounding final surface properties and texturing. The overall amount of surface detail, as mentioned, is largely reliant on the selection of clay coarseness during the initial “construction” as well as intermediate modelling phases. The intermediate conversion of clay is reliant on the voxel density of the piece not being too memory intensive. The sculpture’s smooth surface finish was achieved using the highly interactive size variable smooth, smudge and carve tools. At times, these operations were carried out using the interactive mirror tool allowing the user to achieve symmetrical form. Once the individual parts of the sculpture were complete, the clay coarseness was uniformly converted to a smooth texture in keeping with the sculpture’s organic flowing form. The eyes were exported as separate files due to definition loss during the combining of body form and head (figure 3.7b). The chosen RP print material , ”Polyamide” nylon, does not offer the surface detail that a stereo-lithography resin does, therefore the final object conversion to a coarser clay facilitated easier file translation without compromising detail.

Temporal interaction

The voxel-based, virtual clay surface allows the user to explore properties associated with real clay such as solidity, penetrability and plasticity. These properties, linked to defining the workability of surface tension, were effortlessly interacted with using a selection of pre-loaded modelling and carving tools. During the FreeForm® Modeling™ haptic interaction, attention to mass was more prevalent than linear qualities, hence this software program’s distinctiveness when compared to other 3-D CAD applications. In addition, form exploration revealed that the object’s tactility was dependent on material qualities such as size and the nature of the object, rather than its plasticity. The overall organic structure of the sculpture presents an elevated sensory tactile interaction between user and “construction” modalities. Experiential user feedback during this case study defines that the sensory notion surrounding the haptic user as engaging in a recursive experience of endlessness, duration and repetition during form “construction” is firmly reliant on the ergonomics of the virtual and technological design environment as well as prior knowledge pertaining to form and principals of sculpture. This embodied approach (Gumtau, 2006) reiterates how interactive haptic sculpting establishes as substance of meaning in its “temporal presence”.

3.9.2 Editing and manufacturing issues

Voids occurring between the clay voxels need filling prior to converting the .cly file to a .stl RP ready build file type. Voids occur due to continual clay manipulation, specifically occurring where two or more surfaces do not align during the merging of parts. Although the FFM data report claimed that all voids were filled, due to user “construction” faults, voids were still present in the .stl conversion creating pre-build surface problems (figure 3.8). These were successfully repaired once the .stl file was imported into “Magics Materialize” translator software for pre-build preparation. Surfacing or filling voids as separate objects prior to the final combining of all clay pieces would have prevented the problem.

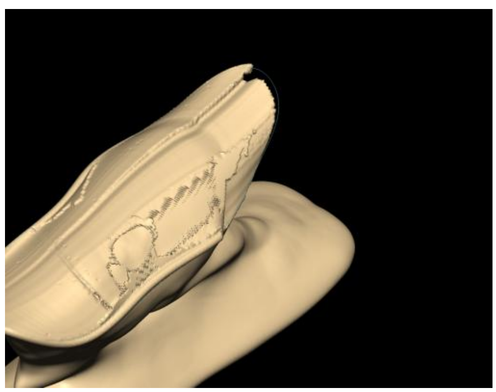


Figure 3.8. Virtual clay voids

Comparative to other 3-D CAD systems, the large operational .cly file size determines the necessity for a high-end operational computer system that in turn determines overall system interactivity. The exporting of the .cly file underwent an approximate 96% reduction to the .stl file in preparation for faultless RP software interoperability prior to the laser sintered “polyamide” nylon build. When re-importing the reduced .stl file initially prepared for the final build back into FreeForm® Modeling™ to implement additional changes, the loss of detail on the clay surface was apparent and therefore could not be used (figures 3.9a and 3.9b). Detail was, however, not lost during the initial 96% .stl mesh reduction for export. The overall mesh reduction merely resulted in less triangular formations on minimal detailed surface areas, thereby reducing the overall mesh count and not necessarily compromising detail. Comparatively figure 3.10a shows the appearance of a reduced .stl file structure and figure 3.10b displays a more compound mesh structure.

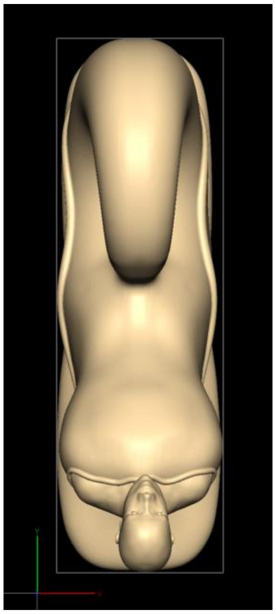


Figure 3.9a. Clay pre-import

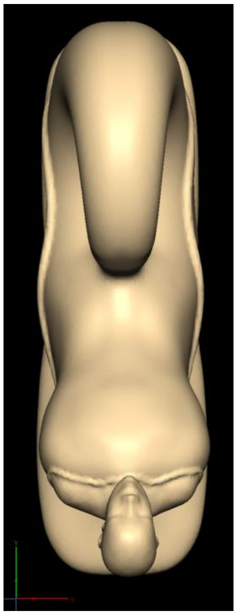


Figure 3.9b. Clay post-import

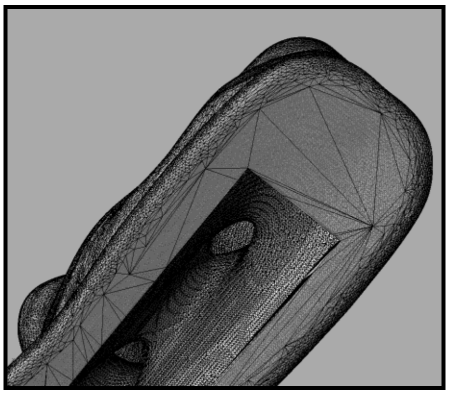


Figure 3.10a. Reduced mesh structure

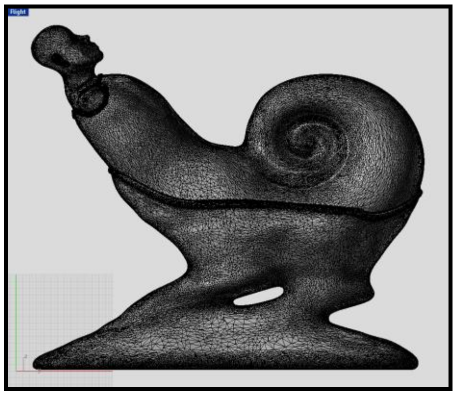


Figure 3.10b. Compound mesh structure

This outcome indicates that when importing .stl files into FreeForm® Modeling™, i.e. converting surface mesh structures to voxel solids, data is lost in translation. The user is required to consider this technical issue as it impedes the procedural user “construction” interface when working with two or more interoperable file exchange systems.

Software tools within this interactive modelling system allowed the artist to emboss name, title of the work and edition specifications on the underside of the form. RP as sculptural medium encompasses manufacturing ethics and copyright issues relating to artistic editions or multiple series productions. These raise concerns as questions surrounding ubiquity, authenticity and authorship, have yet to receive extensive critical attention. The sculptor in this case study has limited the edition to five builds with the first of the five regarded as the artist’s proof (figure 3.11).

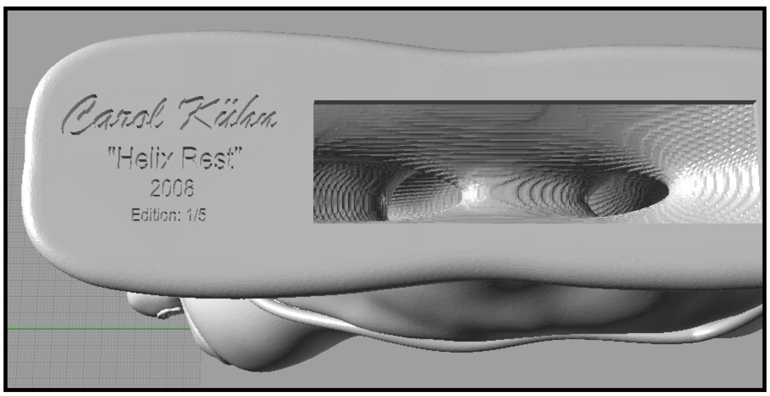


Figure 3.11. Embossing and cavity display

3.9.3 The realisation of form

Build constraints were limited to the AF laser sintering (LS) EOS P385 specifications such as build platform dimensions, tolerances, surface finish and costs. The sculpture was laser sintered using polyamide white nylon. The modelling of form determined by the FFM software voxel properties, as opposed to the popular geometric CAD mesh surface construction, allowed for an organic appearance. Shelling the build to a wall thickness of 6 mm to reduce material costs created an internal cavity, which raised concerns regarding the strength of the material; this, however, is a display item only and not a working part (figure 3.11). The shelling of the form does not reduce build time, only material cost, as the laser is required to follow the full volume platform path at the same speed irrespective of intricate detail.

3.10 Concluding discussion

A systemic approach to interactive haptic sculpting reveals various technological and sensory "construction" modalities that either challenge or expand on existing classifications of sculpture. The spatial–orientation surrounding the human-machine interaction with its cyclical receiving, applying and sending of data, places the user in a pliable state reliant on bodily senses and position. Although a similar creative, embodied interaction occurs during existing classifications of sculpting, the continuous haptic-loop formed in this instance is unrestrained by gravitational forces and weightless mass, thus presenting a renewed aesthetic exploration of medium. Outlining the temporality proposes a reference to "substance" as opposed to existing classifications of "materiality" when dealing with haptic interaction as sculptural medium. This is brought about by the temporal presence and real-time interactivity. These systems act as tactile communicative agents during mechanical and recursive automatism as modes of production both linked by time and medium.

The above elements contribute towards the accumulation of knowledge concerning the "construction" aesthetics of an interactive design approach wherein a relationship between implicit knowledge and intuition is essential. It is, however, the concurrent engineering interdisciplinary approach that this medium is technically dependent on which often questions whether it fits the category of sculpture. Comparative to existing classifications of sculpture, the user is equally dependent on technological parameters such as 3-D form, structural elements, material types, properties and skill. In an attempt to categorise haptic sculpting, the medium merely presents a shift in sculptural paradigm encompassing expanded technical and conceptual principles applicable to sculpture.

As defined and discussed in the chapter, Table 3.1 below schematically outlines the various systemic user "construction" modalities of haptic sculpting. These modalities are embedded within a system of "construction" that forms part of a proposed expanded "synthesis", "construction" and "production" model. Identified within the user "construction" model are five key inscription systems that outline various technological and sensory principles that potentially categorise an interactive sculpting environment for the 3-D artist.

3.10.1 Current limitations

Future technical improvements include degrees of freedom, resolution and bandwidth frequency. Model complexity is reliant on these improvements, as they deliver the stimuli that approximate our real environment. Interaction techniques such as these result in real-time display matching human perceptual capabilities. During the case study, FFM software's high-end system requirements presented the most challenging limitation due to EOM system failure during interactive sculpting.

One can speculate that the overall slow adoption of 3-D haptic modelling and RP as artistic medium is a result of high capital outlay and running costs. Due to these costs, crossing the threshold of commercial viability for the artist has yet to be achieved. According to Potts (2004), medium-based categories (sculpture, painting, etc.) for defining genres of artistic activity commercially cease to enjoy the status they once had, however, they do linger on in art and educational establishments as convenient ways of organising studio and curriculum provision. Contrastingly, at present haptic technologies are best located within art and educational establishments where experimentation with new technologies is key and most often not financially driven by capital outlay.

3.10.2 Recommendations

Haptic technology offers a unique approach for combining physical and digital aspects to be exploited in various phases of product development (Bordegoni, Colombo and Formentini, 2006). Such an example is a collaborative sculpting task in which asynchronous multi-user operation facilitated via network proved to enhance creativity (Gunn, 2006). Other future sculpting modes point towards voice prompt sculpting and hand gestures captured on camera. Irrespective of the interactive haptic sculpting mode, navigating an interactive design approach to sculpture as a “synthesis”, “construction” and “production” systemic model lays the foundation from which future deviation of haptic modalities can be theorised.

CHAPTER 4

Case studies

4.1 Overview

The following entails a brief conceptual outline and procedural documentation of three digital sculptures designed by way of 3-D CAD software and haptic input device. The building of the sculptures via RP AF technologies as outlined in case studies in chapters 2 and 3 not only tests the hypotheses of this research, but also sequentially demonstrates errors and possible limitations of the applied construction and manufacturing processes rooted in digital sculpting as "new medium". The hypothesis being that 3-D CAD, haptic modelling and AF technologies successfully relate to the 3-D CAD design process and AF build of conceptually motivated sculptures without compromising form or content. A concise outline of the conceptual departure point for each sculpture is given, as the problem statement of this research does not include examining the specifics of represented content or conceptual development. However, content does determine form and therefore the two entwine as symbiotic elements of aesthetic design. By briefly defining concepts merely equips the reader with knowledge surrounding the researcher's thought process. Supportive screen image documentation shows sequential technical procedures throughout the virtual sculpting process. A limited number of five sculptures per edition has been stipulated by way of embossed signing, the first (1/5) being the artist's proof. Each sculpture has been embossed with signature, title, year and edition number.

As outlined in chapter 3 the software system architecture used to produce the sculptures (case studies) consists of Windows XP Professional SP2 (32 bit edition) as the operating system used to drive software programs FreeForm® Modeling™ v9.2, Rhinoceros® and haptic hardware device. Onboard hardware system architecture included an Intel Dual Core processor running at 2.13 GHz with 4Gb of memory. The processor running slightly below the suggested minimum for FreeForm® Modeling™ software proved satisfactory in its operation, possibly due to the more than optimal (2MB) installed memory requirement. The entry-level, onboard NIVIDIA Quadro FX 560 compatible graphics card operating with 128MB memory demonstrated adequate display results throughout the design process. The PHANToM® Desktop™ haptic device operating on 6DOF position input and 3DOF force output operation demonstrated optimal resolution, flexibility, back-drive friction and exertable force results. All software revealed data file size restrictions at various stages of the design and file translation processes. Rhinoceros® adequately processed file data less than 100MB where FreeForm® Modeling™ was able to process data in excess of 800MB. However, both programs displayed extensive EOM failure when working with larger file sizes, which presented difficulty during .stl reduction and file conversion in preparation for the 3D, build process. Figure 4.1 below further illustrates the FreeForm® Modeling™, Rhinoceros® software and haptic hardware workflow diagram. Throughout the design of each case study the interoperability between the various 3-D CAD data input and RP output build modes applicable to these technologies was an important concern in order to achieve the desired results.

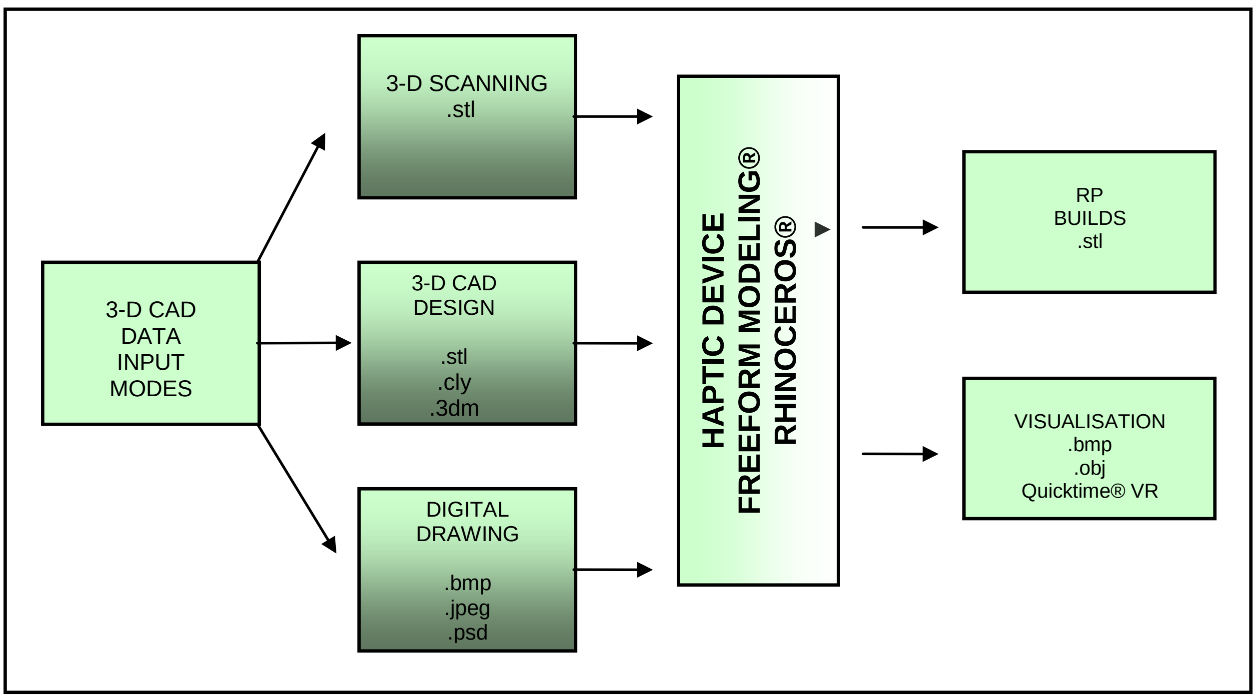


Figure 4.1 3-D Design workflow interoperability

Figure 4.2 illustrates the haptic interface, which is defined as a simultaneous sensory and technological exchange of information between the user and machine. The haptic process updates the force displayed by the PHANTOM® device at 1 kHz. This force computation performed between user, device and computer termed the haptic-loop operates via a collision detection and response system that locates the contact point to stimulate surface properties such as friction and stiffness during the sculpting process.

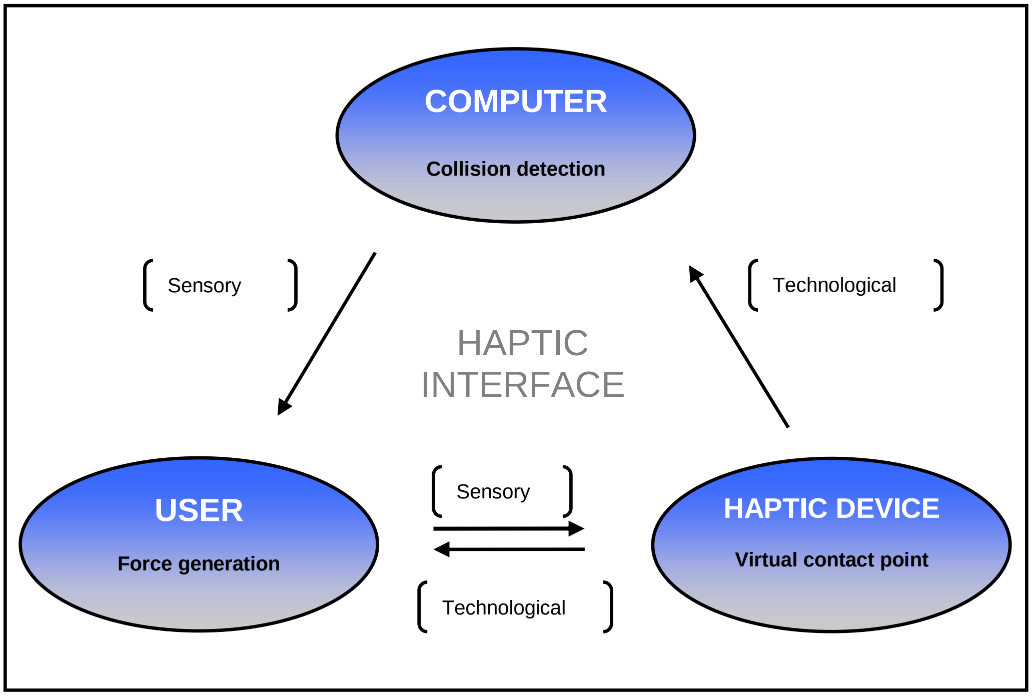


Figure 4.2. Haptic interface

Concepts for the three case studies have evolved from a range of pen and ink pre-conceptualisation sketches (figure 4.3). From these, ideas have either deviated or emerged in their aesthetic development. The aesthetic development of each sculpture is conceptually guided by the researcher's ideology, perception and the way in which these are influenced by various worldviews.

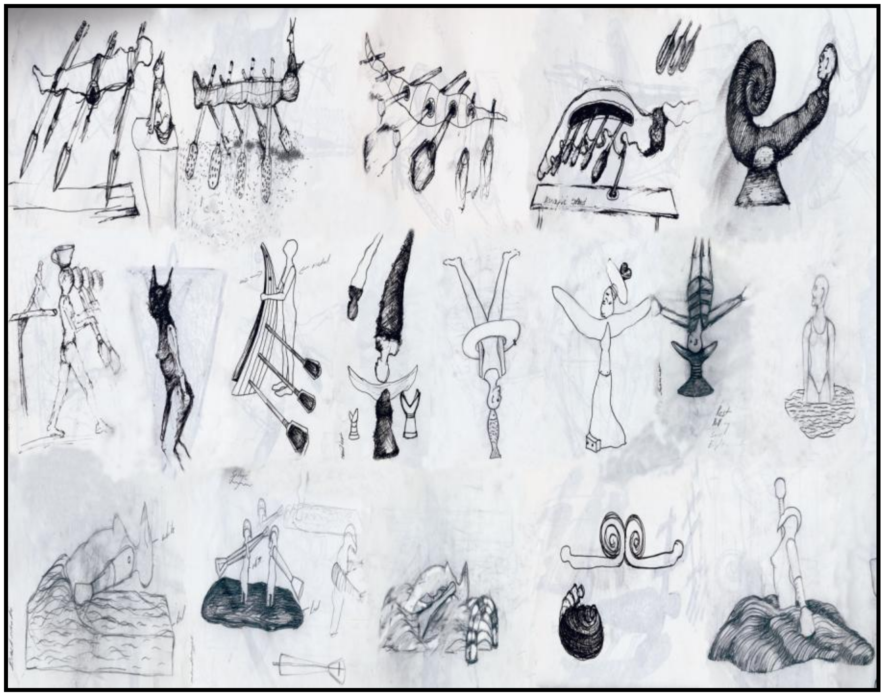
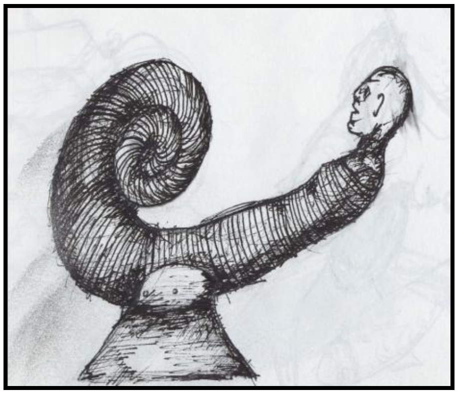


Figure 4.3. Conceptual pre-design sketches

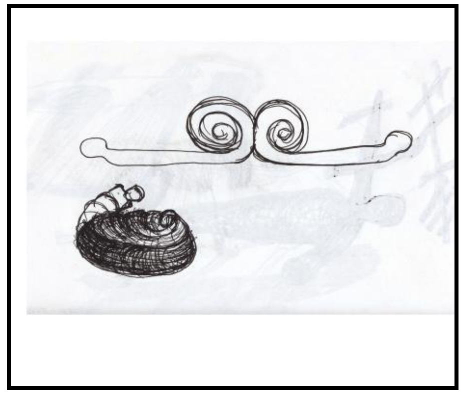
4.2 Case study 1a: "Helix Rest"

This sculpture has evolved from a series of works dealing with the concept of "headrest" as a contemplative object traditionally regarded as a locus for spiritual or meditative communication. In the work, the structure has transformed from previous juxtaposed disconnected elements of meaning to a composite connected form. Therefore, the idea of "detached" and "attached" form filters through in support of concept. The overall symmetric "attached" form references to a generic head, body sheath and foot formation suggesting the integration of figure/object as opposed to the previously explored detachment thereof. The inclusion of the "helix" as representational element carries with it the obvious notion of nature's inherent geometric symmetry and therein precision of form explored as a conceptual analogy.

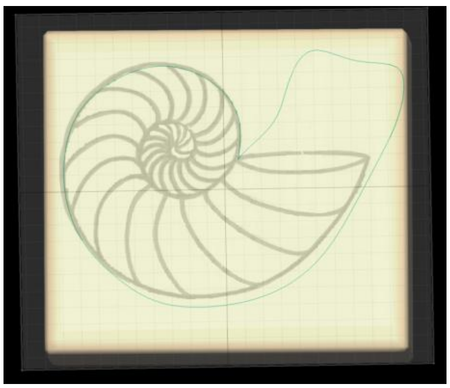
Figures 4.4a - I show the screen images for “Helix Rest”



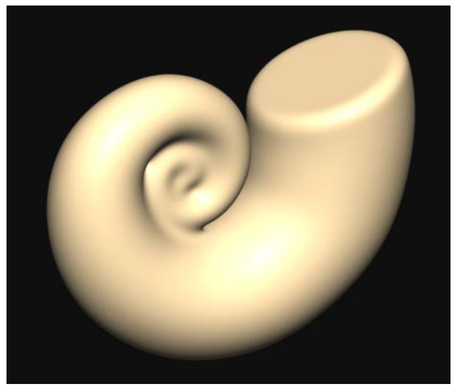
a) Helix pre-sketch 1



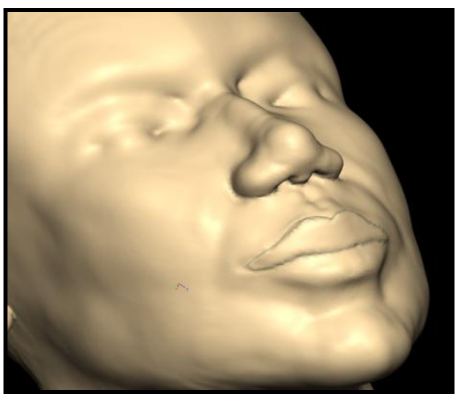
b) Helix pre-sketch 2



c) Sketch import and curve deviation

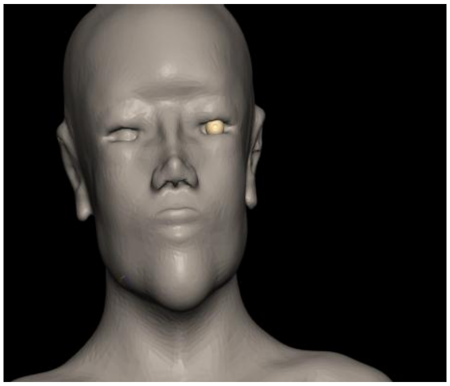


d) Lofted “Helix” form

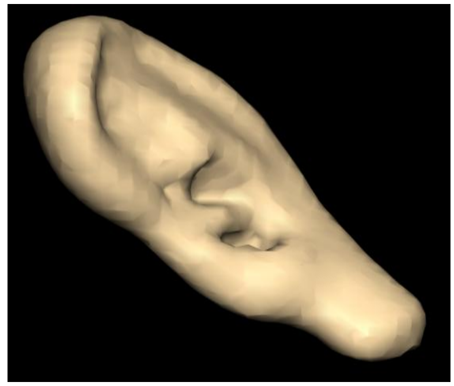


e) Curve embossing

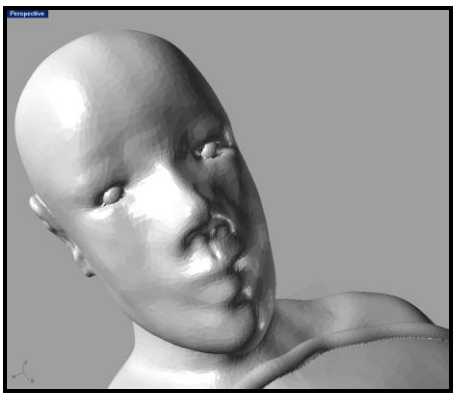
f) Symmetrical mirror tool



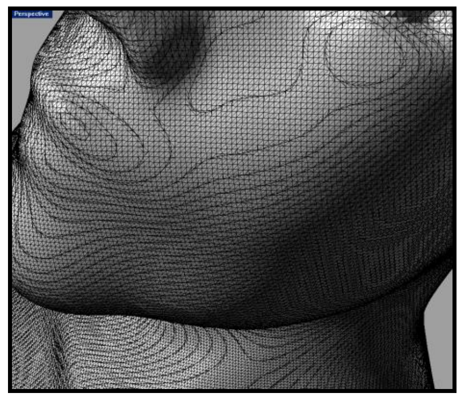
g) Separate objects



h) Detail ear-modelling



i) Shaded .stl file



j) Shaded wire frame

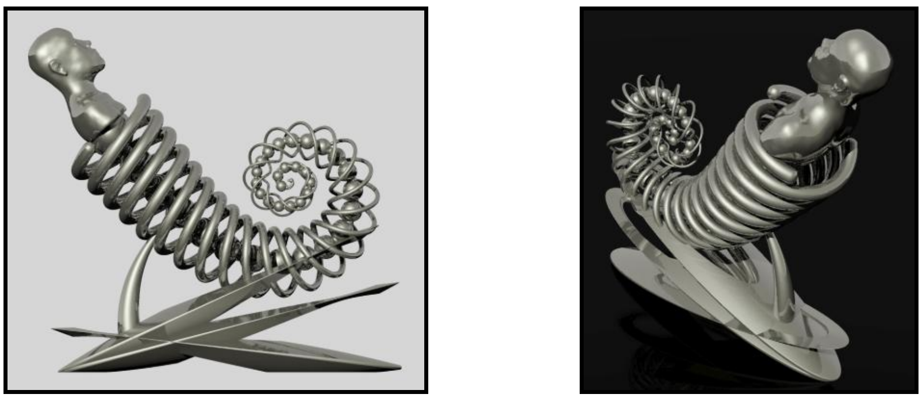
k) Head detail

l) Polyamide nylon build

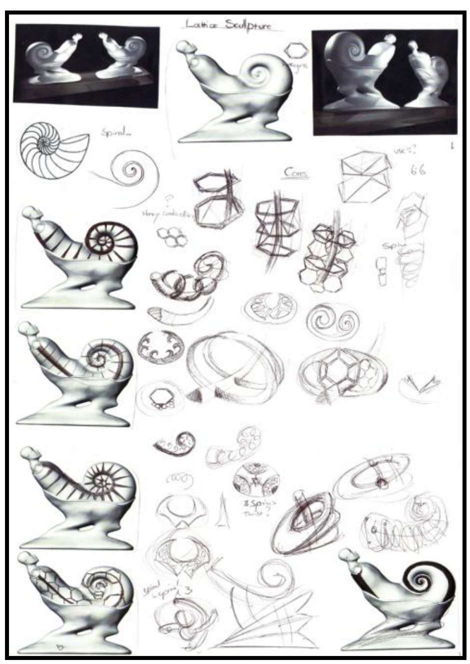
4.3 Case Study 1b: “Entwined Helix”

Case study 1b explores the aesthetic representational shift that occurs when transforming the organic geometry of case study 1a (“Helix Rest”) to a bio-engineered abstract geometry. The shift in meaning is created through changing the construction approach in how the helix formation is achieved. The transformation from solid deformation to skeletal bio-engineered sculptural form was conceptualised in collaboration with software designer Phillip van der Walt using Rhinoceros® software. The FreeForm® designed “Helix” sculpture was transformed by way of designing an entwined thread-like structure that displays flowing formations of entwined digital piping and simplified geometric structural solutions that encapsulate the original form. The aspect of multiplicity within the thread-like bio-engineered unified structure allows for a renewed conceptual reading of the previously unified solid surface. The transition from solid organic to bio-engineered geometry alludes to reading the helix form as a numerically based symmetric structure. The overall conceptual reading furthermore suggests that the locus of such exactitude is embedded in the soul of beings, this explored by the inclusion of a strategically placed human bust thereby reinforcing a reading of body in its sculptural entirety.

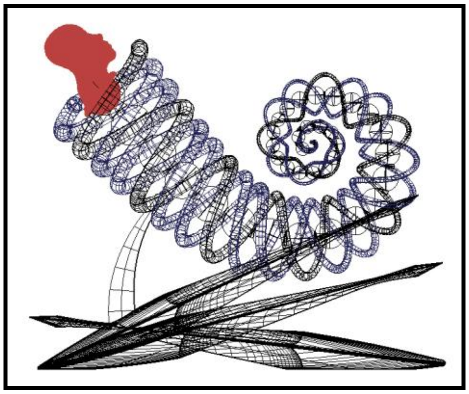
Figures 4.5a – h show the screen images for "Entwined Helix"



a) Entwined Helix

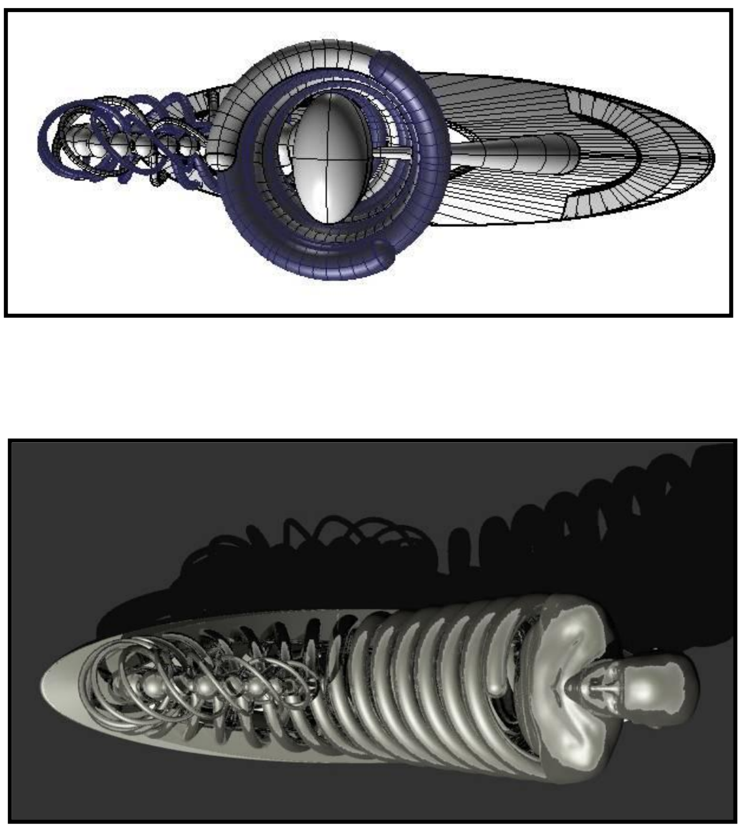


b) Pre-sketch development

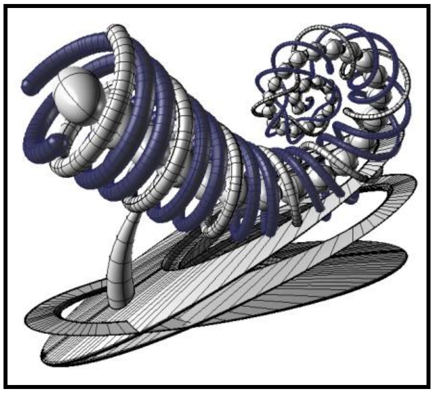


c) Wire frame

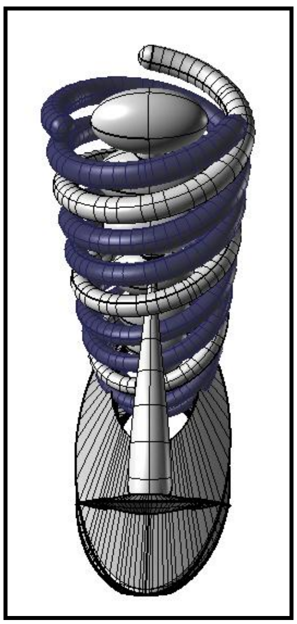
d) Shaded structure

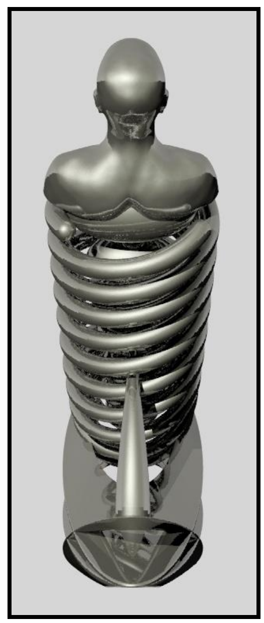


e) Wire frame and rendered top views



f) Wire frame and rendered side views





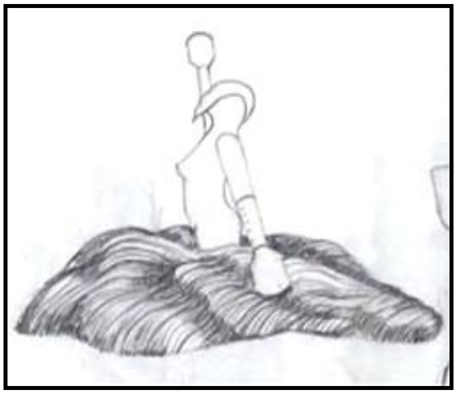
g) Wire frame and rendered back views

h) Final rendering

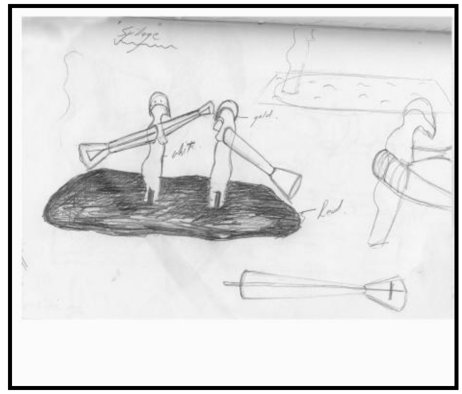
4.4 Case Study 2: “Wave Riders”

In this sculpture, replication of form positioned as detached juxtaposed elements establishes the context and foundation for the creation and recreation of meaning during interpretation. Aquiline bird-like female figures equipped with oars for arms immersed in a swell of water (wave) confrontationally connect with one another. The concept focuses on the discomfited appearance of manoeuvring these impractical paddle-like arms as two of the figures engage. The ambiguous reading of the third figure presents a jettisoning from the confrontation as the force of the water potentially engulfs it. The work is further contextualised by the inclusion of a swimming pool ladder, thereby conceptually alluding to a domestic context.

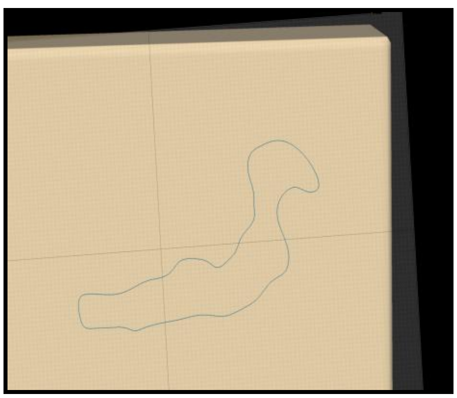
Figures 4.6a - j show the screen images of “Wave Riders”



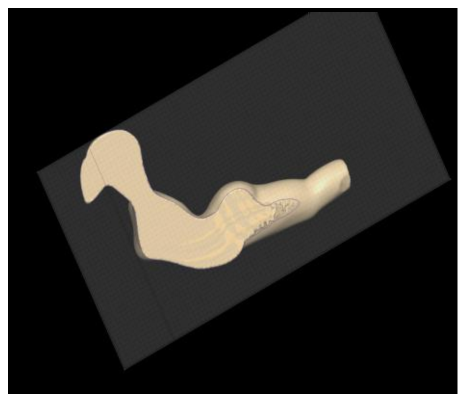
a) Wave riders pre-sketch 1



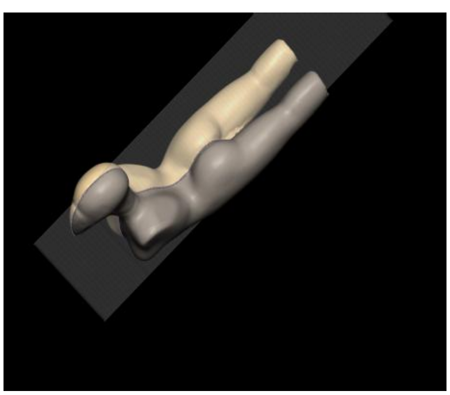
b) Wave riders pre-sketch 2



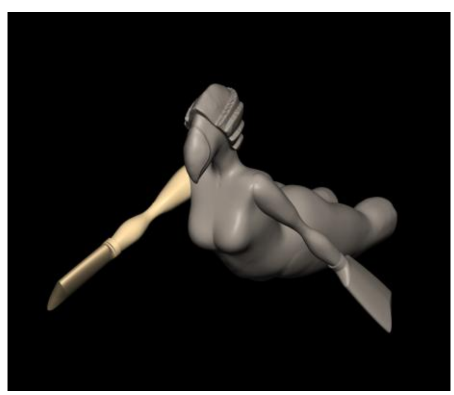
c) Profile curve



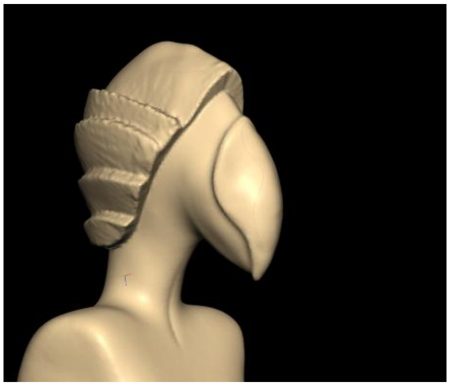
d) Sliced form



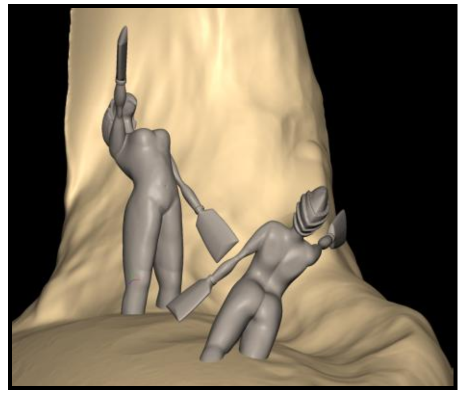
e) Separate object mirror



f) Arm attachment



g) Head detail



h) Figure duplication

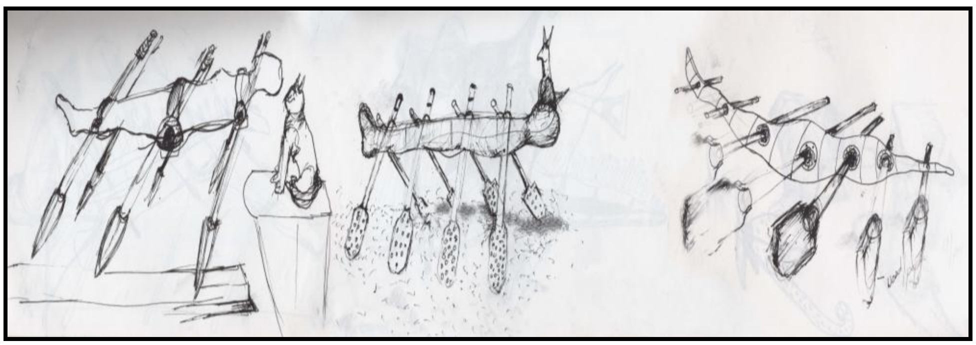
i) Polyamide figure detail

j) Polyamide nylon build

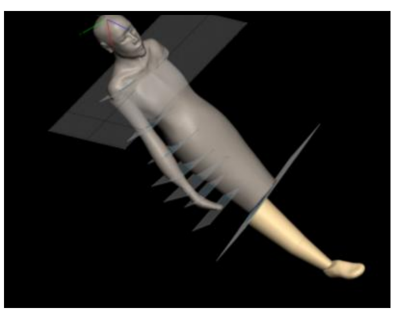
4.5 Case study 3: "Incarnate Journey"

The idea of a spiritual journey as conceptual departure point is explored within this work. The word "incarnate", forming part of the title, refers to the material substance of the embodied figure suspended on a yoke-like structure supported by several oars. The inclusion of oars and wave-embossed pattern reinforces the notion of journey and propelled movement. An adaption of the mythical Egyptian figure the Anubis (jackal) is seated on the sarcophagus below the suspended figure. The strategic placement of the Anubis is intended to suggest the guarding of the sarcophagus, which merely contains an imprint of the body. The imprint as remnant of the figure once contained within the sarcophagus represents the embarking on the said spiritual journey.

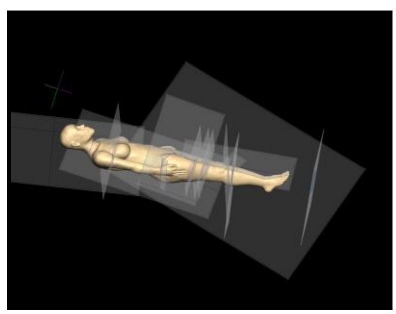
Figures 4.7a – z show the screen images of "Incarnate Journey"



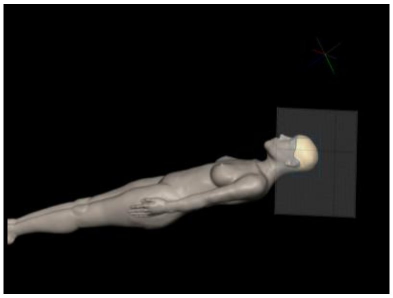
a) Pre-sketches



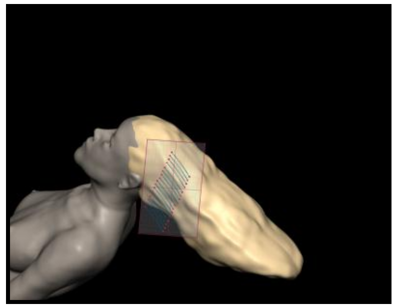
b) Initial figure construction



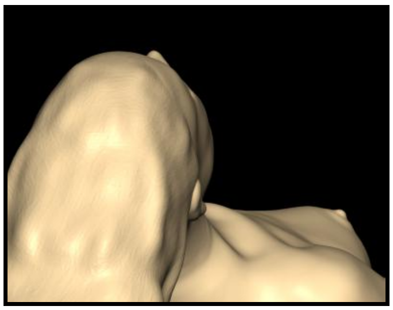
c) Construction profile planes



d) Hair detail



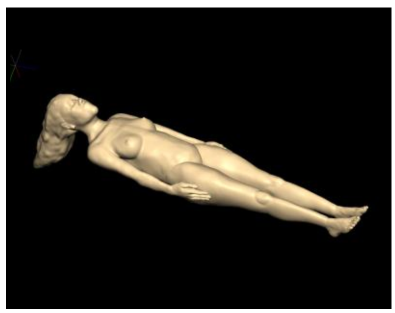
e) Embossed hair profile



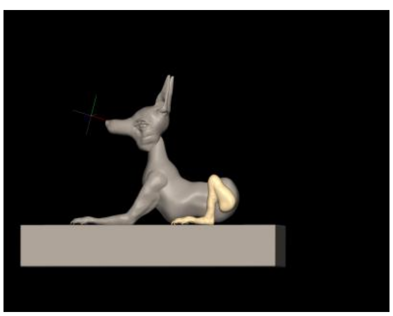
f) Embossed hair texture

g) Feet detail

h) Hand detail



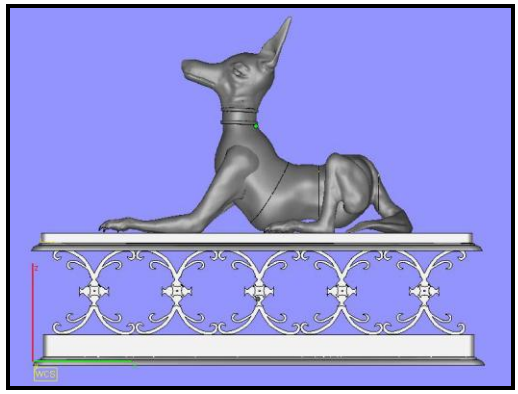
i) Complete figure



j) Anubis construction

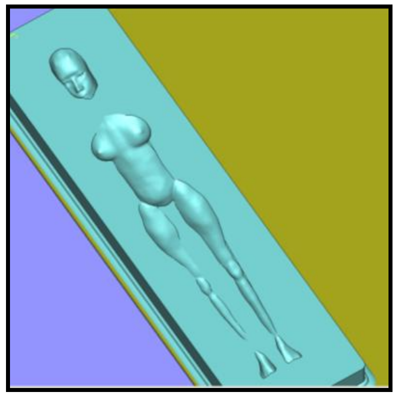
k) Head detail

l) Paw detail

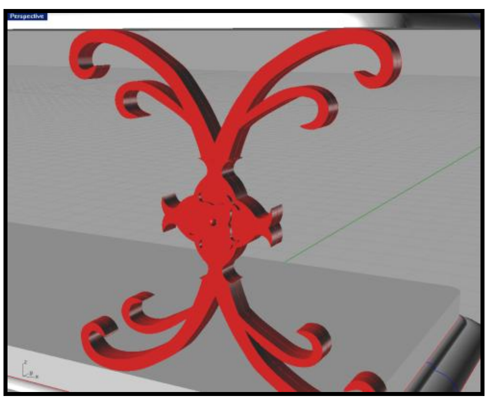


m) Sarcophagus and Anubis placement

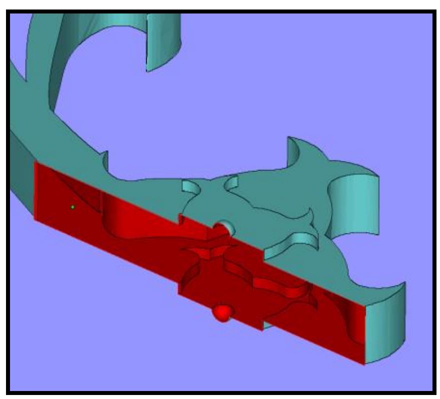
n) Sarcophagus figure imprint



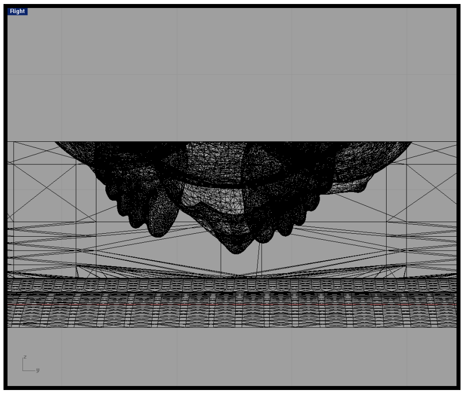
o) Figure imprint .3dm file



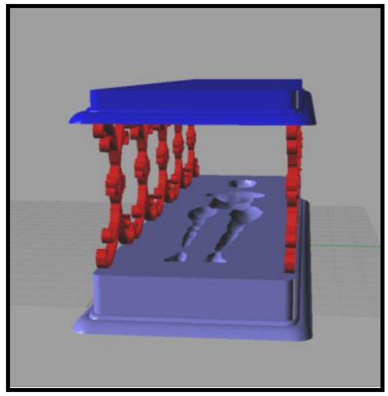
p) Balustrade



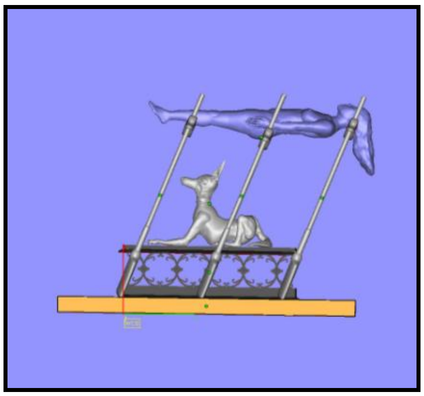
q) Balustrade cross section



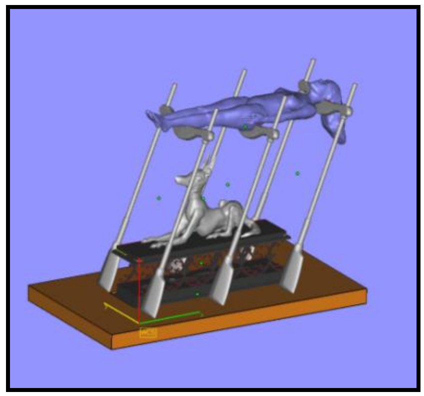
r) Figure imprint mesh file



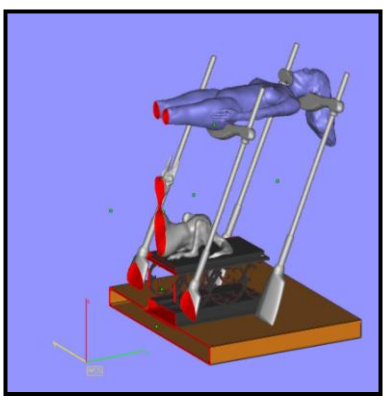
s) Figure imprint



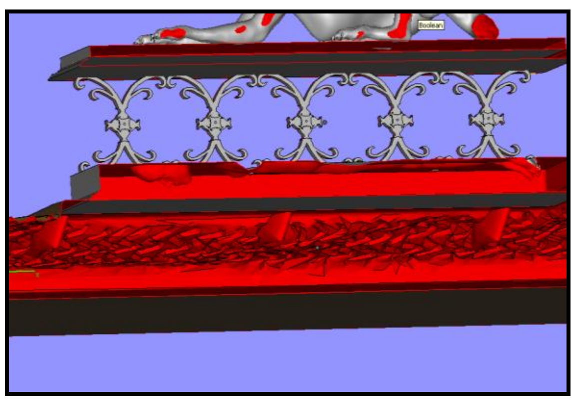
t) Pre-alignment



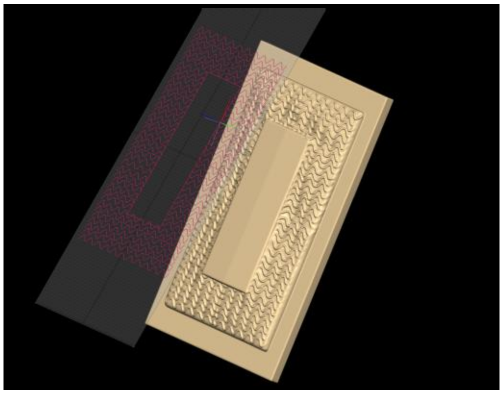
u) Alignment angle view

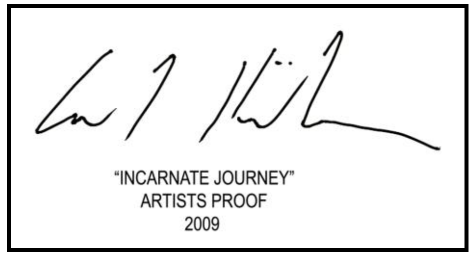


v) Hollow profile cut



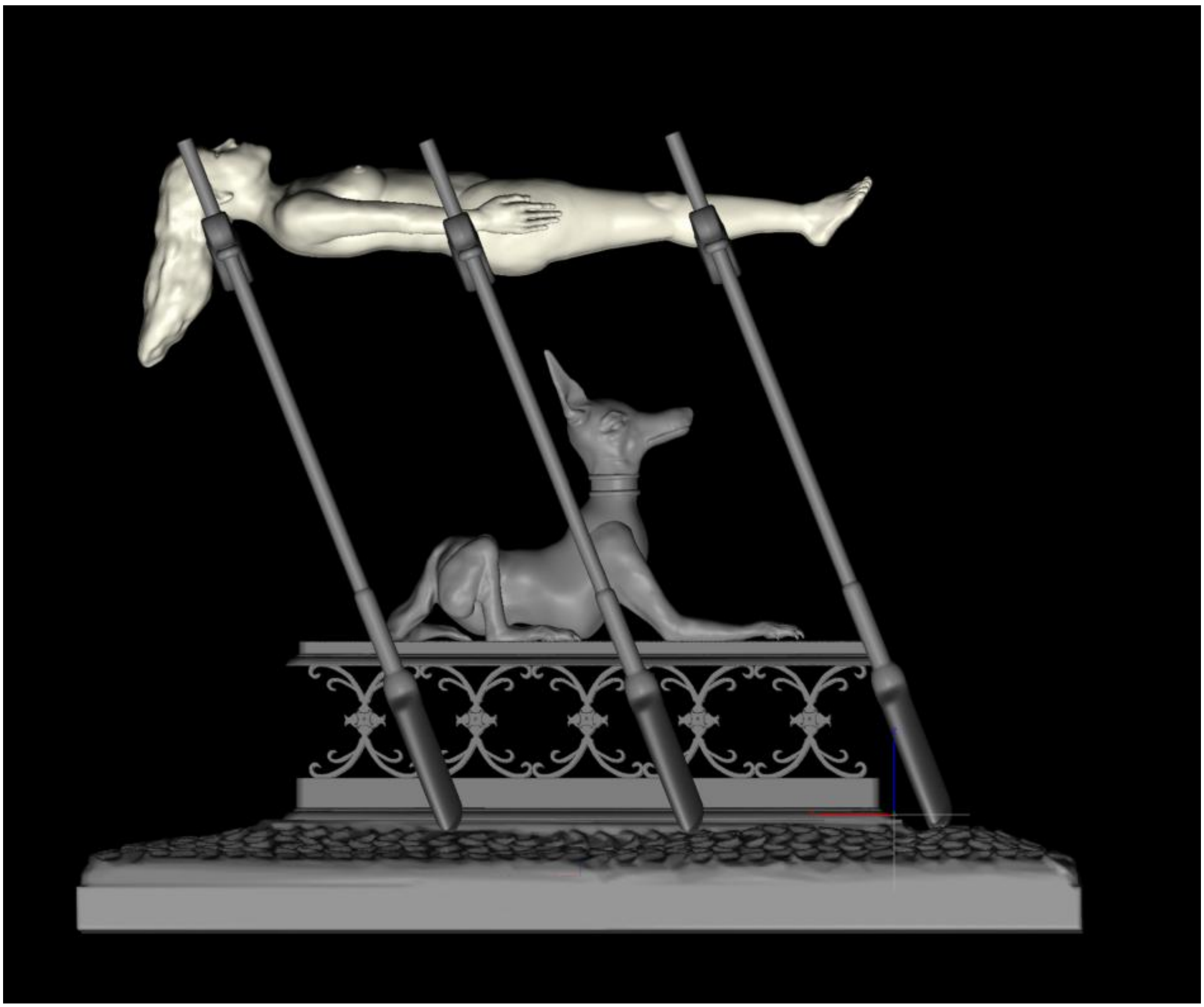
w) Recessed oar placements





x) Embossed water pattern

y) Embossed edition signature



z) Final sculpture

CHAPTER 5

Conclusion and Recommendations

5.1 Chapter 1

Throughout this research, various technological and aesthetic characteristics influencing the design and AF build of digital sculpture have surfaced. During the course of exploring the research objectives, evidence revealed that digital sculpting as medium predominantly relies on a two-way interactive communication system between art and technology. The results indicate that this interactivity is largely determined by the “way” and “means” digital sculpting intersect as a medium of artistic representation. Technical and aesthetic characteristics examined in each of the chapters surrounding these factors elucidate digital sculpting as new artistic medium. The design and build interaction between 3-D CAD, haptic modelling and AF technologies contributed to the development of three conceptually motivated digital sculptures. The three sculptures support the research hypothesis. It can therefore be said that these interfaces, applied as design “construction” tools, adequately facilitate an object-creator recursive interaction as opposed to the notion that these technologies are limited to being 3-D display or engineering-based printout tools alone.

5.2 Chapter 2

The aim of the preceding chapter was to examine the collaboration between the medium of digital sculpture and current engineering technologies by providing a perspective on the synergy of aesthetic and technical issues surrounding current input and output modes applicable to sculpture via AF technologies. To date the conventional idea of artistic representation remains challenged as artists continue to explore “sculptural” within a new digital paradigm irrespective of current technical or aesthetic limitations. Overall, technological developments increasingly reflect that as medium digital sculpting has surpassed traditional manufacturing boundaries allowing for the design and build of sculptural form that facilitates aesthetic uniqueness. The design and manufacture thereof is, however, reliant on an interdisciplinary approach between artist and engineer, where technical and creative problem-solving merge from the onset of an idea. From an engineering perspective, this unique approach is defined as “concurrent engineering”. To engage in the technology, the sculptor is required to free him or herself from a “medium specific” process in order to manipulate this elusive dematerialised technology by participating in the evolution of this technology as artistic medium. However, supporting the individual aesthetic and technical concerns of the sculptor at present within most operating systems presents a need for further development that would in turn facilitate an effective concurrent interdisciplinary approach to 3-D design irrespective of the nature of the product.

5.3 Chapter 3

Chapter 3 aims at outlining “construction” systems of 3-D haptic design as a way of navigating an interactive design approach to sculpture. The schematic outlining of a “construction” system of interactive sculpting reveals technological and sensory modes surrounding haptic sculpting that either challenge or expand existing classifications of sculpture. The chapter explores the interactivity of both medium and tools, which define this form of digital representation. For that reason, sculpting using an interactive haptic device presents a technological advancement as digital medium; with this, the relocation to tactile and kinaesthetic sensory effects produced through user interactivity transfers the emphasis to substance and manipulability of this dematerialised medium. The sculptor’s primary need for human-connectedness therefore re-established with the use of the device. The re-establishing of this primary need points towards introducing “aesthetics of interactivity” characterised by technological and sensory user “construction” modalities. Although CAD and haptic modelling adopt slowly, addressing an ‘aesthetics of interactivity’ within which “performative” qualities are embedded suggests scope for further aesthetic research on this expansive spectrum.

5.4 Chapter 4

Chapter 4 explores concepts surrounding three digital sculptures as well as the documentation of various technical stages of the 3-D CAD design process. As mentioned, these sculptures serve as case studies that support the various research components. Collectively they address one of the aims of this research in exploring a sculptural medium that aids a “sculptural paradigm shift” in the evolution of technology. Throughout this research, these three and additional case studies (addendum 3) reveal that the critical interrogation of 3-D CAD, haptic modelling and AF technologies as medium are largely characterised by their immersed engagement with aesthetic and technical concerns. This concept is supported by theorists Krauss (1999) and Potts (2004) who view medium within contemporary art practices as the material support of an image, substance of an object, the arena of display, mode of viewing, and ideologies of the viewer. This perspective collectively applies to the digital sculpting approach undertaken as support to this research. According to Lovejoy (2004), relying on medium alone for content or presence poses a challenge as electronic media changes the experience of art making and ultimately the nature of what is seen. This statement reflects in the three sculptures outlined in chapter 4 due to the interdisciplinary design and manufacture strategy employed to achieve each. Therefore, 3-D CAD, haptic modelling and AF technologies successfully relate to the 3-D digital design process and build of conceptually motivated sculptures without compromising form or content.

5.5 Recommendations

Appealing properties such as infinite dissemination, multiple reproducibility and new material redefine the function and reception of digital sculpture on both aesthetic and technical levels. When applying these properties to artistic form and content, challenging debate surrounding authenticity, copyright and authorship surface. Rees’s (1999) “desktop manufacturing” prediction surrounding the potential of this technology presents discourse for such a debate. However, this concept reflects the widespread accessibility that digital technology represents, therefore confirming that digital sculpting technologies have moved beyond the constraints of a traditional defined medium, and are therefore in need of in-depth analysis.

The idea of an interdisciplinary design approach or the simultaneous interaction of sensory and technological modes during the design and manufacture of digital sculpture is reinforced by drawing a concluding analogy with earlier postmodern theories. Theories by Baudrillard (1988) and Barthes (1977) surrounding postmodern social analysis reflect the idea of multivalent artistic activity as operating in a “polycentric” world. A similar “polycentric” multivalent engaging approach defines the activity of digital sculpting. This approach has the potential of addressing telematic networking as the organisational framework for a transdisciplinary knowledge production of future digital design tasks. Simultaneously such interaction could present an institutional forum for developing a possible virtual faculty with student-teacher interaction over long distances as these technologies are at present largely based within educational institutions. Three-D CAD applications increasingly facilitate production within most design fields, therefore clearly indicating that conventional art and design training collectively is in need of a shift to suit the needs of industry.

Contrastingly, the outcome of a critical examination outlining the generation of technological innovation as hybridised cultural research undertaken by Michael Century (1999) titled *Pathways to Innovation in Digital Culture* cautions against too much exposure to digital technology as it could lead to a loss of criticality in the arts because of technologies automating as opposed to acting as creative partners. Irrespective of this caution, artists are located in a time where technologies and new media accelerate through using; it is therefore the artists' responsibility and integrity to maintain a balance between form, technique and content. With similar cautionary intensity, Lovejoy (2004) claims that artists wishing to stay entrenched within a traditional fine art discourse will remain confronted with challenging high/low artistic boundaries arising from the merging of fine art with commercial design production.

5.6 Conclusion

Currently digital design technologies explore design and form manipulation through advanced virtual reality headsets and data gloves. Compared to haptic sculpting, these too rely on sensory and technological "construction" modes. Therefore further exploration of user interactivity as an advancing sensory mode of technology indicates the need to undertake critical research with regard to the previously recommended "synthesis", "construction" and "production" systemic representation surrounding 3-D digital artistic interactivity.

Researching the interface between 3-D CAD, AF technologies and sculpture supports the belief that an interdisciplinary approach applied to these as sculpting medium facilitates a "paradigm shift". Although this research directs digital sculpting towards this “paradigm shift”, it is the subtle and at times the deliberate hybridisation of new technology and traditional sculpting principles that anchor this medium firmly within the realm of sculpture as “new form”. The development of hybrid aesthetic strategies examine the symbiotic relationship between artist and computer, and thereby establish margins for educating future artists. Presently these margins are bound by a state of tension between the position of new technology and traditional paradigms continuing to define how representation is attained and interpreted. With this concept in mind, this research reveals the generative quality of aesthetic and technical issues surrounding modes of digital sculpting. Results therefore indicate that 3-D CAD design, haptic modelling and AF technologies applied as “construction” and build tools, adequately facilitate the conceptual design and build processes of conceptually motivated sculptures without compromising form or content.

Below follows a summary of potential research problems that have emerged through this research. These either expand on aesthetic issues or facilitate the development of digital sculpting technologies.

- The development of a curriculum structure that supports a concurrent interdisciplinary approach towards 3-D design.
- Examining digital user interactivity within which “performative” aesthetic qualities are embedded.
- Defining issues surrounding authenticity, copyright and authorship within the realm of digital art and additive fabrication 3-D printing.
- Cultivating the idea of multivalent artistic activity within a “polycentric” world.
- Addressing telematic networking as the organisational framework for a transdisciplinary knowledge production of future digital design tasks.
- Present an institutional forum for developing a possible virtual faculty with student-teacher interaction over long distances.
- Examining the loss of criticality in the arts because of technologies automating as opposed to acting as creative partners.
- Questioning artistic high and low boundaries arising from the merging of Fine Art with commercial design production.
- Evaluate the position of new technology versus traditional paradigms with regard to attaining and interpreting representation.

- The development of a “synthesis”, “construction” and “production” systemic representation surrounding 3-D digital artistic interactivity.

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ADDENDUM

ADDENDUM 1

1.1 Journal publication: Journal for New Generation Sciences

Journal for New Generation Sciences (2009) Vol. 7, No 2. (in print)

Digital sculpture: technical and aesthetic considerations applicable to current input and output modes of additive fabricated sculpture

C. Kuhn[1], Dr R. de Lange[2], Prof D.J. de Beer[3]
[1]School for Visual Art and Design Technology, Central University of Technology, Free State, South Africa
[2]Central University of Technology, Free State, South Africa
[3] Vaal University of Technology, Vanderbijlpark, South Africa

Abstract

This article examines the synergy between aesthetic and technical issues surrounding current input and output modes applicable to digital sculpture built by means of additive fabrication technologies. The scope is limited to select sculptural aspects that either transcend, question or fall short when measured against traditional manufacturing and aesthetic modes. Presented are a range of technical as well as aesthetic aspects that have impacted on this "new form" of sculpture delivery. It is indicated that irrespective of current strengths and weaknesses, for the evolving sculptor, an interactive creative partnership between technologies equally positions this "new form" of sculpture delivery as a leading role player towards defining a new digital aesthetic.

Keywords: Digital Sculpture, Additive Fabrication, 3-D CAD, Aesthetics

1 Introduction

Overall, technological developments increasingly reflect that as medium digital sculpting has surpassed traditional manufacturing boundaries allowing for the design and build of sculptural form that facilitates aesthetic uniqueness. The design and manufacture thereof is, however, reliant on an interdisciplinary approach between artist and engineer, where technical and creative problem solving merge from the onset of an idea. Although recent years have witnessed several technological advances in the 3-D design and build of digital sculptures, most of these 3-D build technologies are engineering-based in their RPM (Rapid Prototyping and Manufacturing) mechanical applications. More accommodating to the artists needs are developments in 3-D free-form computer-aided design (CAD) software applications that progressively allow for innovative artistic intervention during the design input and conceptual planning stages of digital works. The challenge for most 3-D CAD product developers is therefore to facilitate maximum artistic intervention and therein address the ongoing need for human-connectedness during the creative process. Maintaining human-connectedness for the sculptor forms a fundamental creative element from incubation of idea through to the development phase of a conceptually motivated artwork.

Michael Century's (1999) publication titled *Pathways to Innovation in Digital Culture* examines the generation of technological innovation as hybridised cultural research in which he cautions against too much exposure to digital technology as it could lead to a loss of criticality in the arts because of technologies automating as opposed to acting as creative partners. Irrespective of this caution, artists are located in a time where technologies and new media accelerate through using; it is therefore the artists' responsibility to maintain a balance between form, content, technique and idea in order to establish the said creative partnership. With similar cautionary intensity, Lovejoy (2004) claims that artists wishing to stay entrenched within a traditional fine art discourse will remain confronted with challenging high/low artistic boundaries arising from the merging of fine art with commercial design production. Therefore, to engage in the technology, the sculptor is required to free him or herself from a "medium specific" process to explore this elusive dematerialised artistic medium in order to forge creative partnerships within art and technology paradigms.

For the sculptor, the layered manufacturing additive fabrication (AF) technology application is regarded as new artistic form. AF technology has therefore contributed to redefining the function and reception of sculpture on both technical and aesthetic levels. Digital sculptor Keith Brown, founder member of FasT-UK (Fine Art Sculptors and Technology in the United Kingdom), states that digital sculpture has led to a "new order" of sculptural object, a paradigm shift, and the emergence of a new digital aesthetic (Duffield, 2001). In this article, the current technical status and the impact of aesthetic issues surrounding digital sculpting is explored as a technology based creative partnership, towards defining a perspective on this "new order" of sculptural object.

2 Digital sculpture as medium

Digital sculpting encompasses the creative development of an idea in virtual space, with the work being realised in physical space i.e. AF technologies. Author and digital sculptor Christian Lavigne (1998) defines digital sculpture as a linkage of the following three complimentary activities:

- Creation and visualisation by computer of forms or constructions in three-dimensions;
- Digitising real objects and their eventual modification made possible by computer calculations; and
- The production of physical objects by numerically controlled machines that are used to materialise synthetic images.

Digital media often lacks narrative content as a result of it being a technological vehicle. In an attempt to categorise this phenomenon, the medium has been compared to the minimalist sculptures produced during the 1960's, where the modalities of technology become the substance of the work which is modelled, manipulated and juxtaposed with the viewer, to create meaning (Penny, 1999). Edward Shanken (2002) expands on this form of sculpture by stating that computer technologies have played a unique role in the aesthetic value of sculpture delivery, due to advances in technology providing tools that enable artists to cross-examine the conventional materiality and semiotic complexity of art objects that were previously unavailable.

However, William Ganis (2004) questions the conceptual facility of digital sculpture as an output medium and states that it could not be relied on for content or quality artistic forms until such time that technology develops. As mentioned above, this line of thought can be challenged with the knowledge that when producing digital sculptures using CAD design and AF processes in many cases, as with the minimalist sculptures produced in the 1960’s, the technological combination becomes the content of the work and the conveying of narrative content possibly becomes a secondary issue.

Digital sculptors work in a medium of repetition without an original object and have the option of unlimited duplication. It can therefore be argued that such sculptures deny the sculpted materials “aura” of authenticity, the loss thereof first sited by Walter Benjamin (1969), since the electronic data used to develop digital works are easily transported via the internet and can be accurately reproduced by any RP station. The ubiquitous nature of this medium constantly stimulates debate around issues of authorship, originality and copyright, addressed as aesthetic concerns further on in this article.

Several established digital sculptors have emerged producing works that stand on their own as “masterpieces” within both the conceptual and technical boundaries of digital sculpture. After reviewing the working methods of several distinct sculptors i.e. Carlo Sequin, Michael Rees, Christian Lavigne, Mary Visser, Lionel Dean and Bathsheba Grossman, findings revealed that in their works all employed CAD as a fundamental tool in their procedural shape generation, thus indicating a high value for CAD as input mode. The same high value was displayed with all making use of various standard output AF build technologies. Shortcomings in their technological applications indicated a restricted use of varied input devices (i.e. haptic devices, 3-D scanning, data gloves, virtual headsets), reasons which could possibly be linked to cost or accessibility. Each artist has however explored the advanced technology of 3-D colour building as an output mode at some stage or other but none approaching it as a specialist medium, possibly due to current inadequate data translations from CAD to RP machines. The majority of the reviewed artists make limited use of narrative concepts as aesthetic element. Comparatively this displays a lesser overall representational modality with regard to conceptual meaning. For most, a strong focus remains on the intersection between abstract form and mathematics as a conceptual departure point, therefore indicating a high non-representational conceptual modality. One could therefore deduce that there is a growing need for all aspects of the technology to accommodate a representational as well as an abstract non-representational approach to this “new form” of sculpture. Although at present, abstract non-representational sculpted form remains a more predominant mode of 3-D digital aesthetic delivery, therefore questioning digital technologies role as narrative conceptual creative partner.

3 Current 3-D input and output modes

3.1 Three-dimensional design input modes

There are several 3-D CAD programs available on the market, e.g. Maya, Form Z, Solid Works, 3-D Studio Max, ArtCam and Rhinoceros. The latter is an inexpensive, easy and popular software program applicable to the sculptors’ free form design needs. Most 3-D CAD programmes support the Standard Triangulated Language (.stl) suffix needed for RP builds. CAD programmes based on Non-Uniform Rational B-Splines (NURBS) geometry are suitable for 3-D designers who work with free-flowing form. NURBS-based software programs are therefore ideally suited to the design and build of complex sculptural models that explore the synergy of form and content. For the sculptor a benefit of 3-D CAD is that it allows for the pre-examination of form and structure, complex macro and micro viewpoints in a weightless environment prior to the realisation in physical space.

The 3-D scanning of an object by way of reverse engineering is an input mode of generating virtualised object models by measuring data such as the shape and texture of 3-D form. The type of scanner (probe or laser) and its current technological advancement normally determines restrictions. The recent launch of Z Corporations 24 bit colour mobile ZScanner® 700 CX presents potential for the virtual recording of 3-D artworks destined for digital database development and similar recording applications. However, at present this scanner offers a low texture resolution of 250 dpi, which presents difficulty when scanning detailed colour texture resolutions.

The loss of human-connectedness through automation will remain a limitation within this new artistic form until computer technology input modes successfully evolve to replicate the physiology of human sensory touch. In an attempt to break free from the mouse-driven CAD input approach, the development of a less constrained, more naturalistic input mode is the innovative “haptic design interface” device developed by SensAble Technologies (figure 2.1).

Figure 2. 1. Omni PHANToM haptic device, SensAble Technologies, 2007.

The designer’s hand is able to move around the illusional object, virtually feeling its shape while viewing and manipulating it on the computer screen. The system is able to mimic the sculptor’s pushing and pulling of the modelling surface and offers a range of multi-resolution modelling tools, which enhance the modelling of form and 3-D texture. Irrespective of the significant developments of this system, it still operates on a single “patch” area manipulation, which demonstrates a limitation when compared to the physiological sensory application of the human hand. Developments surrounding the “multi-patch” manipulation of the NURBS surface and the addition of more complex modelling tools present research potential that will aid sculptural applications and inturn facilitate the conceptual design process.

Carlo Sequin (2005), computer science professor at Berkeley, University of California, proposes that as technological and mechanical aspects of design improve, 3-D CAD tools need the most development with the speed of real-time interactivity during the early conceptual design phase to ensure that the designer’s creative thinking process is not hindered. Therefore, the CAD input environment will be at its most effective once the artist can process conceptual ideas at the real-time speed with which they are generated in the creative mind.

Renewed developments of design input modes facilitate a more fluid and flexible human-centred digital design environment. In turn, this enhances the overall interactive conceptual design process and therefore shortens the development cycle of producing aesthetically distinct 3-D models.

3.2 Three-dimensional additive fabrication output modes

At present engineering-based AF technologies have prominently infiltrated the 3-D build of complex computer-designed functional form. The accelerated impact of this technology is evident in the unique functional organic sculptural forms produced by UK product designer Lionel Dean (www.futurefactories.com). AF technologies allow Dean to explore the adaptation and personalisation of complex creative form for an emerging Rapid Manufacturing (RM) market. Michael Rees (1999), a USA sculptor working with AF, has termed this accelerated technology “Desktop manufacturing”, which clearly depicts the accessible potential that this technology represents. The current developments of less expensive desktop 3-D RP modellers (uPrint) developed by Stratasys Inc. are able to provide quick feedback during the conceptual design process, a uniqueness that transcends present artistic manufacturing boundaries.

AF technologies vary in cost, process and material and constantly face technological advances. Implementing rapid changes in technology mostly presents financial limitations for the sculptor. However in time, the direct Laser Sintering (LS) of metals (titanium, bronze, bronze-nickel blend, steel) proves to be the way forward for the metal-working sculptor as this system can be used for a broad range of applications: investment casting, direct model building, hard and soft tooling. Stereolithography (SLA), a finer build process best suited to detailed form, wherein liquid resin cures by exposure to ultraviolet light. An alternative to laser sintered materials (LS) is the slower build Fused Deposition Modelling (FDM) process, which feeds Acrylonitrile Butadiene Styrene (ABS) thermoplastics and an investment casting wax through a narrow, heated nozzle, which then fuses over the base plate. At present, the post-processing of the irregular layered surface finish (evident in cheaper builds) and option to post-apply colour presents inexpensive and accessible aesthetic solutions for reintroducing the sought-after creative element of maintaining human-connectedness.

Most RP bureaus are more or less equipped with the above machine types with their various print options. Nonetheless, with the accelerated rate with which the technology is advancing, some of these machines have already been updated with faster build speeds, larger build platforms, reduced pricing and ground-breaking material builds such as the recent Digital Light Processing (DLP) of photopolymer material as an alternative to the widely used LS powders. At this stage, the larger interest is RM and whether build material properties are able to adequately develop in order to meet RM industry expectations (Wohlers, 2006b).

4 Hybridisation of new technology and traditional art processes

Through a collaborative effort since 1995 computer professor, Carlo Sequin and abstract geometric wood sculptor Brent Collins have been exploring the hybridisation of computer technology and the traditional art process by generating various 3-D CAD visualisations of complex structures. The carved, twisted, seven-story, ring, wooden sculpture "Hyperbolic Heptagon" (figure 2a) initially built by Collins and later a combined digital exploration thereof by Collins and Sequin (figure 2b) further stimulated the design of sculptures with much higher complexity, i.e. "Heptoroid" (figure 3). This was made possible by Sequin, who developed a specific computer program (Sculpture Generator) that calculated each complex sculptural configuration as commercial 3-D CAD tools lacked the convenient procedural capabilities. The developed computer program transcended the initial expectation of achieving a means to a speedy template design for the complex geometric wooden sculptures, but instead facilitated the development of a design structure that would not have been possible without the aid of the computer. Sequin (2005) refers to these programs as his, "[…] virtual constructivist ''sculpting tools" and concludes, "[…] the computer thus becomes an active partner in the creative process of discovering and inventing novel aesthetic shapes".

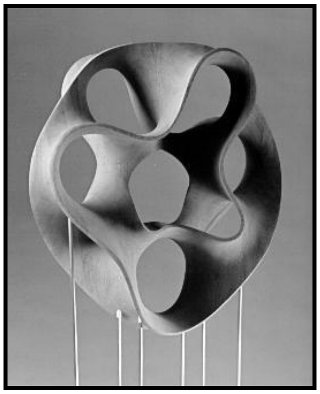

Figure 2.2a. *Hyperbolic Heptagon,*
B. Collins, 1995.

Figure 2.2b. *Hyperbolic Heptagon*,
C. Sequin & B.Collins,
1995.

Figure 2.3. *Heptoroid*,
C. Sequin & B. Collins, 1996.

The hybridisation of new and traditional technology is evident in the direct FDM build of ABS plastics, wax expendable models, LS powder builds and SLA Accura® Amethyst® resin, which can be burnt out during the traditional investment casting process with limited mould defects. The ceramic shell investment of RP master built models is particularly suited to complex forms where it would be difficult to make a traditional flexible rubber mould from an existing master pattern for the casting of a secondary wax. However, the ceramic shell moulding and burnout technique of these RP built models for the investment casting of metals remains a delicate process and an area in need of additional research. Problems occur as a result of the following: residues left within the mould cavity, mould damage due to the expansion of the various material builds during burnout, pattern distortion as a result of warm weather, incomplete bonding of shell layers and surface defects due to pattern porosity (Dickens, Stangroom, Greul and Holmer, 1995). Direct RP methods of arriving at a model are still regarded as more costly than traditional moulding and wax pouring of secondary models currently used by most foundries. However, the disadvantage of traditional indirect model reproduction via flexible rubber mould is that it is restricted to less complex form.

The above indicates how the hybridisation of new technology and traditional art processes remain technical research areas of varied potential that currently not only facilitate the artistic manufacturing process, but also predict that in time the cost-effectiveness of RP technology will allow this technology to become accessible to many.

5 Sculpture: Technical limitations and developments in 3-D CAD and additive fabrication technologies

The medium of digital sculpture and the RP build thereof when measured against traditional "sculptural" characteristics presents varied technical limitations that still need to be overcome. As mentioned a key development is the ability to design intertwined convoluted 3-D form beyond "sculptural" expectations as the RP build process is unimpeded by complexity of form. The sculptor is therefore presented with a weightless platform to explore "sculptural" within a "new paradigm" irrespective of the technical limitations encountered with CAD software programs, colour, surface finish, durability, scale or cost.

Software developer and product analyst Suchit Jain (2006), at Solid Works Corporation, claims that introducing conceptual design tools into the software system of automated 3-D CAD technology is the answer to reducing the current time spent on design analysis, as 60%-70% of product development is spent on the concept design cycle. Currently most CAD designers still prefer to pre-sketch their conceptual designs by hand or to a lesser extent utilise digital conceptual analysis tools. These however are not able to integrate with the 3-D CAD design environment and create real-time delays therefore restricting creative innovation. For the artist this presents a concern as during the conceptual design phase, an unhindered cycle of creative recursion remains a key element in producing innovative concepts and therefore innovative RP builds.

Three-dimensional colour building and AF remain areas of research that have yet to develop to their full potential. The most recent commercial colour RP system introduced by Z Corporation is the ZPrinter® 650, which can build parts in monochrome, multicolour and true black modes at 600 x 540 dpi resolutions. Z Corporation has in addition recently developed the ZPR binary file format that supports colour and texture maps unlike the common .stl file format used to move CAD data to RP machines which do not read colour data (Wohlers, 2006a). The application of colour for an artist generally creates meaning, content and nuance, which, unlike for an engineer, the inclusion thereof is often essential to the work (Rees, 1999). Therefore, the constraints surrounding the development of accessible high-resolution 3-D colour building can be regarded as a limitation, seeking solutions for the long-term development of digital sculpture.

The mineral or geological quality detected on most inexpensive RP builds is a surface property of the layer building technology. To overcome this surface finish problem, most minimal detailed RP builds undergo either tumbling or sandblasting to smooth out the surface. A limitation linked to post-processing the build is the risk of damaging the model, particularly the starch-based powders, as they are brittle. Research opportunities therefore exist in areas to improve model quality and factors that would influence these improvements (Dimitrov, Wijck, Schreve and De Beer, 2003). Surface finish as a build limitation too impacts on the CAD NURBS-based user; since on-screen 3-D objects are digitally created using smooth surfaces, which then due to the lack of an adequate translator from NURBS to .stl, the smoothness during the RP build is compromised (Wohlers, 1992). Various RP software translators are used for the pre-build repairing of unstable or defective file parts. These translators also assist with loading and manipulating the position of the model on the build platform. The correct model positioning in relation to the RP machines' laser beam is able to improve a rough surface finish or prevent the form from "curling".

Presently metallic materials are regarded as the stronger and more durable prototyped material. High strength and durability tests forming part of a comparative analysis between various metal RPM systems using DMLS (Direct Metal Laser Sintering), LS (Laser Sintering) and SLM (Selective Laser Melting) processes overall revealed that high strength is determined by low porosity and high density of material builds. These properties in turn affect the dimensional precision and overall surface finish of the product. Results showed that although the LS metal processes proved rather slow and costly, it was found to be more durable, accurate and a reliable future technology to develop (Ghany and Moustafa, 2006).

The RP build of a maquette assists in eliminating many unforeseen aesthetic and structural problems that may arise, and therefore presents the sculptor with a more accurate preview of the final product. A sculptor needing to produce a larger work would be confronted with having to build a model in sections due to size limitation of the various RP machine build platforms. For a large sculpture, this limitation would possibly increase the number of builds, which in turn increases the build and post-processing time and therefore cost. Dimitrov, Schreve, Taylor and Vincent's (2007) concluding test results on a series of large plastic and metal built components found that the build accuracy and surface finish of components did not measure up to conventional methods; however, they were not too far off the mark either. Increased scale of the plastic builds was restricted to a polyurethane material; however, large metal builds proved unrestricted in metal type. From a design perspective, metal builds seemed to have greater capacity for handling complex form. Ultimately, a significant 65-80% timesaving was reflected in the production of metal components. However, the issue of high cost was set off against non-monetary advantages such as quality and reduced risk management. Therefore, producing large components via RP showed that the process was competitive with traditional manufacturing routes and therefore a viable option for the established sculptor to consider.

An advantage of RP technology is that complex entwined forms are built at the same speed as a solid block of the same size; however, finer resolution machines do build slower. Current material and machine running costs remain to be an element of this technology that renders its status exclusive. However, as the industry grows and technology develops, costs will align with traditional manufacturing processes. Generally, for sculptors, CAD tools and RP processes are slow in being adopted as new technology because users are generally resistant to change, learning the program is a time-consuming process and most future users will wait until the current technology becomes outdated before changing over (Sequin, 2005). For the medium of digital sculpture, these factors play a role in impeding the accelerated development of this "new form" of sculpture delivery.

6 Sculpture: Aesthetic concerns surrounding 3-D CAD and additive fabrication technologies

The aesthetic focus of this article outlines issues such as authorship, authenticity and originality, which are concerns that encompass the use of the medium in a way that differs from what has sculpturally gone before. The 3-D build of digitally designed sculpture is a practice where technologically advanced “new form” and medium bring with it alternate aesthetic considerations regarding authenticity. One such aesthetic consideration would be to investigate the medium as a “new form” of production as opposed to a reproduction process alone. Koed (2005) expands on this aesthetic shift in his prediction that “[…] the diverse characteristics of the contemporary art world might undermine theories of the nature of sculpture that appeal to particular physical properties of materials, or the involvement of specific perceptual modes, phenomena, or sensibilities, as criteria.”

At present the RP build of sculpture is met with much of the same scepticism as was the onset of photography (Lovejoy, 1990), because of a similar loss of human-connectedness and the question of originality. Fifield (1999) comments on originality and the copy by stating “[…] when 3-D photographic reproduction achieves the economic level of print reproductions, sculptors will face much of the same issues as printmakers did when the copy machine first appeared.” He also remarks that with this change of concept, issues about meaning and multiplicity in sculpture will grow. Wai (2001) postulates on the issue of multiplicity by claiming that if RP continues to being limited to the production of presentation models alone, it will continue to be regarded as a limitation when compared to traditional modelling techniques. Presently, this concern is at the forefront of technological development and, as previously noted, the RP industry has significantly shifted its interest to RM, thereby encompassing future issues surrounding multiplicity.

Currently the 3-D reverse engineering scanning process is one of the most commercially utilised tools for capturing 3-D form to a digital format, from which multiple reproductions of varying size can be reproduced via RP technologies. Ellen Thornton (2001), a legal specialist, claims that an aspect of digital copying to consider is that once the form has been scanned, the “copy” now consists of binary data bearing no resemblance to the original. With current legislation protecting artistic feeling and the original material character of an artwork, it could be difficult to defend this claim in the case of a digital artwork. However, as the concept of copying forms the bases for any infringement, for the moment it also includes the mode with which it is stored. This therefore potentially weakens the argument that binary data as a transformed character of the original would not be deemed a copy (South African Copyright Act No.98 of 1978).

As postmodern perspectives blurred distinctions between original artworks and copies at the onset of "appropriation art", copyright and authorship issues have ever since continued to be at the forefront of artistic debate. The 3-D RP build of sculptures via AF too push the boundaries of authenticity and originality within existing definitions of sculpture. This is displayed in the current unlimited RP build and virtual display capabilities of digital sculpture, which are encased with extended meaning by way of its ubiquitous nature.

When the envisaged display moves beyond the 3-D virtual environment to a fixed RP 3-D build, one would assume that the sculpture displayed as a tangible, fixed object requires less debate than a virtual object as laws are easier to apply. However, this "new form" of sculpture delivery has copyright protection issues of its own to consider. The most significant would be the ubiquitous nature of the file data of a digitally designed sculpture, which is easily transported via electronic network to any RP station for the envisaged 3-D build thereof. An aesthetic viewpoint surrounding the concern of ubiquity introduced by Mandelbrojt, Frémiot and Malina (1999) draws an interesting analogy of technological art by viewing it "[…] equivalent to the traditional concept of durability and lastingness, with the infinity of space replacing the infinity of time […]". This thought can be considered as a fulfilling aesthetic prospect; however, within a legal situation one is still left with the nature of the file data presenting an object with no fixed original and unlimited reproducibility.

When analysing the vast abilities of digital sculpture, Rees (1999) speculates on authorship and the possible outcome of future software programs specifically designed to facilitate the creative process by stating that "[…] if sculpture became the agent of ubiquitous computing, then it also becomes the originator of the content and the controller of the context in which it gets interpreted." With all these concerns in mind, a possible hurdle that most mainstream critics and practising artists encounter when confronted with this technology is that it challenges their imbedded consciousness about whether it is sculpture.

7 Concluding comments

Indications illustrate that irrespective of current strengths and weaknesses, for the evolving sculptor, an interactive creative partnership between art and engineering technologies equally positions this “new form” of sculpture delivery as a leading role player towards defining a new digital aesthetic. Appealing properties such as infinite dissemination, multiple reproducibility and new material redefine the function and reception of digital sculpture on both aesthetic and technical levels. When applying these properties to artistic form and content, challenging unresolved aesthetic debate surrounding authenticity, copyright and authorship surface.

The establishing of an interactive creative partnership between the two disciplines determines the “way” and “means” digital sculpting intersect as a medium of artistic representation. It is therefore evident that a sculptor’s user requirements prior to engaging in these technologies need to include a sound understanding of available AF output material builds, their technological parameters, skill of an appropriate input mode(s), structural elements associated with 3-D form as well as an understanding of the aesthetics of conceptual design. This expanded set of 3-D design requirements clearly indicates that conventional 3-D art and design training collectively is in need of a shift to accommodate developing technical and aesthetic requirements.

8 The Way Forward

The technical manipulation of 3-D form increasingly occurs through applications such as virtual reality headsets and electronic data gloves. Compared to the familiar “haptic device” sculpting mode, these too rely on sensory and technological elements. Therefore, the aesthetic exploration of “user” interactivity as an advancing sensory mode of technology necessitates critical aesthetic research in order to define 3-D digital artistic interactivity.

An engaging approach towards forging a creative partnership through multivalent artistic activity within a “polycentric” world characterises the current activities surrounding digital sculpting. This approach has the potential of addressing telematic networking as the organisational framework for a transdisciplinary knowledge production of future digital design tasks. Simultaneously such interaction could present an institutional forum for developing a virtual faculty with student-teacher interaction over long distances as these technologies are at present largely based within educational institutions.

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ADDENDUM 2

Journal submission: Journal for New Generation Sciences

Haptic modality: An inscribed systemic user "construction" approach to sculpture

C. Kuhn[1], Dr R. de Lange[2]
[1]School for Visual Art and Design Technology, Central University of Technology, Free State, South Africa
[2]Central University of Technology, Free State, South Africa

Abstract

This paper outlines a haptic "construction" system as means of navigating an interactive design approach to sculpture. A user system applicable to haptic generated form is sought after by way of exploring 'construction', as 3-D modality comprised of an interrelated synthesised system. The paper schematically outlines technological and sensory user 'construction' modalities as elements towards an expanded 'synthesis', 'construction' and 'production' systemic structure as a way forward for haptic sculpting. 'Construction' modalities applied to the case study explore human and machine haptics where the PHANTOM® haptic device and FreeForm® Modeling™ CAD software developed by SensAble Technologies® are used to generate, manipulate and render the touch and feel of a virtual designed sculpture.

Keywords: Haptic Modality, Inscription, Construction, Sculpture

1. Introduction

Within each process termed sculpture there remains a physiological interaction with material as "substance" involving tactile and supplementary properties. Haptic designed digital sculpture calls for an inclusive understanding of this new medium to enable an exploration of user systems. This paper explores "construction" systems of haptic design as a way of navigating an interactive approach to sculpture. The machine controlled 3-D haptic CAD environment used to generate digital sculpture presents a renewed perspective on the display arena when applying existing classifications on the modalities of sculpture. Outlined are systemic user elements applicable to human and machine haptics where the PHANTOM® (Personal Haptic iNTerface Mechanism) Desktop™ haptic device and FreeForm® Modeling™ (FFM) software developed by SensAble Technologies are used to generate, manipulate and render the touch and feel of a virtual designed sculpture. 3-D 'construction' modalities of haptic generated form are comprised of interrelated existing classifications of visual semiotic resources such as surface, substance and tools. When systemically categorised haptic sculpting emerges as a synthesised inscription system of technology whereby the human hand is re-introduced via a technological "interface" assembling various renewed effects of the meaning of 'surface', 'substance' and 'tools' in their haptic user interaction.

Although Post-Modern art practices generally reject such a systemic approach preferring a separate analysis of object, subject and context, the interactivity of haptic user 'construction' lends towards applying a systemic approach as departure point in defining this elusive 3-D medium. In support of such an approach is Simone Gumtau (2006) who claims that identifying semiotic relationships for haptic variables are the most distinctive design parameters and a step towards determining a possible 3-D haptic design palette. This paper therefore presents a schematic outlining potential sensory and technological 'construction' modalities such as spatial orientation, volume, temporality, form manipulation and tool options towards defining a systemic user 'construction' design palette for interactive haptic sculpting (Table A).

Table A. SYSTEMIC USER CONSTRUCTION MODALITIES OF HAPTIC SCULPTURE

MODALITY **INSCRIPTION SYSTEMS**			**CONSTRUCTION**	
			TECHNOLOGICAL	**SENSORY**
SPATIAL ORIENTATION	**PLIABILITY**		HUMAN SENSORY LOOP (Data: receives/ applies/sends)	
			KINAESTHETIC/ TACTILE (Bodily: sense/state/position)	
	SPATIAL CO-ORDINATES		ERGONOMICS	MAPPING X, Y, Z (Anisotropic, Isotropic ,Oblique)
VOLUME			WEIGHTLESSNESS	SOLIDITY PENETRABILITY PLASTICITY
TEMPORALITY (Substance)	**TEMPORAL PRESENCE**	**TACTILE COMMUNICATIVE AGENTS**		RECURSIVE SUBSTANCE (Endless/Duration/Repetition)
	REAL-TIME INTERACTIVITY		MECHANICAL AUTOMATISM	RECURSIVE AUTOMATISM (Link: time/medium)
FORM MANIPULATION			HAPTIC-LOOP COLLISION/DETECTION/RESPONSE FILE IMPORT/EXPORT VOXEL SOLIDS	VOLUMETRIC MODELLING HAPTIC TEXTURING
TOOL OPTIONS			SYSTEM ARCHITECTURE	MODELLING CARVING CONSTRUCTION RENDERING

2. HAPTIC MODALITY

Mandayam Srinivasan (2007) outlines that to perform a task using a haptic interface; the human user conveys motor actions by physically manipulating the interface, which in turn, displays tactual sensory information through stimulation of human tactile and kinaesthetic sensory systems. User interactivity results in an immediate engagement with substance and process within the computer as a weightless ubiquitous environment.

The CAD interface shift from keyboard, mouse and joystick operation to the haptic device as ‘construction’ tool is no longer revolutionary, as its use has become familiar in simulators for medical training as well as film animation design; however it has not yet impacted as a widespread sculpting medium. The Greek term “haptic” meaning “able to lay hold of” encompasses the tactile action on which a haptic feedback system relies which stimulates haptic perception. Haptic force feedback determined by collision detection and response is reliant on kinematic and sensory system architectures. The bidirectional force feedback to the user through the device is termed the haptic-loop thus creating a sensation of immediacy during the actual manipulation (Hayward, Astley, Hernandez, Grant and Robles-De-La-Torre, 2004). This sensory haptic-loop occurs during both exploration and manipulation of virtual objects classifying the device as a force feedback interface as well as an input apparatus appropriate to the sculptor’s tactile needs.

3. INSCRIBED SYSTEMS OF CONSTRUCTION

3.1. Spatial orientation

The “tactile perceptual field” includes the spatial properties of a haptic designed object maintaining contact with hand-arm displacement (Lederman and Klatsky, 1993). This ‘tactile perceptual field’ primarily activates aspects relating to the overall spatial orientation within a virtual and physiological user design environment. Defining ‘construction’ modalities encompass technological device parameters and interactive sensory user factors, dependent on tactile and kinesthetic pliability as well as activated spatial coordinates within the 'tactile perceptual field'.

3.1.1. Pliability

Digital design has both temporal and spatial qualities; the interactive 3-D virtual design environment facilitates meaning to emerge from a sustained human-machine interaction, termed pliability. Conditions for maintaining pliability as an aesthetic experience within an interactive digital design environment are based on prior experiential qualities and procedural knowledge. Digital designed sculpture that displays a close connected haptic-loop between tactile and kinaesthetic senses can be characterised as having a strong pliable interaction. 'Pliability' within the haptic environment requires these senses to operate simultaneously to provide the user with means to perceive and act on both technological and sensory interactive modalities of 'construction'.

Tactile and Kinesthetic senses

Tactile and kinesthetic senses simultaneously form key operational principals for the duration of the haptic interaction. Kinesthetic senses refer to the bodily sense of state, position and the motion of limbs activated by associated forces; these transmit through sensory receptors in the skin during the interactivity experienced throughout the human-machine haptic 'construction' process. The user is confronted with a relocation of material, texture and substance due to the kinesthetic and tactile interaction.

3.1.2. Spatial co-ordinates

Ergonomics

The ergonomics surrounding haptic design as an essential technological positioning co-ordinate determines the users' interaction and work place flexibility with the device as well as the model within the virtual display area. The direct point based PHANToM® stylus used for interacting with the digital clay operates freely on an articulated armature. Indirect ergonomic options available in the software program facilitate manipulating the virtual clay surface through a range of multi-resolution modelling tools. Direct or indirect the correct ergonomics maintains the necessary tactile relationship between user, device and model.

Mapping x, y, z

The sensory nature of this immersive spatial design experience relies on fundamental orientation co-ordinate mapping (x, y, z) properties of the design arena. Familiarisation with the defined orientation processing of form and spatial user haptic properties, allow the user to engage in an enhanced tactile-field.The spatial modality of haptic user 'construction' is therefore reliant on exploratory conditions relating to the various directional planes/stimuli (horizontal, vertical, oblique) which prove crucial to the production or reduction of gravitational forces. In this instance, the user is therefore required to consider the role of gravity and the coding of an orientation in space to ensure an accurate manipulation of the desired form. Simultaneously the user needs to rely on a "working memory" of prior knowledge (Gentaz, Baud-Bovy and Luyat, 2008).This termed a "cognitive stock" resource within each individual on which the haptic user relies to achieve the mental synthesis that is necessary to construct a representational object within the 'tactile perceptual field'.

3.2. Volume

Mass defines as a system embedded with features such as the object's centre of gravity, its relation to the horizontal, solidity, impenetrability and the way in which it interplays with surrounding space. The 'construction' of haptic sculpture engaging with the body of the user in relation to various spatial properties of volume becomes characteristic of virtual mass (0'Toole, 1994).

Weightlessness

Merleau-Ponty's (1962, 1968) view on artistic making as a perfect symbiosis of eye, mind, and hand challenges the medium specific sculpture due to a logistical separation between weight and substance. This idea of a split in mental conception and physical substance with virtual haptic-sculpting requires reconsideration due to the weightless unrestrained 'construction' environment. As a result, haptic sculpting facilitates Merleau-Ponty's proposed symbiotic sculpting process.

Plasticity/ solidity/penetrability

To explore the plasticity of virtual clay as simulated haptic sensory volume element, characteristics pertaining to real clay need consideration. Three main characteristics are prevalent: 1) moist properties of the calculated clay body through water saturation 2) volume preservation during deformation 3) increased surface tension due to saturation prohibiting material disintegration. Guillaume Dewaele and Marie-Paule Cani (2004) performed comparative plasticity tests on interactive global and local deformations for virtual clay. The aim was to simulate virtual clay characteristics via computation models to maintain the substance effects of a real clay body. The proposed model relies on fluid mechanics and mathematical computations to push, pull, twist and bend the virtual objects. Overall findings in the above plasticity case studies reveal that the main characteristics of real clay simulated in real time at a low computational cost providing the user a realistic interaction with clay as modelling substance.

3.3. Temporality

The term medium within real world sculpture mostly refers to the physical material of the sculpture. Pamela Lee (2004) proposes a more primary understanding of medium that emphasizes its influential value as a communicative agent between two points and in doing so; a dialogue establishes between artwork and beholder. Within a haptic user 'construction' interface, temporal presence and real time interactivity encapsulate such a dialogue as communicative agents.

3.3.1. Temporal presence

The overall temporality of 3-D haptic sculpting generates a renewed perspective on how real world-sculpting modalities apply. Michael Fried's (1998) definition of temporality as endlessness, duration bound and repetitive recursive experience, and Simon Penny's (1999) reference to digital technology as substance implicit of meaning entwine as sensory ‘construction’ modalities inducing a temporal presence within a haptic system of ‘inscription’.

3.3.2. Real time interactivity

Due to the mechanical user interface of the PHANToM® haptic device and its association with sculpture it would be suitable to assign Rosiland Krauss’s (2000) aligned interpretation of “automatism” as a mode of production of a reality based interactive character wherein a beholder’s presence is suspended through mechanical manipulation. In this systemic instance, “real time interactivity” driven by ‘automatism’ inscribes as an inseparable system consisting of the users’ physiological circumstance and the parameters built into the haptic device system architecture. For that reason, ‘automatism’ with its sensory and technological user interaction (haptic-loop) applied as a ‘time’ based system embedded in temporality suitably equates a haptic ‘construction’ interface activated during user interaction with the medium.

3.4. Form manipulation

Haptic-loop

Technologically, the force feedback of the haptic-loop operates as a delayed frequency designed to compute geometric data via a collision detection/response module. In its delayed design structure it receives, applies, and sends data (Bordegoni, Colombo, Formentini, 2006).The efficient functioning of the haptic-loop can however be interrupted by system architecture failure as a result of edge of memory (EOM) issues that force modelling to exit resulting in lost data. EOM problems are caused by: 1) high clay resolution, 2) large model file size.

Collision detection and response

During user operation, collision detection and response occur when the PHANToM® stylus touches the virtual surface during contact positioning and/or surface manipulation. At this point, a computational mechanistic model calculating the reaction force during every servo-loop alters the surface of the probe point. The inside/outside property of the function enables a slight collision between the sampling points and surface of the probe. Once a collision point detected inside the probe surface area, it mathematically responds via modified force vectors, which feed back to the user through the haptic device. (Gao, Gibson, 2006).

File Import/Export

To facilitate user 'construction' FFM can import a variety of file formats, which allow conversion to virtual clay for further manipulation thereby enhancing program software interoperability. However, in some instances due to the lack of standardization among various software applications, some geometry does not import as expected, requiring extensive form manipulation prior to 'construction'.

Voxel solids

The mechanical file structure of haptic designed FFM models are comprised of voxels. A voxel is defined as a three-dimensional pixel with a numerical volume unit that is represented by its specific position in x,y,z coordinates; these units of information make up digital clay. Voxel's do however limit the surface quality for downstream product development requiring that the model be exported as a compatible file conversion for further program interoperability or the Rapid Prototyping (RP) thereof.

Volumetric modelling

FFM via haptic device enables a point-based sensory interaction with digital clay for the 'construction' of volumetric objects made up of voxels as defined above. Mandayam Srinivasan and Cagatay Basdogan (1997) explain the computational operation encased in a voxel as haptic interaction properties consisting of bytes of information such as material density, density gradient, colour, stiffness, and viscosity assigned to each voxel that computes at the haptic interface point. Operations within FFM are controlled by force and torque feedback, enhancing realism by stimulating a general tool-object interaction as the users' sculpting tool passes over the implicit surface (Gao, Gibson, 2006). The realism experienced with tool-object user 'construction' facilitates a fluid modelling interaction better suited to the sculptor's tactile needs.

Haptic texturing

Two approaches define haptic texturing. Firstly, an image–based texturing; allowing the user to access a range of pre-loaded synthetic textures. Secondly procedural haptic texturing; which generates synthetic texture fields using mathematical functions for determining the height field of the required texture from which the gradient vector at the contact point is calculated in order to agitate or transform the surface geometry of the object (Srinivasan, Basdogan, 1997).

3.5. Tool options

System architecture

Defining the technological and sensory force variables is dependent on the hardware and software, as well as the interface architecture. The visual haptic process facilitated by adequate system architecture involves sculpting and rendering the model, processing user input, transforming values for haptic and image-based texturing and editing surface properties of the volumetric representation. The haptic process includes; updating the force feedback displayed by the PHANToM® collision and response detection feature, finding the contact point, simulate surface properties such as friction and stiffness, and executing the optimal ~1 kHz vibration force computation within the haptic-loop.

Modelling /Carving/Construction

Virtual clay deforms according to the users intended manipulation through simulated pushing and pulling of the virtual surface. For this, there are three main groupings of ‘construction’ tools: curves, planes, and virtual clay. Editing options in each of these tools assist to generate form; these include control points, direct manipulation, free form deformation and variation modelling. The overall possibilities of editing form and varied tool selections contribute to the users’ dependence on a dynamic interaction between model properties and tool options within the haptic ‘construction’ system.

Rendering

The FFM rendering function applied to ‘constructed’ virtual clay models, surfaces, and solids is most often used to replicate the envisaged virtual display or explore; 3-D material build properties, surface colour, and texture. To enhance overall haptic perception the software application is able to create individual QuickTime virtual renderings of valid views running 360° around the model.

4. Case study

‘Construction’ related modalities from conception to fabrication align this artistic medium within the paradigm of sculpture. The sculpture (figure 1) was modeled using a high-end Windows operating system and graphics card to run FFM and haptic device.

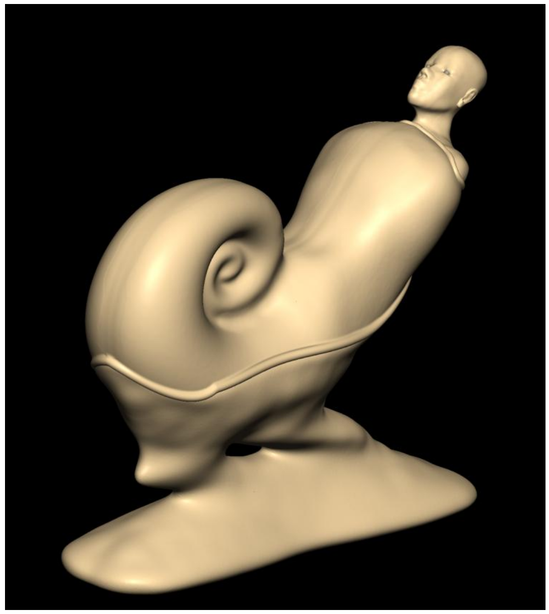
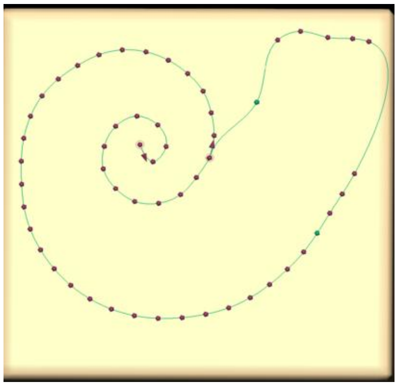


Figure 1) “Helix Rest”

4.1. Generation of form

Profile construction

Starting a haptic virtual clay modeling process begins with the generation of a basic closed curve or import of pre-drawn sketches (figures 2a, 3a). Sketch files are projected onto a clay surface determining the required form from various x, y, z profiles. This process allows for extensive editing options of the profile curve facilitating a more controlled user interaction. Prior to further manipulation the curve can be inflated as clay piece or cut away from a pre-constructed geometric shape (figure 2b).



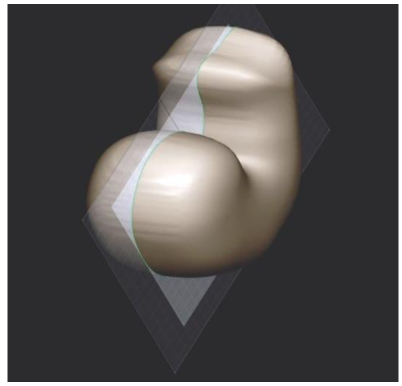


Figure 2a) Closed curve profile

Figure 2b) Inflated curve profile

Haptic feedback and RP strategies align to artistic activities where disruptions to surface finish may be required as opposed to rigid design practice. Edmonds, Soufi (1996) refer to this practice as “emergence” where ambiguous mark making develop through concept sketching. User deviations from curve profiles and initial form ‘construction’ developed into an expansion of idea. Represented in figures 3 a, b, c are sequential screen renderings from sketch to interactive sculpting depicting the results of such form deformation.

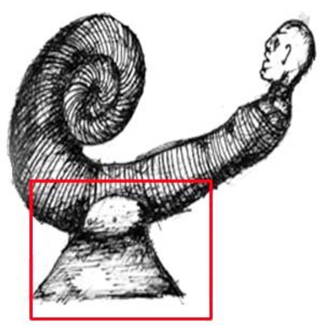


Figure 3a) Initial sketch

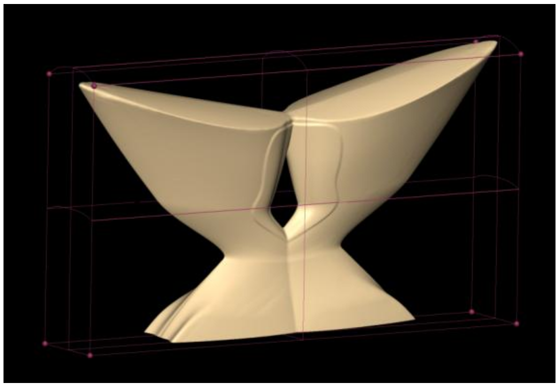


Figure 3b) Initial clay construction deviation

Figure 3c) Further deviation

<u>*Approximation of form*</u>

Initial form was achieved through a volumetric 'construction' approach. Due to the level of detail required for the RP of the form, the clay coarseness was initially set to a fine resolution thereby increasing the voxel density and file size. As a result, the haptic interaction between sculptor, device, and virtual display at times exceeded its virtual memory limit resulting in data translation delay and loss. The user should approach 'construction' as separate objects, thereby facilitating a speedy data translation of reduced voxel density or file size prior to the merging of objects. Due to the intensity of the facial detail, a separate 'construction' approach was applied to the sculpture with the intention of combining the pieces at the final stage (figure 4a, b). Separate objects are indicated by different clay colour's, which also indicate which clay parts are active (yellow) or inactive (grey).

Figure 4a) Separate active/inactive clay objects

Figure 4b) Head detail

The mapping of the global or local x, y, z triad co-ordinates allow the user to locate the object. The same co-ordinate translation is required when repositioning two objects to align at an exact collision point. Alternatively, the object can manually be orientated using the “grab” tool option. Applying the co-ordinate translation is however a fast accurate option when two objects are weightlessly floating in infinity. Spatial orientation of this technical nature presents to the sculptor an adjustment in co-ordination dynamics that influences the mechanical automatism experienced as an engaging characteristic of real time interactivity.

Surface deformation

The amount of surface detail is largely reliant on the selection of clay coarseness during ‘construction’. The sculptures smooth surface finish was achieved using interactive size variable smooth, smudge, and carves tools. At times, these operations were carried out using the interactive mirror tool allowing the user to achieve symmetrical form. Once the individual parts of the sculpture were complete, the clay coarseness was uniformly converted to a smooth texture in keeping with the sculptures organic flowing form. However, the ”polyamide” nylon RP build material, does not offer the surface detail that a stereo-lithography resin does, therefore the final object conversion back to a coarser clay facilitated easier file translation without compromising detail.

Temporal interaction

Real clay properties linked to defining the workability of surface tension were manipulated via a selection of pre-loaded modelling and carving tools. Exploration revealed that the objects tactility was dependent on material qualities other than its plasticity, such as size and the nature of the object. Experiential user feed-back during this case study, defines that the sensory notion surrounding the haptic user as engaging in a recursive experience of endlessness, duration and repetition during form ‘construction’ is firmly reliant on the ergonomics of the virtual and technological design environment as well as prior knowledge pertaining to form and principals of sculpture. This embodied approach (Gumtau, 2006) reiterates how interactive haptic sculpting establishes as substance of meaning in its ‘temporal presence’.

4.2. Editing and manufacturing issues

Voids occurring between the clay voxels need filling prior to converting the .cly file to a .stl RP build file type. Voids arise due to continual clay manipulation, specifically appearing where surfaces do not align when merging parts. Although the FFM data report claimed that all voids filled, due to user 'construction' voids were still present in the .stl conversion creating pre-build surfacing problems (figure 5). Translator software "Magics Materialise" repaired the imported .stl file in preparation for the build thereof. Surfacing or filling voids as separate objects prior to the final combining of all clay pieces would have reduced the amount of voids present.

Figure 5) Virtual clay voids

When importing .stl files into FFM, data is lost during translation; due to converting surface mesh structures to voxel solids. The user is required to consider this technical issue as it impedes the procedural user 'construction' interface when working with two or more interoperable file exchange systems. The exporting of the .cly file underwent an approximate 96% reduction to the .stl file. Detail was however not lost during the initial 96% .stl mesh reduction for export as the overall mesh reduction merely resulted in less triangular formations on less detailed surface areas thereby reducing the overall mesh count and not necessarily compromising detail. Comparatively figure 6a shows the appearance of a reduced .stl file structure and figure 6b displays a more compound mesh structure.

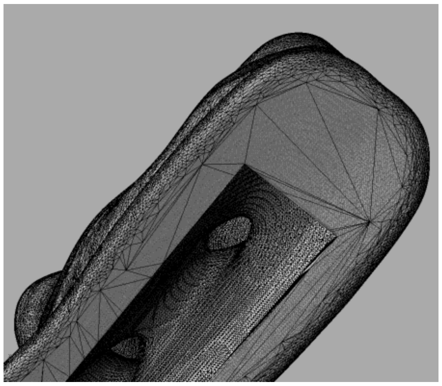
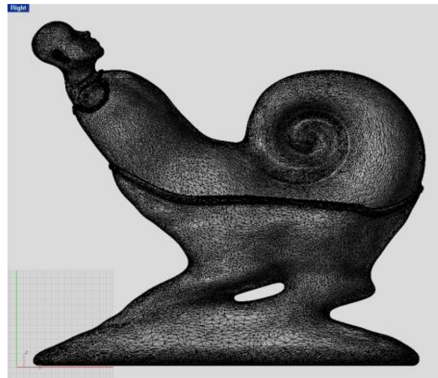
 

Figure 6a) Reduced mesh structure Figure 6b) Compound mesh structure

Software tools within this interactive modelling system allowed the artist to emboss name, title of the work and edition specifications on the underside of the form. RP as sculptural medium encompasses manufacturing ethics and copyright issues relating to artistic editions or multiple series productions. These raise concerns surrounding ubiquity, authenticity, and authorship, which have yet to receive extensive critical attention. The sculptor in this case study has limited the edition to five builds with the first of the five regarded as the artists proof (figure 7).

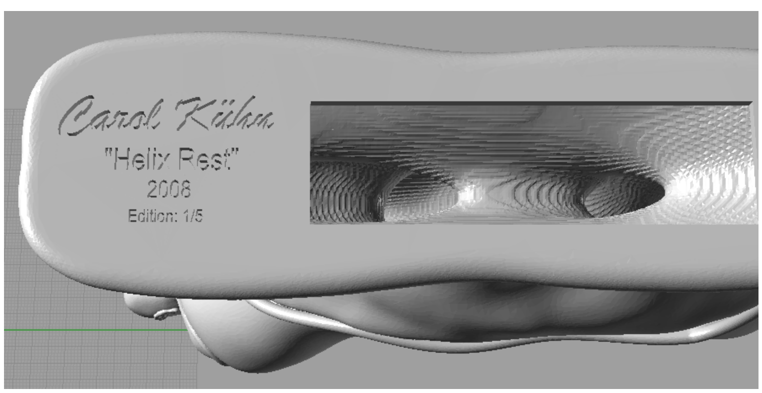


Figure 7) Embossing and cavity display

4.3. The realisation of form

Build constraints were limited to the additive fabrication Laser Sintering (LS) EOS P385 specifications such as; build platform dimensions, tolerances, surface finish and costs. Shelling the build to a wall thickness of 6mm to reduced material costs created an internal cavity, which raised concerns regarding the strength of material; this however is a display item only and not a working part (figure 7). The shelling of the form did not reduce build time only material cost, as the laser is required to follow the full volume platform path at the same speed irrespective of intricate detail or volume.

5. Concluding discussion

A systemic approach to interactive haptic sculpting reveals various technological and sensory 'construction' modalities that either challenge or expand real world classifications of sculpture. The spatial–orientation surrounding the human-machine interaction with its cyclical receiving, applying, and sending of data, places the user in a pliable state reliant on bodily senses, and position. Although a similar creative embodied interaction occurs during real world sculpting, the continuous haptic-loop formed in this instance presents a renewed aesthetic exploration of medium. Outlining temporality proposes a reference to 'substance' as apposed to existing classifications of 'materiality' during haptic interaction as sculptural medium. As a mode of production linked by time and medium, temporal presence and real time interactivity act as tactile communicative agents during mechanical and recursive automatism.

Current limitations:

Model complexity is reliant on technical improvements that deliver the stimuli to approximate our real environment. During the case study FFM software's high-end system requirements presented the most challenging limitation due to regular EOM system failure. The overall slow adoption of 3-D haptic modelling and RP as artistic medium can be attributed to high capital outlay and running costs. Due to this, crossing the threshold of commercial viability for the artist has yet to be achieved. At present, these technologies are best located within art-educational establishments where experimentation with new technology is key and not driven by financial capital outlay. The technically dependant concurrent engineering approach to this medium often raises questions as to whether it fits the category of sculpture? Comparative to real world sculpting the user is equally dependent on technological parameters such as 3-D form, structural elements, material types, properties, and skill. Therefore, in an attempt to categorise haptic sculpting the medium merely presents a shift in sculptural paradigm encompassing haptics as an expanded technical and conceptual principal applicable sculpture.

Way Forward:

Future sculpting modes point towards voice prompt sculpting, camera captured hand gestures and collaborative sculpting in which asynchronous multi user operation facilitated via network prove to enhance creativity (Gunn, 2006). Irrespective of the interactive haptic sculpting mode, navigating an interactive design approach to sculpture as a 'synthesis', 'construction', and 'production' systemic model lays the foundation from which future divergence of haptic modalities can be theorised.

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ADDENDUM 3

3.1 Journal submission: Digital Creativity

This addendum presents an additional, collaborative-authored article that has been submitted to the journal *Digital Creativity*. The authors await an outcome from the peer review panel. In this article select viewpoints surrounding digital sculpting coincide with introductory literature on digital sculpture explored in chapter two; this is however intended to provide a background to digital sculpting in support of the case study discussions that follow. Section 5 includes the sole contribution by co-author Dr M. Shaw and 6 is largely contributed to by Dr R.I. Campbell.

Digital sculpture: extending the language of sculpture through the adoption of additive fabrication

C. Kühn[1], Dr M. Shaw[2], Dr R.I. Campbell[3]
[1]School for Design Technology and Visual Art, Central University of Technology, Free State, South Africa
[2]Loughborough University School of Art and Design, UK
[3]Dept. of Design and Technology, Loughborough University, UK

Abstract

In this article, developments in digital sculpting technology and practice are introduced and explored as a new artistic form by way of adopting an interdisciplinary approach between artist and engineer. Through this approach it is proposed that the language of sculpture can be extended beyond the current domain via 3-D design input and additive fabrication (AF) Rapid Prototyping (RP) output modes. This new form of sculpture, therefore, influences a shift in sculptural paradigm, which is supported by future technological developments. Several case studies are presented that explore digital sculpting technology as a sculptural language which can be broadened through the variation of contrasting internal and external digital geometries within a given form. The case studies have shown that the combination of transparent structure and transparent material extends the geometry of a singular form through illusory as well as physical deflections to geometry. Included are discussions relating to aspects applicable to form generation as well as issues impacting on the realm of digital sculpting as medium. The article concludes that digital sculpting technologies have embedded their role in forging this new digital aesthetic.

Keywords: Digital Sculpture, Additive Fabrication, 3-D Computer-Aided Design

1 Introduction

This article examines recent developments in digital sculpting technology and practice. Recent years have witnessed several technological developments towards the 3-D manufacturing of digitally designed sculptures. Most of these 3-D printout technologies are based on Additive Fabrication (AF), traditionally the realm of engineers. Free form design developments in Computer-Aided Design (CAD) software applications have progressively allowed for innovative artistic intervention during the design input and conceptual planning stages of digital works. As a result, the concurrent digital design and manufacture of 3-D AF sculpture benefits from an interdisciplinary approach between artist and engineer. Most of the developments reported here have come from work that has necessitated collaborative action between artists and engineers, a trend that is likely to continue.

Throughout recent years, the role of the computer in 3-D design has been to stimulate the creative process through the exploration of varied design alternatives. It does this acting as an extended visualisation tool for complex sculptural structures prior to them being built by additive fabrication machines. This application of layered manufacturing is generally regarded as new artistic form, and it can therefore be said that additive fabrication has contributed to redefining the function and reception of sculpture on both technical and aesthetic levels. Digital sculptor Keith Brown, founder member of FasT-UK (Fine Art Sculptors and Technology in the United Kingdom), states that digital sculpture has led to a “new order” of sculptural object, a paradigm shift, and the emergence of a new digital aesthetic (Duffield, 2001).

This article attempts to show that by treating digital sculpting as a new artistic form, rather than as a replication of traditional methods, the language of sculpture can be extended beyond the current domain. A historical background to digital sculpting is given followed by a review of the input and output methods that have been used. Exemplary case studies of work that have embraced the digital realm are presented, in particular demonstrating the ability to extend the language of sculpture. A discussion of the impact this new form is believed to have on the future nature of sculpting follows, together with an overview of how it must be supported by future technological developments. Finally, a conclusion is drawn as to the importance of this work.

2 Historical background to digital sculpture

Lucy Lippard (1973) suggests that the dematerialisation of the art object was significantly brought about by the rapid expansion of the mass media during the 1960's and 1970's. This statement aligns with the current status of digital input modes. As a result of this and general developments in technology, purist modernist views and approaches towards art during the second half of the twentieth century were challenged, specifically the impact which electronic information and imaging had on art. The American theorist and art critic Jack Burnham curated the 1970's exhibition "Software, Information Technology: Its New Meaning for Art" which drew parallels between the transient nature of computer software and the emerging dematerialised art object prevalent at the time of experimental art. In Burnham's (1970) visionary publication *The Aesthetics of Intelligent Systems,* he states that with the intervention of the computer, artists are finding themselves forced to dismiss the classical view of art and reality, as artists found themselves dealing with an art mode wherein the aesthetic dimensions were not yet fully comprehended by the artist. In this publication, Burnham (1970) also suggests how a dialogue between the computer program and the human subject evolves allowing both participants to move beyond their original state, therefore creating a two-way interactive communication system in art.

During the 1990's, many sculptors started experimenting with the production of "digital sculptures", where virtual space is used for the creative development of an idea, with the work being realised in physical space by means of manufacturing technologies. Author and digital sculptor Christian Lavigne (1998) defines digital sculpture as a linkage of the following three complimentary activities:

1. Creation and visualisation by computer of forms or constructions in 3-dimensions;

2. Digitising of real objects and their eventual modification made possible by computer calculations; and

3. The production of physical objects by numerically controlled machines that are used to materialise synthetic images.

Both subtractive (material removing) and additive (material adding) machines are available, but additive fabrication has proved to be superior due to the flexibility of geometry that can be achieved. Unlike machining processes which are subtractive in nature, additive systems join together liquid, powder or sheet materials to form parts. Bathsheba Grossman (2008), a digital sculptor who has used additive fabrication technology as a manufacturing medium since 1998, claims that the medium has freed her from the traditional constraints that are associated with sculpture, allowing her to produce works with intertwined complexities of form (Wohlers, 2006).

An ongoing discussion surrounding digital media is that it often lacks narrative content, as a result of it being a technological vehicle. William Ganis (2004) questioned the conceptual facility of digital sculpture as an output medium and stated that it could not be relied on for content or quality artistic forms until such time that technology develops further. In an attempt to challenge such criticism, the medium has been compared to the minimalist sculptures produced during the 1960's. That is, the modalities of technology become the substance of the work, which is modelled, manipulated and juxtaposed with the viewer to create meaning (Penny, 1999) and the conveying of narrative content possibly becomes a secondary issue. Edward Shanken (2002) claims that computer technologies have played a unique role in the aesthetic value of sculpture delivery. This is due to advances in technology providing tools that enable artists to cross-examine the conventional materiality and semiotic complexity of art objects that were previously unavailable.

Pioneering computer artist Jasia Reichardt (1971) observed that historically there had been no significant works associated with computer art; however, the medium had contributed a distinctive significance both socially and artistically. According to Rush (1999), the lack of historically distinctive computer artworks can possibly be attributed to the anti-technology sentiment that emerged among critics and artists in the mid 1960's and 1970's. Since then, several artists have emerged producing digital works that stand on their own as "masterpieces" within both the conceptual and technical boundaries of digital sculpture. Examples of such artists are:

- Robert Michael Smith (New York, USA / archetypal forms as structures of nature)
- Keith Brown (Manchester, UK / biomorphic form)
- Michael Rees (Washington, USA / anatomical elements and organic form)
- Christian Lavigne (Berkley, USA / mathematical geometric form)
- Carlo H. Sequin (Berkeley, USA / mathematical approach)
- Michael LaForte (USA, architectural approach)
- Mary Visser (Texas, USA / gender issues)
- Bathsheba Grossman (USA / mathematical and commercial applications)
- Brent Collins (Missouri, USA / mathematical distortion of object)

Typically, these artists use some form of CAD software as an input mode and directly or indirectly access various standard output additive technologies. Many of the artists have explored 3-D colour printing as an output mode at some stage, but none have approached it as a specialist medium. Some of the artists explore a narrative conceptual approach; however, the majority focus on the intersection between abstract form and mathematics as a conceptual point of departure. Therefore one can deduce that there is an enquiring need for technology to accommodate the conceptual manipulation of this "new form".

3 Current digital sculpting input and output modes

3.1 Three-dimensional design input modes

There are many 3-D CAD programs available on the market, e.g. ArtCam, Maya, Form Z, Solid Works, 3-D Studio Max and Rhinoceros ®. Many of these systems are based on NURBS (Non-Uniform Rational B-Splines) geometry, which is an industry standard for designers who work in 3-D where forms are free and flowing. NURBS-based software programs are therefore ideally suited to the design and build of complex sculptural models that explore the synergy of form and content. A benefit of 3-D digital CAD design for the sculptor is that it allows for the pre-examination of form and structure, complex macrocosmic and microcosmic viewpoints in a weightless environment prior to realisation in physical space. Most commercial CAD systems can directly output .stl files, the *de facto* standard format for 3-D printers and prototyping systems.

Reverse engineering an object by way of 3-D scanning is an input mode for generating virtualised object models by measuring data such as the shape and texture of 3-D form. The type of scanner (probe or laser) and its current technological advancement normally determine restrictions that are encountered when engaging in this technology. Currently, technology within this field has developed to such an extent that the main difficulties that are encountered are logistical (e.g. manipulation of large data sets) and not necessarily related to the technology itself. The current status therefore surpasses an early prediction by George Fifield (1999) that the technical development of "resolution" alone would determine the ultimate success of 3-D scanning and the future impact it will have on sculpture. Fifield (1999) also predicted: "[…] as photography changed the meaning of painting, 3-D object photography will change the role of the artist's hand in traditional sculpture."

At present, for the sculptor, the loss of human-connectedness through automation will remain a limitation within this new artistic form until such time as computer technology input modes successfully evolve to replicate the physiology of human sensory touch. In an attempt to break free from the mouse-driven computer design input approach, the development of a less constrained, more naturalistic mode of design input has been explored with the innovative "haptic interface" device developed by SensAble Technologies (figure 1). This is a device that resembles a pen on an articulated armature, whereby the designer's hand is able to move around and through the virtual object, actually feeling its shape while viewing and manipulating it on the computer screen. The system is able to mimic the sculptor's pushing and pulling of the modelling surface as well as offer a range of multi-resolution "virtual clay" modelling tools, which enhance the modelling of form and 3-D texture. Irrespective of the significant developments of this system, it still operates on a single point or "patch" area manipulation, which demonstrates a significant limitation when compared to the physiological sensory application of the human hand. Future "multi-patch" manipulation of NURBS surfaces and the development of more complex modelling tools will aid sculptural applications and possibly facilitate the conceptual design process.

Figure 1. Omni PHANToM haptic device (SensAble Technologies, 2007)

Carlo Sequin (2005), computer science professor at the University of California, Berkeley, proposes that as technological and mechanical aspects of design improve, CAD tools need most development in the speed of real-time interactivity during the early conceptual design phase to ensure that the designer's creative thinking process is not hindered. The CAD environment will be at its most effective once the artist can process conceptual ideas with ease by means of CAD input at the speed with which they are generated in the creative mind.

Therefore, 3-D design input modes should pursue a significant shift towards a more fluid and flexible human-centred digital design environment, which specifically supports the conceptual interactive design process and potentially aids shortening of the development cycle.

3.2 Three-dimensional additive fabrication output modes

Current additive fabrication technologies vary in cost, process operation and available materials. They are constantly improving with technological advances that in time may overcome limitations currently experienced by the sculptor. Laser sintering (LS) is particularly flexible when it comes to supporting the work of metalworking sculptors as this system can be used in a number of ways. The laser sintering of a range of metals (e.g. titanium, bronze, bronze-nickel blend, aluminium, steel) is already possible. For the purpose of building sacrificial moulds for metal casting, durable ceramic sand can be sintered through this process. LS models can be produced that are suitable for burning out as part of the traditional investment casting process. Stereolithography (SLA) is an AF process that cures liquid resin using an ultraviolet light. It is particularly suited to creating a smooth, highly detailed build and can also be used for investment casting. The fused deposition modelling (FDM) process feeds a thermoplastic material through a narrow, heated nozzle. Acrylonitrile butadiene styrene (ABS) plastics are available in a range of primary colours, which could be used by the sculptor as final aesthetic properties. Once again, models can be used for investment casting purposes. In the past, the ceramic shell moulding and subsequent burnout of AF models for the investment casting was very problematic. Significant problems have occurred as a result of residues left within the mould cavity, mould damage due to the expansion of the material during burnout, pattern distortion as a result of warm weather, incomplete bonding of shell layers and surface defects due to pattern porosity (Dickens, Stangroom, Greul and Holmer, 1995). Many of these issues have been addressed but investment casting from AF still remains a delicate process and an area in need of additional research.

Michael Rees (1999), an established American sculptor working with AF, termed the additive fabrication technologies as “desktop manufacturing”, which clearly depicted the accessible future potential that this technology represented. This desktop terminology envisaged the speedy design and build of convoluted form in an office (or studio) environment, thus facilitating artistic possibilities that transcended current manufacturing boundaries. The recent development of several smaller 3-D desktop office modellers has realised the provision of rapid 3-D feedback during the design process. This is particularly beneficial where the pre-examination of a maquette is necessary to reveal any aesthetic flaws not noticed on the computer screen or anticipated in the final full-scale build of a sculpture. The 3-D printing technique from Z-Corporation is a lower-cost system that builds models by printing a binder onto powdered material. One distinct advantage of this technique is that dyes can be introduced into the binder to produce a fully coloured model. It gives the digital sculptor the unique potential to create a faithful, physical realisation of a multicoloured on-screen model.

4 Required Developments in Additive Fabrication

Of significant concern to the sculptor is surface finish. Currently on most AF builds, a mineral or geological quality is expressed by the evidence of the powdered material used by certain processes or the building layers used by them all. To overcome this surface finish problem, most parts undergo either tumbling or sandblasting to smooth out the surface. An issue linked to this post processing is the risk of damaging the model or loosing geometric definition. Research opportunities therefore exist in areas to improve model quality and factors that would influence these improvements (Dimitrov, Wijck, Schreve and De Beer, 2003).

A sculptor needing to produce a larger piece of work would be confronted with having to build a model in sections due to size limitation of the various RP machine build platforms. This would increase the number of builds, the build and post-processing time and therefore cost. Dimitrov's concluding test results on a series of large plastic and metal built components found that the build accuracy and surface finish of assembled parts did not yet measure up to conventional manufacturing methods (Dimitrov, Schreve, Taylor and Vincent, 2007). More work is needed in deciding how to decompose models and ensuring accurate physical assembly. However, producing large components via additive fabrication is feasible and would present a viable option for the sculptor to consider.

5 Case Studies

Four sculptures are presented that demonstrate how digital sculpting can contribute to the sculptural language. Created by Dr Michael Shaw as part of an AHRC fellowship in the creative arts, they seek to expand the parameters of Donald Judd's (1965) sculptural concept "Specific Objects", through which unified objects were championed as being devoid of relational composition. In other words, Judd sought singular sculptural form in which any relationships between parts were minimised. This formal aspiration produces an interesting dilemma, namely how to create a form of sculptural significance with both variation and unity. These sculptures have sought to exploit the CAD AF process to help address this challenge.

In seeking to resolve the dilemma that the concept poses, the sculptures test the possible coexistence of variation and unity in a singular form through the deflection of geometry. It is evident that the CAD/CAM environment allows deformations to geometry to be effected with a precision and liberty not feasible when using more traditional techniques of sculpture-making. Naturally, the first step towards a finished artefact is virtual modelling, in this case undertaken in Maya. Exploiting complex 3-D software means that axes of deformation (bending, twisting, skewing, extruding and tapering, for example) can be subtly moved off-centre to destabilise the horizontal and vertical meridians and overall symmetry. Additionally, areas of a form can be modulated in isolation in terms of scale and orientation using hulls and lattice deformers. Most importantly, all these deformations can be effected without compromising the underlying unity of a form's *gestalt*. Therefore, the basic topology of simple forms such as the torus can be maintained whilst effecting the consistency and "perfection" of the source geometry. Additive fabrication can then make these forms manifest rather than virtual hypotheses. The following sections explore the four sculptures in greater detail.

5.1 Case Study 1 - Contrasting internal and external geometries

This sculpture's predominant quality is its contrasting internal and external geometries, in other words one surface does not simply follow the other's surface offset by the cylinder's thickness (figure 2). The original geometry of the interior was defined by an oscillating line or sine wave, distorted to produce the shape that was revolved through 360° into three-dimensional form. The sine wave effectively creates a continual cycle between concave and convex. The apexes of transition act as perceived edges that may be altered in relation to one another to create variance in geometry.

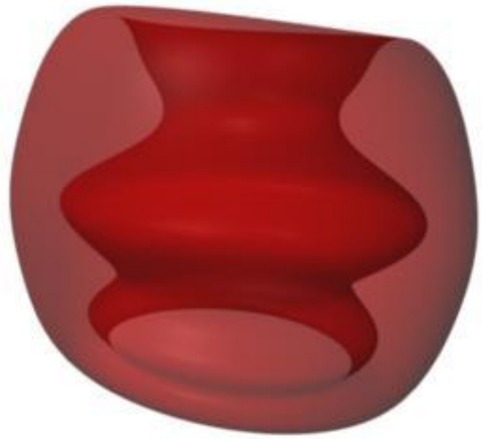


Figure 2. Internal geometry defined by distorted sine curve

The perceived edges can be manipulated by rotating their axes in relation to one another, distorting their geometry by making one aperture circular and the next elliptical, angling their relative orientation or shifting the epicentre away from that of its predecessor or successor. This enables what might be described as concentric deviance as demonstrated in figure 3. These operations appear particularly adept at suggesting movement, and can also imply that a singular form is on the verge of metamorphosis. The wonderment of CAD is that experimental deformations to the internal geometry can be explored and refined without affecting the sanctity of the exterior's singular geometry. Such articulation of form would prove beyond the powers of many experienced modellers in the real world, and in all probability lead to unwanted distortion in the consistency of the overall geometry; furthermore, very subtle deformations would be exceptionally challenging to reproduce. The sculpture was built on a 3-D Systems SLA 7000 machine (figures 4a and 4b), and, needless to say, the strata by strata manufacturing process enabled the flawless manufacture of the complex internal geometry, which by hand would have been challenging in the extreme.

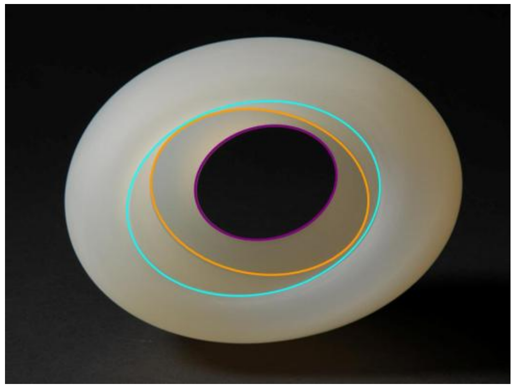
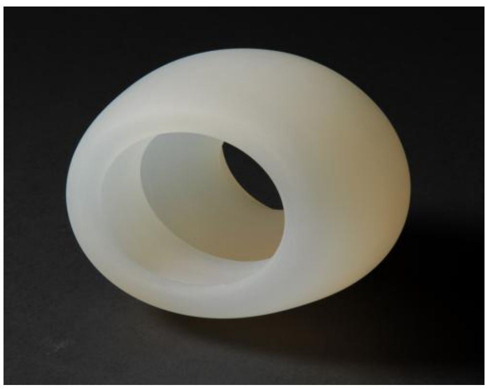


Figure 3. Concentric deviance of internal “edges”



4 a. ¼ view

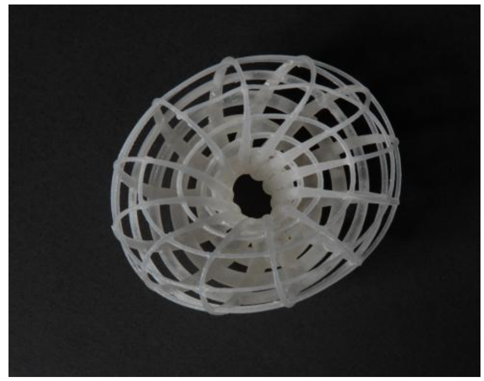
4 b. Front view

Figure 4 a and b. Stereolithography model of study 1

5.2 Case Study 2 - Transparent structure

This sculpture was manufactured using two additive fabrication technologies: laser sintering (in white nylon) and on the InVison machine. The InVision technique prints in a translucent material surrounded by wax supports that are melted away once the build has finished. It can, therefore, facilitate the creation of transparent structures in a translucent material. The white nylon version (figure 5a) is opaque and fairly unresponsive to light, whereas the more recently built translucent version (figure 5b) is a conduit and barometer of ambient light. It constantly absorbs, reflects or diffuses light according to ambient conditions. Additive fabrication has enabled a coherent union between the flowing spatial dynamics of the cage and the material’s translucency.

Suffice to say that with traditional casting techniques, it would be practically impossible. The sculpture demonstrates how the combination of transparent structure and transparent material could extend the geometry of a singular form through illusory as well as physical deflections to geometry.



5 a. Laser sintering

5 b. InVison

Figure 5 a and b. Additive fabrication models of study 2

From a sculptural perspective, the diameter of the struts of the cage play an important role in defining the form's dynamic. In this first attempt the maximum diameter of strut is situated at what might naturally be described as the bottom of the piece. This concentrated the mass there, hence lowering its centre of gravity so that the sculpture could only remain upright or upside down (as shown) with a rather static relationship with the ground. Remodelling the geometry with the greatest diameter of strut on its side would shift the centre of gravity thereby enabling it to engage the ground in a much more active fashion with the potential for rocking movement.

5.3 Case Studies 3 and 4 – SLA Quickcast™

These two sculptures investigate the consequences of manufacturing a form using the SLA Quickcast™ technique. Ordinarily this would be used to create a model that can be easily burnt out from an investment mould. This is possible because the normally solid mass of the object is replaced by lightweight low mass scaffolding; however, these sculptures exploit this honeycomb structure purely for aesthetic purposes.

Both sculptures incorporate an oscillating line that either defines their internal or external geometry. In study 3, the sculptures' apertures and twisted internal chambers have a dynamism that is carefully counterbalanced by the simplicity and compactness of the exterior (figure 6).

Figure 6. Internal geometry of study 3

Figure 7a and 7b shows just how effective a contributor the Quickcast™ scaffolding is to the dynamism of this sculpture. It clearly demonstrates that the patterns that form due to the curved slicing of the hexagonal support structures enrich the sculpture, whilst its response to light creates illusory deflections of geometry. The resulting patterns, whilst not identical, resemble somewhat the Fibonacci packing patterns visible on a sunflower seed head. The density of light captured and diffused changes according to variations in the wall thickness, further enhanced by the movement of the viewer and their relative position to the sculpture. These effects contribute to a kind of denial of gravity, and the perception that a light source may be located within the sculpture.

7 a. Front view

7 b. Rear view

Figure 7 a and b. SLA Quickcast^{TM} model of Study 3

In contrast, the fourth sculpture investigated the consequences of using an oscillating line to underpin the geometry of the exterior, meaning it appears to have three distinct bands visible (figure 8). Even though the fourth sculpture's interior-when considered in isolation-is quite clearly singular and unencumbered by needless additions (figure 9), it is the complexity of the exterior that dominates. The latter suggests that external geometry is the key to a singular reading of the whole and moreover that a singular exterior has the potential to encompass and override an interior with far greater complexity.

Figure 8. SLA Quickcast^{TM} model of Study 4

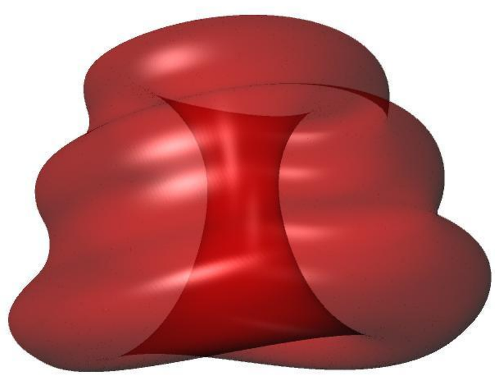


Figure 9. Showing internal geometry of Study 4

Digital sculpting has been instrumental in these four studies, which hint at how the sculptural language might be broadened through variation between internal and external geometry and the synthesis of transparent materials and structures, two characteristics that can both be exploited to modulate light and by consequence perceptions of a singular form. Therefore the digital sculpting route is a particularly welcome technical addition to the lexicon of the traditional sculptor.

6 Discussion

As digital sculpting technologies continue to develop in areas relating to both input and output modes it is evident that, prior to engaging in these technologies, a sculptor must have a sound understanding of available additive fabrication techniques and their associated strengths and weaknesses. Only then can the new form on offer be used effectively to create outputs that break into a new paradigm. In the case studies presented here, CAD and AF have been instrumental in enabling forms that would be virtually impossible to create by hand. They have facilitated singular sculptural forms in which unity has been challenged by illusory and physical deflections to geometry without it being eliminated completely. The digital realm has been essential to the form-generation of the sculptures for several reasons: it is liberated from the constraints of gravity and the physical difficulty of manufacture and it can save sequentially increments of activity supported by infinite duplication, copying and pasting. All these advantages contribute to a working environment and state of mind that encourage experimentation, risk-taking and exploration of boundaries.

There are some negative aspects, also. Sometimes the capabilities of digital sculpting may prove to be too seductive. Almost no geometry is too complex for production, from a working ball bearing to an intact Russian Matryoshka nesting doll. However, it should be emphasised that “just because one can, does not mean one should”; the need to define valid, coherent and dynamic geometry continues despite the majesty of the technology. Digital sculptors work in a medium of repetition with no original object and unlimited reproducibility. As a result, it can be argued that such sculptures deny the traditional “aura” of authenticity, the loss thereof first cited by Walter Benjamin (1969). The electronic data used to develop digital works is easily transported via the internet and can be accurately reproduced by any additive fabrication system. Fifield (1999) comments on originality and the ability to copy by stating: “When 3-D photographic reproduction achieves the economic level of print reproductions, sculptors will face much of the same issues as printmakers did when the copy machine first appeared.” He also remarks that with this change of concept, issues about meaning and multiplicity in sculpture will grow.

7 Conclusion

Case studies presented in this paper have indicated that the language of sculpture extends beyond the current structural and material domains through the manipulation of internal and external geometries of 3-D form. The technologies of CAD input and additive fabrication as output therefore present modes of form-generation that suitably equip the technologically advanced sculptor. Rees (1998) comments on additive fabrication and sculpture as a way forward by stating the following: “Despite all of the technical advantages that AF has to offer, and they are many, its real contribution to us is to imagine ourselves more broadly; to increase our ability as sculptors to participate on a root level in the evolution of technology”. The authors concur and would argue that the importance of this work lies not in the specific technologies, materials or artefacts presented, but rather in the demonstration that digital sculpting has a role to play in forging a new digital aesthetic within this extended paradigm of sculpture.

8 Reference list

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ADDENDUM 4

4.1 Group exhibition 2008: University of the Northwest Art Gallery

Guest Speaker: Ian Marley
Opening: 15 October 2008, 19h00
Ends: 6 November 2008

North West University Gallery, Potchefstroom
Gallery-hours: Monday - Friday: 10:00 - 16:00
Contact: Christina Naurattel (018 299 4341) or
E-mail: christina.naurattel@nwu.ac.za

Openingspreuker: Ian Marley
Opening: 15 Oktober 2008, 19h00
Eindig: 6 November 2008

Noordwes-Universiteit-galery, Potchefstroom
Galery-ure: Maandag - Vrydag: 10:00 - 16:00
Kontak: Christina Naurattel (018 299 4341) of
E-pos: christina.naurattel@nwu.ac.za