Hybrid re•Assemblage

Bridging Traditional Craft and Digital Design

Amit Zoran

Submitted to the Program of Media Arts and Sciences, School of Architecture and Planning,
in partial fulfillment of the requirement for the degree of Doctor of Philosophy at the
Massachusetts Institute of Technology.
September 2013

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Abstract

Hybrid reAssemblage is a design gestalt that lies at the cross-section of digital design practice and the tactile qualities of traditional craft. It spans a territory in which the value of artifacts is produced through automated production as well as human subjectivity. This work is an exploration of two divergent realms: that of emerging computational technologies, and traditional hand-hewn practice. Hybrid reAssemblage proposes a new way of thinking about the machine, as generator of control and efficiency, and the unpredictable and singular nature of the raw and the manual. I illustrate Hybrid reAssemblage through three diverse projects:

FreeD is a digital handheld milling device for carving, guided and monitored by a computer while preserving the maker's freedom to manipulate the work in many creative ways. It reintroduces craft techniques to digital fabrication, proposing a hybrid human-computer interaction experience. In addition to the technology, I present a user study, demonstrating how FreeD enables personalization and expression as an inherent part of the fabrication process.

Chameleon Guitar exploits a selection of acoustic properties via a set of replaceable resonators and by a simulated shape, merging real-wood acoustic qualities with a simulated guitar body. It marries digital freedom with the uniqueness of acoustic instruments, and demonstrates a hybrid functionality platform. Focusing on the production of sonic qualities, this project is evaluated acoustically, pointing to the significance of attention to detail such as craft and wood qualities.

Finally, *Fused Crafts* is a collection of artifacts that are part handcrafted and part 3D printed, visually demonstrating the potential of combining these practices to create hybrid aesthetics. I illustrate this visual concept with two examples: intentionally broken ceramic artifacts with 3D printed restoration, and 3D printed structure that is designed to allow the application of hand-woven patterns. This project is a search for an approach where both technologies can benefit from each other aesthetically, enriching the final product with new qualities.

This dissertation begins with a contextual background, leading to the presentation of the projects. In the last part, I evaluate the work through feedback received from a panel of design, craft, and HCI experts.

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Acknowledgments

This dissertation required a great deal of searching, designing, building, testing and writing; it could not have happened without the support, friendship and help of many people. Above all, this work also belongs to my wife Tamar Rucham, who shaped the ideas and influenced the process at every step of the work. I could not have done this work without her, and without my family at home: mom, dad, Liati, Gili, Uri, Roti, and Uzi. My 10 month old baby-girl Inbar, had a mysterious impact on the work that may never be truly understood.

I would like to thank my committee, Joe Paradiso, Sherry Turkle, and Leah Buechley, and to all the scholars who supported this work with their feedback (Gail Wight, Stuart Kestenbaum, Glenn Adamson, and Mark D. Gross). I would like to thank Pattie Maes for her support during the last several years. I thank Hiroshi Ishii, Ofer Bar-Yosef, Michael Bove, Mitchel Resnick, Azra Aksamija, and Joi Ito for their advice and help. A special place is saved for Bill Mitchell, who sadly left us three years ago. I will always remember him and be grateful for his wisdom and kindness. We miss you Bill.

Many thanks to my colleagues and friends who supported and helped me so much during the last six years. Thanks to Nan-Wei Gong, Eli Cook, Roy Shikrot, Yonatan Friedman, Jennifer Jacobs, Liraz Greenfeld, Marco Coppiardi, David Mellis, Inbal Prion, Yadid and Ifaat Ayzenberg, Konstantin Mitgutsch, Susanne Seitinger, Jie Qi, Peter Schmidt, Nicholas Gillian, Marcelo Coehlo, Pranav Mistry, Jean-Baptiste Labrune, Nan Zhao, Dana Gordon, David Merrill, Anette von Kapri, Casandra. Xia, Kelly Ran, Gershon Dublon, Doug Fritz, Nadav Aharony, Sajid Sadi, Adam Kumpf, Cati Vaucelle, Mark Feldmeier, Brain Mayton, and Guy Hoffman. Thanks to Meir Rivkin for being Meir Rivkin.

MIT Writing Center helped to make this work readable, and special thanks to Marilyn Levine for her infinite support. Thanks to John Difrancesco, Martin Seymour, and Tom Lutz for their assistance in the Media-Lab shop. Thanks to Steve Otis, David Reed, Geoff Wilson, and Robert Swartz who helped prepare patent applications. Thanks to

Alexandra Kahn, Jeannie Finks, Jen Hirsch, Ellen Hoffman, Paula Aguilera, David Chandler, Janine Liberty and Stacie Slotnick who helped to bring my projects to the public. Thanks to Taya Leary, Cynthia Wilkes, Linda Peterson, and Amna Carreiro for their administrative help.

In addition to all the people mentioned above, for each project I received valuable help and advice from many people. For the *FreeD* project, thanks to Andy Payne, Arthur Petron, Jonathan Ward, Yaniv Sterman, Juergen Steimle, Fredo Durand, Suranga Nanayakkara, and Kian Peen Yeo.

For the *Chameleon Guitar* project, I would like to thank Nick Makris, Hadi Tavakoli Nia, Shawn Burke, Ken Parker, Jasmine Florentine, Melodie Kao, Aridne Smith, Pual Crowley, and Kristin C. Hall who supported and helped during the process. Thanks to Webb Chappell for the great photos. I would also like to thank all the instrument-makers who gave me advice and shared their experience: Steve Spodaryk, John Svizzero, Jeb Hooker, Alan Carruth, DJ Parsons, Donald Lambe, Thomas Knatt, Daniel Wangerin, Kevin Kelly, Aaron Green, and TJ Thompson. I would like to thank the old friends from Neocraft, especially Person, Kobaishi, Shahaf, Noam, and Itamar who showed me it is possible to combine music, technology, and fun with work.

For the *Fused Craft* project, I especially thank Darrell Finnegan and friends in the MIT ceramics studio and the Student Art Association (SAA), who shared their knowledge and assistance. I would like to acknowledge Dena Molnar, and to specially thank to Thitaku Kushonya, who shared her knowledge and opened a door to the world of basketry. This work was funded in part by the Council for the Arts at MIT and Objet Geometries, Inc., and could not have happened without them. The *Hybrid Ceramics* project is dedicated to the in memory of Bill Mitchell, who was my advisor when this project began to evolve, and Avihai Haklay, my cousin, who crafted the original bowl featured in Chapter 4.

Finally, I would like to deeply thank all the craftspersons I met in the last several years, who shared their work, experience and knowledge. And for my other friends, if I forgot someone, please forgive me ☺.

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It is rather the soul than the hand, the man than the technique, which appeals to us - the more human the call the deeper is our response.

Okakura, Kakuzo. The Book of Tea (1964)

The experimental rhythm of problem solving and problem finding makes the ancient potter and the modern programmer members of the same tribe.

Richard Sennett's *The Craftsman* (2008)

Chapter 1
Introduction

Hybrid reAssemblage is a new design paradigm that combines the irregular nature of the real world with digital practice, and merges the singular qualities of non-computational media with computational ones. It proposes a new way of thinking and challenging a long-established polarity: the disciplined digital machine and the unpredictable nature of the non-engineered world. In my work, I demonstrate Hybrid reAssemblage with three design projects, visualizing a diverse potential for hybridizations. *FreeD* reconstructs the notion of human-computer interaction, allowing for manual involvement in the process of digital fabrication to achieve design personalization. *Chameleon Guitar* demonstrates hybrid functionality of real wooden resonators with computer simulation. Finally, *Fused Craft* visualizes hybrid aesthetics of artifacts made by both machine and man. In this chapter, I foreground my contextual framework and motivation, presenting the foundation for my three design projects.

In new developments, engineers rely on prior technical work and search for optimal solutions, reducing the design process to as few parameters as possible. While this process minimizes risks, seeks efficiency, and enables automation, it misses the mark when considering values that cannot be easily quantified, such as the engagement and involvement of an intimate creative process. However, these qualities are inherent parts of the traditional craft process. They express the maker's personal style, his sense of personal integrity, as shown in the FreeD's study presented in Chapter 2. Moreover, while the engineering search for control supports the development of easily manipulated materials, manual practice allows for careful treatment of non-homogeneous sources, from organic to inorganic materials (Chapters 3 and 4). As a result of the human involvement, handcrafted products are unique and visualize a personal signature of their makers, contributing to design pluralism and egalitarianism.

All Things are Imperfect

My work is an exploration of craft as the foundation of our material culture, examination of the relationships between people, handmade artifacts, and technology. However, it is not easy to define craft. There are many scholarly definitions that take up this question from different perspectives.[1, 2]. For my work, I find David Pye's definition, which ties craft to risk taking, especially useful and evocative.

> *(Craftsmanship) means simply workmanship using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgment, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making; and so I shall call this kind of workmanship "The workmanship of risk".* [3]

For Pye, the look, feel, and shape of the crafted object is never predetermined, thus introducing a risk for not being able to guaranty certain results from a given investment. It also means that the outputs of a craft process are unique and personal artifacts, each subject to the judgment, dexterity and care of the craftsperson during the particular time they were made. Such artifacts can never be faithfully reproduced, and cannot be fully predicted. These singular qualities of craftsmanship have a unique place within *Wabi-Sabi* - the Japanese aesthetic - as is nicely summarized by Leonard Koren [4]:

Figure 1.1: Sitka spruce grains: a personal interpretation, following Wabi-Sabi. Photo by author.

- ***All things are impermanent**. The inclination toward nothingness is unrelenting and universal.*
- ***All things are imperfect**. Nothing that exists is without imperfections.*
- ***All things are incomplete**. [All things] are in a constant, never-ending state of becoming or dissolving.*

The imperfect, dynamic nature of the manual process and its natural resources leaves a mental space for pluralistic observations and reflection. Things that are not complete call for the reaction of our imagination: the mind responses to the evasive world of the unknown and unpredictable.

> *The minimal progress of imagination responds to the wordless question posed to it by the materials and forms in their quiet and elemental*

> *language... An interaction takes place between purpose, space, and material.*
> Theodor Adorno, [5]

In my dissertation, I seek to reintroduce traditional craft qualities, such as unpredictability and imperfection, to digital design. However, integrating these qualities presents a challenge: predictability and perfection are inherent in the definition of modern computational technologies. The discrete logic and the analytic process of computation, together with the dominant economic, do not encourage unpredictability. We separate functionality from other means of value, to optimize the qualities that can be quantitatively measured.

> *The modern concept of technology decomposes craftsmanship into the separate components of rational-technical operations and expressive art. To focus on song and craftsmanship rather than language and technology is to foreground the poetic and performative aspects of speech and tool-use that have been marginalized by rationalism.* Tim Ingold, [6]

This, of course, was not always the case. Prior to the industrial revolution all material artifacts were crafted, subject to the workmanship of risk. With the rise of repeatable machine-driven production, artifacts became cheaper and were of a consistent quality, but they also became less unique. Along with this change in the nature of objects came a change in society's view of the craftsperson. Since machines could replicate the work of the hands, the social values of products were lost, and commodity fetishism redefined the lost meaning of artifacts [7]. Meanwhile, the ability to envision and plan for the construction of objects, to design separately from fabricating, was elevated. This movement away from craft and toward design arguably reached its apex in the United States in 2002 when the American Craft Museum in New York City changed its name to the Museum of Art and Design [8].

Figure 1.2: Salt and pepper shakers, glazed ceramics, by Avihai Haklahi.

It might seem that traditional craft is becoming less relevant to modern society, indeed losing economic value. Yet at the same time that the American Craft Museum was changing its name, craft was experiencing a renaissance. Today, craft techniques and approaches are increasingly employed in contemporary art, fashion, and design [9, 10]. Craft practices are also infiltrating other disciplines. For example, a growing community of technology and design researchers is investigating how to blend craft with electrical engineering and computer science [11-14]. My work is in this spirit of a new integration of craft into digital practice. In particular, I examine how craft practices can be combined with digital design and fabrication, to reintroduce unpredictability and involvements (thus call for the act of the imagination) into contemporary design movement. But first, let us have a closer look at the nature of the digital movement, and its impact on contemporary design and fabrication practices.

The Digital and the Predictable

Digital fabrication is a process whereby the design for an object is created on a computer, and then a machine automatically produces the object. Digital machines re-define the role of the maker in the process, allowing continual reprogramming. A digital design is thus not only easily repeatable but easily modified. While the analog fabrication machines use physical molds, within the programmable machine (such as a 3D printer) the mold is replaced by a virtual design, an abstract ideal without a particular physical existence.

In craft, makers incorporate the irregular and non-uniform qualities of raw materials, developing unique artifacts reacting to particular conditions. Automation, on the other hand, requires generalization for efficient operation and control, and singular conditions are not welcomed. Machines can repeat the same job over and over again exactly in the same manner, making products that are instantiations of a universal design. With the machine, the unique is being rejected, and operations can easily be repeated, separating the fabrication process from human labor.

Digital fabrication machines can be roughly sorted into two categories: subtractive and additive [15]. Subtractive approaches use drill bits, blades or lasers to remove material from an original material source, thus shaping the three-dimensional object. Additive processes, on the other hand, deposit progressive layers of a material until a desired shape is achieved. These digital fabrication technologies evolved in parallel with the graphic technologies, which enable computer-aided design (CAD) and Computer-Aided Manufacturing (CAM). Design and engineering were radically altered, and today makers can modify their designs, simulate its performance, and easily share it with others.

Today, dedicated parametric tools for fabrication are demonstrating new shapes and aesthetics. Their impact is significant [16]: digital fabricators become smaller, cheaper, and more pervasive every day. Machines like laser cutters and 3D printers - once found only in large factories - are increasingly present in universities, high schools, community work spaces, and even garages.

As these machines become commonplace, they will alter the types and quantities of objects we own, reshaping our relationships to things. Researchers have already explored ideas which could not have been implemented with traditional fabrication technologies, such as a functional concert flute printed with no need for human assembly (beside springs, see Figure 1.3 and [17]); a synthetic titanium complete lower jaw implant [18]; or even a provocative operating ABS gun [19]. The popular media promotes the image of digital fabrication as the “next big thing,” associating this technology with a potential social impact equal - or bigger - to that of the industrial and computational revolutions [20, 21].

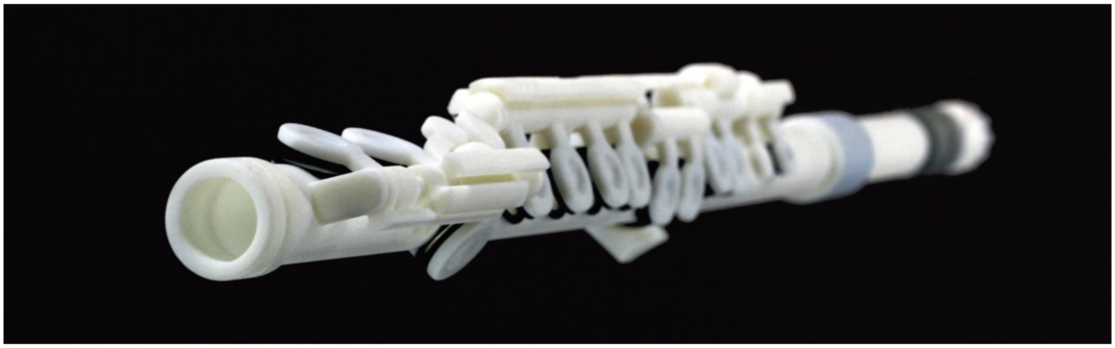

Figure 1.3: Multilateral 3D printed flute, using Objet Connex technology, designed by the author.

As personal digital fabrication becomes accessible to individuals, it reveals itself as a technology that seems in many ways supportive of craft. In particular, it enables small-scale production and design. However, the two approaches contrast: there is, by definition, no risk in an automatic fabrication process. A digital design file specifies exactly what a machine will produce; the file predetermines the result. There is no involvement of the maker‘s dexterity and judgment in the fabrication process. Furthermore, once a design file is created it is infinitely reproducible. Both the quality of the digital process and the quality of its products are radically different from those of craft, when digital efficiency and control eliminate imperfection and unpredictability. In addition, the plural and irregular nature of a handcrafted artifact is replaced with the virtual accessibility to the making process, in which unskilled makers can easily take a part.

Phenomenological Context

The dichotomy between traditional making practice and modern technology is not new to Neo-Marxism and Postmodern discussion. However, movements of social criticism rarely have an impact on the development of new technologies. The reasons for this are complex. The economic forces that drive new technologies are not impacted by social criticism. Engineers are often not aware of the criticism of their work in the world of social theory. If they are aware, they often don't see its relevance. Finally, engineers are trained to build upon prior technology when they innovate. Humanities scholars are on a different track. They are not proposing technical solutions, thus they are not "speaking" the engineers language.

Seeking a theoretical framework, several social-critique movements inspired my work. Especially relevant are two phenomenological campaigns: the first originated in Germany and focuses on authenticity as an existential value, while the second, evolving from France, focuses on fragmentation as a deconstructive process, with its impact on contemporary architecture.

Figure 1.4: Deconstructivism: Daniel Libeskind's Ontario Museum in Toronto, merging the old and the new. From http*://knibbdesign.com/blog/constructing-desconstruction*

In *The Work of Art in the Age of Mechanical Reproduction*, Walter Benjamin uses the term *aura* to describe the uniqueness of the physical artwork and its present quality in space [22]. According to Benjamin, this aura - a precious quality that cannot be copied, simulated, or faked – cannot survive the process of mechanical reproduction. The aura is a fragile, un-visible quality emerging from an interactive relationship between the mind and the object.

Along the same lines as Benjamins's aura, for Martin Heidegger, the existentialist philosopher, authenticity means being in the world, having an immediate, unbiased, direct experience of time, in contrast with historical, universal or metaphysical experience [23, 24]. Authenticity evolves from the unpredictable and singular nature of reality, while modern culture and technology are not authentic for Heidegger, because they alienate us from reality and spiritualism.

Aura and authenticity are linked with uniqueness, a quality rarely encouraged within mass-production systems. In addition, the appeal of handcrafted objects, the sensation of blowing wind, and the feel of a grain of sand are all too complex and too authentic to be fully modeled by today's computers. While digital technology is capable of generating randomness, the reductionism of computational paradigms fails to fully represent the richness and complexity of the real world. Computers possess sublime qualities, but they lack the essence of material authenticity, where the space of possibilities is unlimited, unconstrained, and timeless. At the same time, the virtual environment frees us from physical constraints, allowing repeating and recreating the same experience. Ironically, it is this very unconstrained experience that keeps this technology from leading to authenticity. Moreover, within digital fabrication, we extrapolate this quality into physical matter, recreating physical aura. However, the essence of the digitally fabricated artifact may always keep reference to its virtual ideal, suggesting repetitive reproduction when the unpredictability of the real world impacts perfection.

To introduce singular qualities to contemporary technology, thus achieving aura and authenticity, we first need to deconstruct the notion of digital technology, re-configuring its abstract meaning, which evolves from the very basic concepts of Modernism. *Deconstruction,* the phenomenological movement founded by Jacques Derrida, calls for the exact same action [25], fragmenting and reconstructing cultural paradigms. The architecture movement of *deconstructivism* adopts the deconstruction philosophy, when architects as Frank Gehry and Daniel Libeskind (Figure 1.4) break traditional aesthetic paradigms to fragments, then reconstruct structures in demonstration of unpredictable forms. However, deconstructivism is limited to structural reconstruction, relying on critique as the foundation of any creative suggestion. In my work, I would like to extend deconstructivism to a wider range of design opportunities, in the search of the imperfection, unpredictable and personal in contemporary digital design. Inspired by the work of Benjamin and Heidegger, I propose a new technological paradigm, reconstructing the tradition with the modern, as presented in the next section.

Building a Bridge: Hybrid reAssemblage

> *Good joinery… is difficult to design and even more difficult to execute. It should be thought of as an investment, an unseen morality.*
>
> George Nakashima [26]

In my work, I suggest to merge digital technologies with the singular qualities of the non-computational practices. Similar joinery approaches were already considered by scholars and researchers in varying interdisciplinary fields. Malcolm McCullough, in his book *Abstracting Craft* [27] articulated a vision of the digital practitioner as craftsperson, being an early bird to a new research field. Academic interest in merging traditional with computational practices has grown in the last several years. Few examples are the *High-Low Tech* group in the MIT Media Lab, the *Craft Tech Lab* at the University of Colorado Boulder, and the *Autonomatic*, *3D digital production Research Design Centre* at the University College Falmouth, all fuse digital technologies with craft.

Hybrid reAssemblage is, in a sense, a proposal for a new way of thinking about these polarities: the efficient, disciplined machine, with the unpredictable nature of the non-engineered world. Focusing on contrasting values, I hope to bring new substance to the argument for engaging in a new hybrid territory for investigation and discovery - a territory, in which design practice is being re-constructed to reveal synergy between machine and man, automated production as well as personalized artifacts. Instead of a well-defined design process prior to production, and the use of predictable process and materials, Hybrid reAssemblage promotes the conservation of the uncontrollable.

My dissertation presents three projects, each facing the challenge from a different design perspective. While the design work presented in the following chapters was already published elsewhere, this dissertation is my first opportunity to assemble all ideas to a unified document. Due to their different nature, each of these projects is evaluated with different methods.

FreeD (Chapter 2) is a digital handheld milling device for carving, guided and monitored by a computer while preserving the maker's freedom to manipulate the work in many creative ways. It reintroduces craft techniques to digital fabrication, proposing a hybrid human-computer interaction experience. As demonstrated through a user study, such hybrid interaction enables users to personalize their work, introducing unique style that evolves throughout the manual process, even from its early stage.

Chameleon Guitar (Chapter 3) exploits acoustic properties via a set of replaceable resonator and simulated shapes, merging real wood acoustic qualities with a simulated guitar body. It provides digital freedom with the uniqueness of acoustic instruments, and demonstrates a hybrid functionality platform. An advanced acoustic study shows the importance of craft and material irregularity, contributing to unique acoustic "personality" in both digital and physical environments.

Fused Crafts (Chapter 4) is a collection of artifacts that are partially handcrafted and partially 3D printed, visually demonstrating the potential of combining these practices to create hybrid aesthetics. The visual concept is shown with two examples: intentionally broken ceramic artifacts with 3D printed restoration, and 3D printed structures that are designed to allow the application of hand-woven patterns. As a conceptual-visual work, this project was presented in design exhibitions and published in peer review art venues.

Finally, I close the document with a summary and discussion. I present comments and feedback I received by panel of HCI, design, and craft experts, and conclude on the potential impact and future directions of Hybrid reAssemblage.

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Chapter 2

Hybrid Interaction:

FreeD – A Digital Carving Tool

I present an approach to combining digital fabrication and craft, emphasizing user experience, and demonstrating a hybrid interaction paradigm where human and machine work in synergy. While many researchers strive to enable makers to design and produce 3D objects, this work presents a new approach to fabricating unique personal artifacts. To that end, I developed the FreeD, a hand-held digital milling device. The system is guided and monitored by a computer while preserving the maker's freedom to carve and manipulate the work in many creative ways. Relying on a pre-designed 3D model, the computer gets into action only when the milling bit risks the object's integrity. It prevents damage by slowing down the spindle's speed, while the rest of the time it allows complete gestural freedom. In the following pages, I describe the key concepts of my work and its motivation, and present the FreeD's architecture and technology.

With the FreeD, I explored three human-computer interaction methodologies for carving. The first is a novel set of interaction techniques for fabrication of static models: personalized tool-paths, manual overriding, and physical merging of virtual models. I also present techniques for fabricating dynamic models, which may be altered directly or parametrically during fabrication. I demonstrate a semi-autonomous operation and evaluate the performance of the tool.

An extended user study reveals how synergetic cooperation between human and machine ensures accuracy while preserving the expressiveness of manual practice. This quality of the hybrid territory evolves into design personalization. I conclude on the creative potential of open-ended procedures within this hybrid interactive territory.

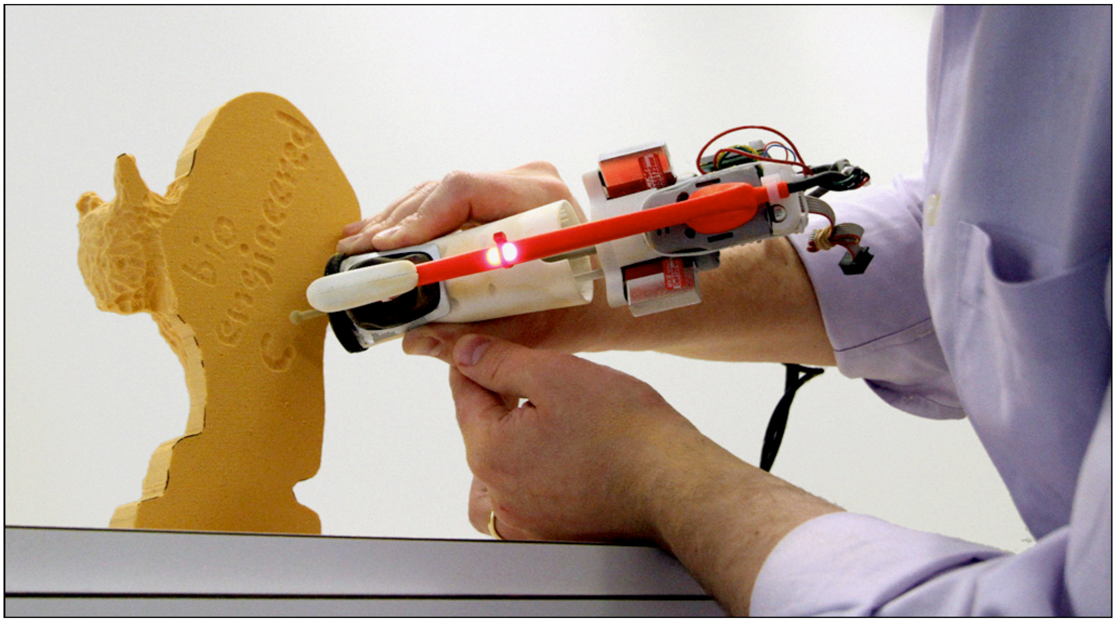

Figure 2.1: Peter using the FreeD to curve a model of a cat in balsa foam (see User Study section).

Introduction

Over the last several years, digital fabrication technologies have altered many disciplines [1]. Today's designers can easily create, download, or modify a computer-aided design (CAD) model of their desired object, and fabricate it directly using a digital process. In developing new manufacturing technologies, engineers seek an optimal solution, reducing the process to as few parameters as possible, and separating design from fabrication. Ease of use, accessibility, proliferation, and efficacy grow as this technology matures. However, qualities such as creative engagement in the experience of making are lost, while the nature of interaction with the fabricated artifact is rarely the focus of new developments.

While the process of engineering minimizes risks, seeks efficiency, and enables automation and repetition, craft is about involvement and engagement, uniqueness of the final products, and authenticity of the experience [2]. Engaging in an intimate fabrication process and enjoying the experience of shaping raw material are inherent values of traditional craft. As a result of this engagement, handcrafted products are unique and carry personal narratives [3].

My research interest lies in the cross-section between digital fabrication and the study of the craft experience. With this work (as published in [4-6]), I wish to allow designers to engage with the physical material, not only the CAD environment. I hope to encourage the exploration of an intimate digital fabrication approach, introducing craft qualities into the digital domain. My contribution is a system merging qualities of both traditions: minimizing fabrication risk by using a small degree of digital control and automation, while allowing authentic engagement with raw material to achieve unique results.

FreeD is a freehand digitally-controlled milling device (Figure 2.1). With FreeD I harness CAD abilities in 3D design while keeping the user involved in the milling process. A computer monitors this 3D location-aware tool while preserving the maker's gestural freedom. The computer intervenes only when the milling bit approaches the 3D model. In such a case, it will either slow down the spindle, or draw back the shaft; the rest of the time it allows the user to freely shape the work. My hope is to substantiate the importance of engaging in a discourse that posits a new hybrid territory for investigation and discovery - a territory of artifacts produced by both machine and man.

In addition, FreeD allows manual and computational design modification during fabrication, rendering a unique 3D model directly in a physical material. My intention is to explore a territory where artifacts are produced in a collaborative effort between human and machine, incorporating subjective decision-making in the fabrication process, and blurring the line between design and fabrication.

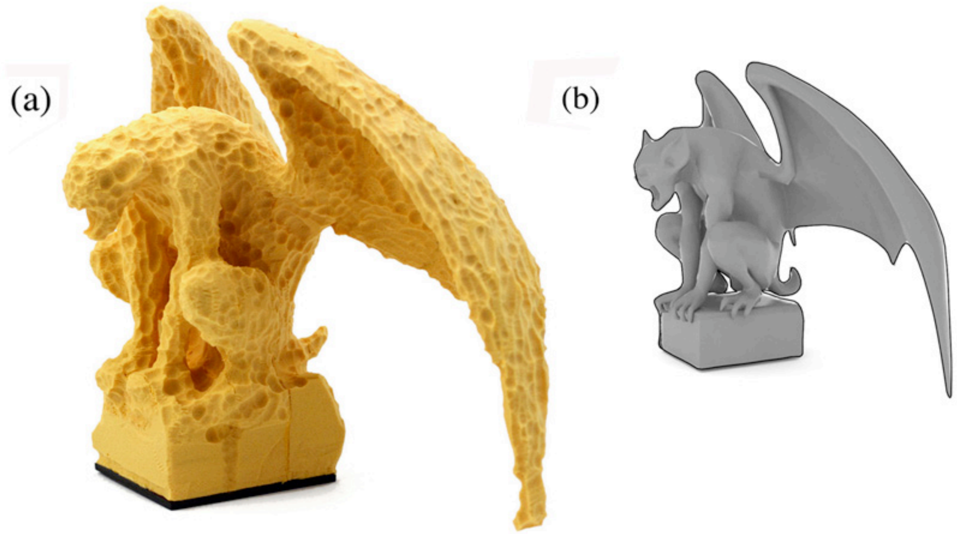

Figure 2.2: A gargoyle sculpture (280mm width) made with the FreeD (a) based on a model (b).

In the course of this work, I discuss different hybrid interaction methodologies (work in collaboration with Roy Shilkrot at [6]). While the tool assists inexperienced makers carving complex 3D objects (static-model mode, see Figure 2.2), it also enables personalizing and changing of the underlying model (dynamic-model mode). In the second case, FreeD doubles as an input device, where the user moves and the computer reacts. I present several novel modes of interaction, such as switching between virtual models through the work; overriding the computer; deforming a virtual model while making it; or searching interactively for an optimal parametric model. In addition, the new tool can operate independently for tasks such as semi-automatic texture rendering.

In addition to the technical details of the FreeD, I present an extended user study that has not been published elsewhere, combining quantitative and qualitative evaluation with experienced makers. The study supports my initial hypothesis that hybrid interaction contributes to a personalization of the fabricated object; and that the nature of tactile, hands-on engagement has an impact on design decisions during the process that support the maker's style and identity, even in the case of fabricating a static model. In addition, the study sheds light on the subjective perspectives makers take on the hybrid practice, which will help in defining crucial roadmaps to clearly develop this hybrid interaction territory.

Related Work

There is a rich history of HCI researchers exploring the domain of creativity using motion tracking and gestural inputs. Several projects studied the 2D creative domain of painting and sketching [7-9], and others enable 3D creative outputs, from 3D CAD output [10], to the control of the fabrication of 3D objects. Willis et al. developed several devices using real-time inputs to construct physical forms [11]. Olwal et al. combined a computer graphics interface with physical objects, working with a lathe [12]. Rivers et al. developed a position-correcting 2D router, achieving accurate cuts on large-scale surfaces, while allowing the free guiding of the tool [13].

A similar 3D interaction concept is the Precision Freehand Sculptor (PFS), a compact, handheld tool that assists surgeons in accurate bone-cutting tasks [14]. The computer retracts the tool's rotary blade based on data from an optical tracking camera to ensure high accuracy. A few other approaches for the integration of robotic systems in surgical operation were studied in the past. The *da Vinci Surgical System* enables surgeons to perform delicate operations remote from the patient, with increased vision, precision, dexterity and control [15]. In their early work, Dario et al. analyzed and reviewed robotic systems for computer-assisted surgery, and presented a classification of such systems based on the degree of "intelligence" of the devices [16]. A new approach present by Zahraee et al., who studied the kinematics of the end effector in a robotic hand-held surgical device for laparoscopic interventions to improve the surgeons' dexterity [17]. Stetten et al. presented a method for magnifying forces perceived by an operator using a tool, to create a proportionally greater force between the handle and a brace attached to the operator's hand [18].

These last projects allow accurate results, but they do not explore the domain of a free-form 3D fabrication, and instead focus on aligning the device's cutting head to a pre-design tool path. A more relevant example is the Haptic Intelligentsia, a 3D printing device using a robotic arm and an extruding gun. The user freely moves the gun, receiving real-time haptic feedback. When the tip of the gun is moved into the volume of the virtual object, the arm generates resistance, allowing the user to feel the object [19]. While applying an additive approach, the Haptic Intelligentsia shares similarities with our device. However, the FreeD frees the user from obstacles and limitations inherent in the use of a robotic arm, fulfilling a freeform handheld device, a major interactive quality in our work.

Additional concepts assuming purely manual practice were previously implemented by 3D clay sculpting with bare hands or manual tools [20, 21]. I found Copy-CAD by Follmer et al. [22] especially interesting, allowing users to copy 2D elements of physical objects, re-assemble and then fabricate these elements into a new 2D shape.

FreeD can be used to modify the virtual model during the work. Gustafson et al. studied the use of hand-gestures in free-air as a control input for a virtual shape without visual feedback [23], Song et al. [24] used annotation squiggles with a pen, Arisandi et al. [25] employed specialized handheld tools, and Cho et al. [26] used a depth camera to track hand gestures in shaping a virtual object using a virtual pottery wheel. Recently, similar ideas were integrated with fabrication technologies, such as laser cutters [27, 28], or RepRap 3D printer [29].

Digital Practice and Traditional Carving

Prior to developing the FreeD, I investigated a range of carving practices. For several years I worked closely with a traditional violinmaker who uses only hand-tools in his process. Last year I began ethnographic work with several African wood artists (mostly Makonde carvers and Bushmen artists, see Figure 2.3). This study helped define the interactive philosophy of the FreeD, by outlining the craft qualities I would like to impart to the digital fabrication environment. I designed the FreeD to allow complete gestural freedom - similar to working with a chisel or a knife - and to allow an intimate tangible experience with a raw material. Nevertheless, the FreeD also gives the user a “safety net” by relying on a pre-designed CAD model, similar to working with a digital machine.

Unlike the woodcarver, a digital designer has access to a rich digital history, and can both monitor and control the design process. A digital design file specifies exactly what a machine should produce. This fabrication process doesn't depend on the skills and involvement of a human maker. Typically, the job of the designer is finished before the fabrication process starts, while the wood carver invests the majority of effort in the making process itself.

Figure 2.3: Ju/'Hoansi maker curving an Oryx, Nyae-Nyae conservancy, Namibia.

Let us examine this process more closely. The violinmaker relies on well-known references, mostly iconic designs, executing a plan that was selected beforehand. He uses drawings, photographs, and calipers to guarantee the perfection of the product. Similar to a designer who uses a 3D printer to precisely fabricate a model, the violinmaker relies on previously tested designs. However, unlike digital practice, in craft the maker is constantly putting the work at risk of being damaged. More than that, despite sharing similar designs, violins differ from each other in quality of the material and work: the detailed design interpretations of the makers.

The FreeD integrates some aspects similar to the violinmaking process into a digital practice. A pre-defined model serves as a guideline, alleviating the risk inherent in handcraft - damage to the intended design. However, the FreeD lets the user reinterpret the pre-designed model by making on-the-spot creative decisions.

In traditional practice, carvers use a variety of methods when removing materials from a raw block. When arching the violin's plates, for example, the violinmaker uses an organized procedure. He attaches the wood to a workbench, removing wood with chisels and gouges in consistent patterns from one side of the block to the other. On the other hand, the African artisans I visited never relied on graphic references and instead visualized the design solely in their minds. While carving, they can change the working procedure during the process, switching carving directions or even designs intuitively.

With the FreeD, the raw material is bound to a table – similar to violinmaking - and is not held by hand. The maker is allowed to choose the method of operation, developing a personal approach to the process. The maker can use an organized procedure (like the violinmaker), a more intuitive one (like the African artist), or a mix of both. This expressive method of operation will influence the quality of the final artifact. My major contribution is giving the designer direct engagement with the material, allowing her to create a unique signature: structural, chaotic, or both, making decisions during the work. Together with the freedom of interpretation mentioned previously, the FreeD re-introduces some values from traditional craft into digital fabrication.

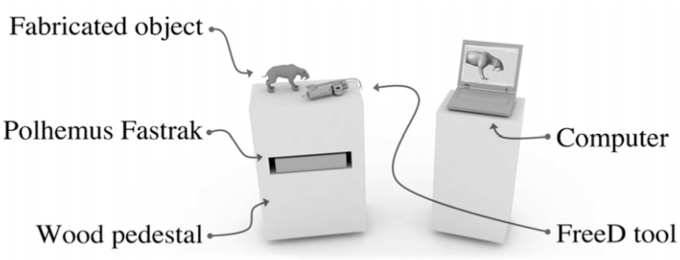

Figure 2.4 The FreeD, work environment, computer, and MMTS.

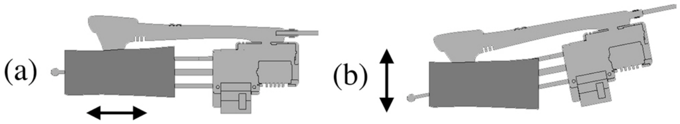

Figure 2.5 The multiple-axis bearing allows the milling bit to move in 3 degrees of freedom: 2 in the carving-plane, and a forward-backward motion.

Design and Technology

The FreeD device is one element in a complete system (see Figure 2.4), which contains the handheld tool, a magnetic motion tracking system (MMTS), the fabricated object, a computer, and software distributed over the computer and the tool. The tool is usually held with one hand, while the user is free to move it in 3D, limited only by the length of power cables and the MMTS. Over a period of a year and a half I developed several versions for the tool (Figure 2.6); the one presented here was previously discussed in [6] under the name FreeD V.2.

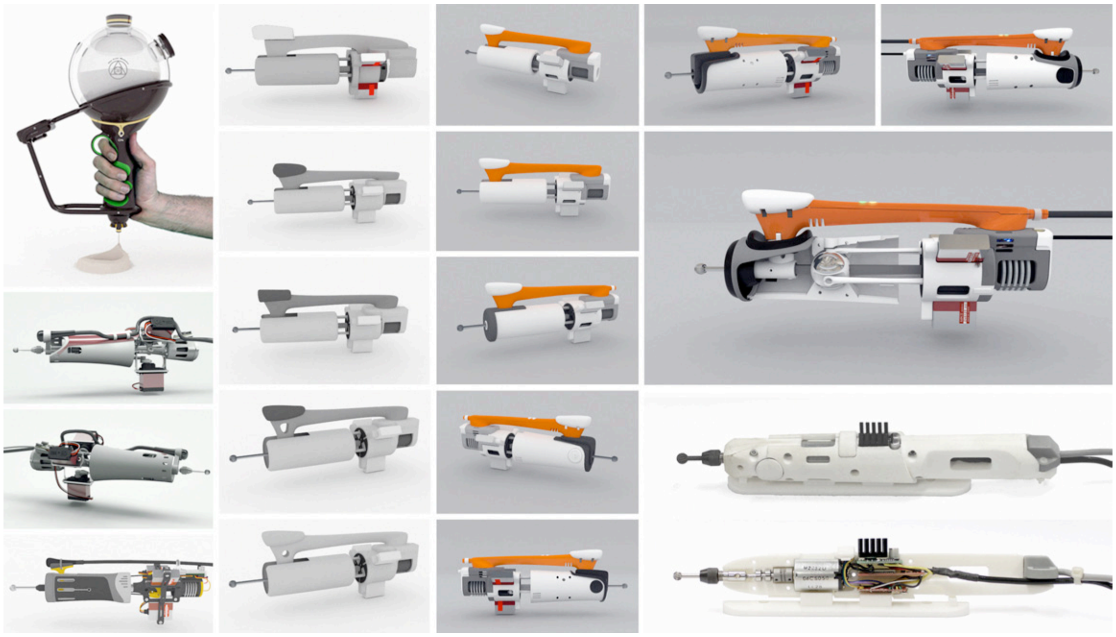

Figure 2.6 Top left to bottom right: early design concept of an additive device; early subtractive prototypes; iterations of the FreeD version presented in this chapter; and the latest working version. All figures are computer renderings, beside the bottom right, which is a photo of the real device.

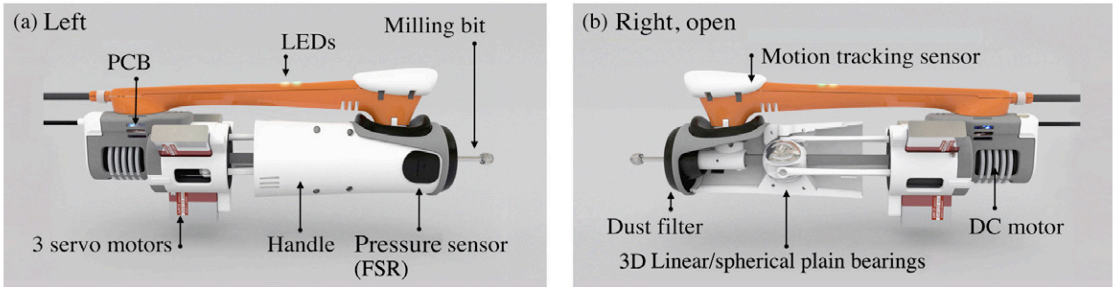

Figure 2.7 Renderings of the FreeD discussed in this chapter: (a) a left view of the tool, with its main components, and (b) a right view of the opened device.

The FreeD, with an overall weight of 300g, contains a custom milling mechanism (spindle) built on top of a long shaft (Figure 2.7) with 12V DC motor (Micro-Drives M2232U12VCS with up to 10,000 RPM with no load, and up to 5.2mNm torque). A custom 3D bearing mechanism is located underneath the handle, sitting above the titanium shaft, and enabling three DOF movements at an approximate spherical volume of 20 mm (see Figure 2.5). Three servomotors (MKS 6125 mini servos, with up to 5.8 kg-cm for 6V), aligned perpendicular to the shaft near the spindle motor, determine the shaft's position. An electronic circuit on the PCB (with an ATmega328 microprocessor and a MC33926 motor driver, powered with 5V and 12V signals) communicates with the main computer via Bluetooth to control the shaft movement and the spindle speed.

A force-sensing resistor (FSR) sensor is located on the handle, allowing the user to override the computer. The DC motor speed (*Sp*, where 1 is the maximal value) is a linear factor of the pressure read from the FSR (*Pr*, when 1 is maximal value) and the risk to the model (*Rs*, 1 is maximal risk – see Figure 5 (a)-(c)):

$$S_p = 1 - R_s(1 - P_r)$$

Two LEDs are located on the tool, providing the user with visual feedback. The first LED's blinking frequency correlates to the pressure detected by the FSR. The frequency of the second LED corresponds with the distance between the bit and the surface of the model (when the bit touches the model's surface the light is constant). In addition, the operating frequency of the DC motor (PWM), controlled by the motordriver, changes from ultrasonic to an audible range (around 2KHz) to give the user an alarm when the bit is within 4mm of the model surface.

The major part of the computation is done on a general purpose computer (Alienware M14x Laptop with i7-3740QM Intel core, 12GB DDR3, and 2GB NVIDIA GeForce GT 650M graphic card). The computer also provides the user with a visual feedback on the screen (see Figure 2.8 (d)-(f)). For tracking (MMTS) I use the Polhemus FASTRAK system, an AC 6D system that has low latency (4ms), high static accuracy (position 0.76mm / orientation 0.15 RMS), and high refresh rate (120Hz).

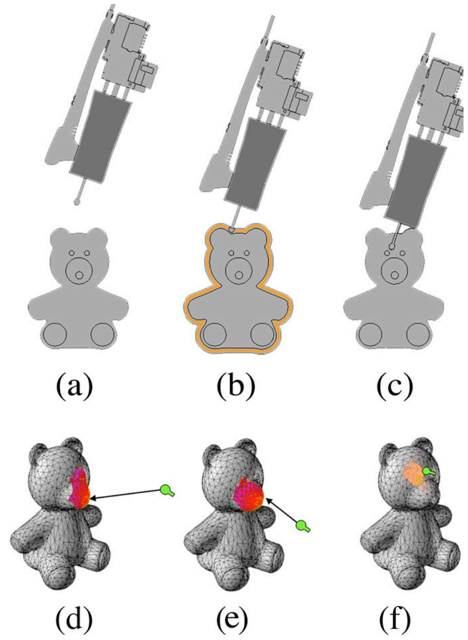

Figure 2.8 Risk management with the FreeD. (a-c) Low, High and penetration level of risk. (d-f) Heatmap visualization of the risk zone.

On the computer, where the virtual model resides, the software runs in Grasshopper and Rhino. The input is the 6D location and orientation of the tool, and the outputs are commands to the control PCB on the FreeD. A prediction of the next position of the bit is extrapolated by a spline of the 4th order (using the current location and the 3 previous ones). The software calculates the distances (*D*) to the CAD model (using Rhinoscript function *MeshCP*()) from both the current location and the predicted one, estimating which point puts the model at higher risk (i.e., closest to the model).

While the DC motor's speed is calculated on the tool as a factor of P_r and R_s, the parameters themselves are calculated by the main control software (values in mm):

$$R_s = \begin{cases} 0 & \text{if D} <= 100 \text{ and D} > 4 \\ D/8 & \text{if D} <= 4 \text{ and D} > 0 \\ 1 & \text{elsewhere} \end{cases}$$

The default shaft position is fully extended, with a 20mm potential to absorb the offset and retract. Unlike an early work [4, 5], in the current FreeD design, I use the servos for an independent tool operation rather than a penetration protection mechanism.

Operation and Interaction

To operate the FreeD, the user typically sits in front of the material (balsa foam), which is attached to a wooden table. The physical working area is calibrated to the virtual workspace. He is free to investigate any milling approach, such as extruding lines, drilling holes, trimming surfaces, or using an arbitrary pattern. The computer slows down the spindle as the bit approaches the model, stopping it completely before it penetrates the virtual model (see Figure 2.8 (d)-(f)). This enables the user to cut along the boundary of the virtual model where desired. He can leave parts of the model unfinished or override the computer using the pressure sensor. Further, I will discuss modes of operation in which the system can dynamically alter the model based on user actions or operate autonomously.

While milling, the FreeD responds to the users' actions when these put the model at risk. These responses, whether they are changes in the spindle speed or movements of the shaft, inform the user of the relative location of the bit with respect to the surface of the model. Together with the PC's screen, this information supports the user in both learning and controlling the shape he is fabricating. The screen can be used as a reference to the virtual model. On the screen, where the CAD model is presented, a virtual mark represents the current position of the FreeD's milling bit. If he wishes, the user can rely on this mark during the work, especially in the initial stage where the virtual shape is not yet revealed in the raw material.

In this sub-section, I survey several original interaction modes with the FreeD as presented in [6]: the static CAD model mode where the computer assists only by preventing the user from damaging the model (the first part of this section, Tool-path personalization, was partially discussed in my early work); a dynamic mode where the computer numerically controls the model, responding to the user's actions; and the autonomous mode where the computer can operate independently of the user for tasks such as semi-automatic texture rendering. Together, these modes span a new space, where both human and computer work in synergy, contribute to the final product.

Fabrication of static models

In the fabrication of a static model, the user cannot alter the CAD model, and the boundary of the virtual object remains static. This approach resembles traditional digital fabrication technologies, where the virtual model is fixed and prepared beforehand. Here however, the user (rather than an automatic process) determines the tool-path. This enables personalization of the work, and may also circumvent complicated CAD challenges such as merging 3D elements into a single object.

Tool-path personalization

As discussed earlier, the FreeD gives the user direct control over the milling tool-path. The final surface smoothness and resolution are determined by the size and shape of the bit and the tool-path. Usually in fabrication, a manual process renders a chaotic surface pattern whereas an automatic process renders an organized network of marks. This is mainly because in a manual tool-path, a consequence of the maker's dexterity and patience, the operation never repeats itself and evolves into a unique texture, for example in the fabrication of a sabertooth tiger model (Figure 2.9). The final texture (b) reflects the user tool-path (c), properties of the material, bit size, and latency of the system. The parts left unfinished (legs) demonstrate decisions made during the work.

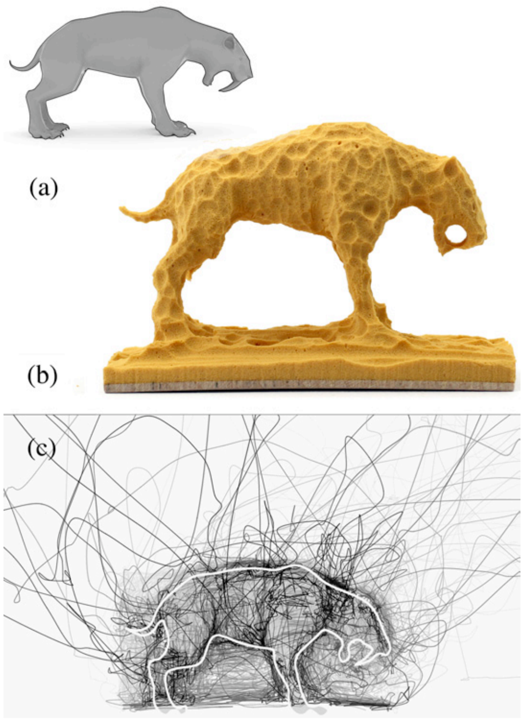

Figure 2.9 Sculpting a static model of a sabertooth tiger (80 min fabrication time, length 125mm). (a) The 3D model, (b) the end result of the sculping process, (c) and the toolpath projection. The tool is capable of achieving a smoother surface, with deliberate intent.

Physical Merging

As the FreeD encourages the user to work intuitively, the user can switch between different reference virtual models during the work. The fusion of these models need not be determined numerically, only physically, relinquishing the need to solve mesh intersection problems in making a single CAD model, as in the merging of a sabertooth tiger model with dragon wings and deer horns (Figure 2.10).

Manual Override

Here, I present an approach foreign to most digital fabrication methods: allowing intentional destruction of the fabricated model. By overwriting the computer, the user minimizes digital control on the shaft while keeping the advantage of digital guidance with a sonic alarm and LED. In addition to leaving parts unfinished, the maker can intentionally ”damage” the model, working around or inside the virtual shape allowing for improvisation. Beyond Figure 2.8b, in Figure 2.11 the user continued to manually remove parts of the model to achieve a unique artifact.

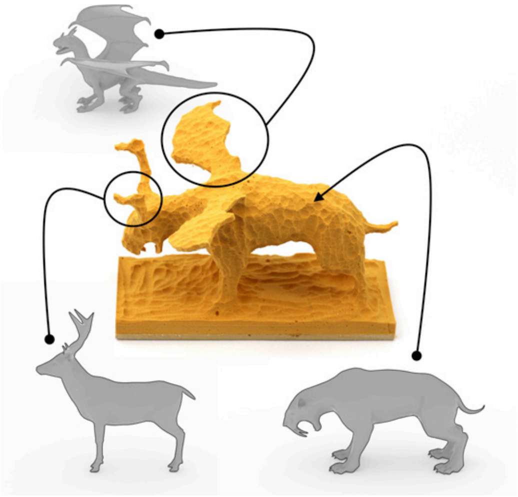

Figure 2.10 Hybridization of meshes while sculpting (100 min fabrication time, model length 120mm). The final 3D shape does not exist virtually; it only exists in the carved model.

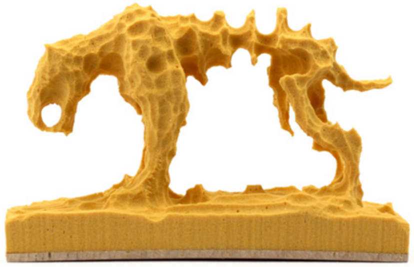

Figure 2.11 The result of overriding computer guidance is a completely different design (90 min fabrication time, model length 120mm). The artist takes risks and produces a unique artifact.

Fabrication of dynamic models

Today, digital fabrication technologies require models to be designed beforehand and no changes can be made during fabrication, as in the static approach presented in the last section. In contrast, craftpersons are free to deform the subject during the making process, as long as the remaining material allows. Aiming to re-create this freedom, we (Roy Shilkrot and myself) present a novel capability to allow the modification of dynamic virtual models during fabrication, exploring three types of interaction with dynamic models: Direct shape deformation, Volume occupancy optimization, and Data-driven shape exploration.

Direct Shape Deformation

The first order dynamics in our interaction model is to allow for direct deformation of a CAD model. Unlike manual overriding of a static model, in direct shape deformation the computer keeps track of subtracted material: when the user presses the override button and penetrates the virtual model, the computer deforms the mesh to ameliorate the penetration.

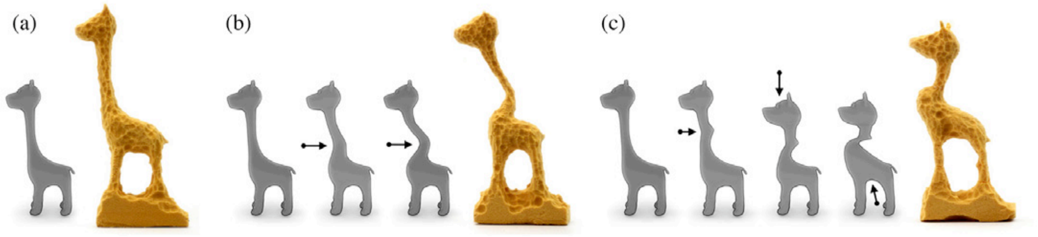

Figure 2.12 Model deformation while carving using the override mechanism. The model is smoothly deformed in proportion to the bit's penetration of the material. (a) The original model, (b) deformation from the left, (c) and deformations of the model from multiple directions.

Recent related methods of mesh deformation [30] seek to preserve local features under deformation. Here, we used a simplified weighting scheme for local deformation with respect to the user's action. As the weights for the offset vector of vertices (O_v, where v is the vertex index) we use a Gaussian decay over the distance from the nearest vertex to the bit, to create an effect of a smooth deformation:

$$O_v = T_v * e^{\frac{-(d_v / s)^2}{0.005(10-P_r)^2}}$$

Where P_r is the value read from the override FSR button (0 is no pressure and 1 is maximal pressure), T is the penetration vector (the vector between the point of first contact to the deepest bit position), d_v is the distance from v to the penetration point, and S is the number of affected vertices, a constant number that can be defined by the user (and thus define the affected area). See Figure 2.12 for an example of deforming a mesh while fabricating.

Volume Occupancy Optimization

Further examining the art of carving, we face a common challenge: fitting a shape to a given volume of material, for example in the case of an irregular piece of wood, where the artist may try to maximize the volume of the shape while bounded by the material. The FreeD allows working in this fashion, using optimization of volume occupancy.

We illustrate the idea of volume occupancy optimization through a simple parametric bowl with three parameters: inner and outer radii (r_i, r_o) and height (c). Let us $\Theta = \{r_o; r_{in}; c\}$. Spheres and cubes were used to create the model of the bowl with Constructive Solid Geometry (CSG) boolean operations (using the *Carve CSG* library [31]). See Figure 2.13-(e) for examples of parametric bowls.

In order to fit a shape in the material, we first determine the remaining volume. After the FreeD carves out a part of the material, we keep only the tool-path points that are inside the volume in question (see Figure 2.13-(b)). Each point describes only the center of the bit, we therefore randomly generated 10 points on a sphere with radius 3.2mm (the real bit size) to simulate the whole bit as it passed through space. A solid shape is created out of the point cloud using the Alpha Shapes method [32] (see Figure 2.13-(c)). Once the removed portion is established, the remaining volume is easily obtained with a boolean CSG operation (see Figure 2.13-(d)).

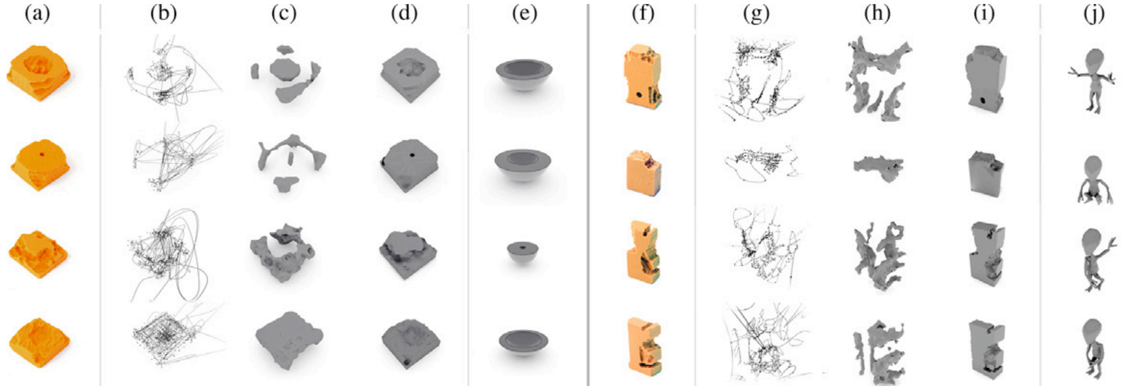

Figure 2.13 An initial iteration in a parametric fitting process of bowl and humanoid forms: (a), (f) the physical carved material, (b), (g) renderings of the toolpath, (c), (h) simulations of the material removed by the tool, (d), (i) simulations of the remaining material, (e), (j) result of the fitting

A parametric bowl is then fitted inside the remaining volume by a score function vector, whose norm should be minimized:

$$
\begin{aligned}
f_1(\Theta) &= \omega_1 * Vremain(\Theta) \\
f_2(\Theta) &= \omega_2 * Vout(\Theta) \\
f_3(\Theta) &= \omega_3 * (1 - c) \\
f_4(\Theta) &= \omega_4 * (1 - r_{in}) \\
F(\Theta) &= [f_1(\Theta) \,; f_2(\Theta) \,; f_3(\Theta) \,; f_4(\Theta)]
\end{aligned}
$$

The $Vremain(\Theta)$ marks the remaining volume of material after the bowl was subtracted and $Vout(\Theta)$ marks the volume that the bowl takes outside the remaining volume, i.e. out in the air. These measures should be minimized so as to maximize occupancy and minimize escape. The bowl is made as high and thick as possible using the final two residuals. We used a non-linear least-squares solver [33] to find the solution for the canonical optimization problem: $argmin_{\Theta}||F(\Theta)||^2$. Due to the CSG operations, the function is evaluated numerically.

Data-Driven Shape Exploration

In this dynamic-model mode, we strive to simulate the unbounded amount of possible outcomes that manual carving allows. Using a vast database, the tool guides users while exploring the shape-space in an interactive process. We work with a hierarchical database of over 4000 examples of human poses that were recorded with the Kinect sensor via the OpenNI software stack [34]. The poses were clustered using a K-Means variant, into 50 clusters (meta-poses) of varying sizes, using WEKA [35]. Then, we use the method from [36] to auto-rig the humanoid alien model to a skeleton model that corresponds with the Kinect. For deformation of the mesh we used the canonical Linear Blend Skinning method. Figure 2.14-(a & b) illustrates the database of skeleton poses.

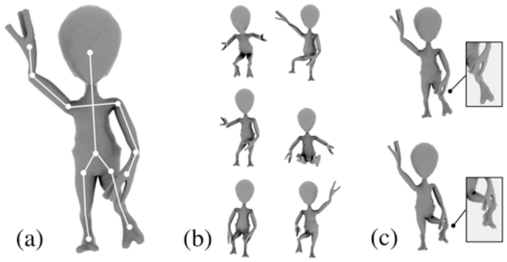

Figure 2.14 The parametric skeleton model of a humanoid creature: (a) skeleton of 14 joints, (b) sample of the database of possible poses, (c) fine-tuning process recovers the best pose to fit the remaining material.

The process of finding the remaining volume (see the previous sub-section) is repeated. Then, an exhaustive search over the database is performed to find the meta-pose that has the least amount of escape from the remaining volume (*Vout*), followed by a search within the best-found cluster. Every iteration presents several options for advancement that the use can choose from. After the database search, fine-tuning ensues for the position of the limbs and for small translations of the entire shape with respect to the volume. Figure 2.14-(c) shows an example of fine-tuning the alien pose.

Autonomous Operation Mode

Digital fabrication technologies incorporate several degrees of automatic motion, while common hand-held fabrication devices do not automatically move but are manually controlled. The use of automatic motion in hand-held devices is rarely considered. Lately this preconception is changing, as was demonstrated by Rivers et al. [13], integrating a 2D actuation mechanism to correct users' paths, and in the early FreeD version [5], where shaft retraction prevents user from accidental penetration of the model.

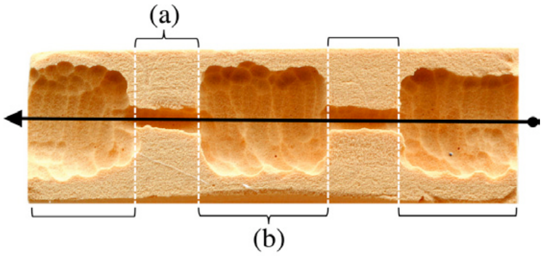

Figure 2.15 Automatic tool operation in a straight line. In (a) regions where there is no autonomous movement, while in (b) regions where the shaft programmatically removes more material resulting in a bigger virtual bit.

An independent actuation of the shaft operates semi autonomously: while the user holds FreeD and makes large-scale movements, the tool makes autonomous smaller-scale movements. For example, the tool is operated as a semiautonomous milling device (CNC, see Figure 2.15). In Figure 2.16 we demonstrate a semi-autonomous texture rendering: when the bit is closer than 4mm to the fur segment, the servos operate with a linear pecking movement (4Hz, 5mm movement range) to achieve a fur texture. The user continues to operate the tool freely, unconstrained by the shaft actuation.

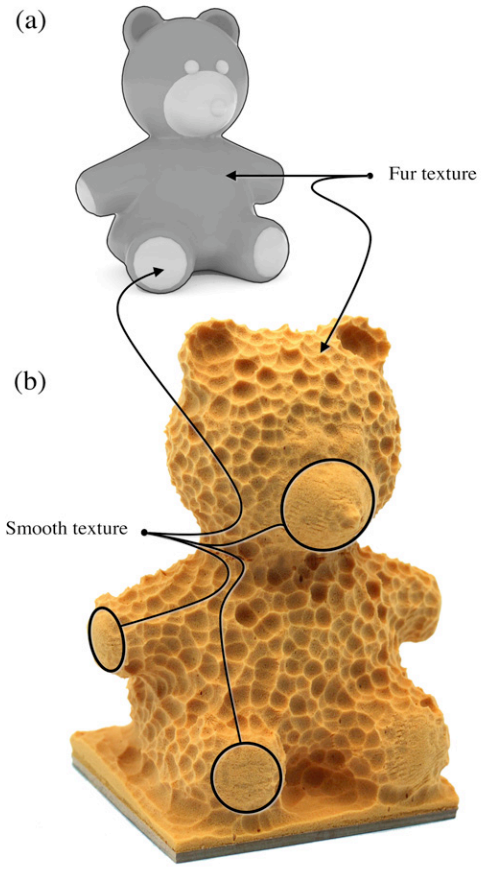

Figure 2.16 Teddy bear model (height 147mm) (a) embellished with fur textures. The mesh is encoded with a rough or smooth texture. The rough texture causes the shaft to move back and forth, creating dimples in the material that simulate fur (b).

Performance and Exploration

In this section, I first present statistical performance measurements collected while working with the FreeD, before discussing the experience using the tool and the user study in the next section.

System performance

The FreeD system was used in the fabrication of 17 complete artifacts, in addition to several 3D sketches and a few preliminary sculptures in my early work. I tested the tool by carving in both high and low-density balsa foams, basswood, and carving wax. All of the studies presented here were done in foam, since it took up to 10 times longer to machine wax and wood. The control software updated at a frame rate varying between 8 to 20 frames per second (FPS). I worked with mesh models of 150 vertices (humanoid) to 5370 vertices (gargoyle), lengths between 120mm (giraffe) to 280mm (gargoyle), and with production times of 40 minutes (giraffe) to 5 hours (gargoyle). The static-bit accuracy (measured by holding the bit in one place while rotating the tool around it) varies between 0.05 mm RMS (20cm from the magnetic field generator) to 0.4 mm RMS (70cm away).

While in my work I seek personalization of artifact rather than production accuracy, I nevertheless found it important to test how accurately the FreeD can reconstruct a pre-designed virtual model. The surface accuracy depends on the frame rate, tool movement speed, and material density. For example, with 15 FPS and 350mm/sec attack speed, the bit penetrated 3.5mm into a dense balsa foam before the system shut down the spindle rotation.

To empirically evaluate the accuracy of FreeD, I designed a model with non-straight angles and a sphere (Figure 2.17 (a)), fabricated it with the FreeD, and then scanned it with Konica Minolta VIVID 910 scanner to computationally estimate the error. I present the following results only to give a general sense of accuracy, as the adherence of the resulting surface to the virtual model is greatly a factor of the maker's dexterity and patience, a complex concept to quantify. The resulting error was smaller than 0.5 mm RMS (samples for this measurement were taken within a grid of less than 1 mm resolution). As expected because of the bit size, FreeD fails to clear out material from sharp corners; however all subtractive fabrication methods suffer from this drawback.

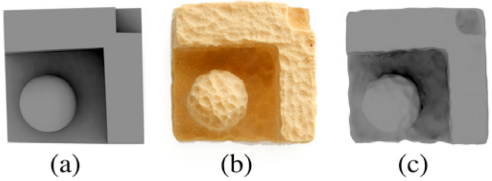

Figure 2.17 An examination of the FreeD V2's accuracy measure. (a) the virtual model (53mm length) , (b) the model fabricated with FreeD, (c) a 3D scanning of the fabrication. The RMS error is less than 0.5mm.

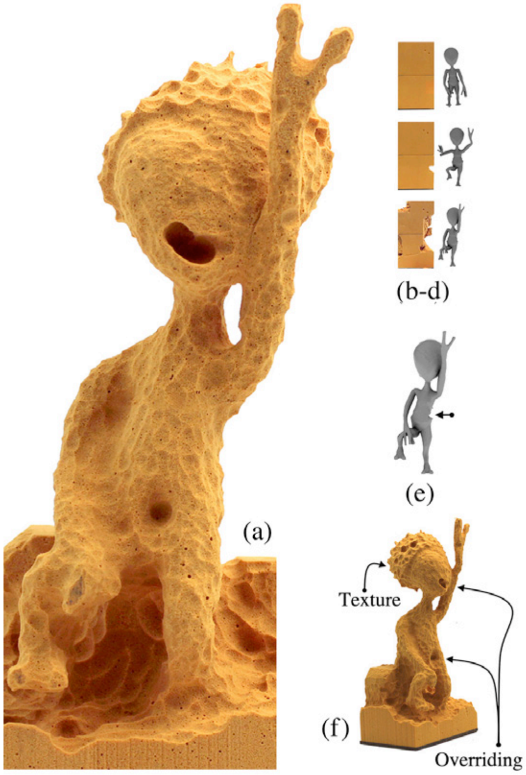

Figure 2.18 Fabrication of a humanoid model (height 222mm) illustrating all methods. (a) The final artifact. (b-d) Evolution of the model as material is removed. (e) Smooth deformation. (f) Texturing hair and deliberate penetration of the model to carve a mouth and navel.

Full Capabilities Integration

Here I discuss the making of a larger-scale model that incorporates most of the functionalities of the tool. Together with Roy Shikrot (a PhD student at the Fluid Interfaces group, MIT Media Lab), we made a humanoid model, an alien figure, which features a large head and elongated arms. The work began by interactively exploring the skeleton database in the same manner we discussed earlier. Figure 18 (b-d) shows the different poses fetched from the database while carving out material.

When a satisfying pose was found, we began removing larger chunks of material. Using the shape deformation method, described earlier, we created a dent in the model to emphasize the sideways motion of the hips (see Figure 18-(e)). We then kept removing material until the general form was fleshed out (see Figure 18-(f) for an illustration) and moved on to texturing and decorating. On the computer we set the alien's head to have a rough texture that will resemble hair. Finally, we used the override mechanism to create completely unguided carvings of the mouth and navel, and decided to leave part of the model unfinished.

User Study

As discussed earlier in this chapter, my objective with the FreeD is to demonstrate the importance of the hybrid fabrication territory, where artifacts are produced by both machine and man. By allowing unskilled users to engage in manual fabrication practice, I advocate for values rarely considered within the contemporary fabrication movement, such as intimacy and the uniqueness of the experience.

The evaluation of the FreeD presents a challenge. Although a quantitative study of the performance of the FreeD is useful, it may not provide information on the subjective qualities of the experience of using the tool. Due to the hybrid nature of the work, the study presented here incorporates both quantitative and qualitative methods. For the quantitative portion of the study, I recorded users' tool-paths and processed them to detect patterns in workflow and technique. For the qualitative portion, I had discussions with the participants about their experiences and perceptions of the process. In this process, I seek correlation between the makers' practices, their experience with the FreeD, and the produced artifacts.

In addition to investigation of the FreeD experience, this study explores future potential of hybrid interaction. All participants were selected because they had a personal interest in the combination of manual and digital fabrication practices. Five participants took part in this study, each with a different background in craft, digital fabrication, or computational design. While one participant uses manual technologies in his daily practice (and two others were professionally trained in craft), most participants spend their professional life in front a computer. I selected people with computational experience over handcraft experts in order to primarily evaluate the FreeD as a supportive tool for computer users, and less so as a technology for traditional craft masters. While FreeD enables novices to craft in ways that are normally only accessible through extensive training, it also creates an opportunity to compare the creative processes of experts and novices.

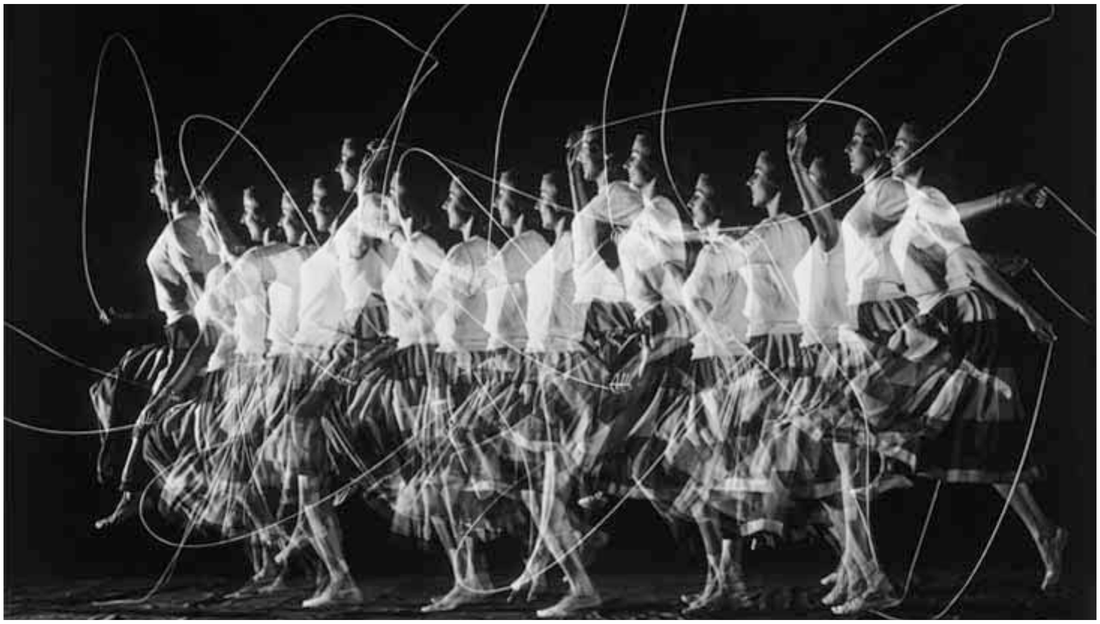

Figure 2.19 Rope Skipping by Edgerton and Mili, using 30 frames-per second multiflash. Image from Edgerton's website < http://edgerton-digital-collections.org/galleries>

Related Studies

Several prior projects inspired this study. Harold Edgerton and Gjon Mili [37] (see Figure 2.19) used multiflash photographs to capture a golf player's swing motion, dancers' movements, and tennis players, to recent gait detection with a variety of sensors [38]. Lapinski et al. developed a multi-sensor acceleration system to study the pitch motion of professional baseball players [39]. These studies focused on observing transient professional actions, while I am seeking a multi-dimensional, high-entropy behavior that takes place over a long period of time. A similar motivation is present in a work by Berman at el., where they studied the behavioral space of flies using statistical methods. This work in particular inspired the quantitative section of my study [40].

On the qualitative side, I build on few important projects to structure the method of my interviews. Adding to the discussion in the beginning of this chapter, Mishler conducted inspiring interviews with professional craftpersons, "who reflect on their lives and their efforts to sustain their form of work as committed artists in a world of mass production and standardization" [41], drawing narratives of identity and their relationships to processional practices. Turkle and Papert in *Epistemological Pluralism and the Revaluation of the Concrete* argued that "computers are a medium through which different styles of scientific thought can be observed" [42], a fundamental observation within my work, justifying the hybrid territory of making. On a closing note, studies of *skill* and *style* to reveal symbolic communication are common ethnographic and archeological practices [43, 44], and influence my attention to aesthetical and stylistic details.

Hypothesis and Objectives

My initial hypothesis was that through tactile engagement during the creative process, makers introduce personal style, with a potential to impact an initial design concept. The FreeD system allows, for the first time, makers with no carving background to participate in a study where they are evaluated side-by-side with professionals. In addition, I assumed that participants' personal creative narratives affect their design style. Therefore, the preserved elements of personal design style should be evident in their use of the FreeD. Finally, I used this study to explore concepts of synergy between human intimate involvement and digital control, by engaging people in a form of hybrid interaction that may go beyond the practice of fabrication, craft, or design, re-considering human interaction with digital systems.

Method

Five participants took part in the study, which took place at the MIT Media Lab shop. Each participant fabricated the same 3D cat model out of balsa foam, using the FreeD. All participants had prior design and fabrication experience, varying from traditional violinmaking to digital fabrication and robotics, and each person had some level of CAD skills. Before they began the fabrication process, I interviewed each participant for 45 minutes. The interviews consisted of a discussion of the participants’ practice and style, their expectation from the experience of working with the FreeD, and their objectives in merging of digital and manual forms of fabrication.

I initialized and calibrated the system; the participants were not aware of this task when they began their own work. For the study, I pre-cut all the balsa stock to an initial contour. The participants could choose to rely on visual feedback from the laptop, placed one-meter away from the workbench, showing the location of the milling bit with respect to side and front views of the model. The tool-paths (6DOF and value of the pressure sensor) were recorded as they were sampled by the control system. In addition, I took photos and videos during the work.

Immediately after the participants finished the work, I interviewed them about their reflections on the experience. A few weeks later, I followed up with a closing interview, investigating questions regarding ownership of the work, and conceptual perspective on the integration of digital technology in the fabrication practice. In the next section I introduce the participants, their practice, and their work with the FreeD. Following that, I present the statistical evaluation, and the closing discussion.

Five Makers, Five Projects

Over all, eleven people used the FreeD: five participants in the study presented here, and five other participants who collaborated on a single carving task. One of my initial observations was that all users share similar procedures when working with the device. The tool was first guided away from the object, removing material from one side to another. As the model became recognizable, the operation changed to tracking the surface manifolds. Changes in spindle speed, when the bit approached the model surface, informed the users on the relative location of the tool with respect to the model and helped to inform their intuition. On the screen, a virtual mark represents the current position of the FreeD's milling bit (Figure 2.8 (d-f)). Occasionally, users relied on this mark in the initial stage before the virtual shape was revealed in the raw material.

Figure 2.20 Five cats made by five participants using the FreeD, all using the same CAD model.

Drawing a 3D Cat: Jennifer Jacobs

> *It was a big revelation for me when I realized that I could use programming to draw... (I wonder) what about programming makes it a useful tool for generating aesthetics?* - Jennifer

Figure 2.21 An early drawing by Jennifer, as part of a bigger work.

Jennifer (28), a PhD student in the MIT Media Lab, was my first participant in the study. She has Bachelor and Master's degrees in the arts of drawing and animation, but no prior background in carving. In her own research, she is developing tools to combine programming with digital fabrication, enabling the merging of art and design in a novel way to shape creative output.

Jennifer used the FreeD for almost two hours, making the cat model (Figure 2.23). Following the fabrication process, she admitted she wouldn't have been able to accomplish this project without digital assistance. As a developer of design and fabrication tools, Jennifer used the tool as an enabler of design personalization, driving the tool to modify the cat's surface while depending on its guidance. With the FreeD, she expressed her personal style throughout her use of the tool, but did not see a connection between the cat project and her art projects. For her, the FreeD served different purposes as she learned how to effectively use the tool: "The more you use it, you less rely on the tool as a feedback mechanism and override it." She added that she treated the FreeD like a drawing instrument.

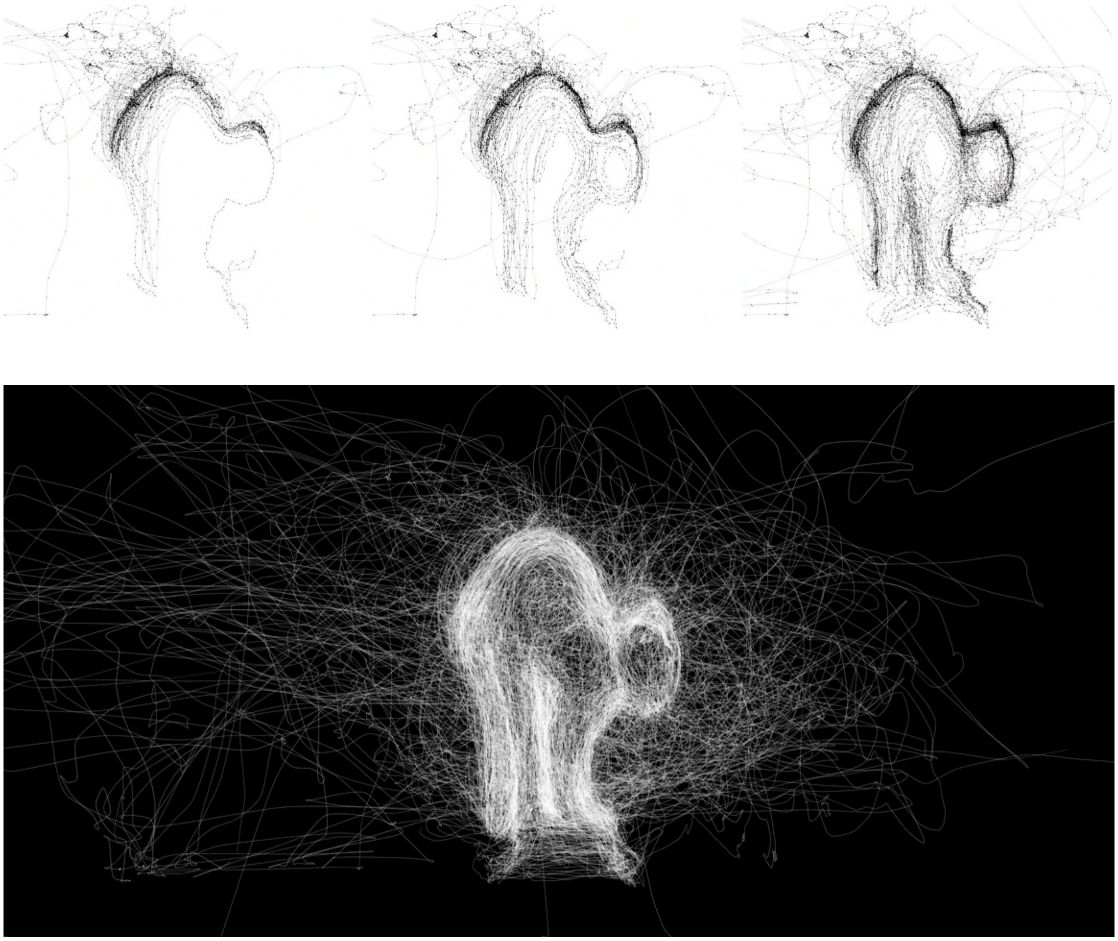

Figure 2.22 Tool-path visualization of Jennifer's work. Top: three early stages, where her circular, contour-like patterns can be easily seen. Bottom: documentation of two hours tool-path of her work.

Jennifer is used to thinking about sets of lines when illustrating, a thought process that is evident in many of her works (Figure 2.21). She re-interpreted the cat design in a way that resembled her illustration aesthetic, where lines are used as a way to transverse the composition (Figure 2.22). Looking at her final cat creation, this linear style is particularly evident in the detailed face, structural bone, and muscles she added to the original design.

Smoothing for Contrast: Tamar Rucham

Figure 2.23 Jennifer's final cat, where the contour pattern revels figurative details such as structural bone, facial details and leg muscle.

Prior to working as a computer programmer for over five years, Tamar (31) had mastered the crafts of silversmithing, goldsmithing and blacksmithing, running her own practice. In making jewelry, she loved to search for shapes in abstract forms, and developed a technique of heating silver until it melts in order to create amorphous structures (Figure 2.26). Never guided by a plan, she decides during the process how to use the output.

> *I like random processes, I like the unexpected and the surprises, letting life guide you. When you just copy things, there is not search. For me it was always about searching something inside the material... a journey, not knowing its end.* – Tamar

Tamar's search for abstract forms evolved into an aesthetic of contrasts; her works reveal a dichotomy between the rough surface of the molten material, and the smoothed areas where she sanded the material. This same duality appears in Tamar's cat (Figure 2.24), where she similarly sanded the cat's head and base. Tamar was unaware of the similarity of her cat and the style of her jewelry. Rather, she interpreted her action as a desire for details: "I wanted to go farther in smoothing what the tool can do..."

Figure 2.24 Tamar's final cat, with a smooth head and base.

Unlike Jennifer, Tamar is skilled in figurative wax carving. She therefore didn't force the tool to express her style, and switched to a different technology when needed. She used the FreeD for 90 minutes, and was the only user who used sandpaper, smoothing the face and base of the cat, and re-introducing the aesthetic she developed – and deserted – years ago.

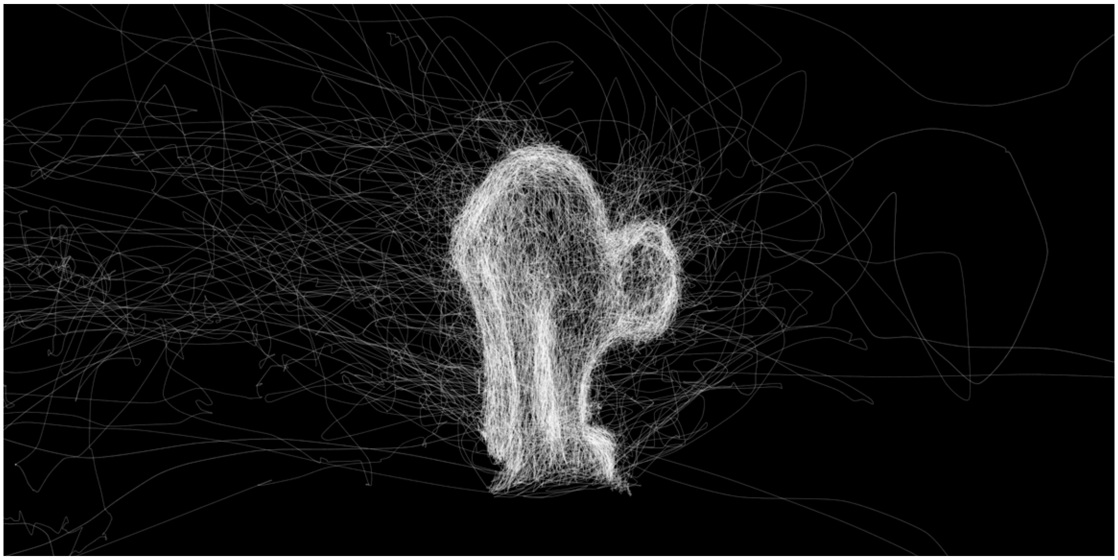

Figure 2.25 Tool-path visualization of Tamar's work, documenting the whole carving process.

Figure 2.26 Tamar's silver melting jewelry making technique.

From Search to Pattern: Santiago Alfaro

Santiago (36), a product designer and a PhD student at the MIT Media Lab, developed a new working methodology with the FreeD, evolving into a radical design modification. His technique with the FreeD bears a strong similarity to his perspective on the formulation of manual practice.

As an experienced practitioner of pottery and glass blowing, Santiago feels computer interfaces are too formulated. In his research, he seeks to design devices that interact with a broad range of human senses. Santiago prefers glass blowing to pottery, because he feels pottery is too difficult to predict and requires a great deal of manual training. For him, the methodological procedure of glass blowing is compelling, because it combines precision and control in material manipulation with a full-body tactile experience.

> *After I had to do a lot of coding, I understood that what I really like is the manual feel… I do find myself attracted more to the intuitive, hands-on experience than to everything that is computer based…* - Santiago

Because he had no prior experience in carving, Santiago took longer to complete his model than many of the other participants. During this time, he experimented with many different carving techniques, searching for a method. Exploring what the tool could do, he poked the shape while studying the design. His methodology then evolved into drilling patterns of holes to expose the underlying model (Figure 2.27). Santiago tried to prevent accidental drills and at the same time deliberately used his drilling technique to make a pattern at the cat's back (Figure 2.28).

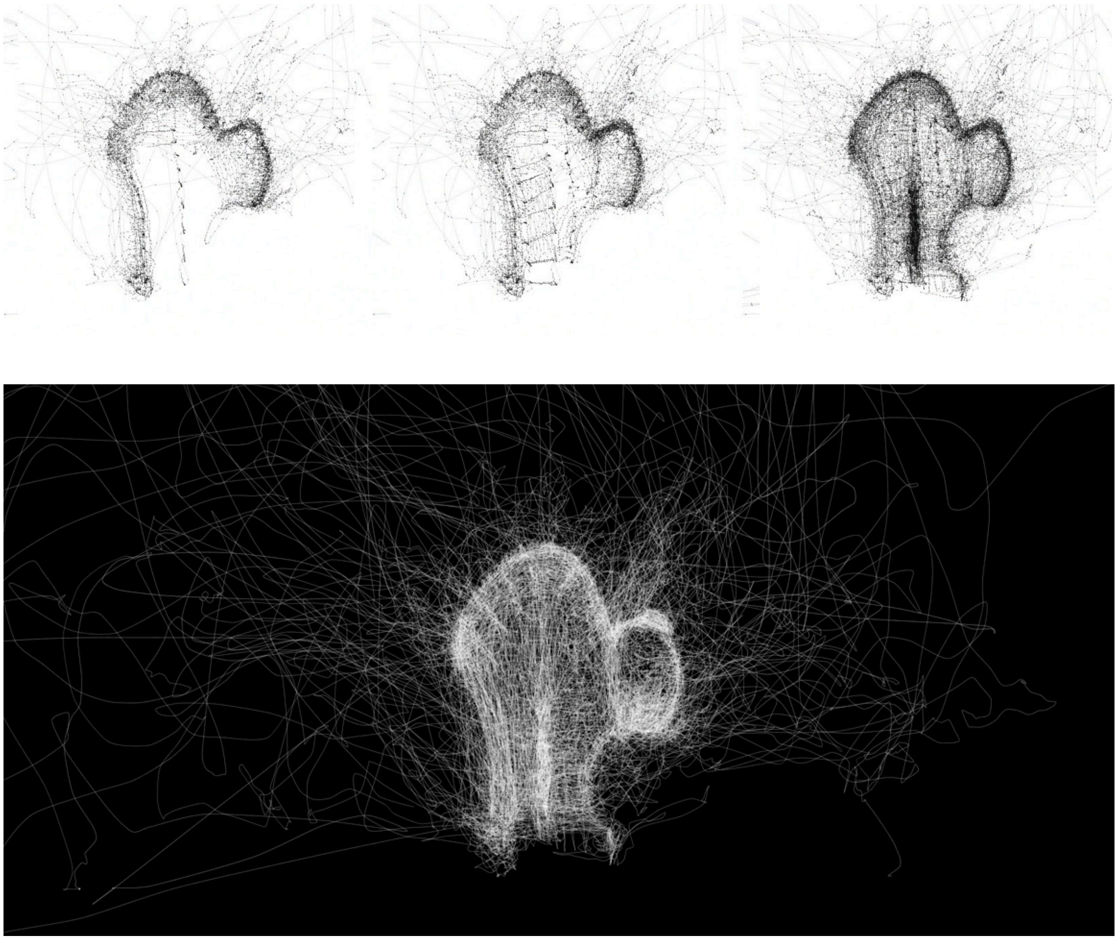

Figure 2.27 Tool-path visualization of Santiago's work. Top: three early stages, where he develops his drilling methodology. Bottom: documentation of two hours tool-path of his work, showing the final pattern in the cat's back.

Dynamic, Static and Precise: Peter Schmitt, PhD

Unlike Santiago, who continuously searched for a method, the final two participants used the FreeD in a way that demonstrated their confidence in carving, gained from many years of prior experience. Peter (35) is a mixed-media artist, trained as a traditional sculptor, but later specializing in digital fabrication, kinetic sculpting, and robotics.

As an artist, Peter is searching for dynamic and organic qualities in mechanical artifacts. He has developed printed gearboxes and clocks, laser cut servomotors (see Figure 2.30), and milled bearing mechanisms that later provide the building blocks for more elaborate works of art. In all his mechanical designs, Peter expresses the tension between static and dynamic qualities of the machine, contrasting mechanical elements with static constraints such as containing cases.

Figure 2.28 Santiago's final cat, showing his unique pattern.

Figure 2.29 Peter's half cat.

Figure 2.30 Peter's laser cut plywood servomotors.

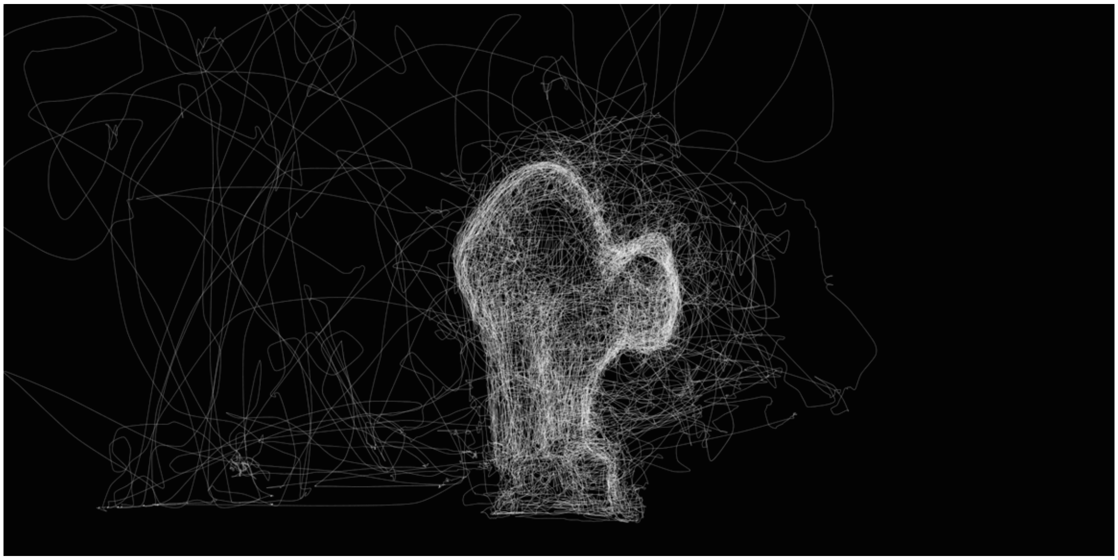

Figure 2.31 Tool-path visualization of Peter's work, documenting the whole carving process.

The same tension appears in Peter's cat, where he decided to leave one half unfinished (Figure 2.29), contrasting the cat with its material origin. As a maker of CNC machines, Peter explained that he wished to reveal the process of making in the artifact. In the unfinished side of the cat Peter added a personal inscription, which read: "bio-engineered cat for Amit" (see Figure 2.1). Peter invested almost ninety minutes in carefully milling the half cat. Having a lot of experience in both manual carving and mechanical fabrication, Peter showed confidence in his work, using an organized tool path and creating a relatively accurate surface finish, with no special intention to override the surface.

Executing a Plan: Marco Coppiardi

Marco (45) was the last participant in the study: a violinmaker with thirty years of experience, making top-end, hand-made violins, violas, and cellos, using traditional tools and techniques. Marco is highly skilled in carving, and would not normally require a tool like the FreeD to complete a model similar to the cat. He worked faster than all other participants, completing the cat in only eighty minutes, executing an accurate replica of the design (Figure 2.33).

Although it took him ten years to master his craft, Marco doesn't have a special attachment for any specific tool. For him, the key to making a good instrument is in the way all the parts are perfectly assembled together.

> *(Today) working with a musician is more interesting than roughing and carving wood; it is about design, and fine-tuning the whole process… in the beginning it was just about making the objects.* – Marco

Figure 2.32 Marco's violin-making process, carving traces with gauges in the rough stage of the work.

Figure 2.33 Marco's final cat.

Marco does not object to the use of automatic machines (although he does not personally use them), assuming he can still refine the resulting instrument manually. Thus, for him carving tools have no special value besides being a fabrication agent with a well-defined procedure that moves him one step closer to the final artifact. This perspective is seen in the way he worked with the FreeD, applying an organized tool-path to remove material from one side to another, keeping the model's integrity with a confident technique (Figure 2.32 – 2.34).

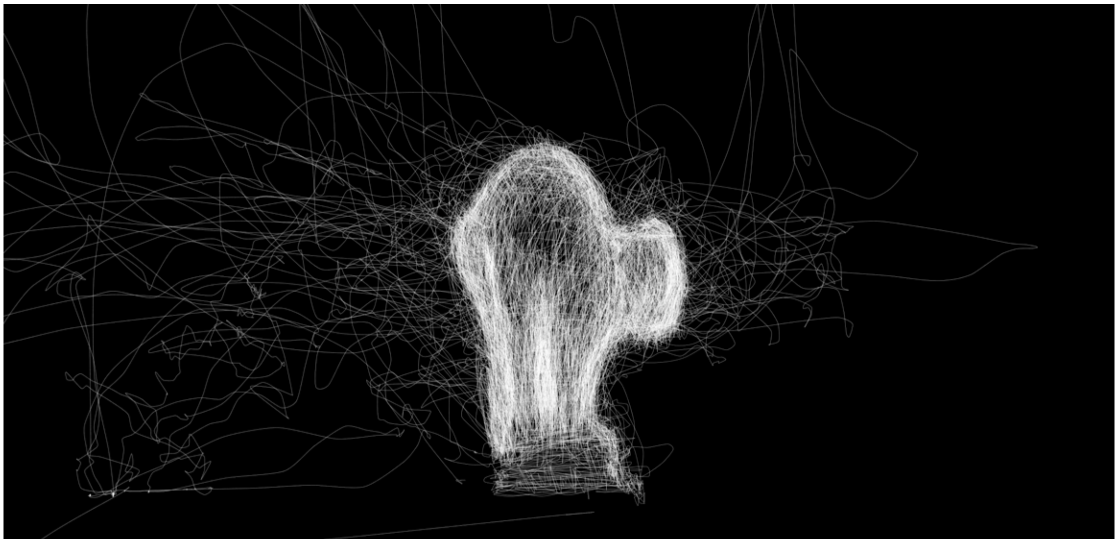

Figure 2.34 Tool-path visualization of Marco's work, documenting the whole carving process.

Quantitative Evaluation

In the quantitative section of the study, I used statistical methods to extract identifying features from the recorded data, including a 6DOF tool path (which corresponded to the milling bit position), tool orientation, and the value of the pressure sensor (overriding value). I assumed these features would sufficiently represent the working style of participants as they operated the device over time. Through several forms of computational analysis of this data (see Figure 2.35), I detected twenty-one modes of work (i.e. techniques) across all of the participants, I created a series of visualizations containing the dominant techniques. These visualizations identify a unique working style for each participant (Figure 2.38). Assuming short time variants have a weak correlation with the high-level cognitive working approach, the data is analyzed in a higher-level perspective, integrating two and half minutes in one window for the final visualization.

The data from all participants was processed together as a long series (with a frame rate of approximately eight frames per second), and features were selected using a clustering method, either K-Means variant or Gaussian Mixture Models (GMMs), depending on which method resulted in a better separation. The features data was then filtered twice: first with a Median filter to remove local outliers, and then with a Wiener filter to smooth the data while preserving significant variations. A posterior matrix of clusters probabilities was calculated for each time sample (see Figure 2.36), before all the data was clustered again into twenty-one *working techniques*. In the remainder of this sub-section, I describe the extraction of the five elementary data features, the techniques detection algorithm and finally an analysis of the results.

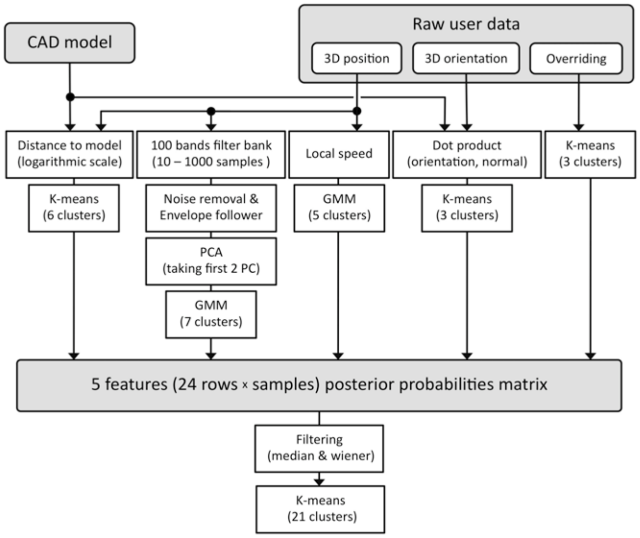

Figure 2.35 Technique detection procedure: feature extraction and clustering process algorithm.

Distance

For each time sample, a distance D from the model is calculated as follows:

$$i_N = dsearchn(M_M, P_N);\ for\ j\ ==\ 1:N,\ D_j\ =\ \left|M_{i(j)} - P_j\right|$$

Where M is a vector of the CAD model vertexes, P is a vector of the tool-path position samples, *dsearch*() is a *Matlab* function that returns a vector of closest points in the first argument to the points in the second argument. The *for* loop builds a closest-point distance vector D with respect to points P. In order to improve the resolution near the object, I map the distance to a logarithmic scale (any value smaller then -5 is trimmed), before it is clustered, using a K-Means variant, to six groups:

$$LD_N\ =\ \log(D_N\ -\ \min(D_N)\ +\ \varepsilon)$$

Spectral pattern

To identify repetitive motion patterns, a few additional stages are required. Each axis is processed separately, through a filter bank of one hundred bands, with window sizes that vary from 10 samples (a bit more than one second) to 1000 samples (almost two minutes), implemented using Finite Impulse Response (FIR) filters. A noise threshold is used prior to an envelope follower for each spectral band. In the next stage, energy values of the three separate axes are summed together for each of the spectral bands, assuming the overall spectral operation of the tool is more important than the direction of this operation.

Having a matrix of one hundred bands, two-dimensional Median and Wiener filters smooth the data. I then use a Principal Component Analysis (PCA) to compress the data, selecting the first two components for GMMs clustering of seven segments.

Speed

The temporal speed feature *S* (see below) is calculated as a local derivative of the position of the bit, filtered and then clustered to five groups by GMMs.

$$S_i = 0.5\sqrt{(\partial P_{i-1}\hat{x} + \partial P_{i-1}\hat{y} + \partial P_{i-1}\hat{z})^2 + (\partial P_{i+1}\hat{x} + \partial P_{i+1}\hat{y} + \partial P_{i+1}\hat{z})^2}$$

Dot Product

The dot product indicates the tool's angle with respect to the object surface. Since the system operates with a mesh model, the model inherently contains information about vertex normals. This feature is extracted directly by calculating the dot product of the tool orientation vector with the vertex normal at the closest point (as explained in the *Distance* section), and then clustered using a K-Means variant to three clusters.

Overriding value

Probably the simplest feature to extract, overriding values were calculated using the recorded FSR button pressure value in each time sample. Samples were clustered using a K-Means variant to three clusters, representing three major modes: no override, soft override and a manual operation mode. Since the pressure value read from the FSR is less noisy than all previous data, representing relatively low frequency user input, there was no need to smooth the data before clustering.

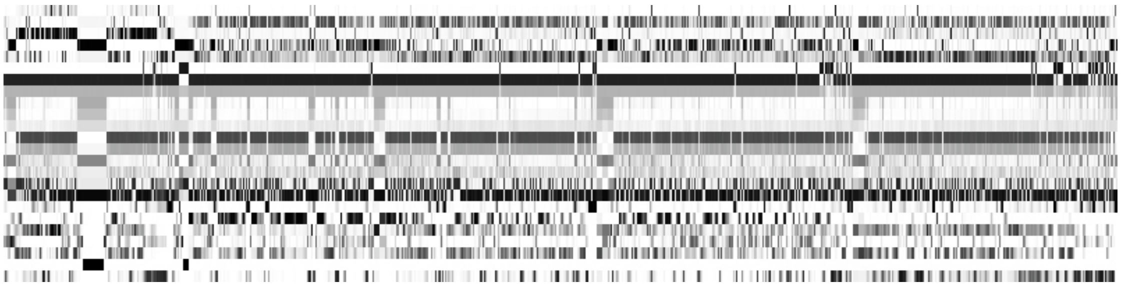

Figure 2.36 A posterior probabilities 24 x 214118 matrix of clusters probabilities for each sample.

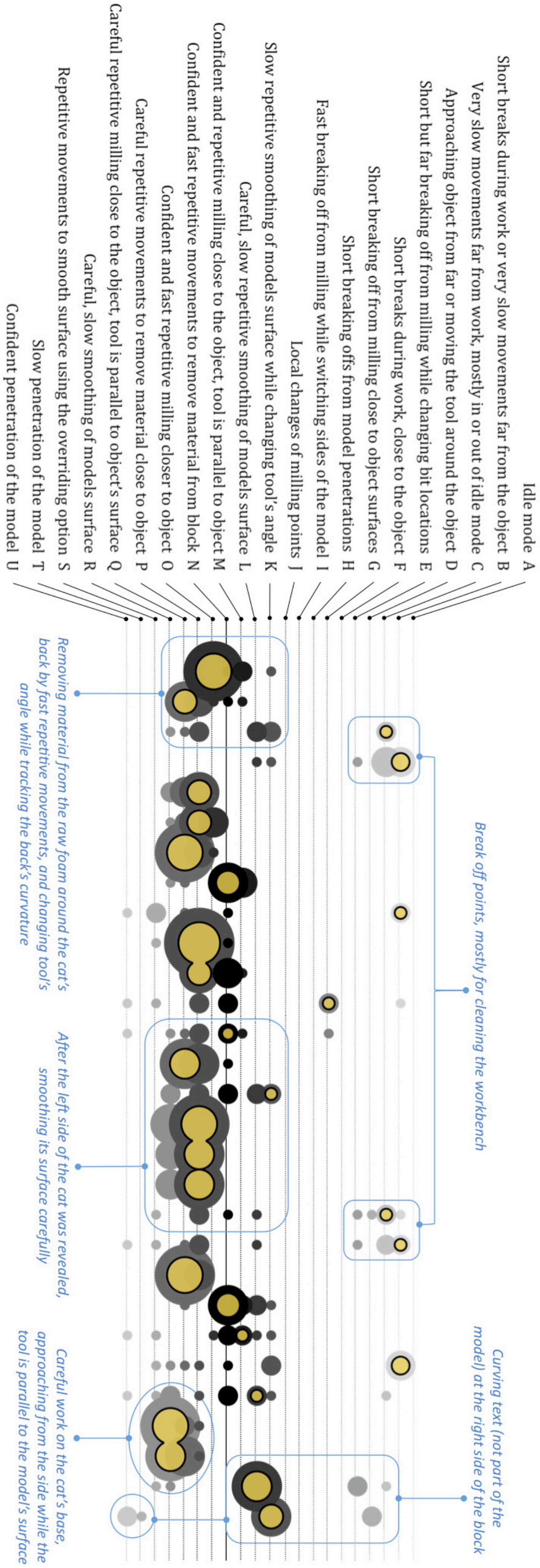

Figure 2.37 Twenty-one different techniques (A-U), demonstrating Peter's tool-path, where timeline is constructed by averaging time windows of 2.5 minutes. The size of the bubbles represents the relative time in that state in a given time point, while the yellow mark represents the dominant techniques.

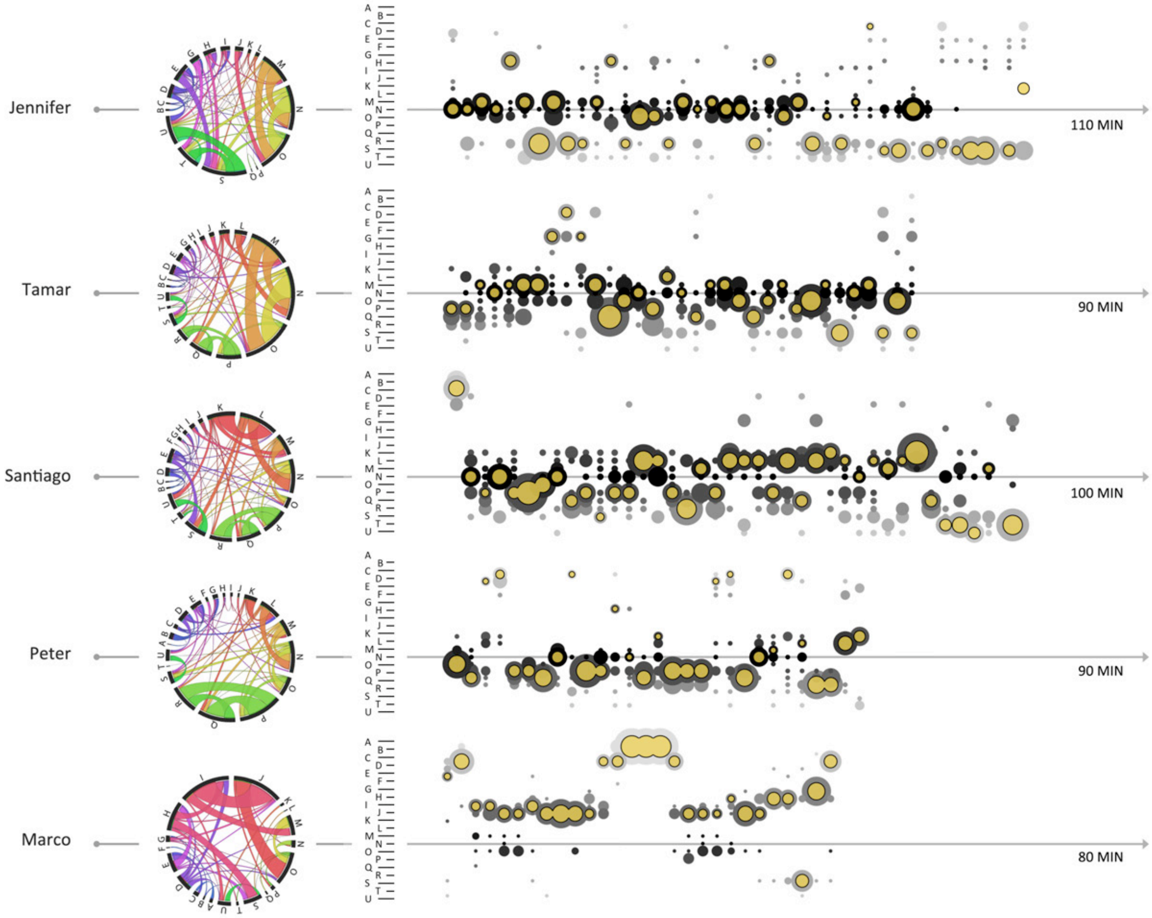

Figure 2.38 The techniques detected for the five participants. Left: circular visualizations of the transition matrix between techniques, as a unique signature of the participants work. Right: timeline of techniques with an averaging time window of 2.5 minutes. The size of the bubbles represents the relative importance of states in a given time point, while the yellow mark represents the most dominant techniques in that time.

Detecting the Participants' Working Techniques

The five features construct a twenty-four row matrix, at the length of 214,118 samples (all participants together, see Figure 2.36). This matrix represents the probability of a given sample to belong to each of the feature clusters. After PCA, the first nine principle components (preserving ninety percent of the matrix energy) are used for K-Means variant clustering. In order to determine the optimal amount of clusters, I used Silhouette Width Criterion, searching for the K with the maximal value. Iterating from three clusters to fifty, the search converged to twenty-one clusters with the highest score.

The detected clusters represent twenty-one different working techniques (or states, see Figure 2.37). Starting from an idle mode, through a variety of tool movements far from the object’s surface, to different milling procedures and model penetration, I describe each of the states in Figure 2.37. A few examples are *Idle mode* (A), *Very slow movements far from work, mostly in or out of idle mode* (C), *Fast breaking off from milling while switching sides of the model* (G), *Careful repetitive milling movements close to the object, tool is parallel to object’s surface* (Q), or *Slow penetration of the model* (T).

Figure 2.38 shows the results of the technique analysis for all participants, and demonstrates a significant difference between each individual's techniques, and their style of work over time. The left side of the figure visualizes the transition matrix between states, as a *style-signature* of the maker. The right side represents the working procedure and use of techniques over time (integrating the data with a two and a half minute time-slot).

Overall, there was a correlation between the work techniques used and the carving experience of the participants. For example, Marco, the violinmaker showed high levels of confidence and used a small number of work techniques, finishing the work faster than all other participants. Marco was also the only participant to take a long break during the work, “to let the hand rest.” However, Santiago, who had never carved before, used the tool for a longer amount of time than Marco and switched between working techniques to search for the best style. This correlation supports the discussion in the next section, where I integrate all the data collected during the studies into a concluding discussion.

Discussion

With the statistical performance of the tool discussed earlier, now I would like to focus on the users’ performance and experience. However, it may be useful to start with a summary of the participants' response to the functional properties of the tool.

Several participants noted it took them a while to trust that the tool would prevent errors that would result in damage to the model. A few participants complained the tool was a bit too heavy (especially its backside where the motors are located), and that the handle was slightly too large for their hand. In addition, several participants showed interest in replacing the current milling bit, which cannot be easily done with the current design. Moreover, dust entering the bearing mechanism creates friction problems, requiring constant oiling of the ball bearings.

Overall, the tool did not exhibit major problems during the work, enabling the participants to continuously work in their own style while completing the model. While developing the tool, I received comments from a number of colleagues concerning the lack of virtual or augmented reality feedback, however the participants in my study did not complain about the lack of these features. Instead, they developed their own methods of investigating the form of the model, and looked at the computer for visual reference when needed. The absence of augmented feedback was actually positive, because it helped people develop tactile forms of carving intuition as opposed to relying on a visual interface.

Skills and Style

By comparing the final carved cat artifacts, it is clear that all participants applied a personal style to their work. Each participant's style contains a different meaning. Jennifer and Santiago, the two participants who had no prior carving experience, needed more time to complete the work, however they were still able to realize deeply personal interpretations of the model. Switching between many techniques and studying their interaction with the FreeD ("it is a new tool and deserves a new technique" - Santiago), their lack of experience evolved into an open-ended process, where the end results reflect their investigation.

For Santiago, using the tool was a learning process rather than a fabrication task. Therefore, he cared more about the experience, and less about the execution or result:

> *I really like the idea of NOT planning… the reason I say that might be because, if I don't have enough skill to do EXACTLY what I want, then I can be happy with the end results…* - Santiago

Jennifer's toolpath corresponded to her professional opinion. She believes tools are not "one dimensional" and investigates multiple creative uses for any one tool. Developing hybrid fabrication tools for her own research, Jennifer noted, "the end products are useful to explain my work," hinting it may not be obvious to value the end products over the process itself. Jennifer internalized the FreeD as a tool allowing her to experience a process otherwise unreachable.

On the other extreme, Marco is a professional who carves in his daily practice. Working with the FreeD, he operated quickly and accurately, using a confident carving methodology. Marco's cat revealed the organized procedure he uses in his work, as a result of his technique, rather than an effort to personalize the output. When he makes violins, Marco uses many tools and technologies to finish the surface of an instrument, eliminating almost completely the rough tool marks from early stages.

> *If in one hundred years someone would like to do an exhibition of my instruments, they will all be different… I am not interested in clones.* - Marco

Marco incorporates many different skills in his work: design, selection of materials, a variety of fabrication techniques, finishing, and acoustic fine-tuning. Thus, to my question “does the cat belong to me or to you?” Marco answered, “to you,” since I selected the tool and model and he only executed the rough stage of what he views as a larger process.

On the other hand, Peter and Tamar are both skilled in carving, having a few years of professional training, but currently do not practice the art. Together with Marco, they used the tool without pushing its envelope. Later they commented on their desire to use different milling bits, and modify the FreeD to suit their personal needs. However, unlike Marco, both Peter and Tamar interpreted and personalized the design. Unlike Santiago and Jennifer, Peter and Tamar refrained from using the FreeD to alter the cat’s surface: Peter decided to leave half of the cat unfinished, while Tamar used sandpaper to refine a few details.

Attachment and Gender

> *Objectivity in the sense of distancing the self from the object of study is culturally constructed as male, just as male is culturally constructed as distanced and objective*. [42]

Because I had a relatively small number of participants in this study, I cannot make remarks about gender, learning and working style based on statistics. However, one may suggest that some of the notes discussed by Turkle and Papert (quoted above) can also be applied to manual practice and craft.

Using the FreeD, Jennifer, Tamar and Santiago put more attention and time in making the face of the cat. Moreover, for Peter the face was the only part he completed from both sides. The figurative bias demonstrated in the milling patterns of the participants corresponds to human natural attention to faces. However, while none of the male participants had a clear idea of what they would like to make with the tool in the first interview, the two female participants, Tamar and Jennifer, expressed a strong interest in creating a figurative sculpture.

Before she worked with the FreeD, Jennifer expressed interest in using the tool to do "generative modeling" (referring to her research in parametric design), or a figurative "human face". To the same question, Tamar answered “maybe some type of bird, or a dragonfly… something that flies, since I like contrast, trying to get the balsa foam look light.” Tamar's sandpaper technique was intended to convey this lightness. The sanding not only created a contrasting set of textures but also thinned the base, making the cat lighter and almost detached from the ground. While possibly arbitrary, Jennifer and Tamar were also the closest to each other in their working technique, as shown in Figure 2.38.

When I asked the participants to whom "does the final cat belong?" male participants answered "to you only" (Marco) or "to me and you" (Peter and Santiago). Conversely, Tamar shared ownership with the tool, describing it as an equal contributor to the making process. As she saw it, they both "danced" together to accomplish the work, allowing for a form of interactive interpretation that was based on intimacy rather then authority. Jennifer's objective on the question of ownership was more complex; she expressed deep attachment to the cat ("I love it!") but had difficulty separating the object from the larger making performance. As an additional note, both Tamar and Jennifer were the first to ask for the cats they created, keeping them in their personal possession.

Narratives of Hybrid Interaction

While interviewing participants, I sought their perspective on the possible synergy between manual skills and computational capabilities. When I encouraged participants to conceptualize a futuristic studio where their fabrication vision could be realized, most of them described technological concepts. Peter however felt that the question was meaningless for him, and stated: "as an artist, you are a child of your time." The technical challenges of the present are Peter's medium, and he finds it irrelevant to visualize far-fetched concepts.

All other participants shared visions of a computational environment - that could better fulfill their present desires or needs. Their idealistic visions of future forms of fabrication shed light on what they currently find lacking in their daily practice. Marco, for example, finds himself investing too much time in non-creative labor activities. He does not worship the manual craft elements of his work, but instead emphasizes the importance of the complete creative process. Although Marco is responsible for the entire process of producing a violin, similar to a chef in a restaurant, he doesn't necessarily need to personally execute all of the technical stages of the work. It is difficult for him, however, to find an apprentice with a skill level that matches his own. He would therefore like to have a digital assistant, in the form of a suit with tracking devices, track-able tools, and a scanner to determine the condition of the work. Marco conceived of this system after using the FreeD, explaining that it could record his techniques and train a fabrication robot to replicate the skills of a master. Marco would use this robot to save time, guiding it during the process and checking the quality of the work in important stages. Despite his enthusiasm for incorporating digital fabrication into his practice, he explained that contemporary technologies are still far from his vision:

> *The CNC machine is still too remote... there is a need for connecting (technologically) to the body of the maker who uses the machine…* - Marco

Marco admitted that craft knowledge is gathered by hand, but he doesn't feel that manual practices should be maintained for nostalgic reasons alone. For him, working with a computer is a lot harder than making a violin, but he claims he would be satisfied with a successful result from either discipline. However, he is aware that in order to gain intuition for guiding the robotic system he describes, one would need to practice manual techniques for a long period of time ("it took me ten years to master violinmaking"). While promising liberty for the master, Marco's vision doesn't consider the needs of the beginner.

Unlike Marco, Tamar sees handcraft as form of meditation, where tactile and manual involvement is crucial:

> *I like to do whatever it is that I want, and to let the material lead me… this is the whole point of the world, unexpected…* - Tamar

Reflecting on her experience with the FreeD, Tamar suggested a version where the computer would generate random shapes, allowing her to investigate and search through the shapes as they emerged. Similar to Tamar's silver melting process, leads her creative practice. The unpredictable qualities of craft give her joy because she believes that an artifact's singularity emerges through manual investigation and discovery. While she is aware that her manual fixation may diminish if she practices craft for a long period of time, Tamar added that as a computer programmer she misses this open-ended, tangible experience. Unlike Marco's practice, where the goal is to create a perfect working instrument, Tamar is looking for the process itself, without any pre-defined target.

Santiago is also interested in open-ended investigations, and seeks an intuitive tangible design process. While Tamar sees the experience of making artifacts as her goal, Santiago's FreeD experience made him reconsider the professional product design process, which usually involves starting with CAD and then enaging in physical prototyping. Instead, Santiago advocated for an opportunity to introduce an iterative dialog between physical prototyping and the computational design process, breaking the current order and allowing natural tactile engagement to influence digital design from the beginning.

The temporal and spatial qualities of the hybrid territory were discussed by a few of the participants as performance qualities. Jennifer, for example, claimed the computational records revealed different types of connections and forms of intimacy between the user, the FreeD (and its designer), and the product:

> *There is a lovely quality that makes both the implications (the manual experience and the produced artifact) and record (such as tool-path*

> *documentation) of an event visible, which are two different things to do.* - Jennifer

The making experience made Jennifer rethink how her involvement in the process creates uniqueness; and how the computer can create a unique form of documentation of this singularity while it evolves. Since the FreeD has limited influence on the CAD model, the fabrication process becomes the product of the work, and it is constantly changing. Jennifer is aware that the inherent nature of digital documentation makes it easy to reproduce a final product, independent of temporal or unique qualities. She stated that this disadvantage is overcome by the FreeD, because the tool re-introduces the temporality and uniqueness to the process.

Study Conclusion

The user study presented in this chapter sheds light on the process of learning to use a virtual tool such as the FreeD, while also demonstrating how subjective interpretation can personalize the product. Correlation between personal narratives and the identity of the participants as makers can be observed even in quantitative measurements. This correlation, gained by engagement in the practice of making while facing challenges that appear during the work or ideas evolving while using a carving tool, could not be realized before the fabrication process. This form of involvement allows for a discussion of fabrication skills and design styles, qualities, which are often absent in digital fabrication practices, which separate the stages of design and fabrication.

The user study supports my hypothesis that through tactile engagement during the creative process, makers introduce personal style that can impact the initial design. The study also contributed a few additional conclusions. There is a clear link between the personal identities of the makers and the quality of their products. Furthermore, each of the participants expected a different type of interaction with the tool. Postulating future work, I suggest that a hybrid interactive system will be beneficial for open-ended processes, allowing makers to define the amount of computational control they use. Beginners may need guidance to simply complete the task at hand, while they develop their techniques as part of the investigation. A skilled maker, on the other hand, may require higher-level control, allowing the computer to reproduce his or her skills or alternatively manually seek different objectives, such as introducing random qualities to the process as in Tamar’s meditative vision. The image of human-computer synergy is subjective, and should be developed to be open-ended and variable if it is to support a real creative engagement.

Summary

The FreeD is a novel contribution to the growing pool of digitally-guided craft tools, allowing designers to engage with raw material in a new way and at the same time, integrate subtractive fabrication as part of the creative process. While digital practice separates design from fabrication, I instead suggest a synergy, allowing the creation of unique artifacts from generic designs.

The results of handcraft are unique artifacts, each subject to the judgment and care of the maker. I propose a new technique where digital capabilities integrated with handheld carving tools to assist inexperienced makers, as well as CAD designers in carving complex 3D objects. The FreeD enables interpretation and modification of a virtual model while fabricating it, keeping the user’s subjective tool path as a signature embedded in the texture of the physical artifact. Additionally, it is capable of completing tasks in a semi-automatic mode, generating a physical texture independently of the user. Since the FreeD allow for design manipulation to be integrated within a tangible carving experience, the nature of this work more closely resembles the process of traditional craft than other forms of digital fabrication, while still allowing digital risk management and quality assurance.

I wish to enable creative work in a domain yet unexplored, a new hybrid territory of artifacts produced by both machine and man, fusing automated production with human subjectivity. Blending design with fabrication and automatic process with manual control, I believe the collaborative technology presented here has the potential to alter some of the dominant paradigms in contemporary digital fabrication processes. By introducing traditional approaches to the digital making of artifacts, I hope this intimate collaboration between man and machine will pave the path for a new type of interactions.

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Chapter 3

Hybrid Functionality:

Chameleon Guitar

In this chapter I explore a hybrid approach to fuse contrasting functional values of the physical world and the virtual one, focusing on the singular qualities of organic materials vs. the infinite possibilities of simulation. I study the discipline of acoustic and digital instruments, where this dichotomy is still important to contemporary musicians.

Each acoustic instrument is one of a kind. Its unique acoustic properties are transferred from the physical characteristics of its source materials and a handcrafted touch. In contrast, electronic and computer-based instruments lack this distinguishing trait. Though the technology support in electronic instruments offers great flexibility, it tends to foster predictable and generic results, particularly with common use of easily-cloned digital presets.

I present an approach to the design and fabrication of instruments that combines the functional advantages of acoustic and electric instruments to form hybrid instruments that exist simultaneously in both physical and digital environments. This approach exploits physical/acoustic properties via a replaceable physical object complemented by a simulated shape or other digital signal manipulation. This work aims to demonstrate the possibility of maintaining the qualities found in real acoustic instruments, such as unique spectral and spatial behavior of wooden soundboards, with the flexibility of digital processing. The key concepts of this approach are presented through an example: *Chameleon Guitar*, detailed in this chapter along with evaluation by laser vibrometry, pointing to the significance of attention to detail such as craft and wood qualities. I conclude that detailed acoustic analysis can significantly aid in the construction of new instruments by quantifying the impact of instrument geometry and material properties.

Introduction

In this chapter I present a new approach to the design of string instruments, combining the digital and the physical environments by allowing the player to seamlessly, simply, and simultaneously change both the instrument's acoustic resonator (a replaceable acoustic insert that function similar to acoustic guitar's sound board), and digital signal processing characteristics. The main goal of the work (first published in [1 - 3]) is to merge traditional values and digital capabilities, while preserving the resonator's spectral and spatial contribution to the overall timbre. This perspective is illustrated in the implementation of the *Chameleon Guitar* (see Figure 3.1)[1].

In acoustic musical instruments, natural information embedded in wood can be significant to the functionality of the instrument. Traditionally, the materials and craft of acoustic instruments play an important role in defining these sound. It is difficult to find two acoustic instruments that sound and perform exactly the same, which leads to a strong personal connection and often a deep bond between the player and their instrument. At the same time, electronics are playing a huge and still growing role in creating and processing the instrument's sounds, due to the flexibility that analog and digital processing techniques provide for sound control.

Figure 3.1: The Chameleon Guitar, new design (rendering, 2013): mahogany, ebony and poplar woods, carbon fiber, plastic, aluminum, electronics, and a spruce resonator.

An acoustic guitar owes its sound quality primarily to its wooden chamber. The timbre and volume of a guitar depends on the shape of its chamber and the structure and properties of its material. The type of wood, its quality, the way it is prepared and its inner structure all create a reality where no two guitars sounds the same.

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[1] Sound examples and videos are presented in www.thechameleonguitar.com.

The Chameleon Guitar combines physical acoustic properties with digital processing abilities in an innovative design - a design that benefits from the distributed spatial-acoustic characteristics of an acoustic soundboard (unlike just sampling the surface vibration at a single location). Conceptually, the Chameleon Guitar "separates" the chamber's *shape* from its *material and craft quality,* and re-assembles them in the hybrid territory (a real wooden quality with the simulated shape). A physical resonator, a replaceable piece of material that gives the guitar a distinguishing acoustic behavior, is situated under the guitar bridge (see Figure 3.2). The Chameleon Guitar allows the user to change the acoustic resonator without swapping the whole instrument (and requiring just slight re-tuning) The array of soundboard transducers enables a higher degree of information to be processed in the computer, relative to the typical pair or triad of magnetic string pickups or single contact pickup in common use on guitars today. Through this novel modular approach, sound flexibility and a high level of resonator personality are achieved.

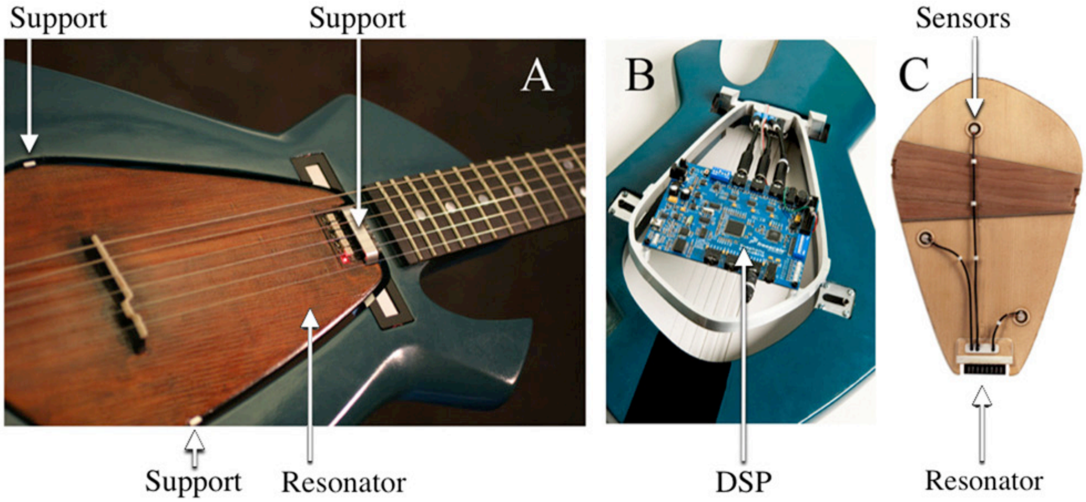

Figure 3.2: The Chameleon Guitar and resonator: (A) a cedar resonator with an arch-top guitar bridge inside the guitar; (B) the rear of the Chameleon Guitar – the resonator tray open, and the DSP unit; (C) the rear of a spruce resonator with koa support and sensors.

In addition to a user study presented in the early publications, I focus here on resonator evaluation, reinforcing the importance of material and craft qualities. Based on work conduced with Stephen Welch and William D. Hunt from Georgia Tech [3], I show that moving sensors, changing soundboard material, adding wax finish, and even swapping between geometrically identical resonators cut from the same board result in data that informs and directs the design process. This demonstrates the benefit of the hybrid approach: achieving sound flexibility while preserving uniqueness, tightening singular material qualities with digital processing.

Background and Related Work

The acoustic guitar design is highly dependent upon a luthier's design and craftsmanship [4, 5]. From the player's perspective, the guitar is an expressive instrument that can be controlled by using different excitation methods, e.g., using a pick or fingers to pluck the strings, plucking them at different locations, damping or bending strings with fretting fingers, etc. Friction and mechanical properties of the finger or pick, as well as the plucking direction, are most influential on the interaction between the string and the guitar body. The strings or the body can be excited or damped in many other ways, giving rise to a large range in native timbre and a multitude of playing techniques. Together with the structural-acoustic characteristics of the wood, the player maintains a personal signature that contributes to the musical style that it fosters and the sound being created.

The Acoustic Guitar

The acoustic guitar and its origin have been the subject of many scientific studies, focusing on diverse and specific details of guitar function: material and construction [6], the soundboard and the air cavity [7], the bridge [8], bracing [9], and the physics of the overall instrument have all come under examination.

The low frequency behavior of the guitar depends primarily on the guitar's chamber: the Helmholtz (air cavity) resonance and the soundboard size are critical to the first and second eigenmodes of the instrument, typically found around 100Hz and 200Hz [10]. As frequency increases, tone is more dependent upon local variations of the wood's mechanical properties. As such, lower eigenfrequencies and corresponding eigenmodes are more easily simulated. Further, this dichotomy leads to a distinction made throughout design and testing. I distinguish between two frequency ranges: low frequency, primarily influenced by the geometry of the instrument and the mean properties of the wood, and high frequency, primarily dependent on local material properties and construction.

This dichotomy dictates much of the design process. By design, the geometry and thus low frequency behavior of the Chameleon Guitar differs substantially from the traditional acoustic guitars I seek to emulate. Thus much of the design process and later signal processing aims to simulate the sonics of a traditional acoustic guitar. Alternately, I seek to preserve the high frequency behavior of each resonator, with an understanding that this behavior is an important part of overall tone.

Unlike flat-top guitars, the arch top guitar family soundboards (top plate) are arched, usually carved from larger wooden blocks, similar to the violin. The strings are tensioned by a tailpiece rather than the bridge. The arch-top bridge was chosen for the Chameleon Guitar, allowing quick resonator replacement, with no need to remove the strings. (see Figure 3.3).

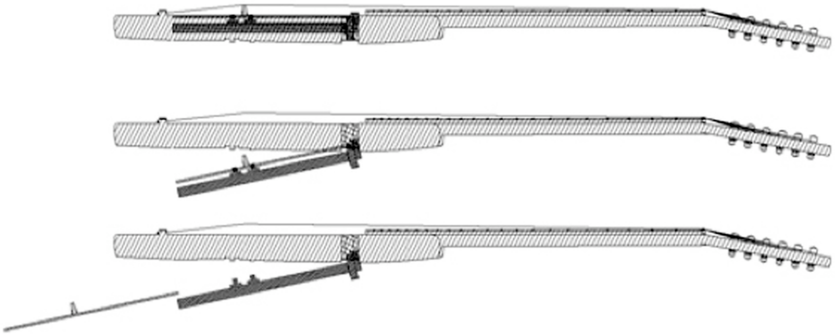

Figure 3.3: The Resonator tray operation.

Simulating the Guitar Eigenmodes with Finite Element Methods (FEM)

Finite Element Method (FEM) is a numerical simulation that allows us to model the vibrational behavior of a complex mechanical system as a set of discrete elements. I discuss the use of FEM later this chapter, as part of the design process of the Chameleon Guitar. The numerical model of the simulated system requires dimensions, boundary conditions, and simulated material constants (density, elastic tensor, and damping). FEM provides a solution to the partial differential equations of the guitar's pressure field, and has been used by Elejabarrieta et al. to identify the guitar's eigenmodes [11-12]. Further, Inta gives an overview of possible uses of FEM in guitar design, and concludes the most practical use of FEM is simulating material types, and top plate and cavity geometries. As frequency increases (generally above 1000Hz) FEM becomes a poor predictor of eigenfrequency and eigenmodes due to the inhomogeneous nature of wood, leaving experimental data the more viable tool. Fortunately, much of the audibly significant behavior of the guitar occurs at low frequencies, making FEM a valuable tool here.

Determining Operational Deflection Shapes (ODSs) with Laser Vibrometry

Many studies have relied on experimentally determined ODSs as an indicator of instrument behavior. Elejabarrieta et al. used roving hammer/accelerometer techniques, Jansson [13] and Rossing [14] used TV holography, and Griffin [15] and Bissinger [16] used doppler laser vibrometry in studying guitars and other stringed instruments. Further, a number of methods of excitation for the instrument under test have arisen. Much work relies on impulse excitation via an impact hammer, while electronic methods have exist including Rossing's work with acoustic excitation via loudspeaker, and excitation via a permanent magnet attached to the soundboard and driven by an electromagnet, and Jansson's work with mechanical excitation via electromagnetic shakers. Further, several signal types have been successfully used to drive electronic forms of excitation including: frequency sweeps, band limited white noise, and sinusoidal excitation.

Here, in an effort to identify and map the dominant ODSs of the Chameleon Guitar while minimally disturbing the instrument, we (Zoran, Welch and Hunt in [3]) have elected to use laser vibrometry to record the surface vibration of the guitar while the instrument is excited acoustically via a loudspeaker driven by a frequency sweep. The experimentally determined ODSs were then used to define the exact sensor locations and analyze variations in resonator behavior.

The Guitar and digital Technologies

Since the dawn of the synthesizer, significant effort was devoted to embed synthesizer capabilities into the guitar [17]. Starting with envelope followers driving active filters and other effects [18-19] and continuing on to analog (then digital) pitch extraction that then can manipulate an entirely synthesized sound source, musicians and engineers tried to merge the world's most popular instrument with state-of-the-art technologies. Examples of this abound, coming from inventors and industry, artists, and academics [20-21], while most academic research has focused on bowed instruments as opposed to guitars [22-24].

One way to achieve sonic flexibility while preserving some degree of expressivity is to first detect the pitch and amplitude envelope of the acoustic signal, and then apply synthetic timbres. In this way, an array of timbral possibilities is achieved via synthesized sound, and the sensitivity of the instrument is preserved through the amplitude and pitch channels. More sophisticated methods, based on articulation detection, can be used to expressively and dynamically control the timbre. In order to achieve this via audio analysis, high-level signal processing capabilities (and sometimes even artificial intelligence tools) are required. The most complicated part of the process is to model and extract the instrument's dynamic transient behavior (at low latency), while preserving nuances in its expression and perhaps some aspects of its unique sound signature.

Guitar synthesizers from the early 70's attempted this through analog signal processing or hardwired digital processing, often using a separate set of processing electronics for each string. These devices were often unreliable, or required particular technique to play well. When MIDI first met the guitar in the early 80's, an easier approach evolved where the guitar controllers sometimes did not even include strings, or used the strings only as sensors for fingers and to determine fret position. The only similarity to the guitar was the way it was held, and sometimes the way it was fingered and perhaps plucked, but, although some interesting channels of articulation were invented, those instruments lacked much in the way of expressivity, especially when compared to what guitars are capable of.

One popular example, the *SynthAxe*, invented by Bill Aitken [25], supported two sets of strings; one set, made from short-length strings running across the guitar's body, was used to detect picking, and another set ran down the fret board to determine pitch (lower cost controllers along similar lines were introduced by Casio and Suzuki). *Zeta Music* also made interesting hybrid guitars in their Mirror series with a multimodal interface that featured a wired fret board for pitch detection, a capacitive touch detector on each string for determining the expected acoustic damping, hexphonic pickups for amplitude detection and pitch bend, accelerometers for measuring the instrument's rigid-body dynamics, and an instrumented whammy bar.

In recent years, as signal processing capabilities have improved, there has been a shift away from the dedicated MIDI guitar controllers and back toward existing, standard electric guitar interfaces that identify playing features and dynamics by running real-time DSP algorithms on the guitar's audio stream, still generally exploiting hexaphonic pickups that derive separate audio from each string. The *Line 6 Variax* guitar, for example, maps the guitar player's input onto a variety of preset sounds [26], from classic acoustic and electric tones to sitar and banjo. It allows the player to plug into a computer and customize a chosen timbre, while the hexphonic piezoelectric pickup, located on the bridge, transfers the signal to a DSP unit located on the guitar. Expressive playing and sound flexibility are enhanced with these digital guitars. Another example is *Fender's VG Stratocaster*, a hybrid electric and digital guitar [27]. The *Gibson Robot Guitar* series also uses a DSP unit on the guitar to control the automatic string tuning mechanism [28]. Modern high-end electric guitars often come equipped with a connector to transfer multichannel digital audio directly from the guitar to a computer network or dedicated processing electronics.

The haptic feedback from the musical instrument, as well as the tactile qualities of the experience, was the focus of many projects. Several projects applied a similar concept in musical instrument design, such as in *The Sound of Touch* [29], or with the Cicada's *Rapid Sequential Buckling Mechanism* [30]. In the work of Cadoz et al. [31], a vibrating device sensing forces and displacements at its manipulation stick was able to produce force-feedback, and allowed users to experience an inter-sensory phenomenon. Howard et al. [32] describe a physical modeling music synthesis system that enables virtual instruments to be controlled in real-time via a force-feedback joystick and a force-feedback mouse.

Design and Technology

The Chameleon Guitar features a replaceable acoustic resonator (Figure 3.2). The resonator is a small soundboard with an arch-top guitar bridge that can be accessed and replaced through an aluminum tray in the guitar rear. Several piezoelectric sensors are distributed on the resonator to capture acoustic vibration. The guitar features a chamber containing both the physical resonator and necessary electronic hardware. As with acoustic guitars, the soundboard (resonator) geometry and material contribute strongly to the overall tone. Unlike previous efforts [33, 34] to simulate acoustic guitar timbre, the Chameleon Guitar's overall sound relies strongly on the physical characteristics of the resonator in addition to a digital signal-processing (DSP) unit to generate a chamber-like effect, imitating the sound of an average size acoustic guitar. An effort is made to preserve the unique timbre of each resonator, allowing the output timbre of the instrument to be changed by swapping resonators. Thus, the Chameleon Guitar comprises three elements: the body, the resonator, and the DSP unit. The body is the platform supporting the two other elements: it is the guitar's interface. Two controllable parts are placed under the guitar interface: the programmable DSP unit and the replaceable resonator.

The main contribution of the method presented, as implemented in the Chameleon Guitar, is to enable musicians to modify the guitar's timbre for instrument development or performance uses. The Chameleon Guitar aims to combine the values of a synthesized guitar with the uniqueness of an acoustic guitar's tone. The replaceable resonator continues the traditional connection between players and their unique instruments, yet greater flexibility is achieved by controlling the DSP unit, which extends the acoustic experience into the digital domain.

The Chameleon Guitar design preserves the unique properties of the wood used in craft guitars, yet through its modular construction, also offers an instrument that musicians can use to customize and modify their guitar's intrinsic timbre and acoustic "personality." Traditionally, acoustic guitars cannot be modified once they are made; it is not part of the player's experience to "tamper with" the structure of the instrument. Acoustic guitars are highly crafted and offer acoustic integrity, but they offer no flexibility for sound design control.

Overall Approach

In the implementation of our proposed method, it was imperative that the Chameleon Guitar function physically as detailed earlier, while performing as sonically close to a traditional acoustic guitar as possible. To meet these design criteria, the Chameleon Guitar needed to: allow for the quick replacement of an acoustic resonator, compensate as effectively as possible for its small size and lack of cavity, and allow for a minimal number of sensors to capture a large amount of low - frequency information. The design process and tools needed to achieve these goals are presented in Figure 3.4. As the figure shows, a rather linear approach to design was chosen, informed by the natural signal path of the instrument, and beginning with an assumed ideal resonator geometry and support system, determined by FEM. The position of the bridge is then taken into account, as the natural exciter of the resonator.

Following resonator design, laser vibrometry is used to confirm FEM results and determine ideal sensor positions. An array of ceramic piezoelectric sensors, located in various positions on the resonator, capture substantially different combinations of the resonator's modes of vibration, therefore it is safe to expect the location of each sensor to play a role in the overall timbre of the Chameleon Guitar.

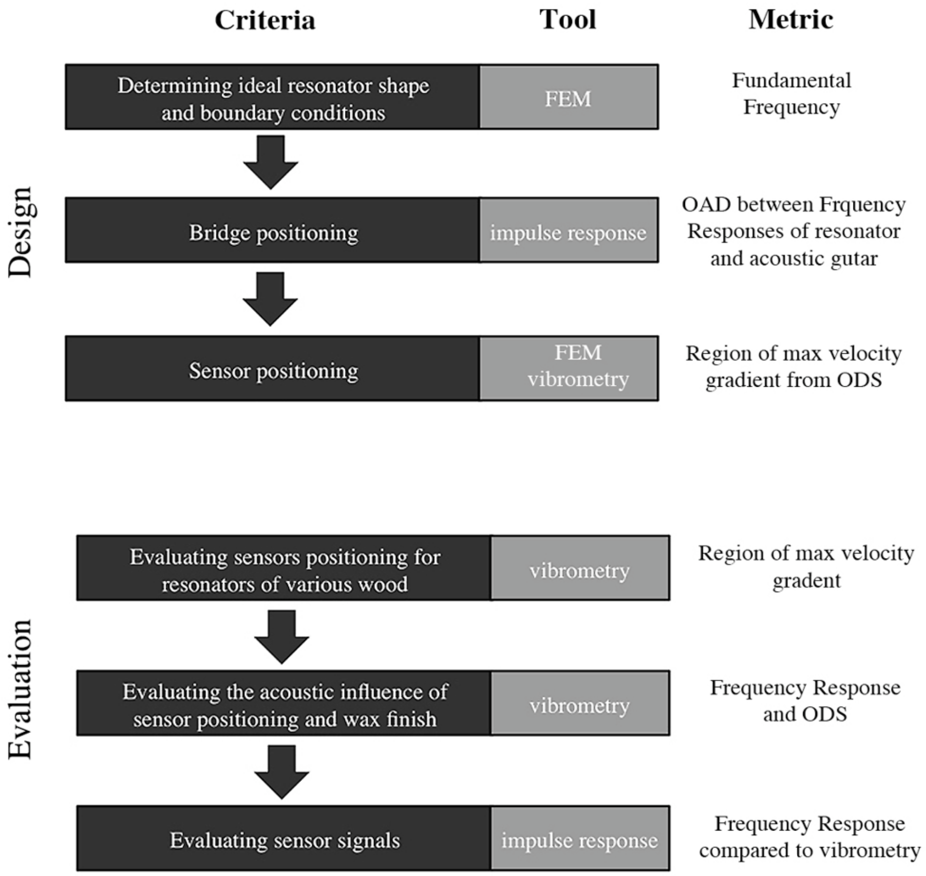

Figure 3.4: The main steps of the research presented and the technology used for each step.

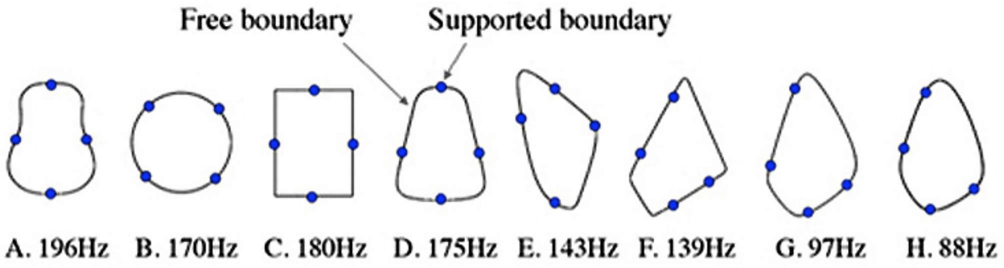

Figure 3.5: Finding the shape and boundary conditions of the spruce resonator: eight resonator shapes with a surface area of A=246cm^2. The blue points are simply supported; the rest of the boundary is free. The first eigenfrequency simulated by FEM appears with each image.

Resonator Geometry and Boundary Conditions

Due to ergonomic constraints (such as the ease of replacing resonators), the resonator’s surface area (A=246cm^2), was chosen to be 25% of *Yamaha FG330* acoustic guitar soundboard, 985cm2. In a typical acoustic guitar the lowest two eigenmodes appear around 100Hz and 200Hz. The goal here was to compensate for the small resonator size, by lowering the resonator's eigenfrequencies.

Various resonator shapes were simulated, using FEM implemented by *Comsol Multiphysics* software, assuming a flat 2.5mm Sitka Spruce resonator, with mechanical properties and procedure as described in [3], and based on Green at el. [35]. The orientation of the wood grain in the simulations and physical resonators is always parallel to the length of the instrument and vertical, as shown in figures. The CAD model of the tested resonator was first build in Rhino 3D modeling software, and then imported into the Comsol environment. The boundary conditions were defined as shown in Figure 3.5, and the system was solved for eigenvalues.

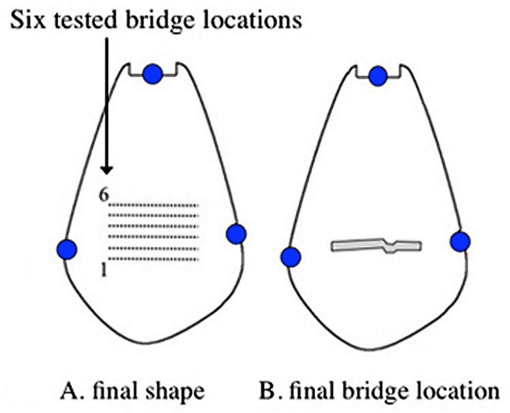

Figure 3.6: Finalizing the resonator design and positioning the bridge: (A) modified resonator shape for ergonomics and stability, including the six location candidates; (B) the final resonator design, including the PCB location and the arch-top bridge location.

A free boundary condition allows for the lowest possible resonant frequency for a given resonator, while a simply supported boundary and fixed boundary yield respectively higher resonant frequencies. As such, design steps were taken to maximize the length of the resonator's free boundary, and to use simply supported legs instead of rigid ones. In order to identify the resonator shape for the lowest possible eigenfrequencies for a given surface area A, various shapes were simulated (Figure 3.5). In the first iteration, the shape candidates have a mixed boundary condition: a largely free boundary with the exception of four support points. The shapes were modified slightly between simulations in the search for a pseudo optimal shape. As part of this iterative, brute-force process, the support locations were moved. Shape H in Figure 4 was selected due to its lower first simulated eigenfrequency (88Hz). Note that this value is an evaluation criterion, and not an estimated behavior of the resonator in real conditions: the described design process assumed a flat, homogenous resonator, with no bridge or string load.

The resonators were built, tested, and embedded into a guitar platform (an evaluation guitar) with string loading and with the bridge located around the resonator's center of mass. In order to stabilize the resonator and prevent it from twisting under strings' load, the resonator's shape and support points were modified – resulting in the final shape of the resonator, with only 3 supports (Figure 3.6). The resonator PCB, which will be used to pre-amplify the sensors' signals and as an electrical connection unit, was located on the top support.

Positioning the Bridge

With the goal of creating an instrument as sonically close to a traditional acoustic guitar as possible, experiments were conducted in which the impulse response (below 1000 Hz) of a resonator with a given bridge location was compared to the impulse response of a reference acoustic guitar, a Yamaha FG330. As detailed by Inta, an acoustic guitar can be approximated as a linear system at low amplitudes. Impulse testing was deemed acceptable to characterize the instrument's behavior under various bridge locations at low frequencies. The MSE between resonator and guitar impulse responses were calculated to quantify the variance of bridge locations.

All impulse testing was performed in a recording studio room with single *MXL USB.008* microphone, located 50cm in front of the guitar bridge, while the instrument was placed on the floor and damped with soft foam. The same tests were repeated for the reference guitar and the evaluation guitar complete with resonator. An impulse response was created by tapping by hand the center of the top of the guitar's bridge with a plastic coated metal rod. Several signals were recorded; the most similar three recordings were averaged to create the system response.

Six location candidates were chosen for the bridge around the resonator's surface center of mass, similar to the bridge location of the reference guitar. The six location candidates were evaluated with impulse response tests (by sliding an un-glued wooden bridge along the resonator). In Figure 3.7 I present the results of this experiment; location number 3 (Figure 3.7C) gives the minimal spectral MSE from the reference and was chosen as the ideal bridge location.

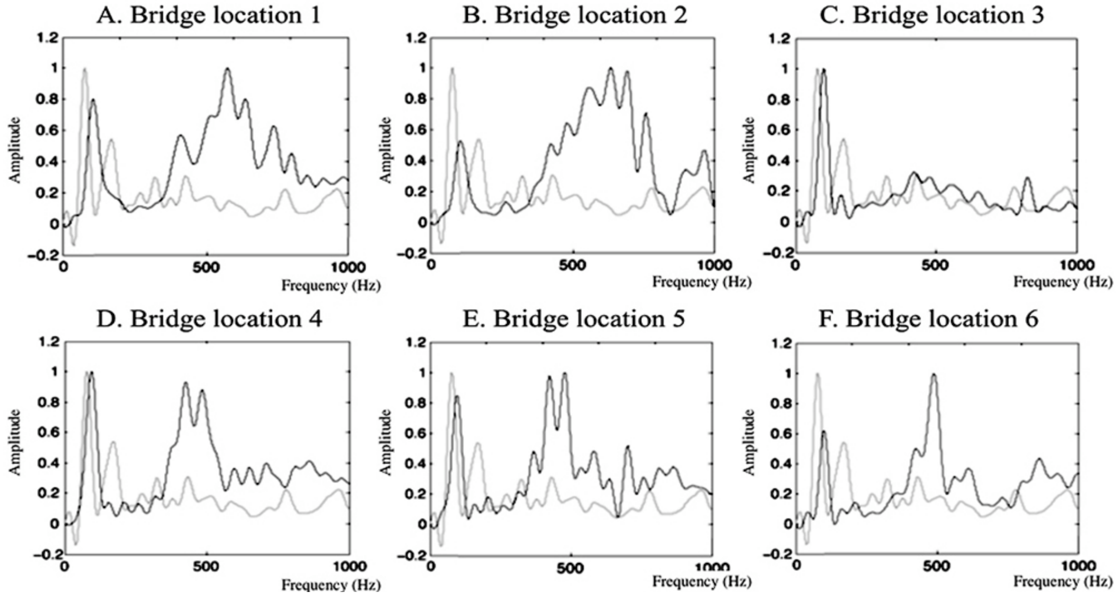

Figure 3.7: Impulse response tests to the candidate locations of the bridge: six linear, spectral plots of impulse response tests (black graphs). Each plot is normalize according to its maximum value. The gray graph is a reference from the Yamaha FG330 acoustic guitar impulse response tests. Location 3, (C) gave the best result in terms of mean square difference. Each spectrum was calculated by the average of three, one second signals' FFT in the length of 1024 samples (44 KHz).

Design of Chameleon Guitar Body

Resonator design created constraints for the overall instrument design. The Chameleon Guitar body needed to support the resonator while being both robust and ergonomic. Guitar ergonomics and playability are influenced by several design characteristics: weight, stability (the guitar will not flip to one direction when stabilized on the leg), body size, thickness and string tension. Designing for adequate string tension proved the most challenging. String tension varies directly with sustain and sufficient sustain times are an important piece of overall playability. Electric guitar designers often increase sustain through a solid body design, however this solution was not viable for the Chameleon Guitar. Ultimately, a long neck scale was used to increase sustain time. This decision comes with its own trade offs, reducing playability through resistance to bending and high string tension. This effect was mitigated by making the non-vibrating parts of the strings longer (from neck to tailpiece and nut to tuners).

Electronics and Signal Path

The electric signal path (see Figure 3.8) begins with piezoelectric sensors, amplified at the resonator PCB and processed in the DSP unit. The sensors are ceramic piezoelectric disks (common for musical applications) with a resonant peak at 7000Hz (± 600Hz) with 9.9mm diameter and 0.12 mm thick. A small disk size was preferred in order to minimize the affected resonator surface. The piezoelectric sensors are sensitive to bending – as such, in order to best detect a given mode of vibration, it is preferred to locate each sensor in an area where the value of the ODS derivative is maximized. Signals are transmitted to the resonator PCB through thin coax wires. As discussed earlier, while high frequency information is preserved, information below 1000 Hz is primarily of interest for signal processing.

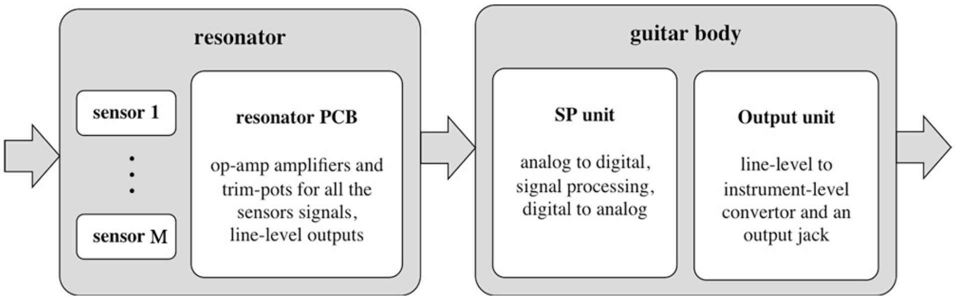

Figure 3.8: The Chameleon Guitar signal path.

Signal Processing

General

The signal-processing algorithms were developed and tested using *Matlab* and implemented on the above-mentioned SP unit in C code, using *Freescale's Symphony™ Studio Development Tools* and based on Freescale's Eight-channel-C-template C code software (48KHz 16-bit, one sampling cycle latency). The development tools included DSP memory and device mapping, as well as analog-to-digital convertor and digital-to-analog converter drivers. In addition to the algorithm discussed below, an alternative algorithm is presented in [1, 2].

Although any DSP sound transformation is possible, from the subtle to the garish, the main goal of the DSP algorithm that I designed here is to implement a virtual chamber based on the physical resonator, i.e., to manipulate at least one resonator signals (resonator no. 1) and re-construct them to minimize the difference *D* between the Chameleon Guitar's output impulse response signal (captured by a microphone, 20 cm in front of an Acoustic AG15 15W 1x8 Guitar Combo Amplifier) and the reference guitar impulse response:

$$D = S_r - \sum_{i=1}^{M}\sum_{j=0}^{N} C_{ij}(S_i \bullet h_j)$$

This is an equalization problem; finding the correct frequencies and amplitudes of band pass filters. The reference guitar's signal is s_r, each sensor's signal is s_i (i is signal's index, M is the amount of signals/sensors), the band coefficient per signal channel is c_{ij}, and the IIR filters are represented by h_j. The minimization of D was achieved here through an experimental, brute-force iterative process as described below. The D value can be minimized by a proper filter bank design (h_j values) and the choice of correct coefficients (c_{ij}). First, each of the raw sensor signals (after sampling) is processed through a filter bank with its bands tuned according to the reference guitar's formants: for each band, the filter cut-offs were tuned (by eye, based on a Matlab graph) to fit the reference acoustic guitar formants, and c_{ij} was tuned to fit the formant amplitude. For the minimization of D, for each band just the ideal s_i was chosen - the best c_{ij} candidates were selected, and the rest were tuned to zero. The amplitude and decay rates of each band were scaled in order to best achieve the required reference level. However, when more than one sensor signal (s_i) produced a good candidate for a specific band, the one with the higher SNR was chosen. After tuning the signal-processing algorithm to minimize D, adjusting it to a sound like a smaller or bigger guitar chamber was relatively easy.

As the acoustic waves in the guitar approach its resonance modes, the decay rates at the corresponding frequencies are slower. An infinite impulse response (IIR) filter can imitate such a behavior coherently; the distance of the filter's poles from its region of convergence (ROC) tunes the resonance behavior of the IIR. The IIR can add a slower decay rate to the transferred band, i.e., by tuning the filter bank's IIR coefficients, we can fit artificial reverberation to selected bands. A filter bank was implemented by a Second Order Section Direct Form II filter (see Figure 3.9). The filter bank implementation is simple, and is based on summing all of the bands in time domain (while ignoring phases).

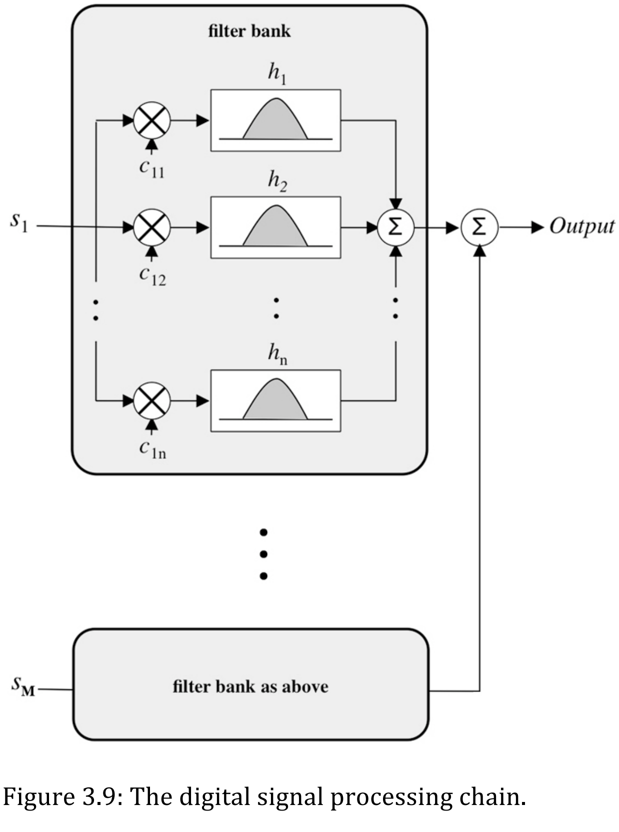

Figure 3.9: The digital signal processing chain.

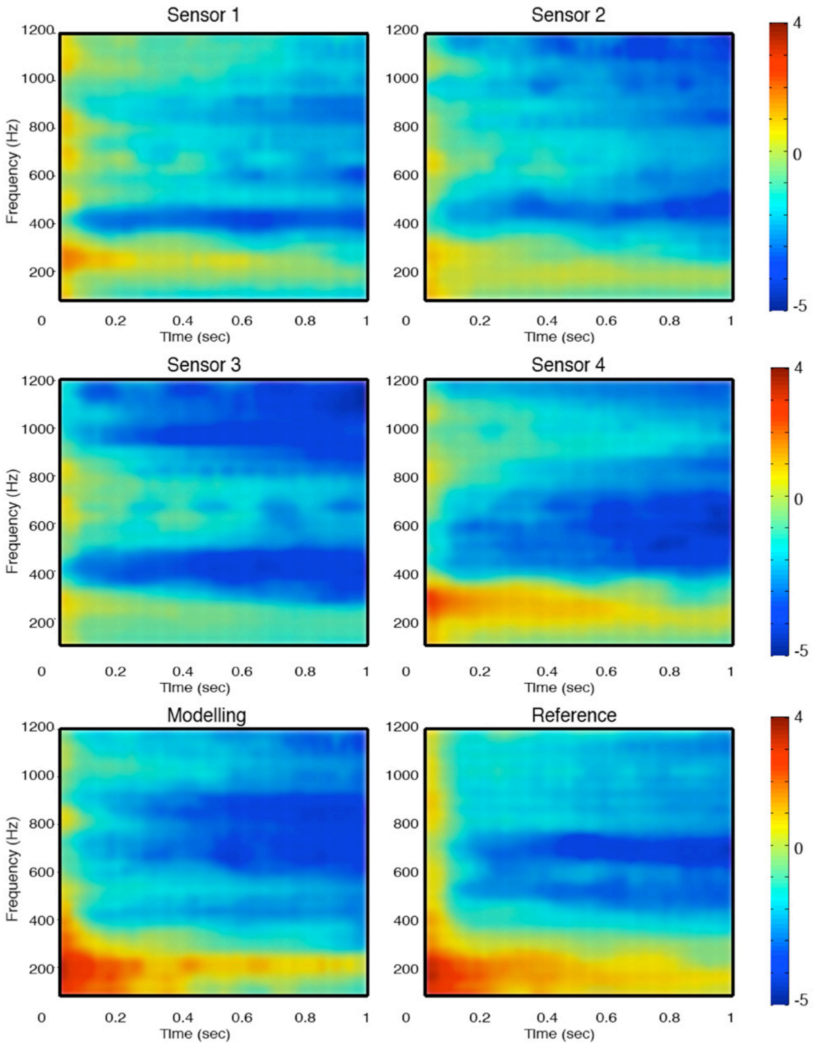

Figure 3.10: Logarithmic, smoothed spectrograms of the impulse response for each sensor (Sitka spruce resonator with a 4 sensors setting), showing also the final SP output as well as the reference.

The impulse response of resonator no. 1 was used for tuning the filter banks. The IIR coefficients were optimized in Matlab's *FDAtool* using a brute-force manual process. This Matlab system required 14 bands and mainly processed resonance modes below 1KHz. It was implemented on the guitar with fewer bands (starting at seven and leading down to four). In practice, the resonators projected an acoustic sound that could not be ignored, which was mixed with the processed sound. Morphing between the guitar's acoustic sound (attenuating directly from the resonator) and the SP unit output (after amplification) tends to give interesting overall results: the sound in the recording studio has a stereo quality, depending on the positioning of the guitar and the amplifier in the room. Overall, I can say that the guitar's digital processing contributes mainly to the lower modes, and the sound reflected directly from the resonator contributes more to the middle and high frequency range.

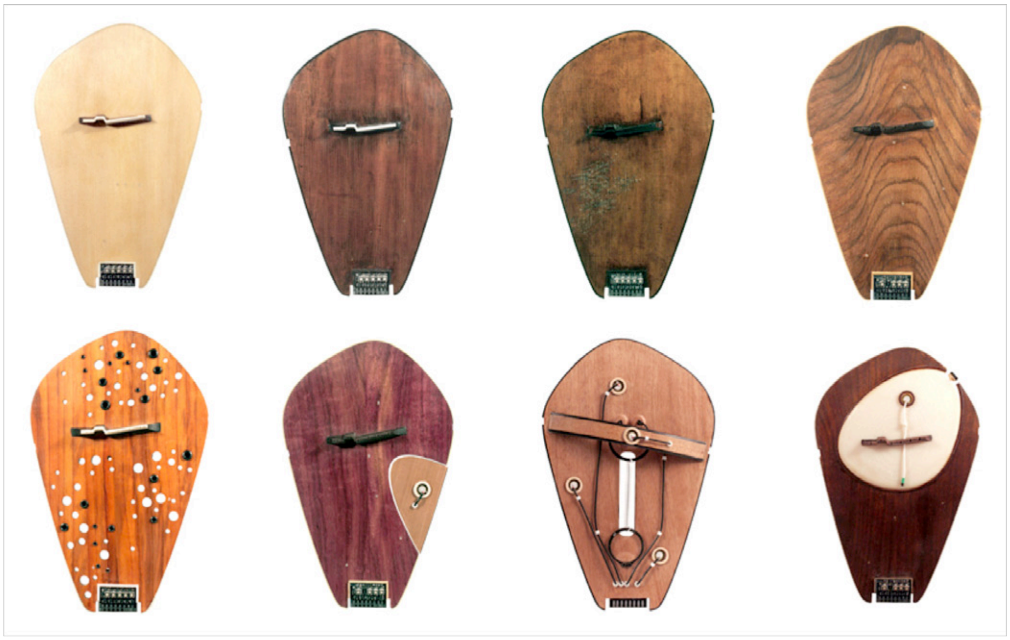

Figure 3.11: Figure 10. Top: A group of eight resonators. The first four are more traditional, made from wood only. The last five are more experimental, including loose screws, springs, free plates or plastic chamber with rice or water. Resonator no. 1 (top left) was used as the reference for algorithm development.

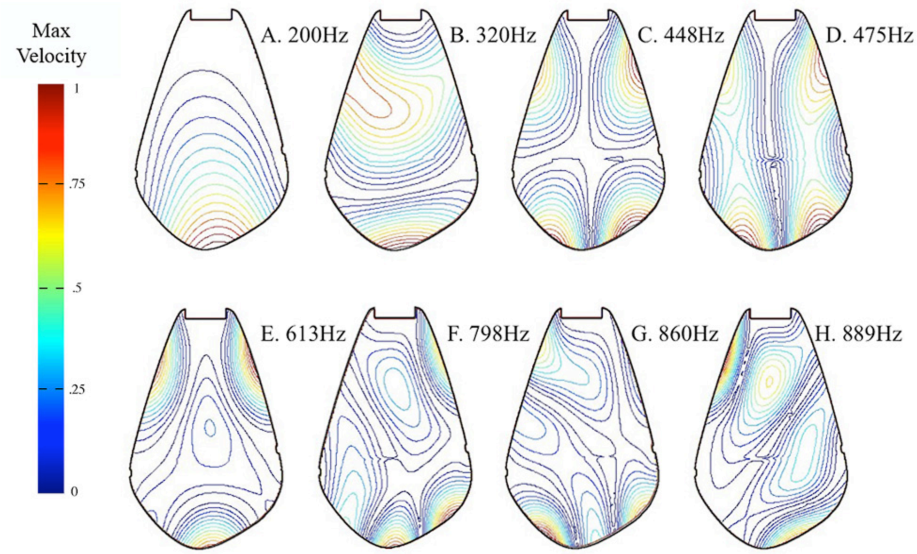

Figure 3.12: First eight FEM eigenmodes of a spruce resonator, 2.5mm thickness, with bridge and the boundary condition as discussed in 2.3, simulated in Comsol Multiphysics. This data in comparison with the Doppler vibrometry data in Figure 3.13, was used to validate the FEM process.

Resonator's Design and Evaluation

The Chameleon Guitar was built to evaluate the method presented for detecting and manipulating the acoustic behavior of the guitar. A detailed user evaluation is discussed in [1, 2], while here I would like to focus on the significance of craft and material details, and their contribution to the overall acoustic behavior of the resonator. FEM simulation, laser vibrometer scans, and impulse response tests that were used to define resonator shape, sensor and bridge locations, and were presented in the previous section. In the current section, data from laser vibrometer scans are used to examine the behavior of various resonators, analyzing how the materials, structure, wax finish, and sensors influence acoustic behavior. This process is important in the overall construction of the instrument, answering questions such as whether one resonator's ideal sensor locations are acceptable for another resonator, and demonstrating the uniqueness in resonator behavior I hope to preserve and study with the Chameleon Guitar.

The resonators' designs were a long process of trial and error. All resonators have four (early design in [1, 2]) or three (latest design in [3]) piezoelectric sensors located in the same place. The first four resonators are more conservative; all of them include wooden soundboards supported by braces and a glued bridge, varying only in their structure and materials (see Figure 10 for a detailed description). The last four resonators test different ideas – embedding springs, an ABS plastic chamber, screws or complex boundaries and connections. Different players have tested all of these resonators.

3D models of the soundboard and the bridge were built in Rhino 3D. Wooden blocks were prepared, sometimes by gluing two pieces to make a joint block, where the wood-cuts and grain direction were selected in a traditional way. Then, the resonator's shape was milled using Shopbot CNC machine and cut with a Universal laser cutter machine. The bridges were made in a similar way, and glued with epoxy to the resonators after location adjustment.

All the resonators were hand-finished, first sanded or trimmed with a scraper[2], then varnished using different techniques for protection and aesthetics. The resonator PCBs were glued to the resonator with epoxy. The sensors were glued with special ethyl cyanoacrylate adhesive, and were protected with a thin balsa ring. Coaxial wires connected the sensors with the resonator PCB, sometimes guided by small

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[2] A sharp steel plate, used for trimming wood surfaces.

plastic elements. All the resonators have plastic or wood bindings at their edges to protect them from damage.

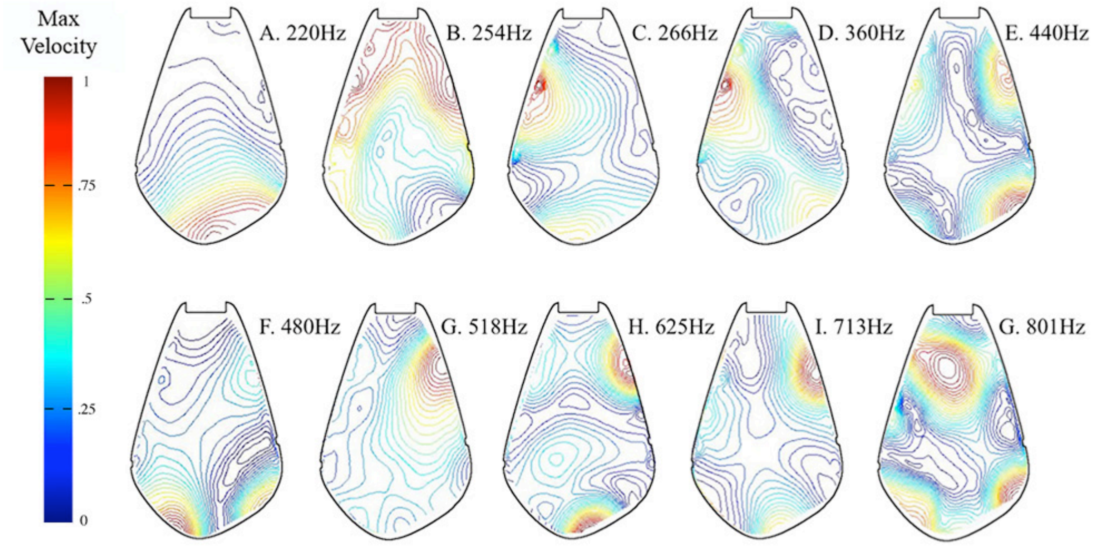

Figure 3.13: First ten eigenmodes of the spruce resonator, determined with laser doppler vibrometry. This data was mainly used to determine the location of the sensors.

Laser Vibrometery Study

Laser vibrometry work was done at Georgia Tech. In an effort to create a resonator environment that is similar to the actual playing environment, the resonators were tested while mounted inside the Chameleon Guitar. The guitar was suspended vertically from a rigid wooden stand via rubber bands secured to the tuning pegs of the instrument. This was done to both isolate the instrument and to create a natural system resonance much lower than the lowest frequency studied. All data was recorded with a Polytec Scanning Laser Vibrometer from 200 data points across the resonator surface.

The guitar was excited acoustically via loudspeaker. An Agilent 3312A function generator, controlled by Polytech Laser Vibrometer Software, generated all test tones. A frequency sweep was used to drive the system. Polytec Laser Vibrometer Software was used to average the motion for three sweeps at each data point. Before each trial, the guitar was tuned to standard tuning and all strings were muted.

Four resonators were studied over the course of two days: a Sitka Spruce resonator, two western red cedar resonators from the same log (cedar_1 and cedar_2), and a hard maple resonator. The flat Sitka Spruce resonator was braced with a koa support underneath the bridge (Figure 2C). Unlike the spruce resonator, the cedar and maple resonators are arched, much like an arch-top guitar, and include a thin (3mm x 3mm) carbon-fiber brace underneath the bridge. This resonator collection allows experimentation along several common dimensions of guitar construction. Resonators, taken from the same log and feature the same geometry, allowing investigation into the significance of each unique sample of wood. Different species of wood allow us to quantify the tonal differences between species long discussed and used by luthiers and musicians. Arch-top and flat resonator geometries allow comparisons between two broad categories of guitar. Finally, the influence of a wax coat and piezoelectric sensors was explored.

Determination of Dominant ODSs of the Chameleon Guitar's Resonators

Given the unique geometry, support system, and lack of resonant chamber of the Chameleon Guitar, the acoustic behavior of the resonator cannot be directly compared to that of a traditional guitar or violin. However, the method by which the eigenmodes of both violins and guitars [14] have been determined aids in determining the important ODSs of the Chameleon Guitar resonator. The depth of exploration required to fully characterize the normal modes of the Chameleon Guitar is beyond the scope of the work presented here, but the general approach used by Rossing is relevant. Additionally, eigenmodes generated through FEM inform the search for the dominant ODSs of the physical instrument.

From the large amount of data generated from each vibrometer scan, some 30 resonant peaks were identified below 1 kHz for a given resonator. The decision to focus on low frequency behavior was informed by prior work [13], suggesting that much of acoustic guitar tonality originates from the first air resonance and the first and third plate resonances (all below 450 Hz). From this data, those ODSs with relatively high spectral amplitude and well defined and unique resonant structures were chosen as representative of resonator function. These ODSs are used to characterize each resonator and as the basis for many comparisons drawn between resonators.

Sensor Positioning

Effective sensor positioning relies on the assumption that capturing low frequency information is very important to almost any signal-processing effort to sonically imitate a traditional acoustic guitar's chamber. Choosing sensor locations based on FEM results or vibrometer data marks an important design decision. Ultimately, comparisons between the two data sets determined which mode structures and subsequent sensor placements would capture the most information. Both FEM results and vibrometer data played an important role in sensor positioning, not for an individual resonator, but for any resonator of the same material.

Figure 3.12 shows the FEM simulation results for the first eight eigenmodes of a 2.5mm thick flat Sitka spruce resonator with bridge and without string loading. Vibrometry data from resonators mounted in the Chameleon Guitar agreed well with the FEM structures presented here. All physical softwood and modeled resonators share a similar monopolar structure similar to Figure 3.12A (or 3.16A), a dipolar structure (3.12B or 3.16B), a 2,2 mode structure (3.12C or 3.16C), and finally a structure similar to Figure 3.12E (or 3.16D), marked by the development of a central antinode.

Given this framework for typical softwood resonator behavior, a method was then developed to select resonator areas with high-expected gradient value. This began with a comparison of vibrometer and FEM data. Similar mode structures and frequencies were selected: (Figure 3.13A vs. 3.12A; 3.13C vs. 3.12A; 3.13E vs. 3.12C; 3.13H vs. 3.12E; 3.13G vs. 3.12F). From this data, shared areas with a high gradient value (a piezoelectric sensor detects the derivative of the pressure field) were searched for (Figure 3.14). Several locations came to the forefront, and the decision was made to limit the sensor number to three. Figure 3.15A shows the final locations for the spruce resonator, as well as the locations for the cedar resonators (Figure 3.15B and 3.15C), defined by the same procedure.

Figure 3.14: Eigenmode gradient maximum values. For each mode, the black areas are sensor locations candidates – the one third of the surface area with the highest absolute value of gradient.

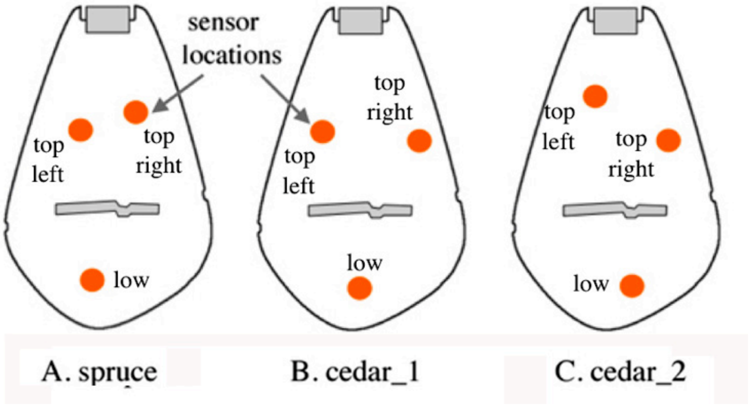

Figure 3.15: Sensors positioning: sensors locations in orange, (A) Sitka spruce resonator; (B) western red cedar resonator (cedar_1); (C) western red cedar resonator (cedar_2).

Softwood Resonators

Sitka Spruce and Western Redcedar (both softwoods), the two most common woods for guitar soundboards, share similar acoustic properties [35]. The design process was based on a Sitka Spruce resonator, with ODSs discussed earlier. Here, data will be presented and discussed from the other softwood resonators studied: two cedar resonators from the same board. The purpose here is twofold: first, to test if the ideal sensor locations for a single softwood resonator are ideal for all softwood resonators, and second to examine the measurable variation between two resonators cut from the same board.

The ODSs of the spruce and Western Redcedar resonators (cedar_1 and cedar_2) are shown in figure Figure 3.16. The same mode structure evolution, as discussed earlier, appears in all resonators – A monopolar (3.16A), dipolar (3.16B), and (2,2) mode structure (3.16C). However, as frequency increases, the ODSs of the spruce and cedar resonators begin to diverge. Further, the frequency response of the cedar and spruce resonators differ significantly at low frequencies (Figure 3.17A-C), the spruce resonator yielding a substantially higher fundamental (220 Hz vs. 201 and 190 Hz). The overall average difference between scans was calculated from the frequency response below 1 kHz, yielding a value of 1.1 between cedar_1 and cedar_2, compared to a value of 2.9 and 4 between the spruce and each cedar resonator. Two scans of the same plate were taken as a reference and yielded an overall average difference of 0.5.

It should be noted that factors beyond the control of the author has a role to play in the vibrometry data collected. Most significantly, each time a resonator is removed and replaced within the Chameleon Guitar, the boundary conditions affecting the resonator are subject to change. This complication is evident, but not exclusively responsible for the 0.5 OAD between scans of the same resonator, and should be taken into account, especially when examining Figure 3.16.

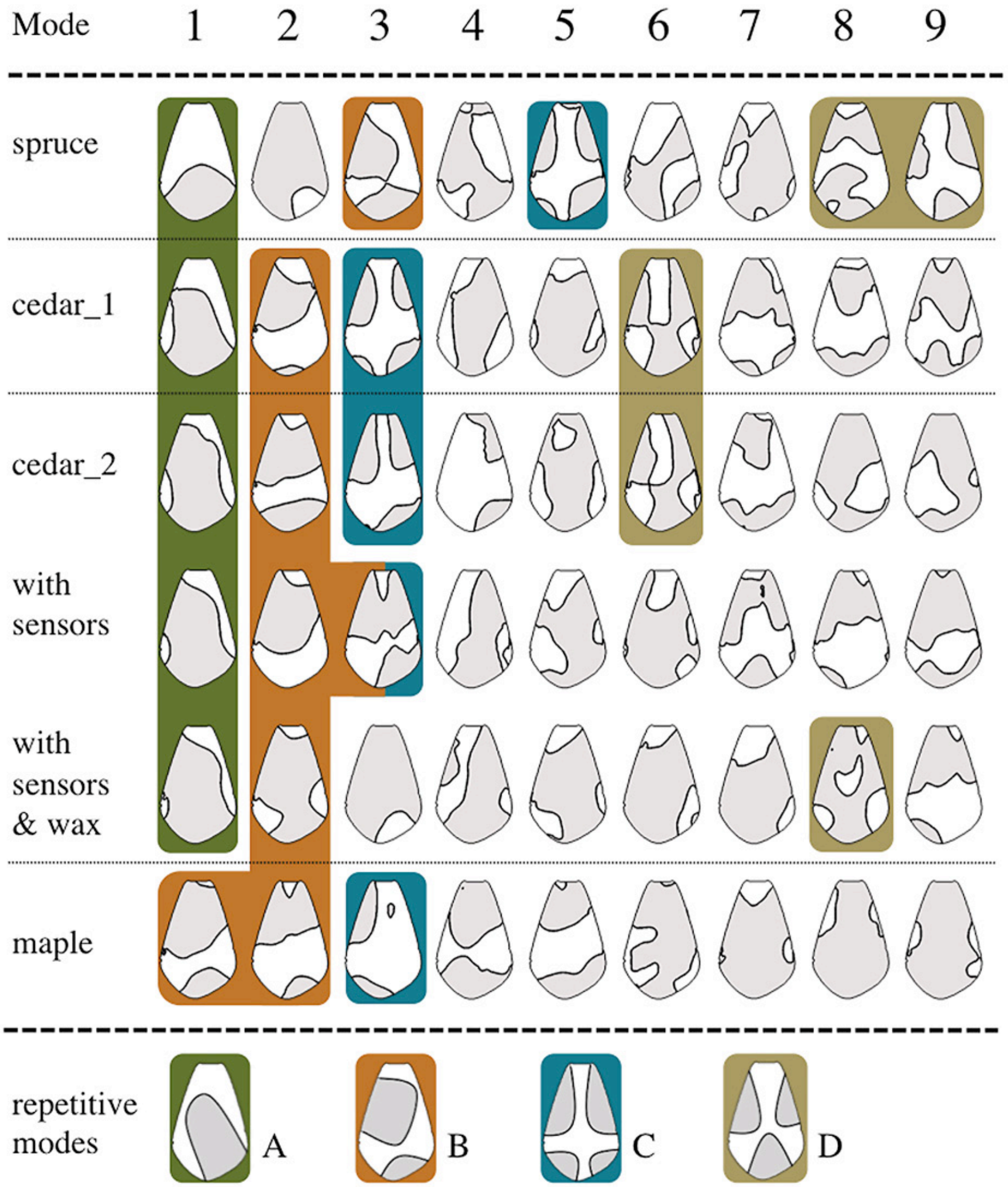

Figure 3.16: Eigenmode shapes (<1000 Hz) for resonators of different woods with no sensors and wax finish, and for the cedar resonator with and without sensors and wax finish, determined with laser doppler vibrometry. Used to evaluate the ability to generalize conclusions regarding sensor locations from spruce to other woods, and to evaluate how the positioning of the sensors influences the behavior of the resonator. Four main shapes were determined as repetitive modes, appearing in most of the tests and grouped into different colors. For each mode, gray areas indicate moving parts.

The cedar resonators' ODSs diverge strongly at higher frequencies, and even similar ODSs do not necessarily share frequencies and amplitudes. This acoustic phenomenon appears even in the lowest ODSs of two resonators of the same geometry cut from the same board of Western Redcedar (a relatively homogenous wood), demonstrating the unique acoustic properties measurable for each resonator. As frequency increases, this trend becomes more pronounced.

There are two implications of these results for the positioning of the sensors. First, there may be enough similarity in the first five ODSs to define consistent sensor locations for all spruce or cedar resonators. As focus shifts towards higher frequency ODSs, it appears preferable to fine-tune the location for each resonator (as can be seen in Figure 3.15, where the locations were based on the first ten dominant ODSs). However, while the detail and accuracy of FEM and laser vibrometry provide a great deal of data for the determination of sensor locations, it has yet to be seen if such fine tuning yields an audibly noticeable effect. It seems that even roughly located sensors, distributed in the bottom, upper right and upper left of the resonators, will be able to capture well the lowest modes of vibration, which are directly influenced by the resonator dimensions, and the captured

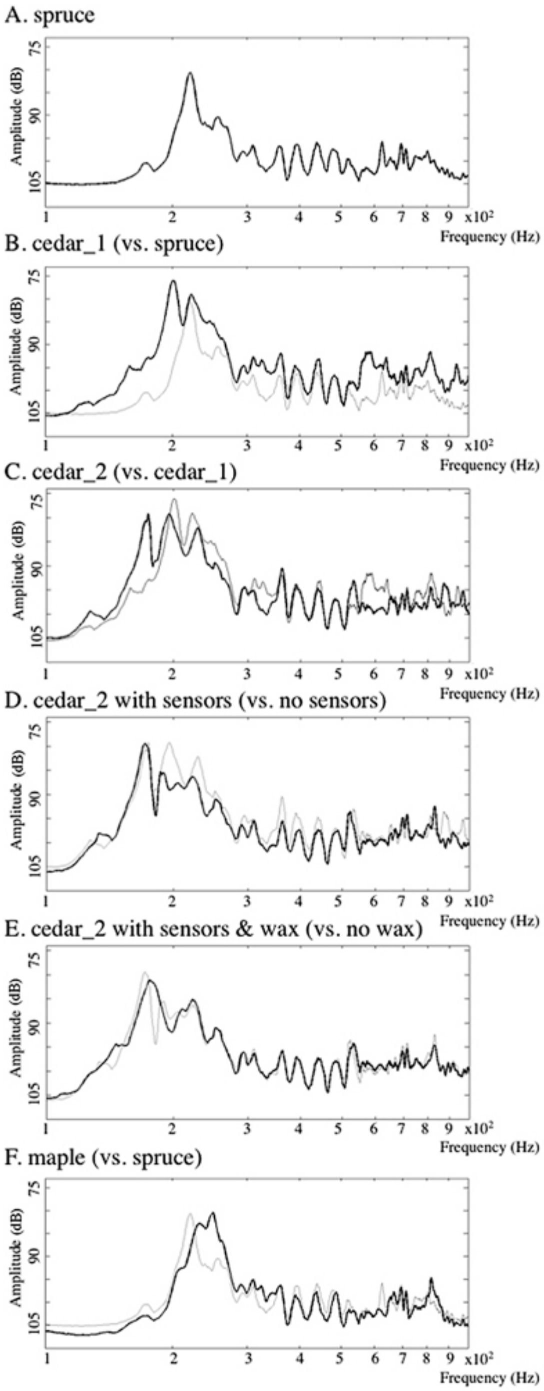

Figure 3.17: Evaluating the velocity spectrums (<1000 Hz) for different woods, and for the influence of sensor's positioning and wax finish, determined with laser doppler vibrometry. (A) spruce, (B) cedar_1 vs. spruce, (C) cedar_2 vs. cedar_1, (D) cedar_2 with sensors vs. without sensors, (E) cedar_2 with sensors & wax vs. with sensors only, (F) maple vs. spruce.

superposition of higher modes could be used to reveal the unique intrinsic properties of each resonator.

Acoustic Influence of Sensors and Wax Finish

Laser vibrometry was used to monitor the design and construction process as sensors and wax varnish were added to a given resonator. Figure 3.16 shows the first nine dominant ODSs of cedar_1, with three Shadow SH 711 pickups (20mm ceramic piezoelectric sensors, coated with thin plastic layer from one side) glued to the back of the resonator. Figure 3.16 shows the ODSs of the same resonator coated with wax following the attachment of the sensors. Figure 3.17 shows the cedar_1 resonator’s spectral responses in its three states (natural, with sensors and with sensors and wax), recorded with laser vibrometry.

Vibrometer data reveals two dominant effects on resonator behavior. The first is the slight lowering of the fundamental resonance, a reasonable phenomenon regarding the addition of mass to the resonator. The addition of wax spreads the spectral energy of this mode, lowering its quality factor. Through both the addition of sensors and wax, the first and second ODSs are largely unaltered, while the spectral response in this lower frequency region is significantly shifted. However, from 250Hz up to 500Hz, the spectral response through all three steps of construction remains similar, with only an attenuation in amplitude following the addition of sensors. For frequencies above those shown, the spectral response between trials become less predictable.

The purpose of the presented tests is to evaluate how the addition of the sensors influences their ability to capture relevant modes, and how wax varnish further modifies this ability. Vibrometer data was used to select ideal sensor locations. While most ODSs can still be well captured by the originally placed sensors, for several ODSs the locations of the sensors are no longer accurate. Following the addition of sensors, two ODSs were no longer well covered, and addition of wax left four ODSs covered less than perfectly. For future resonator design, in order to minimize the influence of sensors and wax on the ability of the sensors to give good coverage to all examined ODSs, it is preferred to coat the resonator with varnish before analyzing its ODSs and adding sensors.

Hardwood Resonator

Laser vibrometry was used to detect the ODSs of a maple resonator (Figure 3.16 and 3.17), with a similar geometry to the cedar resonator. As was expected from a hardwood with a much higher flexural rigidity then cedar or spruce, the lowest resonant frequency was pushed above those of the softwoods studied. In respect to the eigenmodes generated through FEM and confirmed through vibrometry for the softwood resonators, analogs are missing from the maple resonator data. Only the dipolar mode structure seen earlier (Figure 3.16B) is clearly visible in here. The monopolar and (2,2) mode structures seen in softwood resonators are absent.

While the shift in frequency response and ODSs is significant given the maple resonator, the influence of the data on ideal sensor placement in far more relevant to the work presented here. By evaluating the gradients of the ODSs, less correlation was found in the preferred locations for the sensors than with any softwood resonator or condition test (such as adding sensors and wax). However, three sensors still give a good coverage of the first ten dominant ODSs, but a separate, specific positioning process is recommended. Overall, the influence of changing the resonator material from spruce or cedar to maple was much larger than with any other resonator modification analyzed, not just in the spectral response but also in the ODSs influencing the positioning of the sensors.

Sensor Signals

Signals were recorded from each of the three sensors on cedar_1 during impulse testing, in order to examine the captured signals and evaluate the effectiveness of the sensor positioning. Figure 3.18 shows the impulse response spectrum (testing done with same method presented earlier), as was captured by the three sensors. As expected, each sensor detects a different superposition of the resonator's ODSs. The signal taken from the lower sensor (as shown in Figure 3.15B) shows prominent spikes around 200 Hz and from 400 Hz to 500 Hz. When compared to the vibrometer data for this plate, strong antinodes are seen in the region of the lower

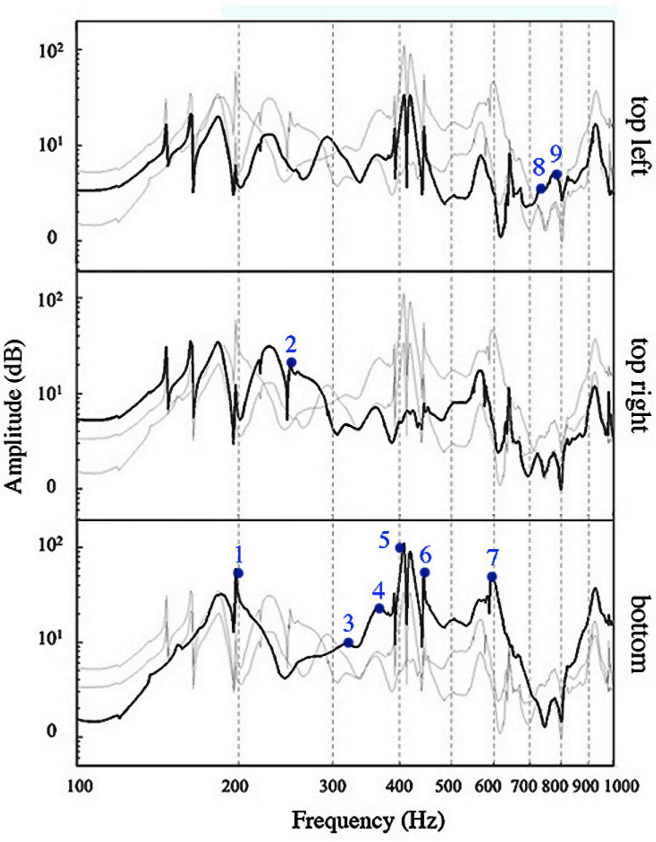

Figure 3.18: Evaluating the sensors signals: impulse response captured by cedar_1's sensors, (sensor orientation shown in Fig. 9). The blue dots are cedar_1 eigenmodes, before positioning the sensors, with respect to Fig. 10. Each dot was marked with respect to the proper representing sensor.

sensor at 201, 393, and 480 Hz, correlating well with the output of this sensor. While the lower sensor signal is a strong match to the vibrometer data in this frequency range, between 600 and 900 Hz the output of the lower sensor no longer correlates well with the vibrometer data of the blank resonator. The output of the other two sensors was analyzed in the same way. The signal taken from the top left sensor has higher amplitude than the other sensors in the spectral band of 200Hz – 300Hz, while the top right sensor has higher amplitude around 300Hz, with moderate correlation to Figures 3.17 and 3.18.

Sensor output was best correlated to vibrometer data at lower frequencies. The addition of sensors increased the resonator's mass and stiffness, altering both frequency response and ODSs. The captured sensor data demonstrates the significance of senor location, and emphasizes the design challenge created by the sensors altering the physical properties of the resonator. In order to minimize effect of sensor placement, a different type of piezoelectric sensor may be useful, e.g., shaped strips of PVDF piezoelectric foil.

Summary and Conclusion

The Chameleon Guitar is the product of a two years and a half of development, inspired from both the digital and the physical musical instrument landscapes. This new approach to designing guitars was tested successfully, and proved itself over time (see user evaluation at [1, 2]). The guitar and its resonators functioned well, were evaluated by fifteen players, and tried by many more. Several mechanical changes need to be made to the current guitar model, such as a new design for the resonator tray and new tuners. Other than that, the guitar is stable, ergonomic, and offers an open-ended selection of timbres.

The main goal of this work was to merge traditional values with digital capabilities. Based on our evaluation results presented here and elsewhere, it is safe to say that it was fairly successful. The main contribution of The Chameleon Guitar lies in its innovative solution to use replicable, acoustic resonators with electronic processing, while enjoying a higher degree of acoustic information captured from these resonators by several sensors (relative to the single surface sensor that is commonly in use in acoustic guitars). While any digital algorithm to create sound can be easily reproduced and copied, each wooden piece is unique and has a spatial-acoustic behavior. Here, I combine this acoustic uniqueness with the digital environment, leveraging the unique acoustic signature of each resonator with a palette of appropriate digital sonic transformations.

Resonator geometry, material, and sensor positioning contribute significantly to acoustic behavior of the resonator, creating a multidimensional design challenge with many viable solutions. The work presented here focused largely on the low frequency, geometrically dependent, instrument behavior as determined through FEM and vibrometry. Low frequency behavior is understood as characterizing much of guitar tonality, and focus on capturing this behavior allows for the best possible virtual "shape modifications", introduced later on a DSP unit, compensating for the dimensions of the resonator.

The Chameleon Guitar was tested using different resonator materials and examining the influence of sensors and wax on the resonator's behavior. FEM simulation of the spruce resonator gave a good prediction of its measured ODSs (although simulated with no string load), introducing several prototypical mode structures also found in cedar resonators and to an extent in maple resonators. Overall, similarity between the behavior of resonators appeared in the lowest ODSs: as frequency increased, resonant structures diverged and differences between the acoustic properties of resonators became more apparent. Still, even two resonators from the exact same log of Western Redcedar differ measurably in their ODSs, demonstrating that even below 1000 Hz there exists substantial uniqueness to each resonator, a characteristic to be explored in the DSP unit.

The external computer interface for modifying the digital content of the instrument is a different topic that requires more research. One can envision, for example, a simple high-level API, that would enable each resonator to bring up a particular set of options and adjustments on an attached PC, allowing the player to appropriately modify the guitar's sound based on meaningful parameters (as opposed to adjusting filter coefficients or directly writing code, although that's always an option for those so inclined). The potential is huge: in this system, we can connect a sound-making object to virtual environments in a very fluid fashion. This connection can demonstrate how physical objects can share in the same media revolution as digital objects, and opens up new possibilities for future forms of interactive entertainment. Such a connection can lead the way in combining craft, tradition, and acoustics with the digital environment, opening up a new future for hybrid design of objects.

The Chameleon Guitar primarily aims to create new ways for players to interact with their instruments through connecting the best of the acoustic and digital worlds. At the same time, the project seeks scientific significance, reinforcing the hybrid design paradigm as a platform for future research and implementation. In describing the steps of its creation and validation, I hope to have shown an instrument that brings together what is already known about stringed musical instruments into a platform that informs further work: with the intent of improving the Chameleon Guitar itself, further understanding the acoustic guitar in general, and making space for the creation of new hybrid instruments. More generally, this approach could be implemented in other string instruments (see Figure 3.19 for an example), such as the violin family, and with a bit more effort could even be developed into a piano solution.

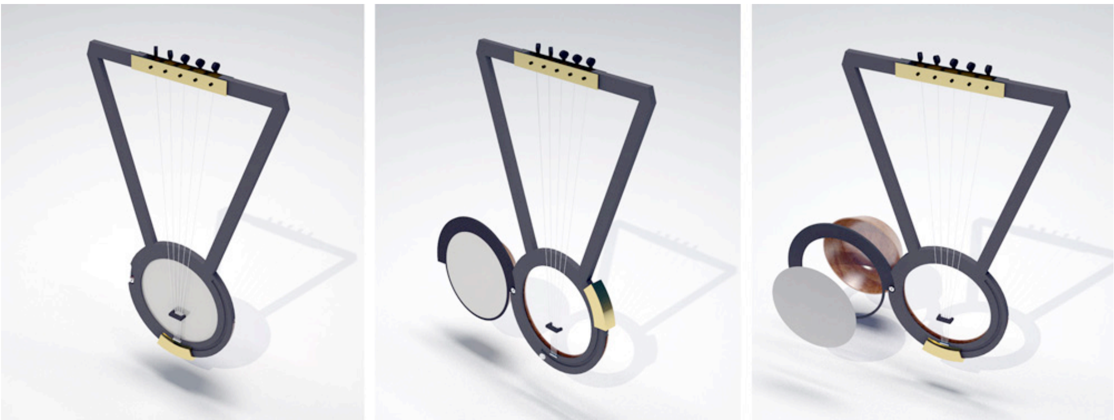

Figure 3.19: A modular krar instrument (an African harp-like instrument), with replaceable resonator and chamber. A concept design by Melodie Kao and Amit Zoran.

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Chapter 4

Hybrid Aesthetics:

Fused Craft

This chapter presents an attempt to merge digital fabrication and traditional crafts in the construction of artifacts. The objective is to fuse the aesthetic and structural qualities of the hand-made with the digitally fabricated.

Inspired by personal experience, this process requires more than merely appropriating handmade methods in the production of automated artifacts. While the *Chameleon Guitar* (discussed in the previous chapter) merges wooden acoustic qualities with digital sound processing, here I demonstrate the aesthetic potential of the hybrid territory. Starting by stating the problem in the first section, *The Phoenix Rising*, I then present two research projects, *Hybrid Ceramics* and *Hybrid Basketry*. These projects seek a visual synergy between the two worlds of digital fabrication technologies and hand-hewn craft.

Hybrid Ceramics combines digital fabrication and craft in a work involving object destruction and restoration: an intentionally broken ceramic artifact and its 3D-printed restoration. The motivation is not to restore the original work, but to transform it into a new object in which both the destructive event and the restoration are visible and the reassembled object functions as a memorial.

Hybrid Basketry is a medium through which 3D-printed structures are designed to allow the growth and development of hand-woven patterns. While the 3D-printed plastic elements constitute the aesthetics of the digital curvatures and manifolds, the hand-woven reed, jute, and canvas fibers infuse the baskets with a unique organic identity, achieving a balanced marriage between the worlds of 3D-printing and weaving.

The Phoenix Rising

3D-Printing and Design Immortality

> *Things are either devolving toward, or evolving from, nothingness…*
>
> Leonard Koren, [1]

Figure 4.1: The original, hand-made swan ring made of silver (A), CAD model of the ring (B), and the 3D printed silver replica (C); the hand-made miniature hands ring (D), and its replica (E).

Digital fabrication, and especially 3D-printing, is an emerging field that is opening up new possibilities for craft, art, and design. The process, however, has important limitations; in particular, digitally designed artifacts are intrinsically reproducible. The existence of a digital design means it is always possible to make another identical copy of a 3D-printed object. This style of production stands in stark contrast to traditional craft—where artifacts are individually produced.

Following the same line, physical artifacts are ephemeral and mortal, without permanence, while virtual objects transcend this limitation, attracting us by the new possibilities they introduce into our lives. My following text, which first appeared in the CHI 2013 Fabrication Workshop [2], demonstrates this dichotomy and draws a link between objects, freedom and mortality.

> Amit: *I met my wife Tamar at Bezalel, the Israeli Academy of Art and Design. She was studying jewelry making, while I was working on my Master's in design. Back then, Tamar specialized in silversmithing, making one-of-a-kind rings using hand tools. Improvising while working, Tamar made unique objects, which I admired, varying from figurative artifacts to abstract shapes.*
>
> Tamar: *When I was making jewelry, I improvised with the material, playing with silver and gold, letting random shapes form into narratives. In 2007, I was working on two rings projects: the first, involving miniature hands, where I used wires to symbolize two hands, almost meeting while embracing*

> *my finger* (Fig. 4.1D)*. In addition, the swan ring was born from the edge of a melted and deformed silver wire, which I shaped into the head of a swan at the top and wrapped around my finger for the body* (Fig. 4.1A)*. These two rings that were born at the spur of a moment were my favorites. I felt they encompassed a sense of freedom and lightness that sometimes is absent in an over-planed work, and I decided to keep them.*
>
> *Unfortunately, despite my attachment to the rings, I lost them, which I regretted deeply. Due to their improvised nature, any attempt to recreate them failed. So I was certain they were lost forever, hoping that whomever found them would give them a loving home. For more than five years, all I was left with were a few photos, taken by my husband.*
>
> Amit*: In the fall of 2011 at MIT, I was in the middle of several projects using 3D-printing. I was searching for an appropriate present for Tamar's 30th birthday, while I was introduced to a 3D-printing process by which an element could be printed in wax and then cast in silver or gold. Based on several photos I had of the lost rings, I modeled their shapes in CAD software, searching for approximate identical copies and filling in the gaps from memory* (Fig. 4.1B)*. I had the models printed, and a few weeks later received two silver rings in the mail, very similar to the original ones* (Fig. 4.1C & 4.1E).
>
> Tamar: *I opened the box and I was puzzled to find my long lost rings there. How could this be? They were lost five years ago and a continent away, and yet, there they were. Amit gave me something I thought was gone.*

In a sense, the lost rings came back to life. They were cloned from their digital DNA, a few photos, used to construct a new CAD file. From now on, we can re-clone these rings with no extra effort, using the same files.

An important quality of contemporary digital fabrication is its accessibility and ease of use in the production of virtual designs. While forms of automation existed well before the development of 3D-printing, 3D-printing helps re-introduce the concept of personal fabrication: any maker, regardless of handicraft skills, will be able to make objects in his shop or workbench using variety of materials.

The digital fabrication and do-it-yourself (DIY) movements borrow narratives from traditional craft, where the intimate engagement between the maker and the produced artifact is central to the fabrication process. A 3D-printed work originates from a digital medium, to which it owes its existence. A virtual work doesn't age in the same way physical work does, and it is always possible to reprint an old, broken or lost artifact (assuming we didn't delete a digital file). While digital work can, however, become obsolete or incompatible with contemporary fabrication technologies, it does not have a sense of material aging, being protected from the real-world risks of damage and loss.

While our 3D-printed rings looked very similar to the original work, there was one difference: now we had digital files. The original rings were a hand-hewn physical investment – of time and creativity, captured in the moment, inherently flawed and unique. Today, the digital copies still carry a meaningful narrative, but from this point on, the "real" rings are machine-made, infinitely reproducible.

Considering the meaning of a digitally-fabricated artifact, the main risk is that metaphysically, the physical instantiation is meaningless, originating from a timeless and immaterial ideal. In contrast, a particular handcrafted object depends on temporal qualities and unique activities: the maker's personal, subjective investment. Both digital fabrication and handcrafting have unique affordances for producing objects, but also present separate forms of risk or loss. The contrast between these mediums motivated me to seek a constructive synthesis between the two, which I demonstrate through the following projects.

Design language is constantly changing. Digital Fabrication is on the rise, and parametric tools are transforming the design landscape. 3D-printing is the hot topic of the day, enabling digital practitioners to rapidly implement their ideas. However, while craft and art are dynamic practices that respond to new technology trends, 3D-printing is still a sterile domain, limited to digital mediums. I seek a dialog between digital practice and traditional craft, merging aesthetic qualities to create a hybrid territory. In this chapter, I demonstrate that tradition can be merged into a visual hybrid, contemporary "making" practice that respects its double origins. While computational digital design enables an exploration of forms and structures free from traditional fabrication limitations, craft contributes an intimate engagement between the maker, the material, and the product.

Hybrid Ceramics

The Dramatic Approach

In this section (first published in *Leonardo Journal* [3]), I present an approach to combining digital fabrication and craft that is focused on object destruction and restoration—an approach that combines an intentionally broken handcrafted artifacts with 3D-printed restorations (see Figure 4.2). The motivation of the restoration is not to restore the original work, but to transform it into a new object, in which the destructive event and the restoration are both visible, and the re-assembled object functions as a memorial. I will present and discuss this approach through three projects—*The Bowl, The Masks,* and *The Vases*. I will then reflect on the importance of mourning and acceptance in the creative process and discuss opportunities for employing both craft and digital fabrication in this context.

Figure 4.2: A digitally restored broken vase. Glazed ceramic, SLS nylon element, epoxy glue, and black spray paint.

Motivation

> *Before I moved to the US, four years ago, I picked several artifacts that were important to me, which held unique value in my eyes, and brought them with me. One of these objects was a handcrafted ceramic bowl. This bowl had a unique texture and was not perfectly round; one could easily see it was a hand-made object, a unique artifact that would not be confused with another.*

> *It represented great emotional value, associated with deep family connections and important events. A year ago, this bowl was accidently broken by a visitor to my house. The visitor suggested paying for the bowl. Of course I refused; there is no price that can restore a memory. The original meanings embodied by the bowl were irrevocably changed.* Amit Zoran

The motivation behind the work presented here is twofold: first, to merge digital fabrication with traditional craft, thereby combining two different creative processes that rarely overlap; second, to explore an approach to restoring artifacts that preserve the form of the original, while at the same time acknowledging the trauma of damage.

I use the destruction of a handcrafted object—not usually a happy moment—as an opportunity for creation. By re-assembling a broken object using contemporary fabrication techniques, I construct a unique artifact that retains traces of the original, yet is distinctly changed. Figure 1 shows a ceramic vase that was shattered and then digitally restored in this fashion. Broken pieces of the vase are held together by a 3D-printed lattice that follows the form of the original. The ceramic pieces that remain suggest what the unbroken vase looked like. The lattice, instead of replicating or replacing the missing pieces, emphasizes their absence. The resulting “restored” vase functions as a memorial—a new one-of-a-kind piece that acknowledges the ceramic original and the act that destroyed it.

I present three projects in which archetypical artifacts are created using craft and fabrication tools, and then transformed through intentional breakage and digital restoration. I argue that this is a new kind of craft process that provides insight into the relationships between traditional craft, modern technology, art, and design.

Background and Related Work

I turn first to a discussion of the areas that lay the foundation for this work - destruction and restoration. Where relevant, I examine of how these two topics are being transformed by new technologies, such as CAD and digital fabrication.

Destruction

The marriage of craft and digital fabrication that I explore is made possible by destruction. It is the act of breaking a handcrafted object that gives us the opportunity to restore it with 3D-printing. Destruction is the ultimate risk a creator takes on when embarking on a project—fabrics can stain or tear, wood can be cut, and ceramics can shatter. By embracing or at least accepting destruction, the craftsperson comes to terms with the essence of the workmanship of risk.

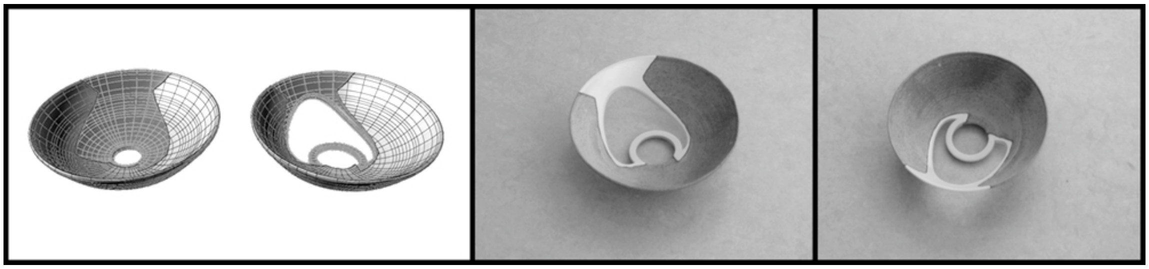

Figure 4.3: The digitally restored bowl. The three biggest broken elements were glued and 3D scanned using Konica Minolta VIVID 910, while the small elements were not used. Left: the virtual model of a 3D scanned bowl and two restoration options, designed in the CAD software (Rhino). Right: the restored bowl, using 3D printed SLS element, epoxy glue and spray paint.

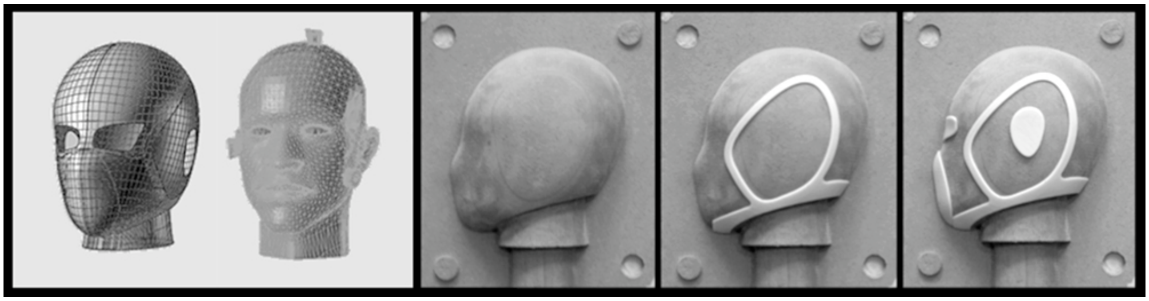

Figure 4.4: The design of the mask-helmet and the head (including pins for the broken elements) in Rhino CAD software (left). Three steps of making the mold (right), from the milled MDF form, to the final mold using 3D printed details from ABS plastic and using a FDM Dimension machine.

Figure 4.5: Six cast masks on a shelf, using three different clay colors, before firing them.

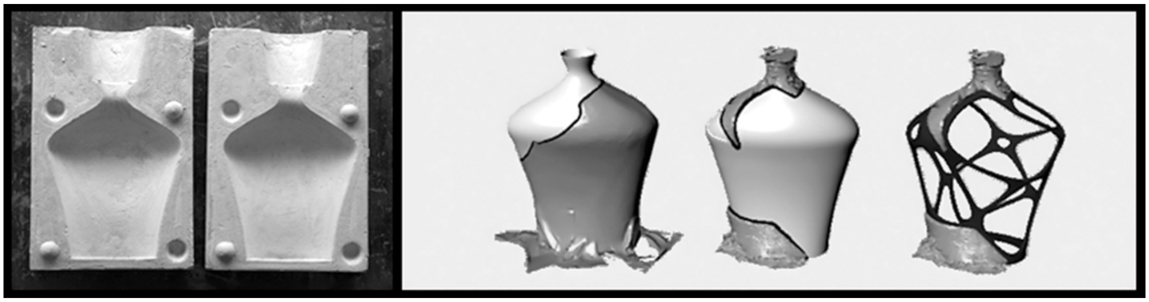

Figure 4.6: Left: two negative parts of the vases' plaster mold, based on the positive MDF milled mold. Right: the evolution of the design of the restorative elements in the CAD software.

The use of destruction as a creative tool has long provided fertile ground for artists to explore issues like impermanence, loss of control, and fragility. Gordon Matta Clark's carved buildings [4] —abandoned homes and warehouses that are cut up into new forms—are one striking example of work in this tradition. Cornelia Parker's 30 pieces of silver [5]—a collection of silver utensils that have been flattened by a steamroller—exemplifies a more lighthearted exploration of (cartoon-inspired) annihilation. Both of these works—though by no means entirely representative of the way this topic has been addressed in art—illustrate some of the enduring appeal of including destruction in creation. The reshaped buildings and the pressed pieces of silver retain the history accrued in their previous lives while functioning both as documentation of the destructive/creative performance and as new beautiful and expressive objects in their own right.

Creative destruction has also been investigated in myriad ways in design. Particularly relevant to our work are designers who have experimented with broken ceramic. In *Vase of Phase*, Dror Benshetrit made vases from porcelain, broke them and then put back together the broken pieces [6]. In *Shock Proof Vases*, Tjep attached polyurethane rubber to the interior of a set of vases. Each rubberized vase was then broken, resulting in a semi-soft surface of shattered pieces held in place by the rubber [7]. As in our work, these forms retain qualities of the original vases while recording and displaying the destructive act. Daniel Hulsbergen in *CenterPIECE* uses an alternative technique, restoring broken ceramic vases using Dutch basketry [8]. This technique of mixing two different craft traditions demonstrates how breakage can be used as an opportunity to join different materials, techniques and aesthetic qualities.

In our work, I exploit this opportunity in a similar fashion to bring together craft and digital fabrication. I use fabrication as a restorative process, a means of acknowledging and coming to terms with the risks inherent in craft.

Restoration

In the restoration of art, the restorer's goal is to preserve the original properties of the work [9] and hide any external interferences. The motivation is to be as true as possible to the artist's creation. Preservation and conservation, as in archeology, have a slightly different focus [10], emphasizing instead the slowing-down of aging. A perspective that is consistent across restoration and preservation is that the craft of the restorer or the archeologist should be hidden. The stage should be left to the original object.

In architecture things operate bit differently. In addition to traditional restoration and conservation, we see modern extensions added to old buildings. In these instances, the hand of the "restorer" is quite visible—the architect builds on top of an old building (or the remains of one) a construction of a distinctly modern nature, thus emphasizing contrasts and relationships between the old and the new.

While the traditional tools of the art restorer, archeologist, and architect are different from each other, in the last thirty years each of these fields have started to adopt digital technologies in similar ways. Moreover, in medicine, CAD and CAM techniques exploited to replace damaged or broken body parts in a similar fashion, as the 3D-printed jaw discussed in the introduction chapter. Increasingly, these disciplines are using design software and computer simulation to create virtual representations of environments and objects, and digital scanners to capture and analyze information about three-dimensional artifacts [11, 12]. Digital fabrication—and especially 3D-printing—is providing new opportunities for restoration by enabling the relatively easy construction of replicas of broken pieces of original works or entire objects. Using 3D scanners and printers, modern day restorers can precisely capture and reproduce the exact form of existing objects.

I argue that the use of these tools and processes can benefit craft by facilitating new creative approaches. The accessibility of CAD software, 3D-printing and scanning, has enabled us to use restoration as an integral part of the craft process. I believe that these new tools can allow restorers, designers, crafts-people, and artists to create works that preserve important features of craft, while at the same time providing new aesthetic possibilities. In particular, we can capture the form of an original artifact and create new restorations of and extensions to it.

Hybrid Ceramics

In three projects—The Bowl, The Masks, and The Vases— I now demonstrate my approach to using digital fabrication to restore broken ceramic objects.

The Bowl

Earlier I discussed how a personal object, a bowl rich with history and meaning, was accidently broken. My exploration of hybrid ceramics was sparked by the desire to restore the bowl, to preserve some of the history and meaning it held. A traditional restoration—gluing all of the pieces back together—did not feel appropriate. Instead, I selected the three largest broken elements, 3D scanned them, glued them together, and then 3D-printed the remaining missing parts. Instead of attempting to recreate the original bowl, I created a restoration that emphasized its destruction. As can be seen in Figure 4.3, the "restored" bowl no longer functions as a bowl—it can no longer hold salad, cake batter, or fruit. Instead it functions as a complete, stable form that memorializes the original, while acknowledging the event of breakage and the subsequent loss of functionality.

In the restored bowl, the contrasts between the new parts and the old are emphasized by different surfaces, forms, textures, and colors. The 3D-printed surface is smooth and white while the original bowl's surface is rough and earthy in color. The new bowl respects both the qualities of the handcrafted object and those of the digitally fabricated restoration; in its new incarnation as a purely decorative memorial, it documents the history of the original bowl, its breaking, and its restoration.

It is important to note that when 3D-printing is used in this way—to restore a unique, handmade artifact—reproductions of the digital restoration are meaningless. The fabricated element gains specific relevance and context by adopting the form of the broken ceramic. After a restorative element is 3D-printed and joined to the broken bowl, there is no sense in re-printing it because there is no duplicate bowl that matches the restorative part.

Figure 4.7: The masks. Glazed ceramic, spray paint, Objet PolyJet 3D printed heads, and epoxy glue. Left: a broken helmet. Middle and right: a broken element glued around a 3D printed head.

The Masks

The bowl project arose from an effort to restore an accidently broken artifact. The process of repairing the bowl suggested other opportunities for exploring the relationships between craft—and ceramics in particular—and digital fabrication and led us to our second set of experiments, the masks.

In the mask project I began to create objects with the express intent of breaking them and restoring them using digital fabrication. I also began to examine other relationships between technology and traditional craft. Here I integrate and juxtapose different aesthetic styles as well as processes and materials. For this particular project, I appropriated the "high-tech" aesthetics of robotic comic book heroes, and applied these to traditional ceramic masks. I also began to selectively apply digital fabrication techniques in our creation of the original craft object.

I began by using CAD software to design a model for the mask. I designed the masks to fit around a digitally designed model of a human head that I purchased from TurboSquid [13]. Then, I fabricated a positive two-part mold of our mask, using a computer numerical controlled (CNC) milling machine and a Dimension Fused Deposition Modeling (FDM) 3D-printer. This mold, shown in Figure 4.4, was then copied into a two-part negative plaster mold and the masks were cast into this mold with slip (a liquid clay). When the clay was dry, the mold was opened and the model was fired. I fabricated six masks using this process, glazing some areas and painting others with spray paint. The finished unglazed masks are shown in Figure 4.7.

I then broke four of these masks by either using a hammer or throwing them on the floor. Finally, I reassembled the broken pieces around 3D-printed models of the head that guided our original design. Three of these broken masks are shown in Figure 6.

The aggressive and random process of deliberately breaking a crafted object increases and highlights risk. It forces the craftsperson to acknowledge the fragility and impermanence of his creations and his labor. It is an experience of hope, regret, surrender, and perverse glee.

In the reassembled masks, I highlight this process. Here, missing pieces are not replaced at all. Instead, a partial reconstruction of the original mask floats around a 3D-printed head. The support structure that holds the broken pieces in place is almost hidden. As with the bowl, the final artifacts serve as memorials, but the emphasis in this case is less on the original objects and more on the documentation and preservation of the demolition.

The Vases

In the bowl project, I created a restorative 3D-printed part by carefully tracking the contour of a broken surface. In the masks project, the breakage was intentional, an integral part of the fabrication process. In the third project, The Vases, I merged these two approaches, deliberately creating and breaking vases and then 3D scanning and tracking broken surfaces to create restorative elements.

I started this process by designing a vase in Rhino and fabricating a mold. As with the masks, I then cast the vase with slip. Three cast vases were fired and glazed. From these three, I selected two vases and broke them using a hammer. I then selected several of the larger broken parts, glued them back together, and 3D scanned them using a Konica Minolta VIVID 910 scanner.

In the design of the restoration, shown in Figure 4.6, I began by making simple solid models of the digitally scanned missing pieces. I then stylized and refined these designs, creating lattice structures to contrast and compliment the glazed ceramic of the original vases.

The aesthetic intention of the restoration, shown in Figure 4.8, was to respect the shape of the original forms and trace the lines of breakage, while at the same time exposing the inner volume, the negative space, of the vases. As with the bowl, the original functionality is lost, but new aesthetic, performative, and cultural meanings are accrued. The 3D-printed parts combined with the original ceramics, creates a hybrid effect, folding several contrasting concepts together: the old and the new; the closed and the open; the hand made and the machined.

Figure 4.8. Three vases - the digitally restored vases (left and middle), and a complete one (right). Glazed ceramic, SLS nylon element, epoxy glue, and black spray paint.

Loss and Acceptance through Craft and Digital Fabrication

Through three projects, I explored how craft, digital fabrication, destruction, and restoration can be integrated into a hybrid creative process. I attempted to preserve the essence of craft—the workmanship of risk—while experimenting with techniques that were at odds with this very premise. I now turn to a closer examination of the tensions and juxtapositions that formed the heart of our exploration.

Though I discussed the role of digital fabrication in restoration, I have not yet carefully examined how we employed it in our craft process. In the masks and vases projects I began my work by creating digital designs for objects. I then used these models to digitally fabricate molds. One could reasonably argue that objects extracted from digitally-fabricated molds are essentially identical, that they do not have the critical aura of a crafted artifact [14]; that they're not unique. However, the ceramic pieces were ultimately created by hand—each mask and vase was individually cast, glazed, and fired. Each ceramic was subtly but significantly different from all of the others and, during the casting, glazing, and firing process, each was subject to the judgment, manual dexterity, and care of their maker. Therefore, I would argue that the workmanship of risk was preserved.

The workmanship of risk is also dramatically emphasized by the process of destruction. This is a process that carries meaning beyond the brief incidence of breakage. The shattering of archetypal artifacts like bowls, masks, and vases - each of which serve as important icons in many cultures [15] - is a symbolic act. The bowl and the vases are containers that, once broken, can no longer hold water or food. The mask - an identity changer - cannot hide the head it covers after it is smashed. Yet the process of destruction is personal and emotional, as well as symbolic. The more time, attention, and care a craftperson has invested in constructing an artifact, the greater the loss when it is broken. The process of making a unique object is always loaded with intimacy between the maker and the artifact. The breaking of one's own work is an especially aggressive and traumatic experience. I see this explorative processes almost as a ritual of mourning with intentional breaking serving a purpose similar to the tearing of a piece of clothing in the Jewish burial and mourning practices. The 3D-printed restorations I introduce to repair this damage are intentionally imperfect. They surrender the original meaning and functionality of the object, and transform it into a memorial. In our eyes, the destruction and re-assemblage is a rite of passage for the maker, who is forced to accept the reality of change.

Acceptance is an integral aspect of risk. In this work, I tried to illustrate a perspective in which modern fabrication technology can be used as an element of compassion and compensation in a ritual of mourning. Esther Leslie, in her assay *Walter Benjamin: Traces of Craft* [16] mentions that for Benjamin, the work of craft is similar to storytelling, in that it can embody time and meaning through practice. For these pieces, the time is the digital age, and the meaning is one of transformed identity - an identity that, while profoundly changed, preserves its most essential qualities.

Hybrid Basketry

The Holistic Approach

Hybrid Basketry (first published in the SIGGRAPH'13 Art Gallery [17]) argues for merging digital practice with craft as a design value, already in the planning process. This is a medium where 3D-printed structures are shaped to allow the growth and development of hand-woven patterns. While the 3D-printed plastic elements contribute the aesthetics of the digital curvatures and manifolds, the hand-woven reed, jute, and canvas fibers infuse the baskets with a unique organic appeal. I discuss my motivation, describe the making process, and present four hybrid baskets, integrating a deeper discussion on the place of craft and tradition within our contemporary approach to design and fabrication.

In the prior section, I merged digital fabrication with ceramic craft in a process that requires an actual restoration of traditional handcrafted objects. I used innovative 3D fabrication techniques to articulate the absent form of the broken originals, thus creating something new while also commemorating what was lost.

In contrast, in the projects presented below, 3D-printed structures are *designed* to accept the development of hand-woven fiber, intertwining the two different practices into a single artifact. In contrast to a fully digitized design process, Hybrid Basketry is a search for agreement and collaboration between practices. Personal investment, the use of organic materials, and uniqueness of the final artifact are sought. Here, I explore a synergy between digital practice and craft, based on equality rather than breakage and trauma as in my early work. Following this motivation, I present four hybrid basket projects that span a creative space blending parametric design with manual artistry. But before delving into the artifacts, I will start by providing some context on the art of basketry.

Context: Basket Makers and Cultural Expression

> *Looking at my work, people have to see many different pieces. Often my work is from dreaming - when I sleep, I dream the patterns and then I draw them; they become clear to me in time and then I put colors together. Each one, for me, is special. None are the same.* - Thitaku Kushonya, workshop brochure

Thitaku Kushonya is a traditional basket maker from Maun, Botswana (Figure 4.9). She learned basketry from her mother, who used to make functional containers for domestic use. Thitaku adapted her mother's techniques to give them a modern interpretation, adopting a Western view on originality, uniqueness, and individuality. She doesn't want her work to be used, but rather to be presented and treated as artwork. Each of her palm-fiber coiled works has a different graphical pattern. Basket-making time can vary from but a week or two up to several months, depending on the complexity of the work. Designs and patterns are not arbitrary; they are influenced by traditional Kavango style and dreams. Thitaku emphasizes the uniqueness of the work and the originality of the graphic. She has her personal intention and technique, so she is the only person producing her baskets.

Figure 4.9. Thitaku Kushonya (right) in her basketry shop at Maun, Botswana.

I first met Thitaku in July 2011 while researching traditional African craft. I was mostly influenced by the level of engagement Thitaku, similar to other local makers, has with her practice - an intimacy that stood in stark contrast to the digital realm of my work. Collecting palm leaves in the Kavango delta, preparing the fibers and their pigments, designing and making the baskets: each of the making stages has potential for creative experimentation. For example, besides the variety of patterns and forms, Thitaku investigates alternative materials, such as fibers made from a green nylon bag mixed with palm fibers. By doing so, she demonstrates the flexibility possible in a traditional form of making that is often considered highly conservative.

Thitaku Kushonya is more than just a gifted maker. She is also the voice of the Botswana basketry tradition. She actively promotes basket making by travelling abroad, visiting local villages to collect baskets, and training other makers to consider themselves as artists, rather than producers of utilitarian objects.. Working with over 450 traditional weavers, Thitaku's organization, Botswana Quality Baskets, empowers makers to use their craft in order to be self-sufficient, assisting the producers with quality training, design, marketing and logistics. In an age where mass-produced plastic and nylon containers are cheaper and more accessible, basketry makers are looking for identity. Contemporary basketry in Africa, like other traditional crafts around the world, is losing its place as a practical tradition. While knowledge is still preserved by older generations, the search for modern identity is moving forward.

* * *

At the heart of basketry lies the practice of intertwining different material elements to reinforce an artificial structure. Unlike woodworking, blacksmithing and pottery, basketry is not tied to a specific raw material or tool. Basketry practice grows from the inside out - like trees growing over time - in an organic and emergent process. This is the art of pattern repetition and structural growth, as discussed by Tim Ingold in his essay "On Weaving A Basket" [18]. But similar to cloth making, most baskets are based on organic materials, which makes it difficult to study their origins [19]. Lately, archeologists have demonstrated the possibility of an early usage of bamboo basketry in Southeast Asia, even with the absence of stone tools [20], by reconstructing early craft conditions of a pre-agricultural period. By comparing evidence from animal (i.e. birds) weavings, it is safe to assume that basketry is one of the oldest practices of humanity.

Ancient as it may be, basketry is a flexible craft that was independently developed by many cultures. It appears in a huge variety of forms, designs and sizes. Raw material varies from bamboo and cane [21] to pine and leaves [22], and today even metal and plastic wires. Many basket traditions borrow elements from other crafts, such as wooden handles and legs. These qualities of basketry: adaptability, changeability, and usage of a variety of technologies and raw materials make it a perfect domain for experimentation. Many contemporary makers have visualized this quality, and beautiful examples are illustrated by Billie Ruth Sudduth's Baskets: A Book for Makers and Collectors [23].

Exploration.

Because basketry is an accommodating and forgiving form of craft, it invites collaboration with digital practices. Technically, the construction of elements use woven patterns, and the discrete nature of the basket's graphics are relatively easy to model. Indeed, over the last few years several projects have articulated the use of computational technology to explore digital weaving. An example is the work by Muslimin [24], who demonstrates the implementation of computational design of woven structures in architecture. While algorithms for digital weaving have been explored in an early work by McQuaid [25], Khabazi enabled designers to study and implement computational weaving using Grasshopper, a parametric plug-in to Rhino3D [26]. He divided a 3D surface to a woven pattern of warps (the longitudinal thread), and wefts (the transverse thread), creating networks of woven curvatures.

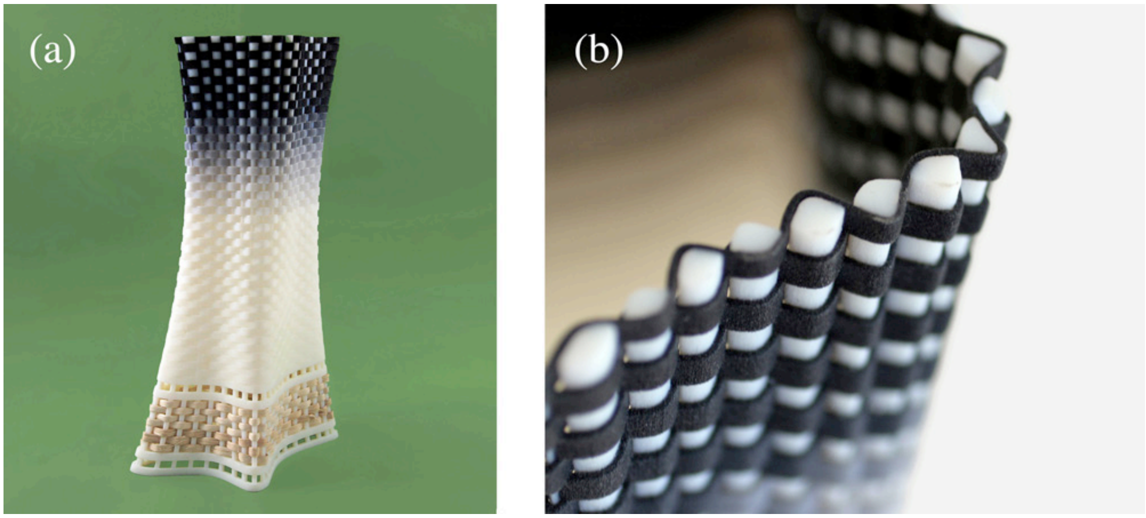

Figure 4.10: The first basket, made by Objet Connex 3D printer, and reed.

This last work served as a starting point for my investigation.

Basket I

Due to its woven structure, I call this first work a basket, but it may resonate more with the traditional shape of a vase. Modifying Khabazi's weaving algorithm, this artifact demonstrates digital possibilities that cannot be implemented in traditional practice (Figure 4.10). Using an Objet Connex 3D-printer, which allows a linear combination of 2 different printed materials, a smooth surface was deformed into a woven pattern by several linear steps (from bottom to up). Basket I demonstrates surface deforming, starting with a smooth texture of a single white color, and developing to a woven pattern with black warps (Objet's flexible material) and white wefts (Objet's rigid material). At the bottom of the basket I manually wove natural reed into the pre-designed 3D-printed wefts, to achieve a simple demonstration of hybrid structure.

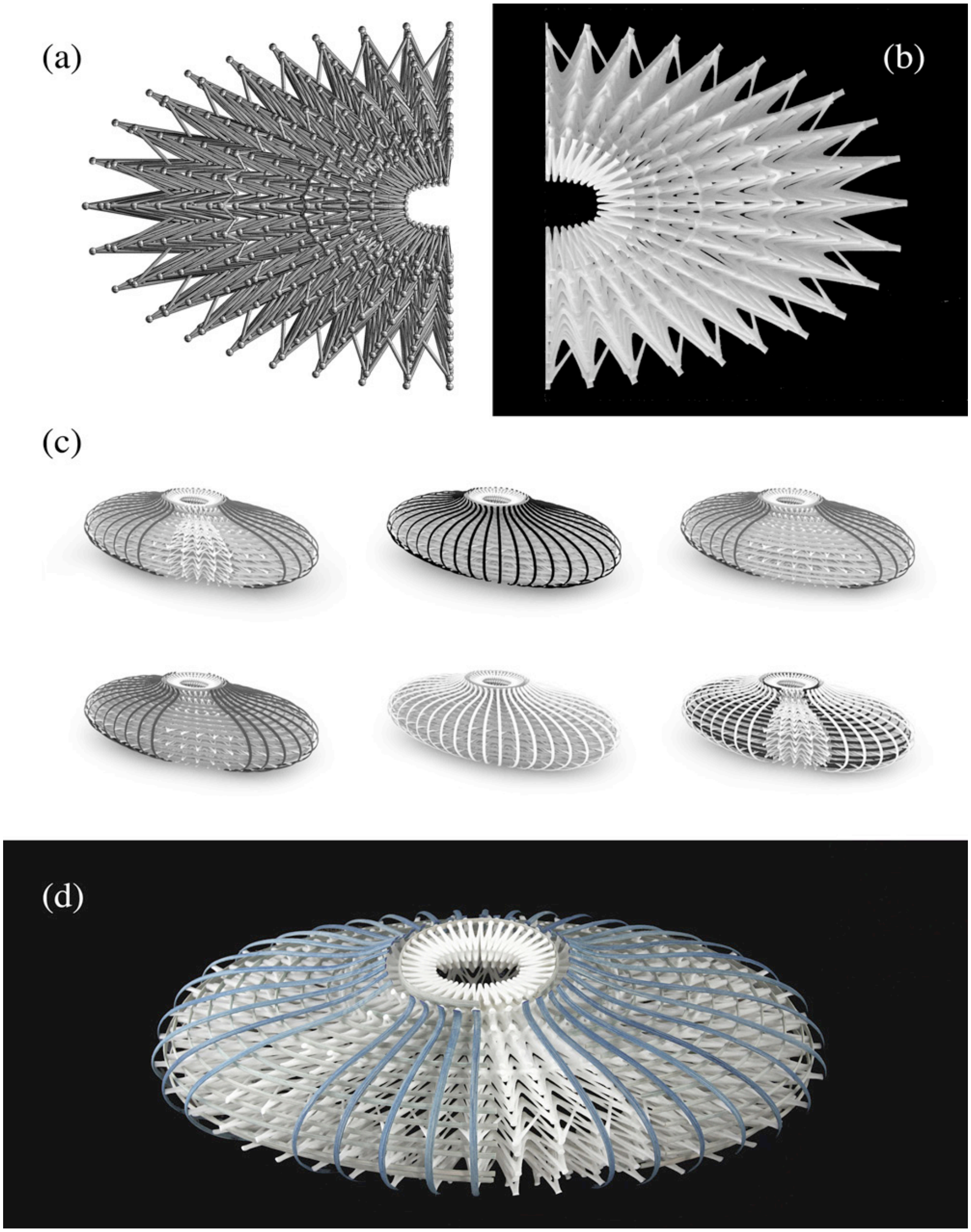

Figure 4.11: The making process of the second basket. (a) CAD design of the 3D printed arms structure. (b) The 3D printed nylon 12 structure. (c) Six renderings of reed colors and arrangements. (d) The final basket (3D-printed nylon, reed, pigments and glue).

In the first basket I demonstrate the potential for revising 3D-printing and digital design to achieve traditional craft aesthetics, such as a woven pattern. Starting by designing a sleeve with freehand deformation of a cylindrical surface, I then decompose the surface to warps and wefts. Based on Khabazi's work, my modification of his algorithm enabled a non-uniform woven development, allowing control of the relative distance of the warps from the base. This virtually-designed structure was printed in one piece, before weaving the wet, flexible reed inside it.

Basket II

Basket I is an aesthetic demonstration of the potential of parametric design and multi-material 3D-printers. However, the manual part of that work is limited, and doesn't show a balanced exchange between the practices. As a digital practitioner, it was my first attempt to design for manual weaving. While Basket II still mainly relies on digital process, it presents a higher degree of investment and skill development for the maker (Figure 4.11).

In Basket II, I am using a new implementation to join reed and 3D-printed structure, rather than a standard weaving technique. Instead, I used a structure of layers, where a system of 3D-printed miniature arms (Nylon 12 material printed by Selective Laser-Sintering process) are the bases of the basket, and two separate horizontal and vertical reed layers cover it from the outside. Due to its size (60cm length), the model of the basket was divided into four parts, which were printed separately and then glued together manually. Several virtual renders were made beforehand, to test dyes and different reed arrangements prior to manually completing the design and gluing the reeds to the structure.

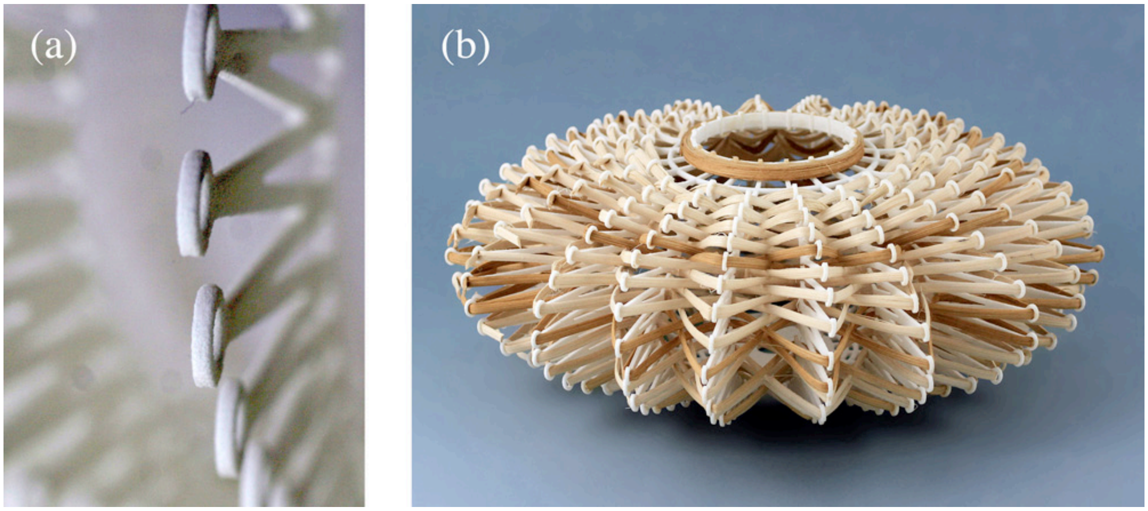

Figure 4.12: The third basket. (a) 3D printed nylon structure, and (b) the complete basket with the dyed reed.

Basket III

Basket III demonstrates a weaving technique, where a 3D-printed lattice guides the woven reed in pre-defined paths (Figure 4.12). Similar to the previous work, dyed reed was manually woven into the brittle 3D-printed nylon object, reinforcing it into a solid artifact. The design of the basket is based on 2D weaving guides (see Figure 4.13) that were rotated to achieve a closed oval shape. The printed nylon acts as the basket's wefts, while the reeds are the warps.

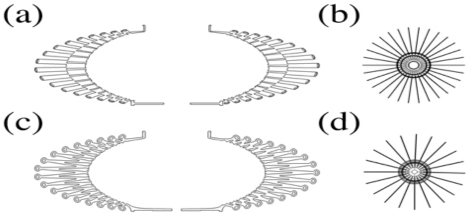

Figure 4.13: The design process of Basket III. (a) An early 2D support structure, and (b) its rotation plane. (c-d) The final basket's 2D support structure with its rotation plane.

This basket owes its shape to the marriage between the two materials. The 3D-printed structure alone doesn't resemble the final form, and the two elements are essential in order to achieve physical stability. In many aspects, the result was a surprise, since the final hybrid shape was not simulated during the design, and the aesthetic qualities of the basket gradually emerged while manually weaving the reed (a process which took approximately 6 hours). For me, this work was the first to demonstrate a "workmanship of risk" within the Hybrid Basketry project - a quality very essential to craft, where the shape of the crafted object is never predetermined.

Figure 4.14: The last basket: nylon 12, jute and canvas ropes, pigments, and a rosewood plate.

Basket IV

The last project is, in a sense, the most accurate manifestation of my intention within Hybrid Basketry (Figure 4.14). Here, unlike the previous projects, the manual investment was greater than the digital one, as it took me almost a week of work (2-3 hours a day) to complete the weaving of canvas and jute ropes inside the 3D-printed construction. While the overall shape of the basket depends on the computational process (and may be difficult to achieve within traditional practice), the woven pattern was only partially pre-defined in the computer, and a lot of freedom was kept for the weaving stage itself.

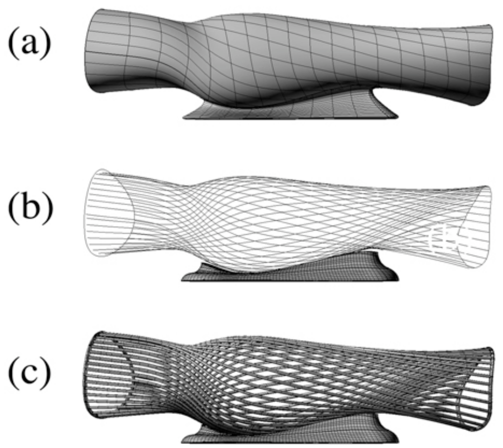

Figure 4.15: Three design stages of Basket IV: (a) lofting and twisting a sleeve surface to create the overall shape, (b) slicing the sleeve to horizontal stretches, and (c) creating a solid structure that can be 3D printed.

The 3D-printed sleeve was designed in a process similar to Basket I: starting by a sleeve and using freehand deformation of a surface, I then sliced the surface into horizontal bands, and used these slices to make deformed cylinders (Figure 4.15). This cylindrical weft structure constrains the weaving's vertical pattern. In addition, the horizontal density of the weaving process, the weaving pattern itself (such as how many wefts should be included in one loop), and the type of rope and its color (canvas or jute) allow for a vast design exploration while working. The result is a unique artifact, with a singular surface pattern. The 3D-printed structure allows for digital freedom, but requires the woven rope for reinforcement and stability. Moreover, the manual work demonstrates irregularity and imperfections, tracing the long weaving process, and rendering aesthetic of values that stands beyond form and structure.

Summary

In this chapter, I explore what has conventionally been treated as two divergent realms - that of emerging 3D-printing technologies and timeless hand-hewn craft. Being a digital practitioner, this work allowed me to be engaged in the making process, investing many hours practicing my new, unique, and manual craft skills. These pieces are, in a sense, a physical manifestation of an intensifying desire to develop a new way of thinking about the polarities of digital fabrication and manual craft: the machine, as generator of control and innovation, and human manual skill, as preserver of artistic production and culture. This work is an investigation of our digital culture and our potential to reclaim a lost material identity in the cyberspace of design and fabrication. Here a set of diverse practices, that of ceramics, hand woven organic fiber patterns, and computationally driven 3D-printed structures, are assembled to become a new territory of hybrid material. My hope is to substantiate this new hybrid territory for investigation and discovery, which enhances the value of artifacts produced by both machine and man. These hybrids can stimulate our excitement for new technological processes, while preserving recognition for the traditional practices from which this technology emerged.

While the motivation of this work was to encourage dialog between material practices, this essay demonstrates work by one individual. Although I mastered the digital design arena, I took only a few steps toward the manual crafts. As such, the scope is limited to my subjective interpretation and perspective. More work is needed, with more participation of creative makers to claim a cultural practice. Hopefully this project will inspire other makers to preserve and integrate, while still innovating and progressing.

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Chapter 5

Summary and Conclusions

In the Introduction, I critiqued contemporary digital design and fabrication practices, writing of how they lacked uniqueness, involvement, and intimacy compared to non-computational practices. I presented three projects -- hybrid interaction, hybrid functionality, and hybrid aesthetics – as different approaches to merging traditional and contemporary design, all exploration a venues for achieving uniqueness in the age of digital design and fabrication. In this dissertation, both hybrid interaction (FreeD) and hybrid functionality (Chameleon Guitar) have been tested to support my design paradigm.

My objective was to promote an alternative paradigm to the trends that dominate the design discussion. Yet, throughout the history of design technologies, makers have tried to create blended practices (see Figure 5.1). Today, the DIY movement influences makers from a wide range of disciplines, incorporating diverse skills and technologies. Artists and craftspersons are using digital tools to investigate new creative territories, while others enjoy the opportunities technology creates for fabrication. In addition to digital design tools, the digital revolution allowing contemporary makers to share their knowledge, instructions, and experience with others via online communities.

My work does, however, offer a new challenge to contemporary design. By presenting a technological deconstruction, I hope to promote a debate and dialogue within the design and HCI communities that leads to design authenticity, egalitarianism, and participation. In this chapter, I summarize my work, present comments from scholars, and conclude with a personal note.

Transitions and Contrasts

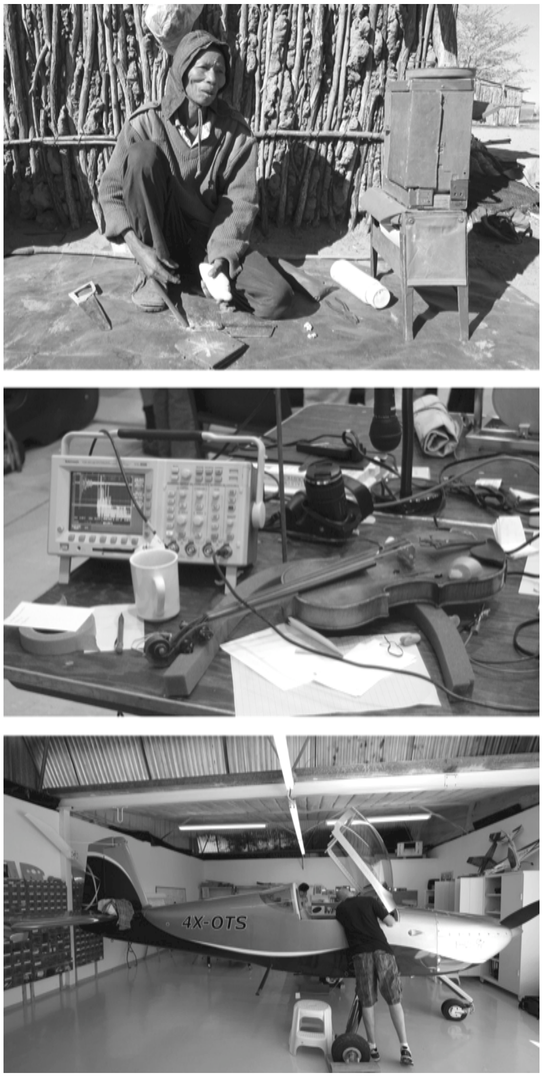

Figure 5.1: **Craft or technology?** Three examples of uncertainty. Top: an ostrich eggshell bead jewelry maker near his electric drill press in the African Kalahari desert, built with spare parts to accelerate production time. Middle: the science and craft of violin making is discussed at the Oberlin Acoustics Workshop in Ohio. Bottom: Tal Shahar's airplane in his garage, built using a kit and custom parts.

Hybrid objects have a long history in fantasy literature and mythology. Each of my projects, presented earlier, has deep conceptual roots. Early as the 1950s, the idea of hand-held smart devices, such as the FreeD, appeared in sci-fi literature. Cyril M. Kornbluth, in his short story "The Little Black Bag," describes a highly automated medical tool kit [1]. Later, in one 1987 episodes of *Star-Trek: The Next Generation,* we are first introduced to an "unusual-shaped wood-sculpting tool" that allows unskilled makers to sculpt in wood [2]. Hybrids of acoustic and electric instruments existed for many years before my explorations. A recent example is a digital tool used to simulate acoustic properties in the design of musical instruments [3]. Finally, even my Fused Craft project was preceded by *Kintsugi*, an ancient Japanese re-construction art, which transformed the meaning and values of a broken artifact by using gold as glue for the broken parts (see Figure 5.2).

Even with this history, my thesis defines a new creative space that articulates a hybrid contrast, or *hybridizes*, in the digital age. The conceptual justification for the projects is the conflicting movements within contemporary design: computational control and personal engagement. By defining this new space, I seek the integration of values from digital and non-digital practices, using technology to demonstrate alternative possibilities for a diverse design paradigm. For this reason, the studies presented in Chapter 2 and 3 are especially important in their support of my initial claims that tactile involvement is vital for achieving personal engagement, and that the introduction of the irregular, natural and unpredictable subsystems in digital mechanisms have important design potential.

Figure 5.2: Kintsugi, Japan, early 18th century (Edo period).
From *the art of repairing teaware | listening to leaves* website
http://listeningtoleaves.blogspot.com/2012/11/kintsugi-art-of-repairing-teaware.html

Comments by Panel of Experts

This dissertation required two phases of evaluation: first, each of the projects was evaluated with respect to its independent claims and contributions, although together all projects implemented the Hybrid reAssembledge concept; and second, evaluation of the concept itself by scholars. I therefore asked for comments and feedback for my Hybrid reAssembledge framework from a panel of HCI, design and craft experts. Their critiques are presented in this section. One group of comments sees my work as an important contribution that promotes human values alien to digital world. The second had a pragmatic concern. They felt that my work oversimplified things. They felt that I had constructed a dichotomy that was too sharp. But they, too, praised the technical quality of my work. I found the comments informative and helpful. Here I present them unedited.

Professor Gail Wight

Department of Art & Art History, Stanford University
http://art.stanford.edu/profile/Gail+Wight/

> *I found (your work) inspiring, sincere, and promising both for you and for the world at large.*
>
> *Your central thesis - that there is a largely unexplored and valuable terrain at the crossroads of hand-hewn traditional craftsmanship and emerging computational design and processes - is a deeply compelling idea. It proposes a gestalt rather than simply a new gadget, process, or single-purpose solution to a problem.*
>
> *Your examples are intriguing in their divergence from one another, making them good illustrations of your gestalt, expanding your audience's imagination of what might be possible at this crossroads. I'd like to touch on each of these examples briefly and then offer some overall thoughts.*
>
> *FreeD and Chameleon Guitar seem like the more evolved projects, being extensively researched and produced. They also differ from your other two examples in that the first is a tool and the second an instrument (a specialized tool). This puts the actual making back in the hands of your audience.*
>
> *Chameleon Guitar is an especially apt illustration, given the extreme digitization and miniaturization of musical equipment - everything from guitars and drums to mixers, amplifiers, and recording equipment. The modeling technology of algorithmic simulation may constitute a form of digital craft on its own, but it subsumes a personal physicality and eliminates the long and still-relevant tradition of the use of natural materials in music. Given that the outcome of reinstating acoustical resonance is immediately apparent, and given that the digital state-of-the-art is so rich in the field of musical instruments, Chameleon Guitar seems the strongest and most readily graspable ambassador for your hybrid gestalt.*
>
> *FreeD enters brand new territory and leaves the end-product less predictable and therefore more adventurous, in a way... The ability to add a handhewn touch to objects constructed with FreeD might seem superficial at first - simply a surface texture on an otherwise prescribed object. However, you make the important point that digital craft is also becoming more readily attainable. When someone can create their own CAD design and carve it with the mark of their own hand, the true abilities of your hybrid tool come to life. If your tool could work with natural materials (wood,*

clay…) this would bring the end product into dialogue with the long history of hand-crafted objects.

The Fused Craft is very different in that here you are designer, maker, and tool fabricator all in one. It's true that you could easily translate these two projects into tools that could be handed to an audience, as with FreeD. However, I appreciated that you took on the role of the craftsperson with these projects. You have a wonderful personal aesthetic, resonant with the natural forms and digital processes underlying your hybrid investigations. This resonance, and a glimpse into your own object-making, lend a sincerity and commitment to your overall thesis.

I did feel that these last two projects were less evolved than FreeD and Chameleon Guitar, beginning with the vague titles you assigned them. They both seem rich with potential, which I hope you'll pursue in the future. For instance, what can your digitally designed frameworks for baskets make attainable that might be otherwise unimaginable or structurally impossible? You seem to be heading in this direction, but the documentation didn't fully support a unique outcome of this hybridization, as elegant as your forms might be.

The broken vases also felt under-explored, yet filled with fascinating possibilities. The vase is a stunning form. Could this be applied to architectural elements? Furniture? Vehicles? Urban decay? There's a playful absurdity to this concept that broadens your thesis and offers a reparative approach. In this case, the balance in your hybrid sensibility takes on a subtle tilt toward a radically different future.

I'd like to comment that your approach toward a hybrid gestalt has a strong personal appeal for me. The Platonic separation of the material world from the world of ideas will probably always persist in some fashion. However, it belies our day-to-day experiences, especially as that experience pertains to learning and to making. It's difficult to untangle learning from making, perhaps impossible. The attempts to do so often result in indefensible social hierarchies (including slave labor), loss of integrity for both self and community, and an impoverished visual environment. The fusions you're creating have the ability to reinstate ways of thinking and being that would lend themselves to the opposite: egalitarianism, integrity, and a rich visual environment.

I believe that there's a strong gadget-appeal to FreeD and a high marketability for Chameleon Guitar, but this is where your other two *projects offer a less commercially viable approach to the same hybrid terrain.*

Stuart Kestenbaum

Director, Haystack Mountain School of Crafts
http://www.deerbrookeditions.com/stuart.html

I think your combination of digital fabrication and the hand is very exciting.

In the work that we are doing at Haystack.. I find that craft makers and artists bring a sensitivity to the materials that can sometimes be lacking in work that is digitally produced. This comes from a more tactile knowledge of materials - knowing how they respond, what the specific capabilities are, and the traditions and uses of the materials too. Developing work that makes use of this form of human ingenuity - the knowledge that is in our hands, our sense of touch - has great implications for bridging divides between our past and our future.

Dr. Glenn Adamson

Head of research at the Victoria and Albert Museum, tutor at the Royal College of Art
http://rca.academia.edu/GlennAdamson

The 3D restoration project seems the most aesthetically resolved and museum-friendly to me (not that those are necessary qualities for your research), whereas the FreeD seems like it might be the most expansive in technical terms.

You should be a little cautious about equating the handmade with 'personal narrative' - craft objects can be extremely generic and derivative (think of tourist objects), and mass-produced ones can acquire deep personal significance particularly later in lifecycles.

I also would encourage you to consider more explicitly the relation between your work and the currently fashionable concept of mass customization, which I am sure you have thought about. The prospect of automated personalization transcends questions of craft and raises more general questions of specificity. This can also be true in the execution of large numbers of units, which can be batch produced in very high numbers, but also unique (the tile works Royal Tichelaar Makkum is a good example). We published an interesting article on this in the Journal of Modern Craft by Joshua Stein, which you might find interesting [4].

Professor Mark D. Gross

Computational Design, School of Architecture, Carnegie Mellon
Universityhttp://mdg.code.arc.cmu.edu/

It would be easier to simply praise the work and move on, for I do indeed appreciate both the technical virtuosity that lies behind this abstract…, and I do value the approach.

The abstract begins by posing a dichotomy… I question this dichotomy. Most materials we use today in craft are engineered: paper, metal, plastics, even wood and clay are to some degree engineered. And we might say the same for machines: machines are 'just' complicated tools—a pencil is a very simple machine – certainly a mechanical pencil is a machine; knitting needles, maybe; a spinning machine more surely so. The new always seems more alien, but soon we accommodate the use of machines and tools into the practice of making things, and then they move into the realm of the familiar.

What the craft maker enjoys is not the experience of shaping raw material, but the exercise of skill and expertise in so doing. It's not the feel of the clay that gives the potter satisfaction, but the dexterity and control that s/he is able to apply in shaping the form.

… although it's true that handcrafted products are (to some degree) unique, I don't see in what way they "carry personal narratives." Even if the maker's personal story is somehow embedded in the product, the product does not tell the story; the story cannot be read. Only in the most poetic sense does the product carry a personal narrative.

Isn't (FreeD) the robotic version of Paint-By-Numbers? Which is to argue that the "expressiveness of manual carving" is valuable (to the craftmaker) to the extent that this expressiveness reflects control and skill. The pleasure and satisfaction obtained from any performing a task relates directly to the degree of mastery exercised therein. Making it easy doesn't make it better.

The Chameleon Guitar project takes a different position in the argument, one I find closer to my own heart.

I'm far more interested in the technical contributions that underlie this body of work, than the rhetoric of individuality, uniqueness, and inherent value of handwork in which it's dressed.

> *Not that the questions raised by this rhetoric are irrelevant, but the positions outlined in this abstract miss the mark. They do provide a starting point for a discussion that can enrich the field, and therefore we may be grateful.*
>
> *My own views are more toward seeing computational artifacts as resulting from a craft-like process. Electronic and computer music has benefitted from the willingness of its practitioners to engage in computational creation, also known as programming (and in the earliest days, also analog electronics).*

Closing Notes

There is so much richness in the real world, a richness that technology still fails to simulate. The feeling of the wind blowing, the authentic touch of a grain of sand, the surface patterns of an oak tree: these are all too complex to be easily modeled. Humans have always engaged with their craft and with nature, intimately creating within their environments. By harnessing the capabilities of technology and benefiting from the richness around us, we have historically developed a deep material cultural heritage.

Yet, in our quest for technological progress, we now put our heritage at risk. Human skills are very diverse, generaly much more than machines and computers. Designers use simulation and synthesis rather than authenticity, often relying on automatic technologies rather than manual operations. Thus, in many respects machines have replaced the craftsperson; plastic has replaced wood and clay; synthesizers have replaced acoustic instruments. Public discussion about design and technology rarely focus on subjectivity and culture, justifying this on the basis of the importance of technological progress.

There is meaning in making, which comes from one's playful relationship with the environment, where the qualities of meaningful practice result in a singular unique artifact. It is important to distinguish this from well-designed, promoted and advertised technologies and their products. In other words, I believe that contemporary design can benefit by embracing a hybrid perspective. While we should certainly enjoy technological development, we should nevertheless reserve territory for subjectivity, uniqueness, and imperfection. The more unique and special our environment is, the more unpredictable our interaction and experience with it should be. Therefore, we should consider investing in the design of artifacts and interactions that are local, one-of-a-kind, and perhaps unexpected. At the heart of my work is the integation of computetional technology, authenticity and uniqueness, seeking cultural richness and diversity.

A Personal Note: The Cutty Sark

The *Cutty Sark*, a British ship built in Scotland in 1869 to speed up tea delivery from China, is one of the only three remaining original clippers from the nineteenth century; today it is found on display in Greenwich, London. There is also a Cutty Sark model at a 1:115 scale, made of walnut, beech, and lime parts. Its fittings include burnished metal ports, white metal anchors, davits and capstans, brass wires, chains, pin nails and ladders. Varying diameters of rigging, cotton sails, and silk-screens are also part of this model. I built this when I was twenty years old. It took me three months to finish, and it is the most important thing I have made. I built it not to create a practical object, but to build simply for the sake of building.

Since early childhood, I built airplane plastic models, remote control cars, and wooden airplane models. I started with Lego machines, buildings, and cars. I built airplane models for years, learning how to create a complete facsimile from a blueprint and raw materials. I started building ship models at the age of fifteen, and I made five different models over the next five years. These were not working models, but rather models to put on the shelf. They looked great, with their wooden bodies, cotton sails, and wires. You could almost smell the ocean. You could almost see the sailors and the pirates.

It is almost seventeen years since I last built any ship. Working in engineering, looking for a stable profession, I did not realize that the joy of making things would become my life's work. In a sense, through working on my dissertation, I found for the first time in my life, a synergy between my digital profession as an engineer and a designer, and my youthful passion, my own Rosebud [5], my Cutty Sark. Hoping this research will touch others, it is first of all a personal jounrey of designing and making as self expression and personal growth.

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