Title
Making in Time: How Timescale Impacts the Experience, Outcomes, and Expressive Opportunities of Digital Fabrication

Author
Hirsch, Mare

Publication Date
2022

University of California
Santa Barbara

Making in Time: How Timescale Impacts the Experience, Outcomes, and Expressive Opportunities of Digital Fabrication

A dissertation submitted in partial satisfaction
of the requirements for the degree

Doctor of Philosophy
in
Media Arts & Technology

by

Mare E Hirsch

Committee in charge:

Professor Jennifer Jacobs, Co-Chair
Professor Yon Visell, Co-Chair
Professor Marko Peljhan
Professor Elliot Hawkes

June 2022

The Dissertation of Mare E Hirsch is approved.

Professor Marko Peljhan

Professor Elliot Hawkes

Professor Yon Visell, Committee Co-Chair

Professor Jennifer Jacobs, Committee Co-Chair

March 2022

Making in Time: How Timescale Impacts the Experience, Outcomes, and Expressive Opportunities of Digital Fabrication

by

Mare E Hirsch

Acknowledgements

Thank you to my co-advisors, Jennifer Jacobs and Yon Visell. I will be forever grateful to you both for helping me understand and appreciate the way art and technological research can work together to contribute something meaningful to the world. The clarity of purpose I leave with is a reflection of the time, resources, and support you both lent along the way. Thank you, also, to my committee members, Elliot Hawkes and Marko Peljhan, who continued to expand my understanding of what was (and is) possible in the work we do.

Thank you to all the wonderful people in the Expressive Computation Lab and RE Touch Lab, past and present. Your collaboration and feedback has helped to shape my work in important and wonderful ways. Thanks as well to the greater Media Arts & Technology Program community—which comprises some of the most interesting, talented, and caring people I've ever met. Thanks especially to all my collaborators across UCSB and beyond, especially those in EEMB. Much of the work we did together will continue to develop and expand as I move on from UCSB.

Finally, thank you so much to my family and friends for the truly incredible and tireless levels of support during this time. To my mom, Beth, and dad, Ed, thank you for making this entire journey possible. You both believed in me even when none of us was quite sure what I was doing and where it was heading. I will never forget the time, patience, and opportunity that you've given me. To my wonderful brothers, Dan and Patrick, thank you both for always being my biggest cheerleaders, encouraging me, and distracting me when needed. Thank you to my partner, Elizabeth, for getting through this insanity together, for being an unwavering source of support and validation, and for always humoring me when I needed mall pretzels. And, of course, thank you to my dog Stevie Von Steuben–you're a very good girl.

Curriculum Vitæ
Mare E Hirsch

Education

2022	Ph.D. Media Arts & Technology (Expected), University of California, Santa Barbara.
2014	M.M. Shepherd School of Music, Rice University
2012	B.M. Conservatory of Music, Lawrence University

Publications

Re:Forming — Body, Agency, Technology Mare Hirsch, Sam Bourgault, Philip Kobernik, brooke smiley Center Stage Theater, Santa Barbara, CA 2020

SK3TCH: Fast, Interactive 3D Printing via Liquid Crystallization Mare Hirsch, Jennifer Jacobs, and Yon Visell. 2019. ACM Symposium on Computational Fabrication,Pittsburgh,Pennsylvania.(Conference ShortTalk)

On Fabrication Mare Hirsch MADE Exhibition Catalog 2019

Abstract

Making in Time: How Timescale Impacts the Experience, Outcomes, and Expressive Opportunities of Digital Fabrication

by

Mare E Hirsch

Digital fabrication is a rich space for creative production. Many computational tools, including those that support automation, precision, generativity, and parameterization, have been developed to support creativity in fabrication. Emerging digital fabrication tools hold the potential to further expand practices and experiences in digital fabrication, by facilitating more fluid, interactive, and experiential forms of making, in ways that may resemble tools for dynamic digital drawing or real-time audiovisual performance.

However, digital fabrication involves physical materials that introduce constraints that are not present in creative processes involving strictly digital media. For example, creative digital fabrication practices are constrained by the substantial fabrication times that are required. New technologies, tools, and workflows that circumvent such challenges could enable new forms of making, and expand expressive opportunities for creation, by allowing makers to engage more fluidly and interactively with machines and with physical media.

This dissertation investigates this emerging space of opportunity through three key questions: (1) How do current digital fabrication workflows support or constrain aspects of efficiency, iteration, interaction, and expression? (2) How do fabrication modalities with different timescales shape the experience and outcomes of making? (3) How can shorter fabrication timescales be supported given the time constraints of digital fabrication, especially additive digital fabrication? These questions correlate, sequentially, to

the three main chapters of this dissertation.

A first part of the PhD research applies qualitative research methods in examining and analyzing digital fabrication workflows used by professional designers. This analysis characterizes the ways that digital fabrication practitioners apply their knowledge of materials, develop custom software, and leverage incomplete design representations to realize creative and commercially viable products. The analysis highlights the ways that expertise with materials and machine processes are applied in expressive practices that yield feasible products, and how designing viable customizable products influences decisions about geometry, materials, and manufacturing processes, while accounting for costs, effort, and marketability.

The next part of the thesis applies autobiographical research methods in order to investigate how unconventional digital fabrication workflows can facilitate interactive making processes. This research highlights the potential for custom software to integrate digital fabrication with real-time interaction. The results demonstrate how shared human and computer control of fabrication processes can expand opportunities for creative expression, and how constraints of time scale impact the development of digital fabrication workflows for interactive art.

Motivated by such opportunities, and the temporal constraints arising in conventional 3D printing processes, the third part of this dissertation presents a novel additive digital fabrication system, the Liquid-Crystal Printer (LCP), that leverages supercooled liquid solutions to enable rapid 3D fabrication. This printing process is based on the deposition and rapid crystallization of supercooled sodium acetate trihydrate solution. The results illustrate how the parameters of this process provide unique opportunities for controlling the attributes and aesthetics of 3D printed artifacts.

This dissertation contributes new knowledge and methods that highlight the influence of process constraints, including timescales for digital fabrication, on workflows used by professionals designers and artists, and the works they create. It also highlights the potential for new processes and interactive techniques that can leverage emerging technologies for rapid fabrication, and demonstrates the expressive opportunities that such systems can provide.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Digital fabrication is now a familiar feature of a variety of creative practices. Today, digital fabrication tools and machines are used by designers, fine artists, sculptors, architects and media artists [7]. With the increased adoption of digital fabrication in these creative fields, new tools and software workflows have been developed to allow for high levels of complexity and expressiveness in the design and fabrication of 3D artifacts [8]. As a sign of this trend, art and design departments around the world have embraced digital fabrication as a component of their curriculum, and it is now common to see a 3D printer in the same studios that house 2D printers, vinyl and laser cutters, along with the computers that allow users to design for and control these machines [9].

As this trend demonstrates the creative possibilities of digital fabrication outcomes, a new space of expressive opportunity is now within view—one where the process of making can rely on the design affordances of computational tools *and* support fluid, direct, and interactive modes of making like those that have long been a key feature of manual craft making. What creative possibilities would be supported if we could interact with 3D printers in the way we interact with computationally-augmented brushes in digital drawing? What new design considerations would we explore if the process of digital fabrication took a form similar to dance or musical performance? With new workflows, materials, and interfaces, digital fabrication has the potential to go beyond current workflows and begin supporting more experiential forms of making—where shorter timescales, like those we see in manual and direct forms of making, allow for greater degrees of interactivity and expressive opportunities. Re-imagined digital fabrication workflows could lead to the creation of 3D objects in real-time sessions and live performances that extend a lineage of creative work that has included sculpture performance, drawing machines, generative art, and human-robot collaborative creation.

These experiential forms of digital fabrication need to support kinds of engagement discussed by McCullough, in which the medium of making stirs our imagination, provides an effect on our senses, and commands our attention [10]. The crucial conceptual and technological advancement required to support this kind of engagement in digital fabrication is to break out of the confines of discrete periods of passive making. Periods of passive making are characterized by a process in which a user sends toolpath instructions to a fabrication machine and waits idly for the machine to execute those commands. Moving away from this form of making towards continuous, real-time control over the fabrication process would move digital fabrication towards the best practices for high degrees of engagement suggested by McCullough.

To realize these engaged, real-time forms of digital fabrication, we must realize digital fabrication workflows with shorter timescales, especially for highly time-constrained forms of making, such as additive digital fabrication [4]. This requires overcoming challenges with the current materials and software workflows used in digital fabrication—which are designed for longer, off-line fabrication timescales. To begin addressing these challenges, it is important to understanding the way timescale impacts aspect of efficiency, iteration, interaction, and expressiveness in current digital fabrication workflows. This dissertation represents a body of work that aims to understand the role of time in digital fabrication and support more expressive and interactive workflows by

1. Analyzing the use of digital fabrication tools in the workflows of professional designers to understand the way timescale impacts workflow features, including efficiency, iteration, interaction, and expressive opportunities.
2. Engaging in artistic research that draws on methods from autobiographical design research to highlight opportunities for new technologies in digital fabrication workflows that support interactive control and performance through the creation of time-based artworks.
3. Developing new materials and workflows for digital fabrication that support shorter timescales in highly time-constrained form of digital fabrication: additive digital fabrication.

1.1 Digital Fabrication: Drawing Parallels to Computer Music and Computer Graphics

A key affordance of digital fabrication is the integration of computational design tools in the making process. Digital fabrication workflows include computational tools that feature elements of precision and automation, generativity and randomness, and parameterization [11]. These computation tools are also important features in other digital media, such as computer music and computer graphics. However, computer music and graphics workflows are no longer subject to the slower, offline timescales that digital fabrication is currently constrained to. This supports forms of highly engagement creation that inspired the new vision for digital fabrication discussed at the beginning of this introduction. The fields of computer music and animation demonstrate how affordances of short timescales, such as interactive control and live performance, grew from advancements in technology and re-imagined workflows. Between 1950-1970, computer music was essentially an offline creative practice; composers wrote programs in software that would often take hours to compile on highly expensive, state-of-the-art computers, in which only a few minutes of music were generated [12]. The 1980s ushered in inexpensive digital chips and microcomputers that enabled real-time generation of computer music and, by the 1990s, programming real-time computer music was feasible from many more generalized programming languages. Today, interactive programming languages, such as those featured in software like Max/MSP and SuperCollider, as well as modern digital audio workstations (DAWs) have made real-time computer music a common feature of live performance [13] [14] [15].

Rendering computer graphics follows a similar trajectory to the composition of computer music. In the 1970s, developments in arcade video games produced some of the first real-time 2D graphics. By 1988, advances in graphics boards ushered in dedicated, real-time 3D graphics processing units (GPUs) that ran in parallel to the central processing unit (CPU) [16]. Through the 1990s and 2000s, GPUs developed to the point where offline-rendering could achieve photorealism and real-time graphics could simulate photo-realism on high-end rendering systems [17]. The performance of real-time graphics engines made it possible for new, real-time-centric graphics software to become a creative field of its own. Artists utilize real-time rendering software such as TouchDesigner and Jitter to create graphics for live performance, often in conjunction with live music and dance [18] [19] [20].

The development of technologies that enabled computer music and graphics to enter live performance venues also enabled new forms of expressivity—blurring the lines between composition and improvisation. Artists leverage the flexibility of real-time tools in order to be responsive to their environment and the dynamics of the performance.

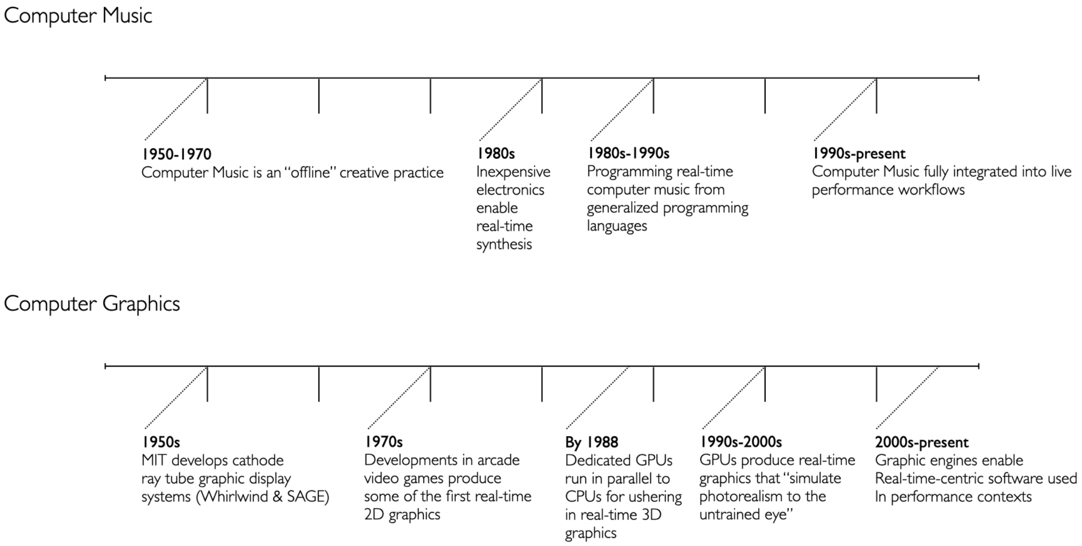


Figure 1.1: Timeline of technological development in Computer Music & Graphics. Advancements in technology enabled shorter durations between input and output, ultimately leading to real-time control over sound synthesis and graphic rendering.

These tools enable instantaneous reactions and decisions based on feedback from both the output of their systems as well as collaborators or other external signals and data.

1.2 Current Workflows for Interacting with Digital Fabrication Tools

The majority of users engaging in digital fabrication do so through a canonical workflow that has been dominant for the past 30 years. First, a user creates a digital 3D model with computer-aided design (CAD) software. This 3D model is then processed by an intermediate software to translate the 3D model into a list of instructions for a fabrication machine–such as a slicer program that generates a G-Code file for fused deposition modeling (FDM) 3D printers. This intermediate stage allows the user to configure settings for the fabrication process, such as specifications about support structures, density, speed, and resolution. The resulting instruction file is then sent to a machine where the object is created, start-to-finish, in a single session. Depending on the scale and resolution of the 3D model, fabrication can range from hours to days.

In recent years, interest in creating more interactive ways to engage with digital fabrication tools resulted in new workflows that enable the user to influence aspects of the machine behavior during the fabrication process [4] [21]. I categorize these new workflows into three primary categories: *turn-taking*, *direct manipulation*, and *experimental workflows*.

In turn-taking, the user "decreas[es] the interaction unit to single requests" which allows her to provide feedback after each input [22]. In addition to lowering the stakes of compounding errors, turn-taking allows for a degree of improvisatory expressivity in digital fabrication, as the user can make design decisions between each interaction unit of the fabrication process. This reduction of the interaction unit maintains the structure of discretized-passive making, where the user waits idly for the machine to complete a toolpath instruction, but it does reduce the duration of each instance of passive making.

Direct manipulation"further decreas[es] the interaction unit to a single feature", resulting in a tighter feedback cycle between the user and the output of the system [22]. These approaches differ from strictly manual forms of fabrication, such as handheld 3D printer pens, since they still rely on the affordances of computational tools. The increase in feedback resolution offers the potential for even greater expressivity compared to turn-taking, though the implementation of direct manipulation on machines such as consumer-grade 3D printers is hampered by the relatively long fabrication timescales. As a result, examples of direct manipulation have often utilized novel, experimental fabrication interfaces and machines that move away from conventional fabrication machines and the associated mode of discretized-passive making [4].

A third experimental approach to interactivity in digital fabrication involves more radical departures from standard digital fabrication workflows. Artists and researchers have reversed the role of human and machine, such as scenarios in which printing instructions are communicated by the machine to the human who then acts as the printer, depositing material along the prescribed toolpath [6]. While this approach is aimed at "those who prefer chance to control", it also provides a dramatically heightened form of expressivity in digital fabrication, as the human printer is able to make real-time decisions at the instant of deposition and choose how faithfully to adhere to the fabrication instructions.

1.3 Interactive and Real-Time Control in Digital Fabrication: Challenges and Opportunities

Despite the recent focus on, and advances in, interactive digital fabrication, the divide between the processes for designing and constructing 3D artifacts remains large. This divide results both from the complexity of conventional digital fabrication workflows as well as fabrication material constraints. Digital fabrication workflows often require "numerous steps to go from design idea to physical prototype"—often involving the use of multiple separate software tools [4].

Material properties often lead to slow fabrication speeds which add to the temporal divide between input and output. FDM printers use thermoplastics that are constrained by cooling times that limit printing speeds to approximately 50mm/s [23]. Stereolithography (SLA) 3D printers, which are gaining popularity, often print faster than FDM printers by virtue of a faster phase transition in photo-polymerizing resins than thermoplastics. However, a number of additional constraints on STL printing make real-time control infeasible, such as the need to move the printed part in an out of resin tanks during printing and the reliance on matrixes of support material to bolster the printed object to the inverted print bed [24]. In limiting the speed of fabrication, material constraints limit the system's opportunities for real-time control.

Recent work has demonstrated that experimental digital fabrication prototypes, featuring simplified workflows and unconventional material, can bring physical input and output closer together [4]. These experimental prototypes feature devices that take real-time physical input to fabricate physical forms. Decreasing the divide between input and output supports digital fabrication workflows that move towards the forms of direct interaction with materials and tools inherent to traditional craft.

Despite the success of these experimental prototypes in reducing the divide between design and construction, [4] highlight challenges that could inform future research in interactive fabrication. These challenges include the potential for unexpected results, the material waste resulting from unexpected results, and the difficulty of creating digital representations in digital fabrication when using unconventional materials.

In addition to new research directions, interactive digital fabrication with real-time input creates new opportunities for digital fabrication as an interactive art form. As characterized by [25], interactive art is an event in which the final formation results from the participatory behavior of "viewers, performers, executors or (co)creators of an artwork-event". Reducing the time and workflow complexity between input and output of digital fabrication could support participatory behavior in ways that mirror those of other interactive digital art, such as those of computer graphics and music previously discussed.

1.4 Structure

This thesis is organized in six chapters: this introduction, a review of related work, three chapters that are currently in preparation for submissions to publication venues, and a concluding chapter summarizing the thesis.

Chapter 2 presents a survey of related work relevant to an understanding of the way time impacts digital fabrication. It provides an overview of (1) computational tools in digital media—such as algorithmic art and design, interactivity, and human-machine collaborative practices, (2) interactive digital fabrication—including aspects of interactive interfaces, direct manipulation, and human-machine collaborative digital fabrication via computationally mediated direct manipulation, and (3) experimental digital fabrication—such as that depart from conventional design and production workflows and digital fabrication with experimental materials and processes.

Chapter 3 presents a study of thirteen professionals who use digital fabrication for low volume manufacturing of commercial products. From interviews with each participant, I describe and categorize the workflows used to produce nine products. I show how participants' expertise of materials, tools, and fabrication shape their workflows and lead to (A) developing custom software, (B) relying on incomplete design representations, (C) anticipating of product feasibility, (D) making interdependent decisions across geometry, materials, and manufacturing operations, and (E) optimizing for cost, labor, and marketing. From these findings, I present implications for future work in building digital fabrication systems that support people in both designing and manufacturing products.

Chapter 4 presents four instances of artistic research involving digital fabrication workflows that draw on methods from autobiographical design research. I present a characterization of these digital fabrication workflows and show how opportunities for creative expression and interactivity were created through a combination of custom software, combining human and computer control of fabrication machines, and optimizing for the time constraints associated with interactive artworks. I conclude this chapter with a discussion of opportunities for research into new material and software technologies identified by my autobiographical design research approach.

Chapter 5 presents a new method for rapidly 3D printing structures via deposition and crystallization of supercooled solutions of sodium acetate trihydrate (NaCH3COO.3H2O) near room temperature. In this chapter I characterize the mechanical behavior of the deposition method and provide a mathematical model for printing freestanding inclined columns. I demonstrate artifacts produced through two printing modalities: direct extrusion and layered deposition. I conclude this chapter with methods for modifying the mechanical and optical properties of 3D printed sodium acetate trihydrate and potential directions for future work.

Chapter 6 summarizes the primary findings of this thesis, discusses the implications of these findings, and suggests opportunities for future research.

1.5 Contributions

This dissertation makes the following primary contributions:

1. An analysis of the digital fabrication workflows used by professional designers. From this analysis I present:
    - A classification of nine product workflows from thirteen professional makers that demonstrate how participants' expertise of materials, tools, and fabrication shapes their process.
    - A characterization of the way participants' material knowledge informs in-house software development and the way incomplete physical or digital design

   representations are combined with prototyping workflow processes to create viable products.

   - An understanding of (A) how material and machine expertise enables practitioners to anticipate product feasibility, (B) how designing viable customizable products requires interdependent decisions across geometry, materials, and manufacturing operations, and (C) how optimizing for cost, labor, and marketing shapes workflows.

2. An analysis of the digital fabrication workflows used in my own creative practice. In this analysis I use a autobiographical design research methodologies to present:

   - A classification of four creative projects that demonstrates the way digital fabrication workflows used to produce interactive artwork differs from those of conventional design processes in digital fabrication.
   - A characterization of (A) how custom software enabled the creation of real-time interactions with fabrication machines, (B) how combining human and computer control leads to creative and expressive opportunities in digital fabrication and, (C) how the time constraints of interactive art informed the prototyping and evaluation processes of digital fabrication workflows.
   - An identification of opportunities for new material and software technologies as potential future research opportunities.

3. A novel, rapid additive digital fabrication system, the Liquid-Crystal Printer (LCP). In discussing this research, I present:

   - A characterization of the crystallization behavior of supercooled sodium acetate trihydrate when deposited from a range of heights and deposition speeds—

as well as the impact these parameters have on 3D printed artifacts produced through liquid deposition.

- A demonstration of freestanding 3D printed inclined columns and a mathematical model that describes the relationship between the printed column's length and angle of incline.
- A demonstration of two methods for 3D printing with the LCP—direct extrusion and layered deposition—as well as artifacts produced through both methods.
- A demonstration of two methods for modifying the mechanical and optical properties of the printed structures: thermal tempering to increase fracture strength and material mixing to easily alter the color of the printed structure.

Chapter 2

Background

This chapter provides a survey of work pertinent to contextualizing and understanding the research I present in chapters 3, 4, and 5 of this dissertation. In particular, the following discussion of prior work in computational digital media, interactive digital fabrication, and experimental digital fabrication address the research presented in chapters 4 and 5. I include an additional background section in Chapter 3 that provides further information on prior work related to computational design and fabrication workflows and digital fabrication systems research.

1. **Computational Tools in Digital Media**: Artists, designers, and researchers have developed and implemented software that supports precision and automation, generativity and randomness, and parameterization in the creative process[11]. The use of these tools highlights opportunities for expression when control of the making process is shared between human and machine. The use of computational tools supports creative practices that can be data-driven, algorithmic, and generative. These computationally-aided practices result in creative output that includes audiovisual pieces and performances, physical artifacts, and interactive artworks.

2. **Interactive Digital Fabrication**: Human-Computer Interaction (HCI) researchers in interactive digital fabrication have developed interfaces, materials, tools, and machines that aim to foster opportunities for manual intervention in digital fabrication workflows. One motivation for this research is reintroducing aspects of traditional craft into digital fabrication, where the relationship between physical input and output are more closely linked. In doing so, interactive fabrication researchers have developed systems that allow for shorter periods of time between between user input and machine output, with the aim of integrating the user's agency into the typically autonomous nature of digital fabrication tools.

3. **Experimental Digital Fabrication**: Researchers, theorists, and practitioners of digital fabrication have investigated forms of making that break or subvert conventional digital fabrication modalities. They do so by re-imagining the relationships between humans, tools, materials, and environments. Experimental and speculative approaches to digital fabrication define new design spaces for creating physical artifacts, generate new theories and techniques of making, and provide critical reflection on the implications of conventional forms of making the individual and societal level.

2.1 Computational Tools in Digital Media

Historically, incorporating high degrees of complexity in art, such as mimicking the behavior of the physical world, required a mastery of manual practice that required painstaking detail and repetition of tedious, low-level tasks [26]. Generative artists have looked to approaches from engineering and computer science to automate these processes by relinquishing some creative control to generative algorithms, such as Perlin noise, reaction diffusion, L-systems, and geometry instancing. These processes have been implemented at the pre-fabrication design stage as well as during the process of fabricating physical objects.

2.1.1 Computational and Algorithmic Processes in Digital Art

Artists that use computational tools often, such as generative and algorithmic art, drawing attention to the underlying processes that govern the resulting form, structure, and aesthetics of the art work [26]. In the mid-twentieth century, artists formed research groups, such as Groupe de Recherche d'Art Visuel (GRAV), and learned to use early programming languages, such as Fortran and Basic, to investigate ways of producing artifacts that leverage algorithmic processes [27]. These investigations yielded artwork in a variety of media, and were especially influential in visual art, where artists created algorithmically-generated images that highlight geometric permutation and variation. In the work of pioneering media artist Vera Molnár, creative control is shared between the human and machine as a the computer software written by the artist governs the geometric permutations of the selected geometry. This approach, which Molnár describes as "the conversation method" avoids premeditated designs and facilitates tuning the algorithms "as the works unfold, favouring an instinctive method that enables greater receptiveness to the unpredictable" [28]. More recently, Nervous System utilize biologically-inspired algorithmic processes to fabricate 3D objects, such as the 3D printed *Floraform Sculptures*, in which the form of the structure is created through the "development of surfaces through differential growth" [29].

These examples demonstrate a form of making in which the artist maintains control over the structure and authoring of algorithmic processes but relinquishes specific control over mid- and low-level features, such as the exact geometric permutations and transformations that occur. In place of the artist's direct control, chance and noise operations often govern the rendering of these mid- and low-level features. Often, algorithms are authored offline and executed at any arbitrary moment the artist decides. The execution can range from near-instantaneous renderings of a digital image to slower processes such as animations and plotter printing. In each case, once the algorithmic process is executed, the artist and audience observe as rendering occurs in accordance with the established set of algorithmic rules.

Given the temporal flexibility of rendering artwork with computational and algorithmic processes, artists often elect to drawn attention to the underlying rules and processes generated by the computational tools they use. These time-based artworks unfold in real-time—during which a system is "set into motion with some degree of autonomy contributing to or resulting in a completed work of art" [26]. The time-based nature of these systems highlight the emergence and evolution of form without manual intervention from the artist. Through his software *Path*, Casey Reas constructs an environment for creating generative artworks that visualize Valentino Braitenberg's notions of the evolution of nervous systems and artificial life. The software enacts an evolving process of line drawing according to Braitenberg's principles that can be run and observed in real-time [30].

2.1.2 Algorithmic Art with External Inputs

Artist working with computational tools have included data from external inputs in the systems they create. These external inputs can range from datasets that influence the algorithmic process to living creatures who's behavior functions as input into the computational authoring system.

In his work *Nowhere*, a "sculpture in the making", Ralph Baecker utilizes real-time data from internet search engines to control the CNC carving of a block of PU-foam [31].

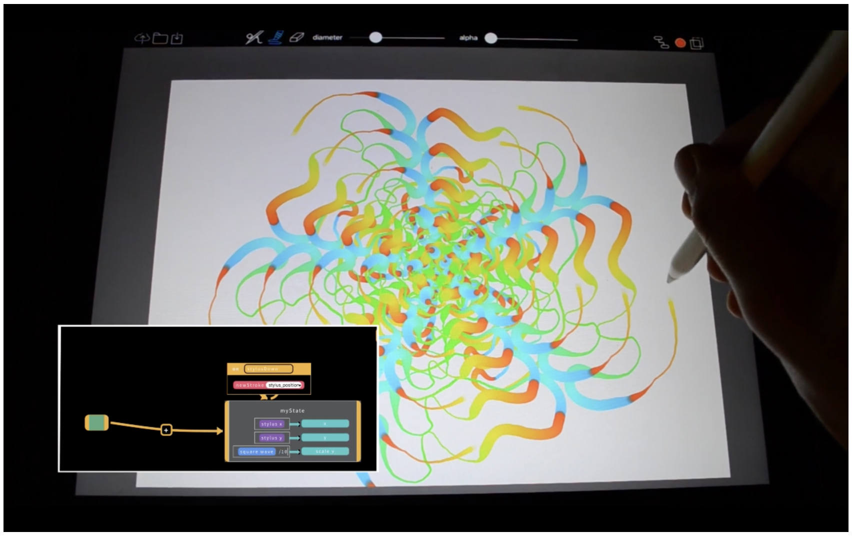


Figure 2.1: Computationally augmented digital drawing with Dynamic Brushes [1].

Similarly, David Bowen shares creative control over toolpath instructions with a collection of flies in *Fly Carving Device*—a time-based, generative sculpting piece in which blocks of foam are carved by a CNC router that is controlled by sensors monitoring a collection of living flies [32].

Like the examples discussed in 2.1.1, artists using computational tools with external inputs include pre-defined algorithmic rules that dictate the process of authoring the artwork. However, once the rendering initiates, the external input continues to influence the mid and low-level features of the artwork. As a result, artworks pieces involving external inputs are time-constrained by the sample rate of external input data, such as the frame rate of computer vision systems monitoring objects moving in physical space or the availability of new events in incoming data streams. Within these time constraints, the artist has a degree of control in authoring the temporal qualities of the algorithmic artwork—such as defining the data-transfer protocols and sensor sample rates.

2.1.3 Collaborative Digital Art

In developing and implementing algorithmic art with external inputs, artists have created computational tools that support increasingly sophisticated forms of interaction between the computational system and artist. These forms of interaction create scenarios in which the computational system and the artist appear to work collaboratively in the creation of digital art.

In creative systems like Jennifer Jacobs' *Dynamic Brushes* (Fig 2.1) and Yuri Vishnevsky's *Silk*, an artist engages with computationally augmented digital drawing tools[33][1]. The computationally augmented tools produce generative behavior beyond the input gestures of the artist—such as instancing an input stroke and applying stylized processes of transformation and rotation.

In the last decade, machine learning—and especially the use of generative adversarial networks (GANs)—has become a familiar feature of the digital art landscape [34]. GANs are frequently trained on large corpora of images in order to generate new "images that are related to the reference images" [35]. This form of generative art allows the artist to maintain control over defining the model parameters and selecting the corpus of training images but turns over control of the training and synthesis to the machine.

Machine learning tools have also supported human-machine collaborative settings for digital art. In *Drawing Operations*, Sougwen Chung uses machine learning to control the movement of a robot arm by training a neural network on input from her own drawing gestures (Fig 2.2). Together, the robot and artist sketch on the same canvas, with the artist responding to the robot and the robot behaving autonomously [2]. In a work for dance and digital animation, Wayne McGregor and researchers from the Google Arts & Culture Lab created *Living Archive*, a AI-human collaborative dance system in which the AI tool, trained on 25-years of McGregor's choreography, detects the poses of the human

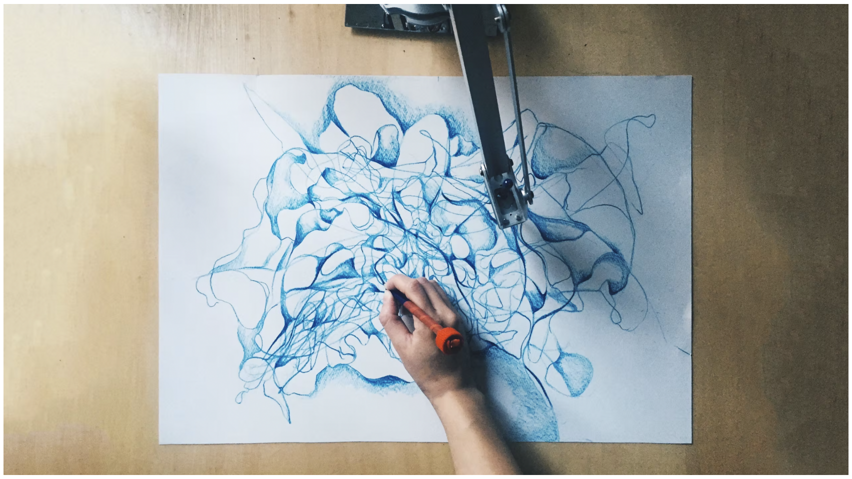


Figure 2.2: Hybrid human-robot drawing in Sougwen Chung's Drawing Operations [2].

dancer through a camera, predicts what will come next and generates choreography for the virtual agent that is dancing with the human [36].

2.2 Interactive Digital Fabrication

In order to create new opportunities for interaction in digital fabrication that resemble the real-time interactions of other digital media, the time between user input and machine output needs to be short enough for users to feasibly make decisions that impact the results of each step in the fabrication process. As discussed by Mueller, most digital fabrication workflows require objects to be fabricated in a continuous, uninterrupted process that can take hours or days [22]. Recent work in interactive digital fabrication has introduced new approaches for decreasing the delays in feedback and fostering opportunities for users to gain control during the fabrication process. Based on the approaches taken by HCI researchers, work towards this goal can be classified in three areas:

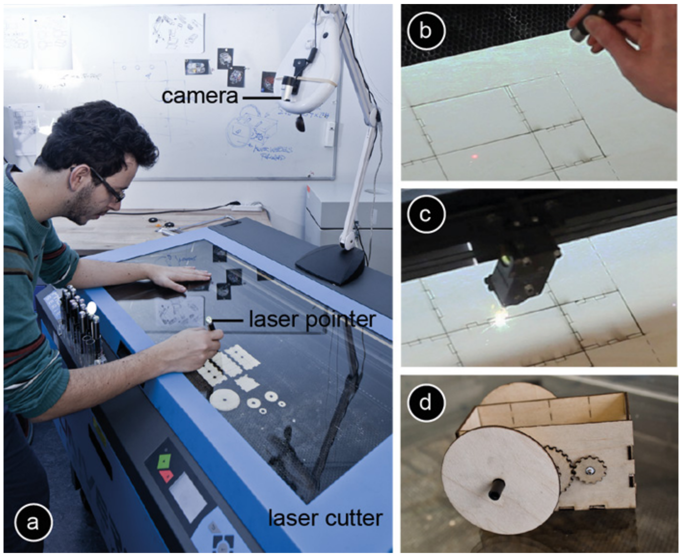


Figure 2.3: Interactive interface for digital fabrication via laser cutter and drafting table metaphor in Constructable [3].

2.2.1 Interactive Interfaces for Existing Digital Fabrication Machines

Existing digital fabrication machines, such as 3D printers and laser cutters, put physical and conceptual distance between the user from the fabrication process. In physical space, objects in these machines are typically fabricated in isolated build areas that are inaccessible to the user. In conceptual space, the design of the object typically needs to be defined in advance as the fabrication process runs from start to finish without interventions from the user.

In *Construcable*, Mueller et al. address these limitations by developing a new interface for digital fabrication via laser cutter in which the user embraces a drafting table metaphor and controls each cut made by the laser cutter through a hand-held laser pointer (Fig 2.3) [3]. This approach to interactive digital fabrication allows for manual intervention at each step of the fabrication process–reducing the time between user input and machine output–and pairs the precision of machines with the expression of human gestures.

Peng et al. take a different approach to decreasing the distance between the user and the fabrication process. In *RoMA*, where a designer uses an augmented reality CAD editor to concurrently design and fabricate physical objects, a 3D printing robotic arm shares a design and build space with the user. The user generates CAD models through an augmented reality editor, where finished features of the design are communicated to the robotic arm allowing for concurrent design and fabrication [37]. The printed features act as a reference for the user as new features are designed. By reducing the time and blending the lines between design and fabrication, the user and the robot share control in a fluid manner. The user can interrupt the printer as needed or turn over full control to the robot to finish printing. Additionally, by removing the design and fabrication process from computers in fixed locations and fabrication machines with fixed build areas, the user and robot are able to design and fabricate objects in-situ.

2.2.2 Real-time, Direct Manipulation Interfaces for Digital Fabrication Machines

While interactive making with common digital fabrication has been demonstrated, real-time control of machines like 3D printers and laser cutters is limited by the slow nature of the fabrication process. These time constraints, due in part to thermal material properties that dictate maximum toolpath speeds, preclude a user's direct manipulation and expressive control of fabrication tools like the form of control inherent to craft making through direct control [38]. The examples of direct manipulation in digital fabrication presented below differ from the manual use of tools like handheld 3D printing pens in that they combine aspects of computational tools and design alongside the real-time nature of direct manipulation.

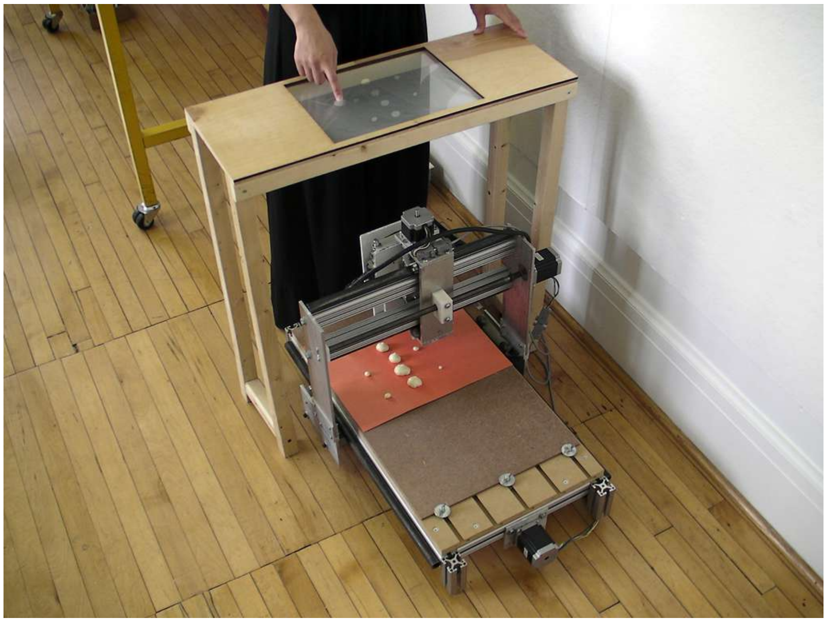


Figure 2.4: Shaper, a three-axis CNC machine that deposits expanding foam controlled by sketch-like gestures on a touch screen [4].

In *Interactive Fabrication: New Interfaces for Digital Fabrication*, Willis et al. reclaim aspects of the creative process that are supported by direct manipulation. They present a series of experimental digital fabrication scenarios and interfaces that remove or decrease the division between the 'designer' and the 'constructor' of artifacts. These prototypes include *Shaper*, a three-axis CNC machine that deposits expanding foam controlled by sketch-like gestures on a touch screen (Fig 2.4), *Speaker*, an interactive sculpting device which uses sound from the user's voice to push and bend a wire into a simplified sound wave contour, and *Cutter*, hand-held hot-wire cutter that records the way a user shapes a foam block and generates a digital model of the resulting foam artifact. In each of these examples the reduction in the temporal divide between user input and machine output enables direct manipulation. This direct manipulation reintroduces the user's creative control into the fabrication process by supporting "new creative possibilities for early stage prototyping, experimental form, improvisational fabrication" [4].

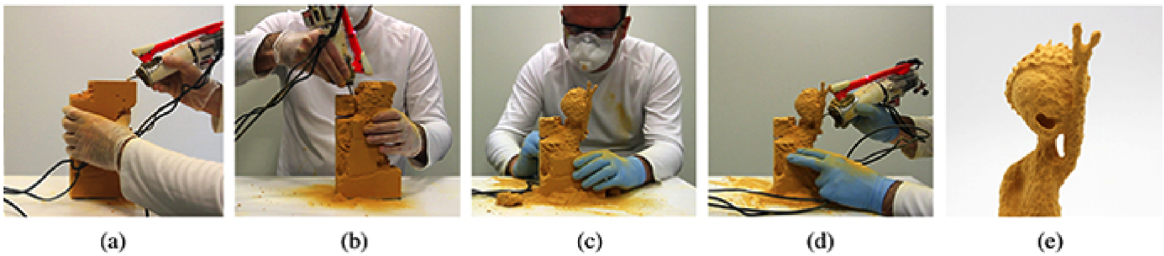


Figure 2.5: FreeD, a handheld milling device that guides the user's fabrication in accordance with a predefined 3D model [5].

Tian et al. address the question of direct manipulation and control by focusing on a system that empowers novice and expert users alike. In *Turn-by-Wire*, a CNC lathe is combined with real-time, haptic control to modulate both position and force and foster a variety of 'interaction metaphors'. In particular, the interface aims to reduce the "extreme" divide between the user and software-controlled lathe through a scenario in which the haptic interactions "communicate intent, perceive state, and acquire technique during the fabrication process" [39]. The immediacy of both the control and feedback in the Turn-by-Wire CNC lathe setup helps to recreate the kind of expressive, direct manipulation that occurs in traditional, analog lathe operation.

2.2.3 Collaborative Digital Fabrication via Computationally-Mediated Direct Manipulation

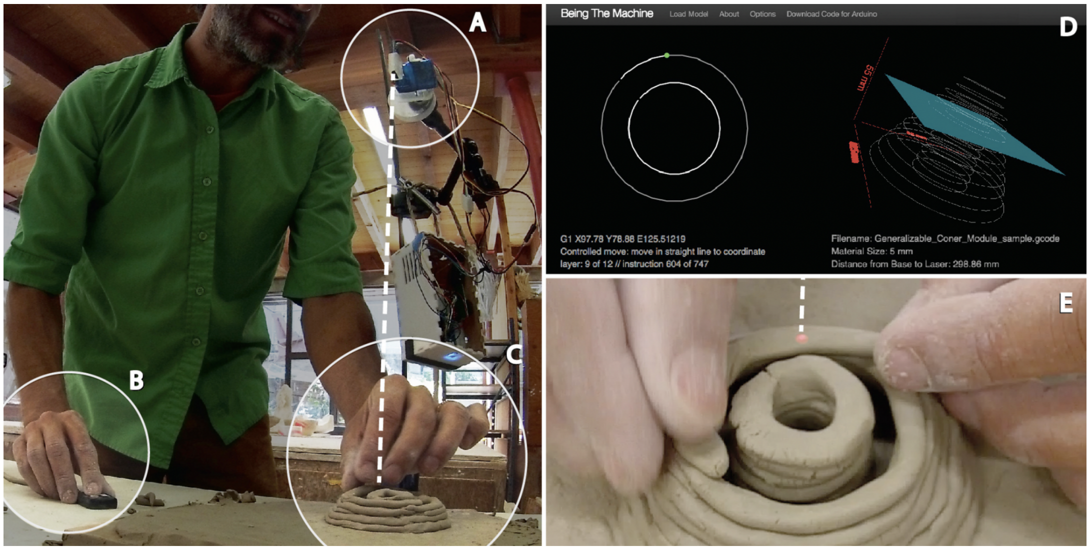
Just as controlling digital fabrication machines through interfaces with direct manipulation aims to lessen the divide between human input and machine output, HCI researchers have also sought to lessen the divide between digital fabrication and handcraft. In doing so, new systems have been developed that allow users to engage directly with the fabrication process in a hands-on way while still leveraging the precision and support of computational control. In this way, users can engage, in real-time, with the expressiveness of handheld tools and the context of digital fabrication.

In *FreeD*, Zoran et al. develop a handheld milling device that guides the user's fabrication in accordance with a predefined 3D model (Fig 2.5). To do so, the system provides feedback to the user when the milling bit approaches the boundaries of the model. This system optimizes for user agency by harnessing the "free expression of handcraft" within the "boundaries of established CAD systems" [5].

Mueller et al. take a more experimental approach to computationally-mediated direct manipulation. In *FormFab*, they introduce a system of "formative fabrication", in which a user designs the geometry of a thermoplastic sheet directly on the physical work piece using hand gestures. These gestures are continuously interpreted by a robotic system that heats the plastic sheet and reshapes it via the pneumatic application of pressure or vacuum. *FormFab* moves beyond the "turn-taking" paradigm of interactive digital fabrication in "a first step towards interactive fabrication that changes the workpiece continuously while the user is manipulating it" [40]. The continuous, physical feedback loop between the user and the fabrication system extend the user's control in the design process by facilitating the exploration of different forms "with a single interaction rather than in multiple turns".

2.3 Experimental Digital Fabrication

Researchers, designers, and artists have investigated forms of digital fabrication that depart from conventional relationships between digital fabrication machines, materials, and designers. The re-imagined forms of digital fabrication use experimental processes and materials to highlight new design spaces, opportunities for creative expression, and provide critiques of more conventional forms of making.



```
G1 X97.78 Y78.88 E125.51219
Controlled move: move in straight line to coordinate
layer: 9 of 12 // instruction 604 of 747
```

```
Filename: Generalizable_Coner_Module_sample.gcode
Material Size: 5 mm
Distance from Base to Laser: 298.86 mm
```

Figure 2.6: Being the Machine, machine-guided manual fabrication of 3D objects in which form is more emergent than predefined [6].

2.3.1 Non-Conforming Digital Fabrication Workflows

In her work Being the Machine, Devendorf et al. disrupt the roles of human and machine in conventional digital fabrication workflows. She creates a fabrication scenario that “places the human between the machine and the materials in order to activate the materials while limiting the control of the machine” [6]. In these scenarios, the human, guided by the machine, engages the material directly with her hands (Fig 2.6). The real-time control shared between the human’s freedom of choice at the moment of fabrication and the properties inherent to the materials in use create a context in which form is “emergent rather than predetermined” [6]. This sharing of control between human and material is reflected in Devendorf’s artistic output, such as her series *Redeform*, which features human interaction with a variety of household materials—from pancake-batter deposition to charcoal drawing [41].

A feature throughout Devendorf’s work is the real-time nature of the interactions between the machine, human, and materials. Due to the fact that the machine only provides guidance to the human, who in turn interacts with the materials, and not rigid control (as with 3D printing), the user can choose the degree of fidelity they wish to adhere to the machine-guidance while working with fabrication materials. This real-time decision making provides an opportunity to deviate, improvise, or fully depart from a pre-defined fabrication instruction.

Artists, especially those interacting with machines, have explored scenarios in which machines provide guidance over a fabrication process but allow for degrees of improvisation and uncertainty in the outcome. In his series of drawing performances, *RoboAction*, Ilic mounts himself to a robot arm, effectively becoming a human end-effector [42]. In these performances, the robot follows a pre-defined or generative motion path, while Ilic draws with an assortment of instruments in accordance with his own aesthetics, style, skill, and judgement.

Artists also create scenarios in which uncertainty in outcomes is featured in real-time making. Artists engaging with drawing machines and plotters have implemented drawing tools and substrates that introduce a degree of uncertainty to the act of drawing [43] [44]. By substituting different tools and substrates, the machine-guided fabrication system can generate many different, and sometimes unexpected, outcomes from the same set of input parameters (toolpaths). This approach to making is expressed concisely in Arnaud Pfeffer's description of the "Satisfying Drawing" concept:

> My work consists in exploring the link between material, support and code, to give form to the unexpected. I work both on the drawing of the path of my tools, but also on the design of them in order to control of the ink level, their dilution, their pressure, the roughness of my brushes, etc. to offer a coherent combination between digital and physical. Through my experimentation I explore the link between the unexpected of the matter and the precision of

code.

2.3.2 Experimental Materials and Processes in Digital Fabrication Workflows

Neri Oxman et al. have explored new design spaces for digital fabrication by embracing biological materials and processes [45][46]. Silk Pavilion I & II and Synthetic Apiary highlight new relationships between digital and biological construction by using CNC fabricated scaffolding to support the fabrication of 3D structures by living organisms—silk worms and bees. These case studies demonstrate the potential for large scale, tunable fabrication in which conventional digital fabrication machines play only a partial role.

The Somme Collective have also used biological processes in the creation of 3D structures for art installations. In Mycocene, slime mold and electronic waste are used to create evolving sculptures, in which the mold culture continues to transform the structures over time [47]. In addition to providing criqitue on the relationship between human-generated waste and living organism, Mycocene highlights a time-based design space in which structures change and grow over time.

Chapter 3

Nothing Like Compilation: How Professional Digital Fabrication Workflows Go Beyond Cutting, Extruding, Milling, and Machines

In order to understand the relationship between timescale and digital fabrication, a detailed understanding of current digital fabrication workflows is needed. In particular, it is important to understand:

- *the aspects of digital fabrication workflows that support expresiveness in the design and fabrication process*
- *the impact material properties have on design and fabrication*
- *the ways designers control aspects of high-level and low-level machine behavior*

The analysis of professional digital fabrication workflows presented in this chapter provides an understanding of these components. The result of this analysis informs my understanding of the way elements of digital fabrication workflows impact aspects of efficiency, iteration, interaction, and expressive opportunities. These include findings surfaced from observations of the way opportunities for expression and design occur throughout the fabrication process and are not limited to common design activities such as creating models in CAD software.

The content of Chapter 3 constitutes a submission pending to ACM Transactions on Computer-Human Interaction (TOCHI).

> M. Hirsch, G. Benabdallah, J. Jacobs, N. Peek, Nothing Like Compilation: How Professional Digital Fabrication Workflows Go Beyond Cutting, Extruding, Milling, and Machines. Submission Pending to ACM Transactions on Computer-Human Interaction (TOCHI).

3.1 Abstract

Understanding professional digital fabrication workflows is critical for future research in digital fabrication technologies. We interviewed thirteen professionals who use digital fabrication for low volume manufacturing of commercial products. Drawing from these interviews, we describe the workflows used for nine products, categorizing different steps to understand how participants' expertise of materials, tools, and fabrication shaped their processes. We show how digital fabrication professionals create viable production workflows by 1) using material knowledge to inform in-house software development and 2) relying on incomplete physical or digital design representations in combination with process prototyping. We discuss how material/machine expertise enables practitioners to anticipate product feasibility; how designing viable customizable products requires inter-

dependent decisions across geometry, materials, and manufacturing operations; and how optimizing for cost, labor, and marketing shapes workflows. We build from these findings to discuss implications for building digital fabrication systems that support people in both designing and manufacturing products.

3.2 Introduction

Products made with workflows that included digital fabrication steps. We examined products made with different materials including wood, concrete, glass, fabric, plastic, and porcelain. A: Robotically milled wooden vase by odk.design, B: 3D printed pendant lamp by CW&T, C: 3D printed concrete table by Fritsch+Durisotti, D: slip cast porcelain cup with plaster mold by Nervous System, E: Jacquard woven textiles by WOVNS F: craft beer glasses by Path Design, and G: 3D printed clay cup by Slip Rabbit. A composite of five pictures of products made with digital fabrication. Clockwise from top left they are a robotic arm milling a wooden vase, a 3d printed lamp, a 3d printed concrete table, a porcelain cup shown with its mold, a porcelain cup running under water, beer glasses, and jacquard woven textiles.

In 2005, the Swedish collective Front Design exhibited an experience at Design Miami where they drew furniture in space using a tracker and a motion capture system [48, 49]. The resulting gestures were recorded and 3D printed as life-sized furniture. Accompanying video showed the all-woman collective sketching furniture shapes in space, with extruded lines following their pen strokes superimposed as augmented reality. Their sketches were 3D printed as life-sized cartoonish chairs and tables. While the furniture itself seemed perhaps unstable, the workflow Front Design demonstrated exemplified many of the core themes of digital fabrication, including: mass customization, precise and efficient robotic manufacturing, and new input modalities and design software that could be directly coupled to fabrication. Digital fabrication has advanced significantly since 2005, but the question that Front proposed through their performance remains: *who gets to design and make now, anyway*?

As digital design and fabrication tools have decreased in cost, they have become available to a broader group of practitioners [50, 51]. This influx of newcomers has fueled a rise in community makerspaces [52, 53], consumer and hobbyist-oriented digital fabrication equipment [54, 55], and novice-oriented digital design software [56, 57]. The overarching goal of democratizing design and production is embodied by the Maker Movement, which celebrates and advocates for a revival of hands-on making, supported by technology. Proponents of the Maker Movement have argued that increased access to digital technologies could fundamentally transform and revolutionize manufacturing practices [58, 59] and blur the boundaries between professional manufacturers and hobbyists.

HCI systems designers have contributed to efforts to support "novice makers" by developing new fabrication tools aimed at simplifying digital design processes [60, 61], reusing and remixing existing 3D models [62, 63, 64], creating playful bridges between digital and physical representations [65, 66, 67], and automating the fabrication of mechanisms and joints [68, 69]. We are also are excited by the potential of digital fabrication to broaden engagement in making. Yet, in addition to targeting novices, we argue it is critical to recognize that many skilled practitioners with diverse forms of expertise engage in digital fabrication. Digital fabrication has been adopted by people who do not identify as "Makers" per se, but as professional artists, industrial designers, or manufacturers. Professional design and production frequently involves collaborations across diverse skill sets [70] and practitioners regularly invest in learning new skills [71]. We believe that by studying people who have already applied digital fabrication in viable businesses, we can develop digital fabrication systems that enable practitioners to *develop* and *leverage* making expertise.

In this paper, we examine the practices of designers and manufacturers who use digital fabrication to create products in low-volume, i.e., in production runs of fewer than 10,000 items. We focus on low-volume production because it requires creators to negotiate tasks unique to digital fabrication, including designing custom items, regularly (re)programming robots and machines, and providing interfaces for consumer-customized design. These practices exemplify the perceived opportunities of digital fabrication promoted by HCI researchers and Maker Movement advocates. This suggests that studying low volume production can inform approaches for supporting both experts and newcomers. Our guiding research questions are:

1. What are real-world workflows of people who use digital fabrication to manufacture products?
2. How do existing digital fabrication technologies and their associated software support the design, manufacture, and sale of customized products?

To explore these questions, we conducted interviews with 13 professional designers, manufacturers, and craftspeople. We limited our inquiry to people who used digital fabrication in the low-volume production of goods that are intended for sale. We excluded manufacturers who use digital fabrication for high-volume production, e.g., Apple CNC milling phone enclosures or Adidas 3D printing shoes. We also excluded people such as educators, contract manufacturers, prototyping services, or fine artists who might use digital fabrication professionally but are not mainly producing products intended for sale in low-volume. Through these interviews, we sought to capture a detailed description of the workflows the participants used for their products and services' research, development, design, manufacturing, distribution, and marketing.

Our work contributes to prior studies of digital fabrication practice. Unlike prior studies of professional fabrication workflows, which largely focus on a single firm [72] or community [73], our research reveals shared practices and barriers for people working across different materials and fabrication methods. These insights suggest opportunities to develop new digital fabrication tools and representations that will generalize for different manufacturers and products in practice. Researchers have previously explored different digital fabrication environments [74] and the attitudes of digital fabrication professionals [75]. Our work is distinct in our focus on product development. Our participants' livelihood depends in part on selling products. As a result, we provide concrete examples of how digital fabrication can be used for manufacturing commercially viable products as opposed to prototypes or personal projects.

Our contributions are as follows: (1) We present a categorization of low-volume digital manufacturing workflows drawn from the documentation and description of nine products and services. Our categorization highlights key stages, transitions, and decision making in low-volume digital fabrication production with respect to the products developed by our interviewees. (2) Drawing from our workflow categorization and specific steps therein, we surface four themes on software development, design representation, process prototyping, and business models in low-volume digital fabrication production. These themes demonstrate specific ways in which professionals use existing design and control software, develop software, and undertake prototyping to produce low-volume goods for sale. We also highlight how participants' attitudes and motivations inform their business models for manufacturing. (3) Through a discussion of our themes and categorization, we surface recommendations and opportunities for HCI digital fabrication research to address challenges of low-volume manufacturing. Specifically, we argue that parametric design technologies should support exploration of machine settings and material behavior in addition to exploring variations in geometry; that educating customers in machine and fabricating processes can open up new opportunities for product customization; and that computational simulation is not sufficient for envisioning the product design space.

3.3 Related Work

Our research on digital fabrication workflows for low-volume production builds on prior work examining how technologies impact craft and design practice, and how design and making technologies are shaped by the people who use them. We also examined current patterns in digital fabrication systems research and describe how our findings align with or diverge from these trends.

3.3.1 Understanding Computational Design and Fabrication Workflows

Early forms of computational design were directly shaped by people with expertise in making things. Starting in the 1960s, CAD enabled the digitization of technical drawings which, in turn, supported digital parametric and constraint-driven design [76]. [70] illustrated the importance of supporting different kinds of users in software. They found that domain experts in design and manufacturing, not professional developers, extended CAD tools thereby removing "the need to expend great effort translating domain knowledge to computer experts." The role of domain expertise in system development has also been demonstrated in more recent HCI studies of professional digital making. For example, the material expertise of craftspeople such as woodworkers or ceramicists informs their explorations of new technology [73] and motivates them to modify and extend technology to suit their practice [72].

Researchers have also investigated digital fabrication through direct engagement in making. By collaborating with craft experts, researchers showed how craft technical expertise can inform digital production [77, 78]. By producing digitally designed ceramic artifacts [79] and [80] show how nontrivial design challenges emerge when moving from software to physical materials, and how material expertise can inform decisions in CAD. Our research contributes to efforts aiming to understand the intersection of physical and digital making by examining real world practice. Rather than focus on the design of a single product, we compare the use of digital fabrication across a range of products that are created with different materials and different machines.

Digital design is a prerequisite for digital fabrication, but design systems create unproductive boundaries in the design workflow. Prior work has shown how designers can use CAD to retain power over other stakeholders in a project [81]. The introduction of Computer-Numerical Control (CNC) and Computer-Aided Manufacturing (CAM) as a way to automate industrial manufacturing equipment was fraught with power negotiations between labor and management: there was a stark contrast between managerial beliefs that CNC machines could be "run by monkeys" [82, p. 270] and the actual machinist skill required for programming and operating CNC mills [82, ch. 11]. Artifacts of these historical boundaries persist to this day and manifest in software. [71] show how digital artists benefit from being able to move between digital and physical manifestations of a design, but encounter barriers when working across black-boxed software representations or high-level automated design functionality. [83] review the divide between digital and physical design in professional architecture settings and argue for the development of ”fluid-feedback based” workflows that prioritize materialization and physical input. Disjoint CAD and CAM software environments also create friction. For instance, designers are hindered by surface-boundary representations in CAD when designing for volumetric fabrication processes like 3D printing [84]. These examples highlight how digital design and digital fabrication is far from seamless, and translating from a CAD model to a production run remains challenging.

Our research is aligned, in part, with previous work investigating the ideals and practices of the Maker Movement. HCI researchers have examined who participates in making and how [85, 86, 87, 88], the relationship between making and sustainability [89, 90], and have also challenged the credibility of the Maker Movement vision [91, 92]. Studies of makerspaces and equipment usage have shown some of the difficulties people encounter when working with existing machines and software tools. [75] conducted workshops with digital fabrication craftspeople, shop technicians, and entrepreneurs and [74] conducted site visits and interviews at school makerspaces to better understand how digital fabrication environments shape fabrication workflows. These studies draw on limitations in existing workspaces to envision future workshops with advanced intelligent tools, ranging from shape-changing surfaces and holographic displays, to advanced artificially-intelligent design. In our research we focus on the digital fabrication workflows for specific products, many of which are commercially available for sale. Furthermore, we present systems building implications that are applicable to existing digital fabrication software and machines. We argue that comparing multiple forms of product development from conception to distribution provides a previously unexplored lens for understanding the affordances and limitations of existing digital fabrication technology.

3.3.2 Digital Fabrication Systems Research

As CNC machines have become more widely available, researchers have developed a range of systems to reduce barriers for designing for digital fabrication. Many researchers have focused on systems that automatically generate geometry for a specific product or fabrication method. These include automating furniture joinery [93], subdividing geometry models into "fabricatable" pieces [94], and producing joints in CAD for laser cutting [95] and hand power tools [96]. Researchers have also developed design tools that constrain modeling operations to the design of forms that are feasible for laser cutting or 3D printing. [97] created a system that restricts people to designing volumes made of finger-joint boxes, [98] developed a tool to preview the packing of components and resulting material usage for lasercutting, and [99] developed a system to guide users in the 3D printing of custom luminaires. Another approach is to automatically convert existing geometry to parametric models [100] or automate alignment and placement of geometry that designers select from a database of existing parts [101]. Parametric design is well aligned with digital fabrication because CNC machines can theoretically fabricate different designs without extensive labor and setup costs for each variation [102]. While prior systems research often focuses on the parametric manipulation of geometry, we also highlight the role of parametric control of machine behavior in the workflows of our participants. While varying in approach, fabrication method, or application, these examples demonstrate a general practice in digital fabrication systems research where researchers use automatically generated parameter spaces and constraints to support "novice", "casual", and "non-expert" designers by removing the "tedious" or "challenging" task of ensuring fabrication validity. A tradeoff of these approaches is that as the degree of design automation increases, machine behavior or physical material performance are also increasingly abstracted for the designer.

HCI researchers have directly demonstrated the design opportunities of modifying digital fabrication machine behavior by developing new form-factors and material properties through experimentation with machine settings for existing digital fabrication technologies. Examples include methods for rapid prototyping 3D acrylic laser-cut forms [103] and modifying extrusion behaviors of fused filament fabrication 3D printers to produce flexible textile-like materials [104, 105]. Unlike past work that examines experimental opportunities and practices of modifying machine behavior, we examine how professionals modify CNC machine behavior for the production of finished commercial products, rather than prototypes.

Supporting new methods of prototyping is another common theme in HCI systems research. Researchers have developed methods to speed up the production of physical prototypes of digital geometry through systems that generate 3D-printable wire-frame skeletons [106], tools that convert geometry into separate 3D printable and laser cut sections [107], or systems that scan manually-sculpted and annotated clay models to generate 3D printable geometry [65]. We show how professional product designers use physical prototypes to some extent, but they rely more often on prototyping as a means to refine manufacturing workflows rather than to inform product geometry.

Domain-specific programming languages and programming environments can enable digital fabrication designers to develop their own software tools for modeling designs and controlling machine behavior. CAD practitioners frequently go beyond stock functionality and customize or extending CAD products [60, 69, 108]. Researchers have developed domain-specific programming tools for specific digital fabrication machines including knit textiles [109], 3D printing [110], and laser cutting [11]; as well as toolkits for custom CNC machine design and operation [111]. We explore how product designers use programming and software development to design niche products and implement viable low-volume production workflows.

3.4 Methods

Our research focuses on a qualitative analysis of nine artifacts' workflows. This approach was necessary to better understand the decisions, goals, and contexts that shaped them. With regards to our RQ2 specifically we chose an approach that could surface the tensions, trade-offs, and attitudes regarding various aspects of these workflows.

3.4.1 Participants

In seeking to understand the workflows of *professional* designers and manufacturers using digital fabrication technologies, we identified three inclusion criteria that we felt reflected this population. We considered:

1. Tools: Participants relied on digital fabrication tools to either prototype and/or manufacture their products.
2. Scope: Participants designed the product with the intent to make multiples.
3. Market: Participants developed their product with the intent to sell it.

Using these criteria, we selected and interviewed thirteen participants about nine different artifacts. Some participants worked and were interviewed together, as is the case of Rosenkrantz and Louis-Rosenberg from Nervous System, and Wang and Levy from CW&T. XTree and Fritsch+Durisotti collaborated on the same project, the CORAIL dining table, at different companies. To focus on a specific workflow, we interviewed participants about one particular artifact. Our selection process was as follows: we initially created a list of potential designers and manufacturers who fit our inclusion criteria. For each potential participant we identified one exemplary artifact. This process included research on the artifacts themselves based on the documentation available on the participants' websites, media coverage, and the authors' first-hand knowledge of production from site visits or conversations. Based on this research and the inclusion criteria, the artifacts were grouped by product size and material (ceramics, PLA, wood, glass, metal, mixed materials). Through this initial categorization process, we noticed that similar materials and scale did not point towards similar workflows. For instance, Nervous System's ceramic cup had more commonalities in terms of tools and techniques with Path Design's series of glass beer pints—both required the use of molds—than with Slip Rabbit's ceramic cup, which was 3D printed. This revealed that similar-looking objects often exist on different design and manufacturing axes, an insight that strengthened the comparative aim of our project. We therefore chose our participants according to a pairing of artifacts that highlighted parallel fabrication strategies and techniques.

A list of the products on which we focused is provided in Table 3.1. For each product, we specify the materials, software, and equipment used in design and production. We interviewed 1-2 people involved in each product, with 13 total participants. A list of the interview participants, their backgrounds, and the equipment to which they have access is provided in Table 3.2. Table 3.3 provides further detail on the business and distribution models for each product.

3.4.2 Interview Methodology

We conducted semi-structured remote interviews with our participants over the course of four months. Interviews lasted 1h30. Participants spoke about their professional backgrounds, the genesis of their company or studio, and proceeded to describe their work-

Product/Company	*Description*	*Materials*	*Software*	*Equipment*
Dropped Pendant Light (CW&T)	set of 100 unique 3D printed lights	PLA, LED bulb and socket	Fusion 360, Rhino + Grasshopper	consumer-grade FDM 3D printer
ListeningCups (Slip Rabbit)	set of 3D printed porcelain cups embedded with datasets of everyday ambient sounds	ceramics	Rhino, Microsoft Excel, Decibel X	porcelain, glaze 3D printer, ceramic kiln
CORAIL Table (Fritsch+Durisotti, 4, 5)	customizable 3D printed concrete table	concrete, glass, and steel	Rhino + Grasshopper, Fusion 360, custom software	proprietary 3D printing head (developed by the company), robotic arm
Coral Cup (Nervous System)	computationally-generated and handcrafted porcelain cup, inspired by the form of brain coral	porcelain, glaze, plaster, silicone rubber, SLA 3D printer resin	custom design software, Rhino, Processing, Blender, Adobe Photoshop	SLA 3D printer, ceramic kiln, vibrating table
Other Vessels (Path Design)	set of beer glasses exploring variations on classic beer glass typologies	glass, aluminum, PLA	Rhino + Grasshopper, Fusion 360	CNC mill, 3D printer, glassblowing equipment
Aestus (odk.design)	series of stratified wooden vases	beech plywood, steel, felt	Grasshopper, custom CNC software	industrial robot with mounted carving tool
AtFAB (AtFAB)	wood furniture and furniture designs informed by digital joinery	plywood	Processing, Fusion 360, Form-Z, SketchUp	CNC mill
WOVNS (WOVNS)	Platform for designing custom woven textiles	textiles	custom software	industrial textile mill
Weft Create (Weft)	Platform for designing and simulating custom woven textiles	textiles	custom software	industrial textile mill

Table 3.1: Summary of Surveyed Products

Interviewee/Company	*Background/Education*	*Access to Tools & Equipment*
Wang, Levy (CW&T)	architecture, computer science, film	home fabrication shop
Tihanyi (Slip Rabbit)	ceramics, visual arts, digital craft	technoceramics research studio
Desjardins (Slip Rabbit)	industrial design, interaction design	technoceramics research studio
Fritsch (Fritsch+Durisotti)	industrial design, architecture	design/prototyping studio
De Bono (XTree)	materials science, robotics	proprietary 3D printing head and robotic arm
Rosenkrantz, Louis-Rosenberg (Nervous System)	architecture, biology, computer science, math	fabrication shop and design studio
Hutchinson (Path Design)	architecture, traditional fabrication	personal studio with small tools, access to industrial CNC equipment through affiliation with Autodesk, partnership with glassblowing facility
Krieg (odk.design)	architecture, computational design, digital fabrication	collaboration with 3rd party robotic fabrication facility
Filson (AtFAB)	architecture, design	affiliation with 3rd party fabrication facility
Molnar (WOVNS)	textile design, weaving	affiliation with industrial textile mill with experience in on-demand services
Hagan (Weft)	industrial textile production, product design, marketing	affiliation with industrial textile mill

Table 3.2: Summary of Interviewed Participants

Product	*Business Model*	*Production Run*	*Distribution*
Dropped Pendant Light	Pre-orders through Kickstarter	100 unique lamps produced during initial campaign, multiples now available on demand	Sales in-house/through Kickstarter, distribution in-house ($125/unit)
ListeningCups	Studio residency	∼20 cups produced for exhibition	Not intended for distribution
CORAIL Table	Tables customized through webapp sold through retail stores	100 tables printed as showroom models. Further custom tables printed on-demand	Sales and distribution handled by Roche-Bobois ($9-18K/unit)
Other Vessels	Product development	Blow molds/initial glasses produced, production run pending	Intended for in-house sale and distribution
Coral Cup	Product sold in own webshop	∼1,200 cups produced and sold	Sales and distribution conducted in-house ($40/unit)
Aestus	Product development	<10 vases produced	Produced on demand through manufacturing partner ($3-10K/unit)
AtFAB Furniture	Designs freely available, royalties from the designs' production	More than 10,000 downloads of design files, 100s individually fabricated or purchased	Fabrication and distribution through OpenDesk ($700/unit)
WOVNS	Web interface for ordering custom woven textiles	Ongoing production of small-batch orders for individual designers and large-volume for industrial-scale projects	In-house sales, distribution through textile mill ($48/yard)
Weft Create	Web interface for ordering custom woven textiles	Ongoing production of custom orders and curated collections of fabric and textile products	In-house sales, distribution through textile mill ($55/yard)

Table 3.3: Summary of business and distribution models for each product

flow according to five main categories: prototyping and design; software development (if applicable); production (if applicable); distribution, marketing and pricing; and documentation. The initial interview framework was developed and refined over the course of the first few interviews to better capture each of our participants' unique process. Participants often shared their screen during the interviews to make visible aspects of their workflows that would have otherwise remained hidden, such as their in-house software or documentation. All interviews were audio recorded and transcribed. After each interview, we met to discuss initial observations and impressions. This process allowed us to fine tune our questions and start forming a broader understanding of the challenges and trade-offs our participants encountered.

3.4.3 Data Analysis

We used two strategies in our data analysis: reflexive thematic analysis and workflow descriptions.

Once all the interviews were completed, each author open-coded a set of interviews. Through this process, we noticed the emergence of two main types of codes. Some codes were *descriptive* and others were *interpretive.* Descriptive codes referred directly to steps in the workflows. These codes led to the emergence of nine workflow categories, which we describe in detail in the following section. Interpretive codes (for instance: *collaboration with engineering experts; labor reuse;* or *tacit representation*) surfaced approaches, strategies, tensions and attitudes towards the workflow itself. The interviews were cross-coded, enabling us to calibrate our codes through discussions. These discussions also revealed early patterns and key points and we eventually identified five main themes, described in Section 5 of this paper.

After completing thematic analysis, we wrote a description for each artifact's workflow. The workflow descriptions surface concise and high-level summaries of each interview. As such, they offer rich vignettes of the digital fabrication workflows and help to understand the diversity of approaches, challenges, and contexts of our participants. We created visualizations for two workflows in Figure 3.5 to better illustrate this diversity, as well as the workflows' non-linearity and the distribution of CAD and CAM work throughout the process. These points and others are discussed in more detail in Section 5.

3.4.4 Limitations

Due to the COVID-19 pandemic, we relied mainly on video conference interviews, which limited access to fabrication spaces and manufacturing facilities, and precluded direct observation of the participants' practices. In-person interviews could have yielded additional insights. The interviews conducted remotely were supplemented with screen-sharing and collection of supplementary data from the participants when available. We also acknowledge the possibility of social desirability bias as a limitation that complicated the interpretation of our data. This factor could have been heightened by the existing relationships between the authors and some participants, namely Nervous System, CW&T, and WOVNS. Finally, our participants were all highly educated and came from well-resourced institutions. This background, as well as their professional experience, provided them with unconstrained exposure to state-of-the-art digital fabrication tools, which shaped their ability to design and manufacture customizable products. This level of access is also hard to replicate. We decided not to include this point in our discussion as we considered that properly engaging with this topic required more space than this paper allowed. Given the importance of this question for systems design, we hope to develop this point in future research.

3.5 Digital Fabrication Workflows

The nine digital fabrication workflow step categories we developed from our descriptive analysis are:

1. **Concept development:** Activities that lead to the concept.
2. **Software development:** Designing and engineering a novel software tool.
3. **CAD work:** Modeling geometry in commercially-available software.
4. **CAM work:** Specifying CNC machine and robot behavior.
5. **Physical prototyping:** Creating physical representations that inform product design.
6. **Process prototyping:** Testing one or more fabrication steps to ensure production viability.
7. **Production:** Any step required to manufacture a finished product.
8. **Marketing:** Communicating company brand or product value to customers.
9. **Distribution:** Selling and delivering physical goods to customers.

Below, we outline the digital fabrication workflows for each of the nine products in the context of these categories. For each product workflow summary, we identify workflow categories that were characteristic or unique for that workflow.

3.5.1 Dropped Pendant Light

CW&T is a design studio based in Brooklyn NY run by Wang and Levy. They design and manufacture goods such as pens, containers, and lamps, which they market and distribute through the crowdfunding site Kickstarter. Their idea for the *Dropped Pendant Light* stemmed from a Kickstarter initiative focusing on runs of 100 products [112]. CW&T sought to make 100 *unique* lamps using 3D printing and parametric design (Figure 3.2B). In their workflow CW&T iterated through a sub-workflow of *CAD work*, *CAM work*, and *production*. They designed parametric models for lamp geometry in Fusion 360 and Rhino and Grasshopper, and used modeling operations such as fluting, scalloping, twisting, and lofting to create variations. They pivoted between Fusion 360 and Rhino to "unblock" themselves from the affordances that each software package contained. After determining appropriate slicing parameters for each new lamp, they manufactured each lamp on their in-house Ultimaker 2 3D printer (Figure 3.1B). They also adjusted the extrusion toolpath to speed up output and minimize failure rates based on different lampshade geometries. They later added additional printers to ramp up production, resulting in an average production rate of one lamp per day. They repeated their design-production cycle for each new lamp until production of all 100 was complete.

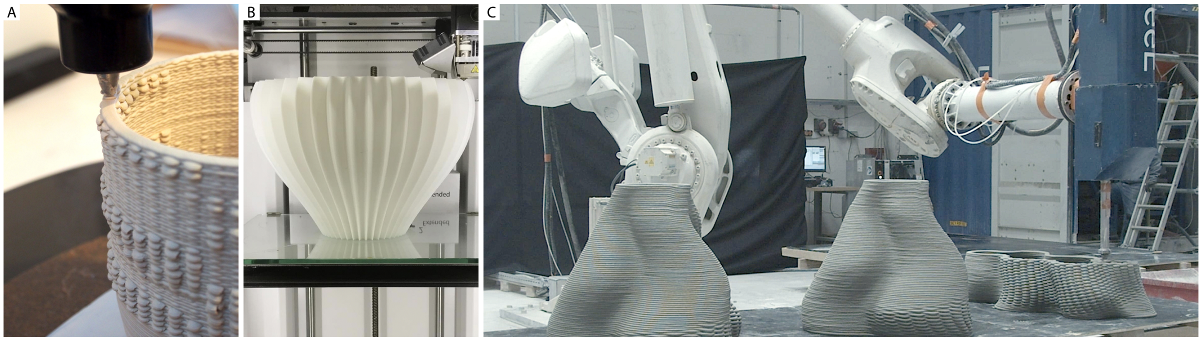


Figure 3.1: Shell structures made from continuous extrusion were used at different scales by three of the products we studied. A: ListeningCups in porcelain, B: Dropped Pendant Light in PLA, and C: CORAIL Dining Table in concrete by Slip Rabbit, CW&T, and Fritsch+Durisotti/XTree respectively.

3.5.2 ListeningCups

Slip Rabbit is a “technoceramics” research studio led by ceramicist Tihanyi in Seattle, WA where visiting researchers collaborate on projects involving ceramics, data, and digital fabrication. The idea for *ListeningCups* came from discussions between Tihanyi and interaction designer Desjardins on ways of creating ceramic housewares representing datasets of everyday ambient sounds. These discussions led to a week-long residency in which they designed and manufactured a series of 3D printed porcelain cups (Figure 3.2G). During the residency Tihanyi and Desjardins integrated *CAM work* and *process prototyping* to develop the surface texture features that communicate audio data (Figure 3.7A). These features could not be represented in CAD, resulting in a design process that occurred exclusively at the level of toolpathing. The initial cylindrical geometry for the *ListeningCups* was exported from a CAD model and converted to 3D printer instructions using slicing software. To incorporate the audio data, Desjardins captured decibel levels in different locations, imported the data into Microsoft Excel, and mapped the decibel level to pause durations in the 3D printer’s toolpath (Figure 3.6C). These pauses were manually inserted into the printer instructions where they would produce bump textures as the printer continued to extrude during the pauses. They further developed the design of the surface texture by experimenting with the 3D printer extrusion nozzle, and evaluating the resulting 3D printed texture. During the residency they printed, fired, and glazed approximately 20 cups.

3.5.3 CORAIL Table

CORAIL is a collaboration between the high-end furniture company Roche-Bobois, the design studio Fritsch+Durisotti and XTree, a company specializing in large-scale 3D printing technologies for materials including concrete, clay, and plaster. The table comprises a textured concrete base and a glass surface (Figure 3.2C). The concept derived from Fritsch+Durisotti 's interest in developing a concrete table where clients could customize form and texture. In creating *CORAIL*, XTree conducted extensive *process prototyping* to develop a printable concrete material, which relies on a time-sensitive curing process that unfolds during continuous extrusion of the concrete. Their process prototyping also involved developing the 3D printing process, which is done on a large scale industrial robot arm (Figure 3.1C). Roche-Bobois contracted a company for *software development* of a customization application that allows customers to visualize the table design and pricing information. Fritsch+Durisotti produced an initial series of customizable CAD models in Rhino and Grasshopper. Roche-Bobois, who distributes *CORAIL*, approved Fritsch+Durisotti 's design for fabrication. XTree ran Fritsch+Durisotti's CAD models through their CAM software, which interfaced the robot's proprietary software with their own code to control the 3D printing extrusion process. XTree 3D printed five prototypes to validate the process. Roche-Bobois then had XTree fabricate 100 identical tables to display in their stores in France. Customers who wished to customize their table could use the web application, which produces a code containing all the design specifications of the customized table. The code is then sent to XTree who 3D prints the table. XTree stated that since the table's release, customers have only modified the standard design in about 25% of all the sold tables.

3.5.4 Coral Cup

Nervous System is a computational design studio founded in 2007 by Rosenkrantz and Louis-Rosenberg. They use generative design and digital fabrication to create art, jewelry, and housewares. *Coral Cup* is a slip-cast ceramic cup with undulating surface ridges inspired by natural forms such as coral (Figure 3.2D). Nervous System outsourced the production of a previous version of the cup, but they were dissatisfied with the level of control in the manufacturing process. They decided to create a new version entirely in-house. Nervous System relied on *software development* to create the cup's design and extensive *process prototyping* to develop each step of the molding and casting processes throughout their entire production workflow (Figure 3.7D). They developed custom software tools to generate reaction-diffusion patterns (Figure 3.6B) and printed them on paper to evaluate which design to use for the cup's surface texture (Figure 3.6A). After selecting a design, Nervous System integrated the ridge pattern into the CAD model of the cup and 3D printed one full prototype. Nervous System worked with a ceramics expert to help develop and conduct the porcelain casting and glazing workflows. They 3D printed molds for casting rubber to create the master mold, which they then used to cast a four-part plaster mold (Figure 3.2C,D). They used the plaster mold to slipcast the final porcelain cup and fired and glazed the cup on in-house equipment. Nervous System produced approximately 1000 cups which they sold through their online store.

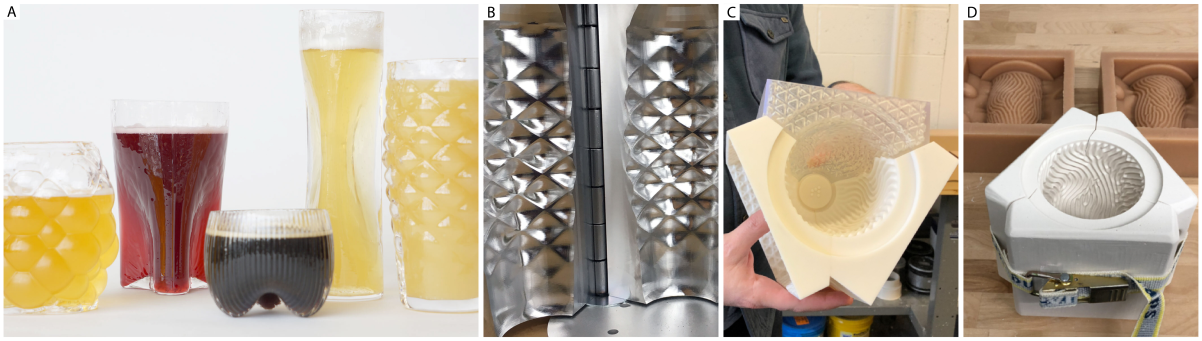


Figure 3.2: CNC-milled and 3D printed molds for blowing glass (Path Design) and casting porcelain (Nervous System). A: Other Vessels glassware for craft beer. B: Hinged aluminum blow mold. C: 3D printed mold for casting silicone mold. D: Resulting plaster mold for slip casting (foreground), cast from silicone mold (background). Cast porcelain Coral Cup shown in Figure 3.2D.

3.5.5 Other Vessels

Path Design is a design studio based in San Francisco. Hutchinson, the founder of Path Design, combines manual craft and digital fabrication to create lamps, furniture, and other home furnishings. *Other Vessels* are a series of five beer glasses created by blowing glass into CNC fabricated aluminum molds (Figure 3.2A,B). Hutchinson created the glasses to explore the relationship between experimental craft beers and new types of glass drinkware. A primary aesthetic feature of *Other Vessels* is the surface texture designed through extensive *CAM work*. Hutchinson also conducted *physical prototyping* to validate the scale and form of the glasses. Hutchinson designed the initial glass geometry in CAD and 3D printed prototypes in opaque plastic. Simultaneously, he took glassblowing classes to inform his CAD and CAM work. Hutchinson created design tools that allowed him to parametrically explore design elements as well as keep track of functional elements of the glasses, such as the volume of beer they would hold. He then created surface textures in the CNC mold by programming milling toolpaths with particular stepovers and directions that would leave marks on the glasses after they were blown (Figure 3.8A). Hutchinson machined five molds for Other Vessels at the Autodesk Pier 9 facility and collaborated with local glass experts to blow the glasses using the molds.

3.5.6 AtFAB

AtFAB is a design and architecture studio co-founded by Filson and Rohrbacher that focuses on distributed manufacturing and open-source design. They created *AtFAB*, a home furniture line made of CNC-milled interlocking plywood parts (Figure 3.3D,E). AtFAB pieces are manufactured by OpenDesk—a platform that hosts furniture designs and connects customers with fabricators [113]. To ensure viable fabrication, AtFAB integrated *software development* and *process prototyping* to develop design parameters in software that would produce reliable joinery in CNC-milled plywood (Figure 3.3C). AtFAB created a joint design that relied on a particular element of CAM, dogboning, in which accounting for material thickness is a critical part of the design process to ensure successful assembly (Figure 3.3E). They developed a Processing application that enabled people to customize furniture within the limits of their joint design and CNC milling. The application constrains aspects of the design to predefined options for product dimensions, material thickness, and joinery style. Customers can save their customized designs for fabrication if they have access to a CNC mill. OpenDesk also features several pre-designed AtFAB furniture models that can be ordered directly without customization. AtFAB receives royalties for each piece ordered through OpenDesk.

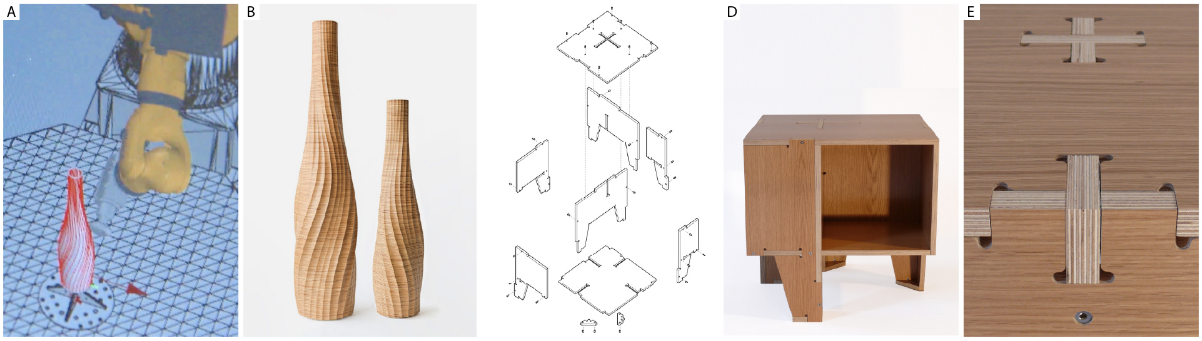


Figure 3.3: Both the AESTUS vases and AtFAB furniture used CNC milled wood. AESTUS vases are milled from laser-cut blanks using 5-axis toolpath planning of a donut-shaped end mill on a robotic arm and with a turntable, then sanded and varnished by hand. AtFAB furniture is milled out of plywood sheetgoods on a 3-axis CNC router and sanded and assembled by hand. A: Robot and turntable toolpath planning. B: AESTUS vases. C: AtFAB assembly. D: AtFAB table. E: Detail of the AtFAB joint with the dogbone cutouts that compensate for inner corner radii.

3.5.7 AESTUS

odk.design is a design company founded by Krieg that creates luxury wooden home furnishings through robotic CNC milling. *AESTUS* is a series of wooden vases. Each vase consists of hundreds of layers of stacked wood segments which are milled by an industrial robot arm (Figure 3.3B). Krieg uses *software development* to create simulation and CAM tools for robotic milling (Figure 3.3A). Krieg produced the vases' primary design feature—non-uniform milled surface grooves—almost entirely through *CAM Work* in his custom software. During the majority of the AESTUS design process, Krieg did not have access to a robot arm to test his designs. He spent hundreds of hours developing software to create parametric vase models based on robot arm milling toolpaths. Krieg rendered the resulting structures in V-Ray to simulate what the physical vases would look like. Once satisfied, Krieg contracted a professional carpentry company to mill the vases from glued layers of laser-cut beech plywood stacked on a steel core. Krieg did extensive software development to create the robot toolpath instructions directly from his software tools, which the carpentry company used to fabricate the vases (Figure 3.2A).

3.5.8 WOVNS

WOVNS is an Oakland-based company founded in 2011 by Dena and Molnar to enable people to design and fabricate woven textiles. WOVNS's customers include students, artists, and designers, as well as a small number of people who manufacture their own textile products for sale. WOVNS's product consists of an online software platform where customers can upload a bitmap image to specify custom textile colors and patterning, and then order fabric at $45 to $48 a yard (Figure 3.4B). WOVNS operates through in-house *software development* for the WOVNS customization platform, and a relationship with a textile mill. The mill handles all aspects of textile *production* and *distribution*. Molnar designed the WOVNS software based on her experience as a textile designer. She created a digital palette where hex codes correspond to thread color and weave patterning, samples of which are shown in Figure 3.4C-D. With assistance from volunteers, Molnar developed a web application that enabled customers to upload design files, select a palette, and place orders for yardage. The mill manufactures customer orders on a Jacquard loom, performs quality assurance, and ships orders to customers.

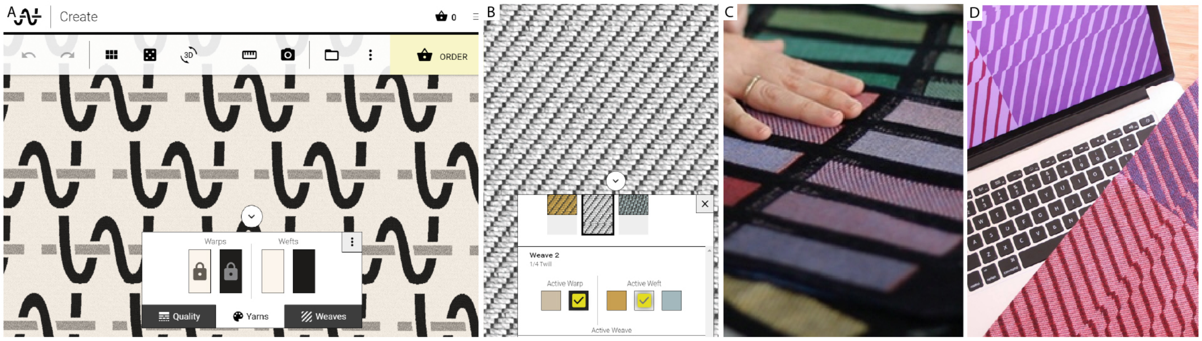


Figure 3.4: Both Weft and WOVNS provide user interfaces for customers to order Jacquard woven textiles quantities starting at one yard. A: The Weft Create interface for uploading artwork and selecting color and weave structure. B: Zooming in on the textile shows a simulation of the resulting weave. C: WOVNS's Talma swatch blanket demonstrating weaves and colors. D: This WOVNS textile shows how the weave structure impacts the resulting appearance.

3.5.9 Weft

Weft is a company based in Providence, RI founded by Hagan that sells custom woven textiles in low volume. *Weft Create* is Weft's online software platform that enables customers to customize and simulate woven textiles and then order fabric at $49 a yard (Figure 3.4A). The textile simulation in Weft Create is the result of extensive in-house *software development*. Weft fabrics are produced at a textile mill that specializes in low volume production. Weft's *production* and *distribution* workflow is possible because they limit designs to high-usage materials. Hagan's experience in textile design informed the concept and user experience for Weft's software. He collaborated with co-founders in Computer Science to develop Weft's simulation capabilities. Customers upload a bitmap image to Weft Create, select from fabric qualities and yarn colors, as well as the specific weave structure for different sections of the fabric. Customers are shown a simulation of their resulting fabric based on a database of tomography-scanned fabric samples. Weft processes about 20 customer designs per week. The designs are manually reviewed by Weft staff, then submitted to the mill. The mill manufactures customer orders on a Jacquard loom, and manages post-processing, quality assurance, and ships orders to customers.

3.6 Crosscutting Themes Across Digital Fabrication Workflows

Our comparison of the nine product workflows revealed extensive variety across workflows, both in terms of when categories of activity occurred, and the relationship between workflow categories and different products or business models. We found that practitioners moved between categories like CAD work, physical prototyping, process prototyping, and production, in different orders or in parallel based on manufacturing constraints that were specific to their product. Products that used similar machines, or companies with similar business models did not necessarily rely on similar workflows. Even companies who used similar fabrication processes, materials, or had the same forms of in-house tool access developed very different workflows directly tailored to the product itself.

Figure 3.5 highlights this variation through visual representation of categorized steps across two example workflows: CW&T's Dropped Pendant Light and Nervous System's Coral Cup. Both Nervous System and CW&T have extensive access to in-house digital fabrication technology, and relied on 3D printing as a core component of their workflow, and both manufacture products in-house and distribute them directly to customers. Despite these similar factors Figure 3.5 highlights how the the different conceptualization and manufacturing approaches of the Coral Cup and the Dropped Pendant Light led to highly dissimilar workflow steps. CW&T engaged in production consistently throughout

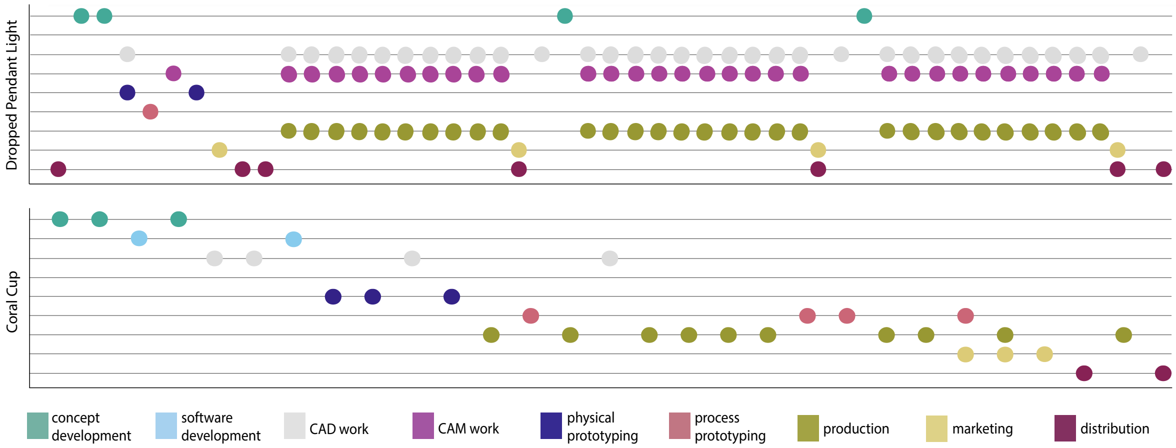


Figure 3.5: Visualizations of the steps taken for Dropped Pendant Light (top) and Coral Cup (bottom). Steps represent distinct instances of activities in the workflow. Time is not represented by steps, rather the visualization shows the sequence and repetition of steps. Categorized steps are shown as sequenced dots, with steps that occurred in parallel shown vertically aligned. Comparing these workflows, we note how Dropped Pendant Light engaged in CAD/CAM work throughout and Coral Cup relied more strongly on software development and process prototyping.

their entire product workflow by virtue of producing finished products on their printer immediately after they created a new lamp design in CAD. Nervous System engaged in production only after an initial period of software development and physical prototyping. Because they used a multi-step slip casting process to fabricate the cup, their production steps are interspersed with process prototyping to refine the slip casting process based on the qualities of their cup design. The variation across all product workflows suggests that digital fabrication enables, and in some cases requires, professionals to develop workflows that are highly specific to a single product or service. Furthermore, this variation demonstrates how creating a viable low-volume product is as much about the process of developing a novel workflow as it is about creating the product itself. This is further reflected in the *marketing* activities of the companies we surveyed. While the workflows themselves varied, one consistent factor across all companies was that they used documentation and descriptions of the workflow as the primary means to communicate the value or uniqueness of the product to customers. For example, CW&T initially marketed the lamps as a set of 100 unique designs, and shared photos of their *process prototyping* on Kickstarter and Instagram (Figure 3.7C).

Building on our categorization and analysis of the digital fabrication workflows of each product, we surfaced themes that were shared across companies and manufacturing methods. In the remainder of this section we describe 1) the role of software development in digital fabrication workflows, 2) how representations used in the workflows often only partially described final products, 3) how process prototyping was used to determine viable production strategies, 4) how designing toolpaths allowed for deeper exploration of material results, and 5) how motivations ranged from commercial considerations to aesthetic and material explorations.

3.6.1 How Software Development Supports Physical Production: From Scripting to Software as a Product

In our workflow categorization, we identified software development as a primary category of activity, which manifested in different forms depending on the company business model and product. All of the companies we spoke with used computer programming to modify or extend the functionality of existing CAD or CAM tools or automate elements of their design process. We note that many commercial CAD tools are designed for extension and feature integrated programming environments for creating user plugins and libraries, e.g., [114, 60, 69]. In this section we consider all forms of software development including programming in CAD environments. For example, Slip Rabbit wrote a script to convert their audio data into G-code for clay extrusion and Hutchinson created a Grasshopper definition to ensure Other Vessels geometry conformed to standard beer glass volumes. These approaches facilitated elements of design and production in important ways; however, they were not the primary factors in the design process.

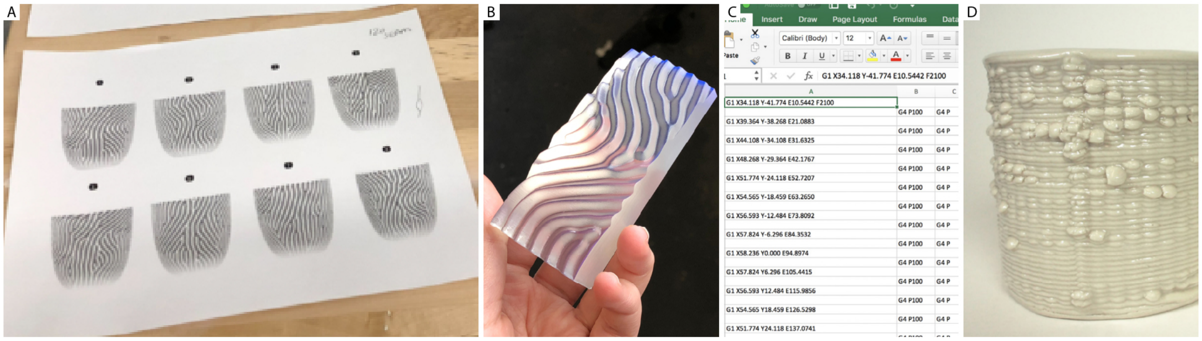
Beyond extending existing software, over half of the companies we surveyed developed standalone software tools as a *primary enabling component* of their business model or product. Nervous System developed the Coral Cup reaction-diffusion surface pattern using a suite of simulation tools they previously developed. Their concept development and process prototyping was determined by Nervous System's ability to extend their reaction-diffusion software to include constraints for a four part mold with minimally visible mold seams. odk.design's concept and production workflow for the Aestus vases emerged through his development of software for milling with robotic arms in Grasshopper. Krieg's software enabled him to experiment with the effects different toolpaths and end mills had on the vase geometry. Like Nervous System, Krieg built on prior software he had developed through his extensive prior work in robotic timber milling when creating Aestus. XTree developed a software tool for real-time monitoring of the concrete mixing and extruding head they designed. Their software enabled them to follow the manufacturing parameters like extrusion pressure in real time as the robotic arm traced the CORAIL table's contours. These examples demonstrate how Nervous System, odk.design, and XTree could not rely on existing commercial software tools to create their products. Furthermore, in the case of Nervous System and odk.design, the practitioners' experience and awareness of their software development capabilities directly informed their product concept.

Software development was also a primary enabling component for companies that developed customizable products. WOVNS, Weft, odk.design, and XTree developed and implemented customer-facing software that included 1) parametric constraints that applied to a specific product or manufacturing process and 2) a user interface suitable for people without prior digital fabrication or manufacturing experience. In these cases, companies relied on their prior experience with digital fabrication to inform the constraints and interfaces of their customer facing software tools. AtFAB's user facing parametric software emerged from their process of developing internal tools for parametric manipulation of their own digitally-fabricated furniture designs. For the CORAIL table, a separate software company developed a browser-based interface for customizing tables. Each table's custom properties were described through a data structure that cataloged curves and textures, and parametric constraints prevented customers from designing an unprintable table. Weft and WOVNS relied exclusively on outsourced fabrication for their business model, therefore both companies invested significant time and effort to develop software features that would appropriately limit customer designs to the constraints of a manufacturing and distribution process that they had limited control over. They also developed mechanisms to inform customers about key aspects of the textile weaving process, either through tutorials in the case of WOVNS or in-software simulation in the case of Weft.

These cases show how software development played a central role in the design and manufacture of low volume products, and how all practitioners went significantly beyond existing features in commercial CAD and CAM tools. Further, these cases demonstrate how business models that center on product customization require different forms and a greater degree of software development labor to create customer-facing experiences. This is in contrast to software development for internal design and production workflows, or as Nervous System put it, “whenever we make anything for ourselves, we make it the laziest possible way and it's much harder to use.”

3.6.2 How Designers Rely on Multiple, Partial, and Ambiguous Representations

Throughout their workflows, our participants relied on design representations that could translate from step to step. Geometry was represented in many ways—as CAD models, code, or specific machine instructions—and materials were both off-the-shelf and custom. Yet, our data shows that a complete representation of the product, such as a full 3D simulation or high fidelity prototype, was not a prerequisite to enter production. In terms of time and resources, high-fidelity representations were either costly or unavailable. Our participants' prior knowledge of manufacturing processes and materials gave them the confidence to move into production with only partial representations. Our data indicated that this expertise enabled professionals using digital fabrication to envision their workflow and anticipate potential challenges.



```
G1 X34.118 Y-41.774 E10.5442 F2100
A                                         B         C
G1 X34.118 Y-41.774 E10.5442 F2100
                                          G4 P100   G4 P
G1 X39.364 Y-38.268 E21.0883
                                          G4 P100   G4 P
G1 X44.108 Y-34.108 E31.6325
                                          G4 P100   G4 P
G1 X48.268 Y-29.364 E42.1767
                                          G4 P100   G4 P
G1 X51.774 Y-24.118 E52.7207
                                          G4 P100   G4 P
G1 X54.565 Y-18.459 E63.2650
                                          G4 P100   G4 P
G1 X56.593 Y-12.484 E73.8092
                                          G4 P100   G4 P
G1 X57.824 Y-6.296 E84.3532
                                          G4 P100   G4 P
G1 X58.236 Y0.000 E94.8974
                                          G4 P100   G4 P
G1 X57.824 Y6.296 E105.4415
                                          G4 P100   G4 P
G1 X56.593 Y12.484 E115.9856
                                          G4 P100   G4 P
G1 X54.565 Y18.459 E126.5298
                                          G4 P100   G4 P
G1 X51.774 Y24.118 E137.0741
```

Figure 3.6: Participants used highly abstracted design representations. A: Nervous System selected their coral patterns just from 2D images. B: To test the Coral Cup's ridge heights, they 3D printed small swatches. C: the ListeningCups' bumps were only captured in G-Code that Slip Rabbit edited in Excel. D: Slip Rabbit 3D printed their G-Code directly to evaluate its properties. In an early test, they noticed that their approach introduced an unwanted seam. To correct this, they re-sliced and then reintroduced the bumps.

Many participants were able to work from highly abstracted design representations. For example, Nervous System reported using 2D black and white images of reaction-diffusion patterns as part of their pattern selection process. For AESTUS, the vase geometry was not modeled directly; rather, it was created from the grooves that an endmill left in the wood. Krieg simulated the final geometry of some vases, but mostly relied on the paths the spindle would take, anticipating the overall pattern effect. In some cases, participants had to rely almost exclusively on formal or abstract representations. This is the case for Slip Rabbit, where Tihanyi and Desjardins manually edited G-Code to create the cups' texture. Tihanyi explains that "the sound information was added to the G-code later. So there wasn't any way for us to visualize it." Tihanyi's 3D printing and ceramics expertise allowed her to anticipate outcomes. Desjardins added that "In the beginning it was kind of just a shot in the dark based on Tihanyi 's experience. And then after maybe the second day or the third day, we could make decisions based on what we had just printed."

Physical representation was an important aspect of the workflow, even if physical prototypes were not high-fidelity. Path Design's glasses were initially 3D printed with black opaque plastic. These prototypes shared none of the material qualities of the final glasses which, for Hutchinson, was "absolutely fine. It's about the surprise when it first comes out of the mill, which is like nothing you might expect." For CW&T, prototypes were created in the flow of design and production, as a way to validate both design and extrusion settings. Even participants who used more complete simulations of their final manufactured product, such as XTree, encountered issues that were difficult to model computationally. De Bono explains his team discovered that when they lifted the CORAIL table the concrete was prone to cracking—a complication that they could not anticipate from their CAD models.

In all of the above cases, production began without a complete simulation of the end result. Rather, aspects of the product were worked out in the manufacturing process. What enabled participants to move confidently into production with only partial representation of their product was often prior knowledge of the materials, tools and fabrication processes. This manufacturing expertise allowed designers and digital fabricators to envision the outcome of their workflow.

3.6.3 How Designers Develop Robust Product-Specific Manufacturing Workflows

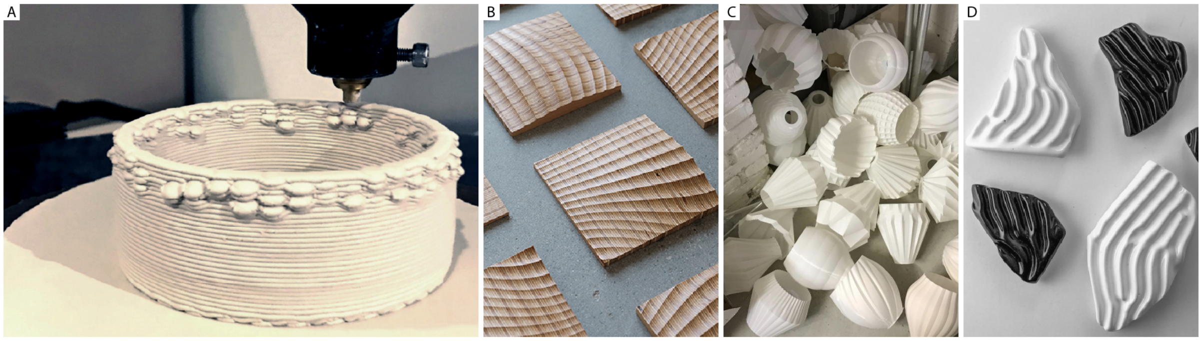


Figure 3.7: Manufacturing process development such as selecting end mills, nozzle sizes, and firing temperatures factored heavily into the product outcomes. A: Pause timing and nozzle size created the unique surface texture of ListeningCups. B: Determining the milling speeds for the specialty end mill in beech plywood enabled odk.design to create crisp and smooth textures that did not need additional sanding. C: CW&T developed a combined slicing profile for their lamps that optimized for high speed and low internal artifacts. D: Coral Cup's ceramic production relied on tuning glaze recipes and firing schedules.

We found that beyond objects such as code or physical prototypes, practitioners relied heavily on prototyping fabrication *processes* to create viable production workflows. In process prototyping, practitioners revised production steps and product designs in response to experience gained when working with materials and fabrication equipment.

For example, while designing Other Vessels, Hutchinson took a glassblowing class. This experience informed the design and production of a first set of CNC molds for glassblowing. Hutchinson tested the molds with professional glassblowers. Through this iteration, he learned about the minutia of blow molds, such as incorporating what Hutchinson describes as "tiny little slots on the molds themselves to let air out at different intervals", or adding hinges to allow single person mold operation. Hutchinson used this knowledge to then design the molds for Other Vessels.

For Slip Rabbit, process prototyping resulted in key design features that weren't present in the CAD model or G-Code of ListeningCups. After creating the G-Code files for the ceramic 3D printer, they experimented with machine-specific choices such as the extruder's nozzle size. Tihanyi described how these choices played a crucial role in determining design features such as "how big the bumps [were]" and "how thick the wall [would] be." The same G-Code file could produce many different iterations due to machine settings and material choices.

Process prototyping also played a critical role in determining the rate and therefore cost of production. Early in their workflow, CW&T determined print settings that optimized the speed of printing for the Dropped Pendant Light, which included relying on continuous extrusion. This subsequently influenced the geometries they used in design.

To reduce the milling time by the professional woodworkers using an expensive industrial robot arm, odk.design started from lasercut plywood shapes stacked around a steel core. This, in combination with his custom robot toolpath planning software, reduced the amount of material the robot arm removed to just a few millimeters of undesirable burnt edges (Figure 3.2A) while still achieving a crisp continuous final line (Figure 3.7B).

Nervous System hired a formally trained ceramicist to help develop and prototype the ceramics manufacturing processes for Coral Cup. They repeatedly revised manufacturing methods throughout their production workflow to address the realities of working in porcelain. Rosenkrantz described how issues included "bubbles in the slip...contamination in the slip...warping in the cups once they're de-molded" and "issues with the glaze." These production details could not have been accounted for in software representations of the design. The level of control Nervous System gained through process prototyping was a determining factor for creating a high-quality product. This control was only feasible because they had direct access to and control over their means of production.

The production processes the participants arrived at shaped the aesthetic and functional features of the products as much as decisions made in software. In each of these examples, defining features of the product—surface texture, manufacturing rate— came from production processes customized to materials and equipment. These material qualities were not present in software representations prior to production and, in some cases, required the practitioners to learn new ways of working with equipment and materials. The resulting products are beautiful and durable in ways that would be difficult to achieve when sending design files out to manufacturing services. Even the low-cost hobbyist equipment some of our participants worked with did not detract from their final products due to their intensive process development.

3.6.4 How Machine Toolpaths are Design Choices

Although creating digital models of products in CAD software was a feature in all of the workflows we studied, we found that participants also developed critical features by designing and optimizing toolpaths. We found evidence of direct toolpath design in a range of fabrication methods, from specifying slicer settings in off-the-shelf software; to hundreds of hours spent on software development for creating custom toolpaths. Participants featured toolpath control in marketing material for their products—emphasizing how digital fabrication machines are part of the product's story. Making design choices through the control of toolpaths resulted in design outcomes that could not be planned, controlled, or even represented in CAD.

To create the primary design feature of the ListeningCups, Slip Rabbit generated G-Code with slicing software and manipulated the resulting extrusion toolpaths by directly editing toolpath pauses into the G-Code in Microsoft Excel. Extrusion continued during

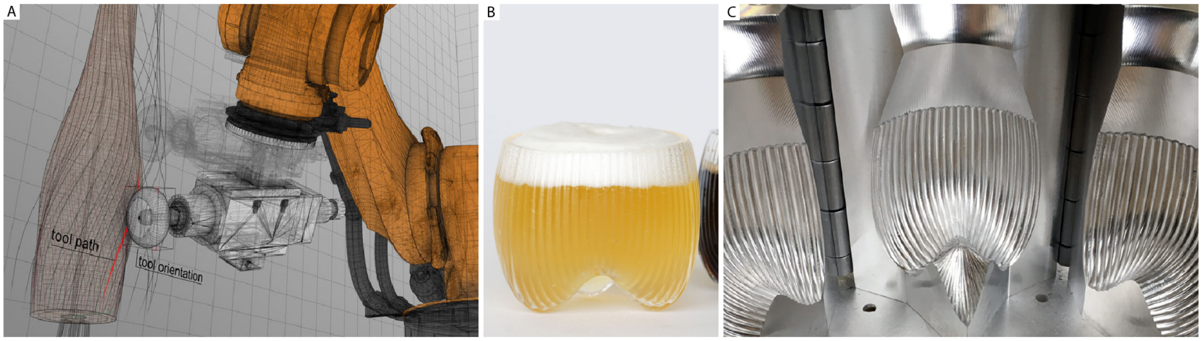


Figure 3.8: Toolpaths were used by multiple participants as distinct design elements of their work. A: The geometry of AESTUS vases came entirely from the toolpaths and tool orientation. The vase emerged from the cutting lines, one of which is shown in red. B: One of the Other Vessels glasses relied on widely spaced toolpaths to create a fluted texture. C: The blow mold used for creating the Other Vessel in B.

these pauses, resulting in “bumps” that functioned as data visualization of previously recorded sounds. The resulting surface textures from the inserted toolpath pauses were only represented in G-Code and printer behavior. To refine their approach to G-Code editing Slip Rabbit created test prints to explore the way different pause durations and sequencing of toolpaths with and without pauses produced different design qualities.

Path Design used commercial 5-axis CAM software for the design of Other Vessels. While prototyping the glassblowing process, Hutchinson observed how ridges and lines from the milled surface of the molds transferred to the surface texture of the glass. Rather than minimizing this effect, he programmed widely spaced toolpaths to create a fluted texture that would transfer to the glass while minimizing parting lines. This texture is not captured in the CAD model, but came from Hutchinson designing in CAM.

Milling toolpaths were a design inspiration for AESTUS. Krieg described milled grooves as “an aesthetic language that hadn’t really been explored so far, particularly because it’s not something you actually 3D model, it’s something that you design by designing the milling paths themselves and see what the result looks like.” To explore this design space, Krieg developed his own software to create custom 7-axis robotic toolpaths.

The industrial woodworking company he partnered with normally generates toolpaths for their clients, but in this case made an exception to run his robot instructions.

Here practitioners relied on directly manipulating toolpaths to create important design features of their products or even define the product geometry in its entirety. Rendering tools were unavailable or gave low-fidelity approximations of the results. Our participants' access to and familiarity with digital fabrication equipment made it possible for them anticipate outcomes despite the lack of simulation of results, but ultimately they relied on process prototyping to make informed design decisions.

3.6.5 What Motivates People to Take on Low-Volume Manufacturing

The participants we interviewed relied on their design and manufacturing expertise to make a living. Their practice was therefore a professional one, with commercial and financial motivations, which changed the stakes of their workflow development and optimization. However, these commercial and financial goals were incorporated into other manufacturing objectives that align with notions of craftsmanship [115]. Practitioners' attitudes emphasized the development of skills rather than scale; problem solving over relying on established processes; engagement in aesthetic and material explorations; and enabling customization. These motivations, while seemingly at odds with the commercial ones, were ultimately what made the products attractive commercially: Nervous System's Coral Cups are hand-crafted using a unique blend of digital and traditional manufacturing processes; CW&T's Dropped Pendant Lights call attention to the variations enabled by parametric design; Weft and WOVNS offer opportunities for custom woven textile designs; XTree's CORAIL tables are unique and designed and manufactured locally. Our participants deliberately showcased their manufacturing processes to emphasize the craftsmanship and tools behind them. This gave them an added value that was specific to the visibility and skill of their manufacturing process.

Production volume was an important factor in the way participants crafted their workflow. Even developers of manufacturing tools such as XTree reported not being interested in developing a high-volume manufacturing business model but rather in discovering new applications for their technology. Nervous System also indicated that high-volume manufacturing held no appeal to them: ”We don’t like having to make 3000 of something in one go. And then if they suck you’re stuck with 3000” explained Rosenkrantz. Instead, production volume is dictated by pre-orders placed online. Many participants we interviewed prioritized “skilling up” rather than scaling up, an attitude reflected in their business models. Filson from AtFAB reported that focusing on low-volume production enabled them to be more experimental. Wang from CW&T indicated that the aspect of the Dropped Pendant Lamp he found interesting was figuring out how to create 100 variations of one thing, but that the manufacturing process itself was less stimulating.

Part of the motivation to create the companies Weft and WOVNS was to level the playing field of textile manufacturing for individual or small designers. Molnar from WOVNS explained:

> the lead times and the whole world of industrial textile production are quite lengthy and they require high minimums. So there’s sort of a high barrier to entry to kind of play in that space. .. So my work was how do we create kind of a 3d modeling tool that could kind of plug into industrial manufacturing to help a designer visualize what a product is going to look like.

Customization is therefore at the core of WOVNS (and Weft) business models, which presents new challenges. Low volume textile manufacturing through these platforms can only happen because the designs uploaded by customers are constrained to a limited color palette and weft threads –constraints implemented in part according to the mill's loom setup. These limits on the customization of textile designs are important when considering that WOVNS's customers did not extensively take advantage of these customization opportunities. Their customized textile service attracts mainly students, who are often directed towards the platform in the context of a course, as well as artists and textile designers –but wider appeal remains limited. XTree offers the option to customize the CORAIL table, although De Bono says that out of the 130 tables they sold, 100 were premade for the Roche Bobois stores and only 30 were customized.

Exploration of novel geometries, manufacturing techniques and problem-solving were key motivations for most of our participants. Krieg explained that the AESTUS vase project came from a desire to explore new aesthetic languages based on CNC toolpaths. For Tihanyi and Desjardins, the ListeningCups project emerged from exploring the visual and tactile design possibilities of 3D printing clay when creating toolpath pauses. Rosenkrantz and Louis-Rosenberg were interested in the aesthetic potential of reaction-diffusion patterns on ceramic cups. Rosenkrantz explained they wanted more control over the design of the cups, with the possibility of creating cups with pattern variations instead of hundreds with the same pattern. The manufacturer they originally worked with in China could not meet these requirements, so Nervous System decided to move the production in-house.

3.7 Discussion

In our first research question, we sought to explore the real-world workflows of people who use digital fabrication to manufacture products. We found that software development featured strongly and that intermediate design representations gave only partial shape to final outcomes. We also observed that process prototyping was necessary for successful manufacturing and that machine toolpaths themselves were not just compiled but actively authored. Finally, we saw that participants were motivated by the expressive and experimental possibilities of digital fabrication rather than purely financial incentives. In our discussion we address our second research question: How do existing digital fabrication technologies and their associated software enable or limit the design, manufacture, and sale of customized products?

3.7.1 Parametric Design Should Support Exploration of Geometry, Machine Settings, Material Behavior, and the Interdependence Among the Three

Parametric CAD models provide an opportunity to constrain output geometry without hard-coding. Our analysis of professional digital fabrication workflows showed that parametric CAD is an important design tool; however, professionals apply parametric design in ways that go beyond CAD modeling and varying geometry. We found that professionals just as often wrote code and software that parameterized the *behavior* of CNC machines. Changing machine settings for digital fabrication machines is currently tedious and typically requires use of clunky machine-specific interfaces. However, interfacing with these systems allowed our participants to explore new fabrication processes and optimize production for efficiency.

Furthermore, when creating parametric CAD models, professionals developed the most effective parametric representations *after* they had direct experience exploring settings for machines and materials. For example, after initial printing, CW&T constrained their CAD models to maximize speed and quality. Nervous System optimized their reaction diffusion patterns for the constraints of slip casting molds. Weft and WOVNS constrained their color palette and weave structure options based on their experience with industrial Jacquard looms. The constraints in the CORAIL table web customization application were the result of XTree's prototyping and manufacture validation process.

Our research shows that professional designers develop parametric relationships in software based on their understanding of existing machine and material combinations. Further, they use parametric methods to explore potential machine and material combinations. Therefore, we argue that future digital fabrication systems research should also focus on enabling parametric control of machine settings and features. This would enable parametric control of material properties, e.g., varying extrusion rates to vary rigidity in 3D printed parts, varying toolpath acceleration to vary milled surface textures, and selectively applying glaze based on surface measurements.

Low-level parametric manipulation of machine behavior also enables people to understand of the nuances of fabrication in a way that is critical to outcomes. Therefore, professionals will not be well served by high-level parametric abstractions that support a narrow set of outcomes. Rather, we see opportunities for digital fabrication systems research to develop end-user programming paradigms for the control of machine settings. Human-centered programming tools for CAM and CNC work could support practitioners in transitioning from parametrically exploring machine and material aspects to deploying them in custom or low-volume production.

The role of machine and material behavior in parametric design also has implications for developing customizable products. People using customizable product services are not expected to have an understanding of the manufacturing process, yet these factors determine product outcomes as much as the geometry. Providing people with access to fabrication tools and customizable design geometry is not enough—CW&T saw little evidence of people printing their own lamps despite the STLs being freely available and the size of hobbyist printer work envelopes. This is in line with the work of [64], who found extremely limited use of parametric geometric models in the Thingiverse online maker community. We argue that future customizable products also need to support customizing material properties and machine operations. This can be accomplished in one of two ways: 1) Customers can be prevented from creating designs that are infeasible within the given fabrication process by enforcing high-level constraints that limit them to general categories of material production or machine operation. 2) Companies can work to inform customers about the fabrication process and material behavior and enable greater awareness of and control over over low-level constraints. The latter approach is exemplified in part by the approach of WOVNS and Weft. Weave structure is critical for visual and tactile qualities of textiles, but is not something that the customers of WOVNS and Weft are knowledgeable in. By creating resources that provide detail and examples of the different choices in the weaves, customers learn how to adapt their own bitmap design files to support their desired textile outcomes.

3.7.2 Simulation Is Not Enough to Imagine Possibilities, As It Relies On A Predetermined Design Space

Our participants demonstrated expertise in domains that were adjacent to digital design and digital fabrication, and this expertise was crucial for steps of their workflows. For example, XTree relied on material science to develop their concrete mixing head, adding components in a timed fashion such that the concrete hardens quickly after being extruded. However, the success of the products did not hinge on a singular key competency tied to a particular step. Rather, participants were able to imagine their products as full workflows early on, demonstrating an understanding of how individual steps were interdependent, anticipating challenges, and strategically investing time working out critical elements of the full workflow. For the CORAIL table, this meant Fritsch+Durisotti and XTree communicated early on about the design affordances of

XTree 's concrete 3D printing. With an in-depth understanding of this novel manufacturing process, Fritsch+Durisotti were able to constrain their designs to ones that XTree could manufacture. Furthermore, they incorporated new process-specific opportunities into their designs, such as introducing texture with wavy toolpaths. This close collaboration between the designer and fabricator was necessary to arrive at the table's design.

CW&T only designed and printed a few lamps before launching their Kickstarter campaign and committing to fulfillment. Despite being experienced with 3D printing, they anticipated the printing process to be a potential hurdle for the lights, which is why they fully tested their 3D printing process before launch. They were confident that if the manufacturing worked, they could handle the design and distribution elements of their workflow, even if that meant that design work would be happening simultaneously with production. CW&T and XTree were not alone in their ability to envision workflows that spanned design and manufacturing. All participants conceived of manufacturing methods that would support specific product features early in their design process. This is in contrast with traditional manufacturing, where R&D and manufacturing rarely overlap.

These findings have implications for the role of computer simulation in digital fabrication technologies. Among our participants, simulating fabrication outcomes of different designs was not sufficient to develop the product design because the manufacturing process itself was also subject to change over the course of the design process. Furthermore, as design and production steps came closer together, they often became interdependent. Our participants were able to design things that might be considered impossible to manufacture and manufacture things that are difficult to represent as CAD designs. These dependencies created key opportunities for making unique and valuable products: the new forms of vases and cups, custom and customizable lamps, tables, and textiles.

The capacity to understand interdependencies of design and production was both a requirement and a creative advantage in low-volume production. Computer simulation is limited in utility in this context if it fails to represent a wide array of design spaces and variations in manufacturing approach. Being able to define and re-define the design space between product form and manufacturing method is at the core of developing viable low-volume products. While it may be theoretically possible to simulate any process, for people producing in low-volume hands-on process development and material exploration are far more critical.

3.7.3 Cost and Labor Cannot Be Ignored When Developing Beautiful Digital Fabrication Products

Although we largely focused on technical aspects of low-volume workflows, another element that considerably shaped these workflows was their larger commercial context. The workflows of the nine products were all developed with the constraint of financial viability and commercialization, which changed the stakes of these projects and shaped the workflows in ways that are different from hobbyist production or design prototyping alone. Beyond form, Nervous System designed their molds for efficient and reliable demolding. For CW&T, the Dropped Pendant Light project was sparked by a Kickstarter “Make100” initiative that assisted with marketing. WOVNS and Weft based several of their platforms’ parameters on the mills’ loom setups. Working within existing industrial manufacturing infrastructures allowed them to optimize for lead time and cost while maximizing options for fabric qualities, palettes, and weaving structure. These examples demonstrate how existing market infrastructures can shape the product timing and concept, and how the commercial dimensions of each product led participants to optimize their workflows for cost and labor.

Industrial manufacturing partners also perceived benefits to working with our participants. For example, the Aestus manufacturer provided the initial robot and laser time to Krieg for free so that they could learn from developing new workflows.

As shown in Section 3.6.5, these commercial realities were deeply entangled and tempered with other values. Participants pursued skill acquisition, creative problem-solving, aesthetic and material exploration, customization, and creating more access points to existing manufacturing infrastructures in addition to, (or sometimes independently of) profit. This combination of commercial and expressive motivations—what Kotipalli calls "instrumental" and "intrinsic" values, respectively [116]—is what made the participants' business models distinctive. Participants switched their business' emphasis from quantities to qualities [117], choosing projects that felt important or interesting to them in terms of material, aesthetic and/or technical exploration.

Participants optimized their workflow for cost and labor not only because they wanted to make beautiful things, but also a living. In order to develop systems that truly support this orientation in manufacturing, it is important to take into account both the design values and the commercial objectives of designers. By understanding these two aspects and how they shape digital manufacturing workflows, we can better envision systems that support people who seek to create beautiful and functional products through digital fabrication.

3.8 Conclusion

Front Desk's 2005 performance of sketched chairs highlighted many promises of digital fabrication. It also exemplified the idea of digital fabrication as compilation: draw something—anything—and the machine will print it. This performance underscores a focus of digital fabrication research in HCI: how to enable expressiveness when making things. This expressiveness is often emphasized without considering *how* things get made.

Our research shows that how things get made is not the simple execution of a digital design, and that creative decisions do not get made in CAD alone. Rather, our survey of nine digital fabrication workflows demonstrates that low-level machine behaviors and material properties are the *crux* of expressiveness for products made or customized with digital design and digital fabrication.

We inquired about the design and manufacturing of nine products, and we saw that designers conceived of their products at the same time as their workflows. The result and the process were entangled throughout the workflow steps. Our participants were creative and expressive not only with the geometry of their products but also with their materials, the machine processes that made the products, and the combination of these three elements in a workflow.

For digital fabrication systems to support the making of expressive *and* viable products, we need to expose the parameters where critical design choices get made—not only geometry, but also low-level machine controls and material behavior.

Access and education also play a role in the workflows we observed. Prior to conceiving of and developing these products, our participants had amassed hundreds of hours of exposure to digital fabrication tools and spaces, often by virtue of professional training or higher education. This exposure was an essential factor for their ability to develop viable workflows. The role of technology access and experience demonstrates a fundamental limit in systems design for digital fabrication: while we can strive to expose machines and material parameters in systems and increase their level of control, there remains a question of how to provide broader access to infrastructures and tools that shape the landscape of participation in digital fabrication.

It is safe to assume that the way Front Desk's sketched chairs were made—like the products we surveyed—was nothing like compilation. Instead, how they were made likely had everything to do with access to tools, machine constraints, material properties, and process development. *Who gets to design and make* depends on how we can integrate the full design space in future systems for digital fabrication.

Chapter 4

How Artistic Workflows Shape the Experience and Outcomes of Digital Fabrication

To understand how different timescales shape the process and outcomes of making, it is important to know how digital fabrication workflows operating in the space of real-time interaction and performance differ from those of conventional digital fabrication workflows. In particular, it is important to understand the way prioritizing the creator's experience of making—as much as the outcome of making—shapes the design and production workflow. Chapter 3 provided an understanding of the aspects of professional fabrication workflows that deal with expressiveness, machine control, and the role of materials. Chapter 4 investigates:

- *the importance of custom software in developing real-time interactions with fabrication machines*
- *the impact of combining manual human control with machine control of the fabri-*

cation process

- *the role of prototyping in real-time and performance digital fabrication workflows*

4.1 Methodology

This investigation is comprised of a research method often described as autobiographical design, where the researcher(s) "build the system, they use it themselves, learn about the design space, and evaluate and iterate the design based on their own experiences" [118]. In this chapter, through autobiographical design, my own creative practice and research serves as a means of generating and communicating knowledge [119]. Three benefits of this approach, as characterized by [120], are as follows:

1. Identifying opportunities for new technology or for advancements of current technology
2. Creating artifacts that provide concrete embodiments of theory and technical opportunities
3. Providing holistic research contributions where novelty resides in the integration of many technical research contributions from a variety of disciplines into a single working system

Additionally, through an analysis of autobiographical design experts, [118] reported findings that highlight strengths unique to this mode of research. In particular, they found that autobiographical design can often "uncover detailed, subtle understandings that they likely wouldn't have found with other user-centered design techniques because they might seem unremarkable". Further, their analysis showed that autobiographical design helped researchers see “big effects”, such as specific elements that could “make or break a system, and genuine, as opposed to discretionary, needs”.

In this chapter I highlight four autobiographical design projects that differ in the materials, interfaces, and machines used in fabrication. This approach offers a “set of epistemological commitments that allows researchers to investigate the lived experience from within, generating deep, evocative, and rich insights” [121]. From my situated, first-person perspective, I discuss findings that provide a window into my creative process that could not fully be accounted for using other qualitative research methods—such as the third-party interviews featured in Chapter 3. The exploratory nature of the creative projects are well suited for autobiographical research. As [118] found, “autobiographical design seemed best-suited for exploratory systems that filled a new design niche, i.e., where there was no existing system or established culture of use.”

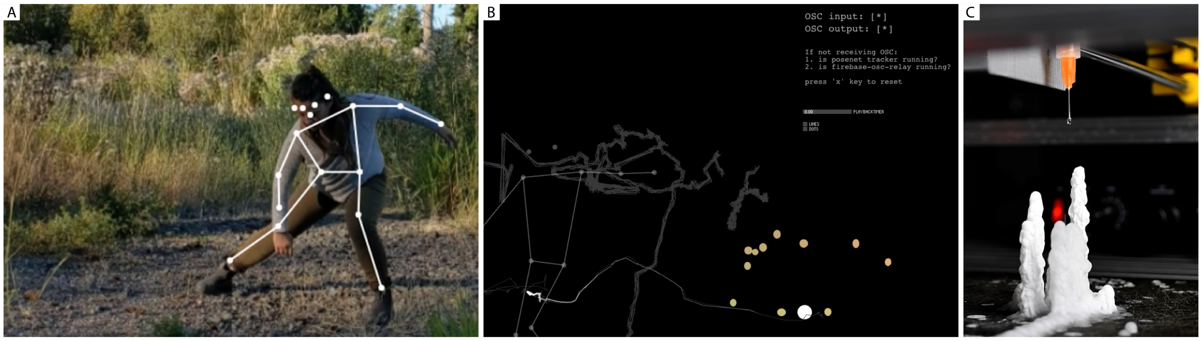
My use of autobiographical design methodologies lead to a personal and intimate understanding of the decisions I made during the fabrication process, from which findings are communicated. The findings from this first-person perspective are communicated through a discussion of three themes: (1) How creating custom software shapes the workflows of producing physical works of art. Findings from this theme include the way custom software was crucial in supporting real-time interactions and mapping input data, such as human pose-estimation or the use interactive interfaces, to the outputs of fabrication. (2) How combined human-machine control creates opportunities for expression in digital fabrication. These findings include the way combined control supports the use of computational tools alongside fabrication modalities with high degrees of direct control, improvisation, and real-time decision making. (3) How time influences prototyping in digital fabrication workflows for art and performance. Finding from this theme include the way prototyping went beyond exploring fabrication outputs, and include aspects of interaction design that account for audience perspective and user experience.

4.1.1 Limitations of Approach

The benefits of autobiographical design research also come with limitations. These limitations derive from the subjectivity inherent to first-person research. In particular, as demonstrated by [118], autobiographical design cannot always be generalizable to broader communities as “a technology’s design may be too tied to one person’s practices”. This does not mean that autobiographical design does not meet a “genuine need”—rather, the need may be genuine to a particular individual or group [118][121]. However, [120] demonstrate that despite limitations on generalizability, technologies developed for one researcher’s needs through autobiographical design can identify opportunities for further technological advancements or wholly new technologies.

4.1.2 Four Autobiographical Design Projects

In this chapter I focus on four autobiographical design projects that feature experimental aspects of digital fabrication, such as live performance, experimental materials, and real-time interactivity. Three of these projects, Kairos, Geometric Operations, and Natural Machine Landscapes, were created on my own while Re:Forming was a collaboration between myself, brooke smiley (dancer/researcher), Sam Bourgault (artist/researcher), and Philip Kobernik (artist/researcher)—Sam and Philip are colleagues of mine in the Media Arts & Technology graduate program at the University of California, Santa Barbara. In the following sections each project is discussed in detail, including a sequential categorization of each step involved in the autobiographical design process. After the project descriptions, I discuss the findings from my autobiographical design process through the lens of three cross-cutting themes.



```
OSC input: [*]
OSC output: [*]

If not receiving OSC:
1. is posenet tracker running?
2. is firebase-osc-relay running?

press 'x' key to reset
```

Figure 4.1: Re:Forming development occurred across remote settings using (A) a laptop camera to capture the dancer's movement, (B) custom software to stream pose estimation data and translate the data to fabrication toolpaths using(C) a 2-axis CNC with the Liquid-Crystal Printing syringe for depositing and crystallizing sodium acetate trihydrate.

4.2 Re:Forming

Re:Forming explores the integration of real-time performance and additive digital fabrication through the lens of dance and 3D printing. This work presents a system in which a dancer guides the fabrication process by interacting with a 3D printer during the printing process. In developing Re:Forming, we were motivated by the expressive potential of computationally-augmented performance, and a desire to uncover opportunities to support new modalities in this domain. Digital fabrication in particular suggested unique opportunities for performance because it supports the manufacture of custom physical artifacts and builds upon previous foundational work that explored some of the basics of interactive fabrication and plotting. However, the use of additive fabrication–one of the most common forms of digital fabrication–in performance is restricted by slow print speeds of conventional materials as well as conventional design tools and workflows. Our work on Re:Forming aimed to leverage rapid additive fabrication materials and systems to support the integration of real-time performance and additive digital fabrication.

In order to facilitate this interaction, my collaborators and I developed a system that interprets pose data from the dancer as 3D printer control signals. These signals

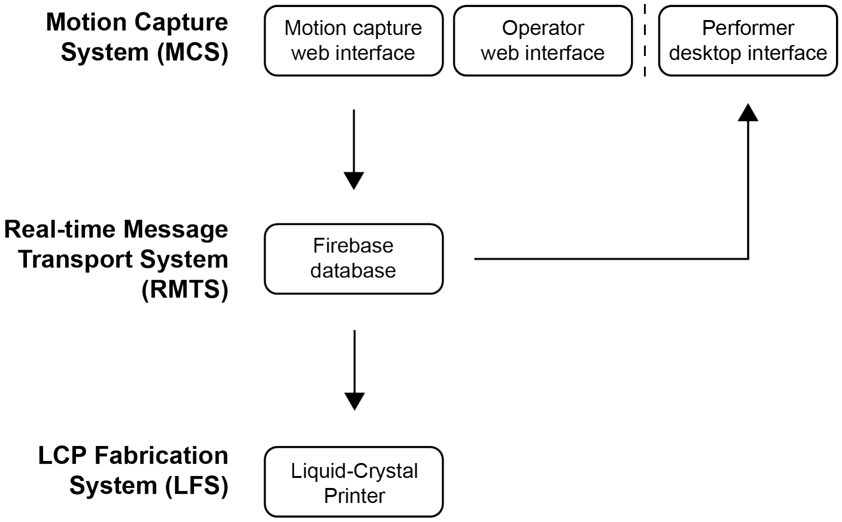


Figure 4.2: Re:Forming system overview

create a sequence of commands that are sent to a novel, rapid 3D printing system, the Liquid-Crystal Printer (LCP), which in turn fabricates structures based on the dancer's movement. Due to the constraints of COVID-19, Re:Forming was designed in, and designed for, a remote setting in which the dancer, fabrication system, and audience remain in separate locations. *The LCP is a primary contribution of my dissertation research. Chapter 5 of this dissertation provides a detailed and systematic characterization of the LCP system, including the research and development of supercooled sodium acetate trihydrate as a novel 3D printing material.*

The real-time system that enables remote controls of the Liquid-Crystal Printer through movement is comprised of three components: a Motion Capture System (MCS) to track the controller's movement, a Real-time Message Transport System (RMTS) to store and send the movement data, and an LCP Fabrication System (LFS) to print a three-dimensional object

4.2.1 Motion Capture System

The Movement Capture System was developed as a web application supporting the pose recognition algorithm (Google Tensorflow PoseNet). This application functions by capturing live video from the computer's webcam, estimating the body pose using PoseNet, and streaming the resulting pose data to our second system, the Real-time Message Transport System.

4.2.2 Real-time Message Transport System

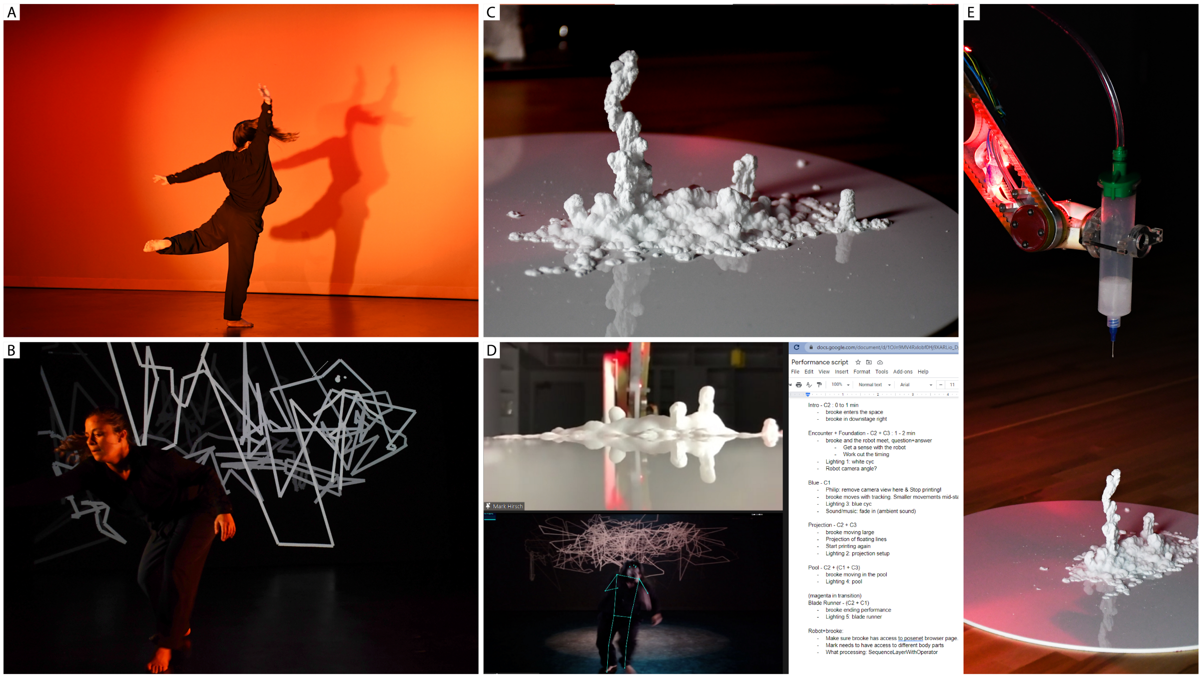
The RMTS was implemented using Google Firebase and a small node.js script that relays streaming pose data as Open Sound Control (OSC) messages on team members' local machines.

4.2.3 LCP Fabrication System

The third system is the LCP Fabrication System (LFS). The LFS subscribes to the OSC message stream of pose data, pipes it into a mapping prototype application, which then outputs a stream of instructions to the LCP via serial port connection.

4.2.4 Performance Workflow

When performing with the system, the performer, brooke smiley, utilizes the MCS to start and stop the recording of short movement sequences using a computer keyboard or via sound input. The sequence is recorded by treating one specific body part as the tip of a virtual ballpoint pen, tracing a line in space to create a motion path (Figure 3.2A). These motion paths are mapped to the build area of the LCP, where they become toolpaths along with the LCP deposits SAT to fabricate physical artifacts. This specific body part is identified by the performer ahead of time.



Intro - C2 : 0 to 1 min
- brooke enters the space
- brooke in downstage right

Encounter + Foundation - C2 + C3 : 1 - 2 min
- brooke and the robot meet, question+answer
  - Get a sense with the robot
  - Work out the timing
- Lighting 1: white cyc
- Robot camera angle?

Blue - C1
- Philip: remove camera view here & Stop printing!
- brooke moves with tracking. Smaller movements mid-sta
- Lighting 3: blue cyc
- Sound/music: fade in (ambient sound)

Projection - C2 + C3
- brooke moving large
- Projection of floating lines
- Start printing again
- Lighting 2: projection setup

Pool - C2 + (C1 + C3)
- brooke moving in the pool
- Lighting 4: pool

(magenta in transition)
Blade Runner - (C2 + C1)
- brooke ending performance
- Lighting 5: blade runner

Robot+brooke:
- Make sure brooke has access to posenet browser page.
- Mark needs to have access to different body parts
- What processing: SequenceLayerWithOperator

Figure 4.3: Re:Forming performance images. (A) brooke dancing on stage at Center Stage Theater in Santa Barbara, CA. (B) brooke with software interface and motion tracking data projected on an on-stage screen. (C) The resulting structure printed during the performance. (D) Images of the build area, motion capture system, and performance outline from the live-stream performance. (E) The robot arm used to house the Liquid-Crystal Printer.

Sequences recorded in the mapping prototype are then sent to the RMTS and received via OSC by the LFS as toolpath instructions. The LCP prints ten layers of each sequence, generating three-dimensional structures that resemble rock, cave, and other natural formations. Often, the sequences overlap, resulting in imbricated structures and arches.

As the control of this system can be cumbersome for the performer when dancing, my collaborators and I also developed a system controlled by a third party operator. The operator web interface has the same controls as the performer: they can start and stop the recording of a sequence as well as change the body part in focus. This operator web interface uses the RMTS to send control messages to the mapping prototype that is part of the LFS.

Table 4.1: Re:Forming Workflow

Category	*Workflow Step*
concept development	motivated by desire to explore what new kinds of artifacts could be created by 3D printing with non-conventional materials
process prototyping	designed and assembled 2-axis CNC as test bed for experiments 3D printing with new materials
process prototyping	developed sand deposition printer prototype, creating 3D structures from accumulation of sand according to programmed toolpath patterns
concept development	hit creative roadblock for interesting applications of sand printing given current system implementation
concept development	explored idea for depositing photocured polymers (too slow, too expensive)
concept development	inspired by Steven Keating's PhD dissertation, began exploring sodium acetate as a fabrication material
process prototyping	attempted to make sodium acetate trihydrate (SAT) crystals from scratch (time consuming and error prone)
material acquisition	ordered two forms of lab-grade SAT for testing
process prototyping	experimented with super saturating SAT to get composition stable enough for interacting with but still able to crystallize upon deposition

physical prototyping	fabricated first set of 3D artifacts by manually depositing SAT droplets using glass eyedropper
process prototyping	developed passive SAT deposition method using enema bags
software development	developed real-time control interface software for small 6DOF robot arm to experiment with robotic deposition of SAT
process/performance prototyping	printed freestanding artifacts through direct extrusion controlled by user-drawn gestures (with pen+tablet)
physical prototyping	printed freestanding artifacts through direct extrusion controlled by generative algorithms
process prototyping	implemented programmable peristaltic pump for greater control over deposition rate
process prototyping	built 2-axis CNC with RepRap controller to allow fabrication based on G-Code toolpathing
physical prototyping	printed SAT artifacts based on sliced geometries
process prototyping	developed new deposition method via syringe, compressed air, and flow controller (due to ongoing issues with unwanted crystallization of SAT reservoir in peristaltic pump)
concept development	began conceptual discussions with collaborators on potential for dance+3D printing performance in remote locations
concept development	received grant from UCSB to fund development

software development	developed motion capture protocol with PoseNet
software development	developed data transport system with Firebase and node.js to transfer dancer's movement data from remote location to facility hosting the fabrication system
software development	developed control software for translating dancer motion data to 3D printing toolpath commands
software development	developed software to simulate LCP fabrication process which the dancer to practice with
performance prototyping	explored different fabrication modalities based on movement data (direct gestural control, looping input gestures to create layers)
software development	developed operator software to control which part of dancer's body to track and transmit to 3D printer
performance prototyping	tested and rehearsed performance sequence in remote locations
performance prototyping	began 1-week residency at Center Stage Theater to further develop aesthetics of performance, rehearse, and test print settings
performance	performed virtual live-stream followed by discussion with online audience

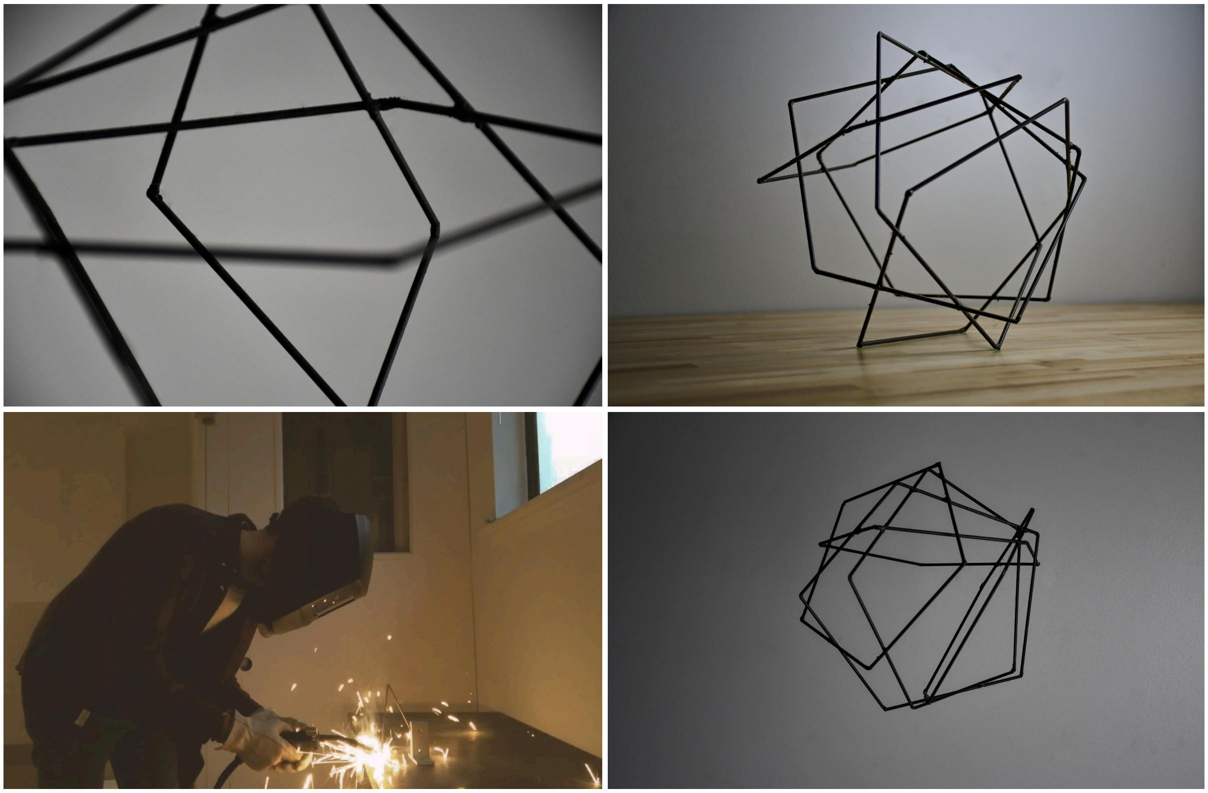


Figure 4.4: Images of the production and a sample structure produced during a Geometric Operations performance.

4.3 Geometric Operations

Geometric Operations is an improvisational fabrication practice that combines craft making with chance procedures mediated by custom software to produce sculptures from welded steel rods. The motivation for this project comes from a desire to fabricate 3D structures within the context of chance-based art pioneered by individuals such as John Cage, Stéphane Mallarmé, and Jean Arp. I chose welding thin steel rods as the fabrication method for the relative speed with which a structure can be created—each welded joint takes approximately three minutes to produce. Short timescales are important to me in this practice because they allow for a sense of flow and continuous making that emulate the other forms of continuous creation, such as improvised music.

Geometric Operations is a project designed to explore the way custom software can extend the complexity of randomness and chance beyond what is feasible with methods such as rolling dice. I developed software that creates a curated experience of making with chance operations—where the artist, in this case me, is prompted to run a sequence of functions that produce randomized results. The output of these functions constrain and inform features of the 3D structure being fabricated. The software is meant to function as a somewhat neutral template for chance-based art of any type. Relatively minor adjustments to the functions in the software would allow the curated experience to conform to other fabrication modalities with different materials.

The Geometric Operations process begins with the artist selecting a geometric primitive, such as a polygon, to use as the building block for the structure. The artist then initiates the first chance procedure by interacting with a custom graphical user interface (GUI), built in the Java-based programming language Processing, which utilizes a random number generator to select which of two design constraint modes the artist will be working under.

In Mode 1, the software provides randomized lengths for each edge of a geometric primitive. Once the software dictates enough edge-lengths to constitute the geometric primitive–i.e. 5 edge-lengths for a pentagon–the artist then cuts lengths of steel rods in accordance with the edge-lengths. The artist then welds the rod lengths together according to her aesthetic preferences. This process repeats for each new instance of the geometric primitive. After the first geometric primitive is fabricated, each new primitive is welded to the previously fabricated primitives, creating an accumulation of geometries that comprise the sculpture. Mode 1 is open-ended, as the artist can continue to generate software-defined edge-lengths until she feels the sculpture is complete.

In Mode 2, the software provides a randomized length that will be uniform for all edge-lengths in all instances of the geometric primitive. The software also dictates the total number of geometric primitive instances the artist will create. In Mode 2, the artist welds all instances of the geometric primitive in advance, and then assembles the primitives together according to her aesthetic preferences.

Geometric operations can be practiced in a studio setting or performed as a sculpture performance. The introduction of chance procedures in sculpting is a way to discover new forms and infuse variation into the creative process through a blend of randomized constraints and the artist's tastes and intuition.

Table 4.2: Geometric Operations Workflow

Category	*Workflow Step*
knowledge acquisition	took welding class through community fabrication space
concept development	drew inspiration from Gego exhibition at Hauser & Wirth Los Angeles
concept development	motivated by interest in chance-based performance practices and wanting to apply that approach to the fabrication of geometric sculptures
physical prototyping	prototyped geometric sculptures with toothpicks to enumerate parameters of design process (geometry, iterations, scale, edge lengths, configuration)
software development	developed initial Processing sketch to guide a sequence of chance operations with a branching structure and constrained random number generators

performance/process prototyping	conducted systematic prototyping experiments in which parameters of the design were either dictated by the chance software or left open to my judgement/control/aesthetics (prototypes still made with toothpicks)
performance/process prototyping	selected a subset of chance/free operation configuration to use in production of the sculptures
software development	re-developed software to improve UX and UI design aesthetics
performance/process prototyping	ordered an array of steel rod samples to test performance with MIG130 welding machine (not as powerful as industrial machines)
performance/process prototyping	physical prototyping ,conducted tests by making partial prototypes of sculptures
material acquisition	placed order for steel rods for use in production
performance/process prototyping	physical prototyping ,used custom chance software to weld two complete sculptures to verify production workflow and software behavior
software development	performance prototyping ,revised software to improve experience for livestream audience
performance	conducted virtual livestreams of chance-based sculpting process over the course of one month (one session per week)
exhibition	installed the resulting sculptures for a week-long solo exhibition at SBCAST

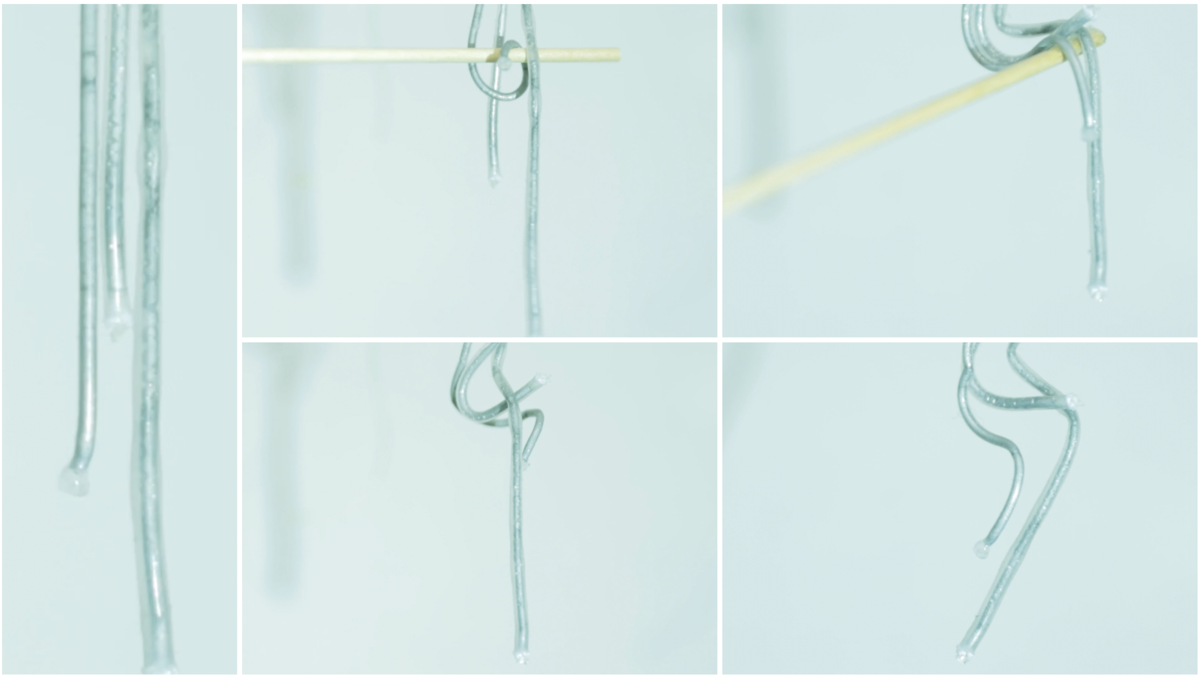


Figure 4.5: Interaction with the Kairos Sculpture. The top row shows manipulation of the eutectic alloy tubes in liquid phase. The bottom row shows the resulting rigid structure that remains after the eutectic alloy cools and returns to a solid phase.

4.4 Kairos

Kairos is an interactive sculpture that utilizes phase-changing materials to create structures that can be formed and reformed continuously by thermally actuating the elements in the structure. This project was motivated by an interest in the way experimental materials can lead to new forms of interaction and structural properties in sculpture. In particular, Kairos is a proof-of-concept for the way artists creating physical structures can have the re-workability of soft materials (such as clay) with the structural integrity of rigid materials (such as metals). Using phase-changing materials, I sought to create a sculpting environment with the flexibility and playfulness of creative toys such as the mechanical drawing toy "Etch A Sketch".

The title, Kairos, is defined as "a time when conditions are right for the accomplishment of a crucial action : the opportune and decisive moment"[122]. This word references the primary feature of the material used to create Kairos—eutectic alloys. Eutectic alloys are alloys in which the phase change between solid and liquid occurs at a single temperature. Unlike other phase-changing materials, eutectic alloys transition directly between solid and liquid without going through a plastic phase. From a structural standpoint, eutectic alloys are attractive for shape-changing structures due to the binary nature of their states (rigid or fluid), creating fast transitions between states through bypassing a plastic phase state. In sculpture, this material property creates an opportunity for interactivity, as changing between phases, and thus rigid and flexible structures, can occur endlessly. This interactivity provides the basis of Kairos.

To create the eutectic alloy elements of the sculpture, I developed a method for fabricating ultra-thin tubes of silicon rubber. First, a two-part silicon rubber was mixed and degassed in the Microfluidics Lab at the University of California, Santa Barbara. Next, a spin-coating machine was used to create a thin, uniform layer of silicon rubber on a plastic wafer. This rubber-coated wafer was then fixed to a platform where a handheld power drill slowly spun a 3mm diameter plastic rod in the rubber. As the rod spins, the rubber begins to solidify producing a thin, elastic tube that can be peeled off the end of the rod. These custom tubes are then used as casing for the eutectic alloy. To achieve this, the eutectic alloy is melted in a steel syringe and injected into the length of silicon tubing. The alloy cools and solidifies, at which point the ends can then be sealed with a small piece of laser-cut acrylic and liquid adhesive.

This process is repeated and the resulting rods of encased eutectic alloy constitute the structural elements of the sculpture. In Kairos, these structural elements are arrange in a line and suspended from above. To interact and create 3D structures from these elements, I use a hot-air wand to thermally actuate the phase-change, manually rearrange the elements, and allow them to solidify once more in a new configuration (Fig 4.5).

Table 4.3: Kairos Workflow

Category	*Workflow Step*
concept development	Inspired by engineering publications on variable-stiffness structures (how could this research be explored in a creative setting?)
knowledge acquisition	reproduced structures from research literature to gain hands-on experience with materials and methods (alloys, granular jamming, nitinol wire)
material acquisition	selected eutectic alloys as material to work with due to low-cost and material characteristics (rapid phase-change at single temperature point)
process prototyping	tested, designed, and machined custom steel syringe for melting eutectic alloy for injection
physical prototyping	prototyped variable stiffness rods comprised of soft tubes injected with eutectic alloy as 'atomic unit' for creating structures
production	lasercut acrylic plugs for ends of alloy-encased tubes
process prototyping	developed method for actuating phase transition based on external application of hot air
knowledge acquisition	conducted tests to characterize relationship between strength of rod and melting temperature for different eutectic alloy compositions

knowledge acquisition	collaborated with mechanical engineer (post-doc in the RE Touch Lab) to derive a mathematical model for eutectic alloy rods based on characterization tests
process prototyping	experimented with internal heating for actuating phase change with embedded resistive wires (joule heating method)
process prototyping	tested many wire types for joule heating in order to find a wire that would efficiently heat the alloy without burning/melting the tubing
knowledge acquisition	conducted tests to characterize load capacity of eutectic alloy rod with embedded wire
knowledge acquisition	conducted tests to characterize the displacement of rod tip (bearing a constant load) as a function of duration of applied current to restive wire
process prototyping	experimented with inductive heating to actuate phase change due to the fact that embedded wires reduce strength of eutectic alloy rod
knowledge acquisition	conducted tests to characterize load capacity of eutectic alloy rod with external heating coil
knowledge acquisition	conducted tests to characterize the displacement of rod tip (bearing a constant load) as a function of duration of applied current to inductive heating coil (much faster than embedded wire approach)
physical prototyping	created series of longer eutectic alloy rods to explore configurations for sculpture

process prototyping	force applied by off-the-shelf tubing caused fractures in alloy due to extended length and thinness (desired for aesthetic taste)
knowledge acquisition	collaborated with mechanical engineer (post-doc in the RE Touch lab) to develop method for creating custom tubing with 2-part silicone rubber mix
production	tube production: combine 2-part silicone rubber, Degas in centrifuge, pour onto plastic wafer, spin coat silicone rubber to produce thin layer, spin thin rod on surface of silicone rubber using power hand drill, peel tube off thin rod once cured
production	injected eutectic alloy into custom tubes
concept development	through process of arranging and re-arranging tubes to find aesthetically interesting configuration, arrived at concept for sculpture as interactive, reprogrammable sculpture
production	created mounting structure for eutectic alloy rods from aluminum extrusions
production	installed hot air wand on mounting structure in order to actuate phase transition for all rods simultaneously
exhibition preparation	documented interactions with sculpture—iterations of heating rods so that they recover to neutral hanging position, re-arranging rods, allowing to cool so they retain new rigid configuration
exhibition preparation	edited documentation footage to a stylized film for use in exhibition

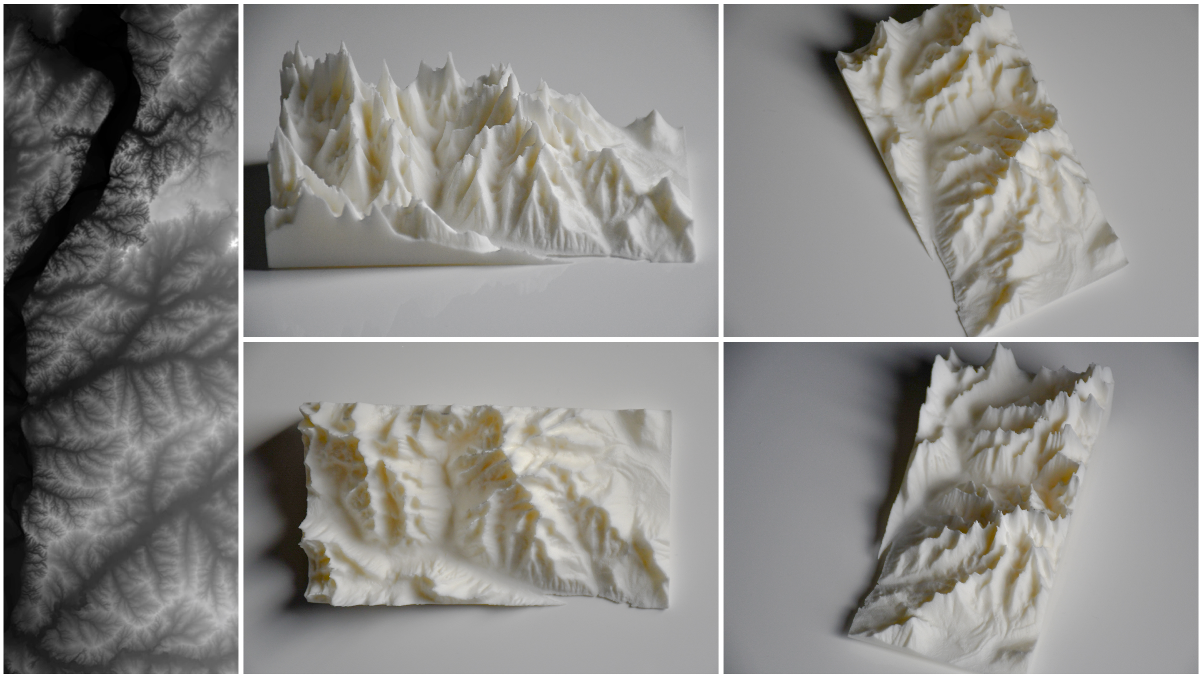


Figure 4.6: Natural Machine Landscape sculptures. Left: An example elevation image used as training data for the GAN to produce synthetic elevation images. Right: Multiple views of a 3D printed sculpture produced by mapping a synthetic 2D elevation map to a 3D structure.

exhibition	exhibited sculpture video at MAT End of Year show

4.5 Natural Machine Landscapes

Natural Machine Landscapes (NML) is a speculative design and sculpture project that leverages Artificial Intelligence to imagine synthetic landscapes. My motivation for this project came from a desire to move creative work with machine learning tools from 2D digital space (pixels on a screen) in 3D physical space. Artists and designers have produced a variety of work generating synthetic images with the use of artificial neural networks—especially generative adversarial networks (GANs)—but less work has been done to find ways of creating physical objects using these same machine learning and

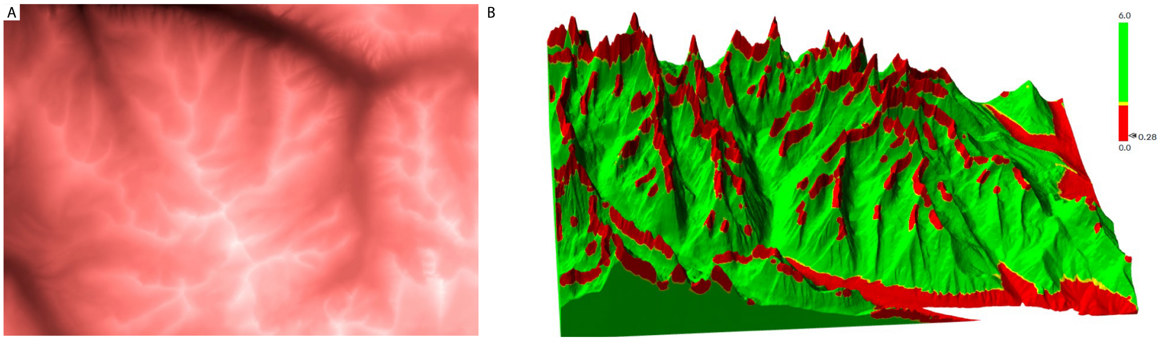


Figure 4.7: (A) An example synthetic elevation map produced by the trained GAN. (B) Areas of the 3D model that generated errors for the 3D printing software due to the regions in red being too thin for fabrication. These errors were resolved by scaling the entire model.

AI tools. NML extends the creative AI workflow by producing designs that are meant for fabrication. In particular, I train a GAN to produce 2D elevation maps that I then process to create 3D digital models for 3D printing. The physical synthetic landscapes are intended to provide a point of reflection on the future of technology's interactions with reality and the implications of synthetic experience in a world where the boundaries between the virtual and the physical continue to blur.

The NML workflow begins by scraping a large corpus of elevation data from the internet through custom software that automates the search process within the Tangram Heightmapper. The software I wrote moves across Earth's latitude lines with a fixed window size, zooming in on images from the windowed region of elevation data, and downloading the images to the dataset. This process resulted in a corpus of 10,000 elevation images.

I then use the image dataset as training data for a GAN that I built in the Perceptilabs framework. Once trained, the GAN produced new, synthetic elevation maps that resemble those of the original data. I evaluated the resulting images for aesthetic qualities and selected images to be curated for exhibition alongside images from the training data for comparison. For a subset of these curated images, I converted the 2D image into 3D models using custom software written in Python. Using Autodesk's Meshmixer, I prepared the 3D models for printing and sent them to the online 3D printing service Shapeways for fabrication.

Table 4.4: Natural Machine Landscapes Workflow

Category	*Workflow Step*
concept development	inspired to explore how digital/visual artifacts produced by machine learning systems can be more tangible and embodied
knowledge acquisition	took online courses to gain experience creating images with deep learning systems
concept development	inspired to work with elevation maps as they exemplify the digital/2D abstraction of 3D physical structures (landscapes)
process prototyping	manually downloaded a small set of elevation maps to experiment with
software development	developed custom Processing script to produce 3D objects by mapping 2D monochrome pixel values to 3D height values
software development	developed parametric tool for adjusting height mapping, density of points (resolution), and interpolation between points (smoothing)
process prototyping	exported 3D maps to .stl files
process prototyping	sliced and 3D printed small section of map to validate design and fabrication viability
software development	developed custom Python script that scrapes elevation maps for a specified range of locations

software development	developed script to reduce dimension and resolution of maps in order to create training dataset for deep learning
software development	implemented a Generative Adversarial Network (GAN) based on prior online courses using map training data
software development	process prototyping,trained model and periodically output sample images to assess model status visually
production	produced a set of synthetic elevation maps from GAN
concept development	selected images to convert to 3D based on fitting two categories: “real looking” maps and maps with conspicuously non-real artifacts
production	ran selected images through custom software to generate 3D models
physical prototyping	3D printed two full elevation map prototypes
process prototyping	quality of materials and resolution of 3D printer weren’t sufficient for aesthetic taste
outsourcing	submitted order for two prints through online 3D printing service Shapeways
outsourcing	went through 3 iterations of adjustments of the model based on poorly explained notifications that model wasn’t printable (resolved by scaling up the model)
outsourcing	purchased only one 3D print through Shapeways (as new scaled up version of model was cost prohibitive)

exhibition prep	developed DIY spinning pedestal for documentation of resulting 3D printed elevation map

4.6 Theme I: How Creating Custom Software Shapes the Workflow of Producing Physical Works of Art

For all the projects featured in this chapter I developed custom software to facilitate different parts of the workflow. Given this ubiquity, it is important to understand how the process of developing custom software impacts the creative workflow as well as the resulting artifact and/or performance. In the case of these four projects, I created three different types of custom software:

1. *performance-oriented*: software used in live performance and exhibition of physical artifacts
2. *material-characterizing*: software used to gain a deeper understanding of a material's low-level features and behaviors
3. *form-describing*: software used as a design tool to synthesize a material's low-level features into complex forms and physical artifacts

Each type of custom software shaped the project workflows by facilitating opportunities for creative exploration as well as defining the design space and constraints for a given material and fabrication process.

4.6.1 Performance-Oriented Software

Of the four artworks I discuss, three featured aspects of performance and interactivity, where a performer or participant would engage with software to control the fabrication of physical artifacts in real-time. In the case of Geometric Operations and Re:Forming, custom software was developed to create a run-time performance interface.

In Geometric Operations, the software interface provided a series of chance operations that dictated features of the geometry, such as edge lengths and polygon type, that the artist fabricates by welding together steel rods. I developed this software through an iterative process featuring cycles of 1) improvised welding of geometric structures to identify aesthetically interesting features, 2) encoding those features in software as parametric design constraints, and 3) developing a graphical user-interface to communicate the parameters to the artist during the fabrication performance.

These iterative cycles of software development shaped the overall flow of the performance. I moved continuously between physical production and software development to create a sense of dialogue and collaboration between myself and the software. This dialogue was emphasized in the performance in two primary ways. First, the physical placement of the welding setup and the computer setup were arranged in symmetrical positions in order to highlight the equal status of each system. The two systems were also placed at a distance that required me to walk several paces when moving between the two systems—which was meant to further accentuate the dialogue-like nature of the fabrication process. Second, the user-interface featured a simple controller comprised of two push buttons that were used to get the next parameter from the software. The minimal interface, in contrast to a more robust keyboard/mouse setup, was intended to create a greater sense of agency in the software system by staging my interaction with it as a request for additional information to inform fabrication.

For Re:Forming, I developed custom software to create an interface between the dancer and the novel robotic liquid-crystal 3D printing system. Development of the software was informed by periodic meetings with the dancer to discuss conceptual goals, aesthetics, and how the qualities of the dancer's movement could be translated to 3D printed structures. Between meetings, my collaborators and I would implement new features and functionality in the interface for the dancer to explore and experiment with.

Unlike Geometric Operations, where software development grew out of my development of the fabrication performance, experimental features of the Re:Forming interface were added as a way to prompt new ideas and interactions between the dancer and the 3D printer. As new modes of interaction were implemented, the dancer could explore each and create movement and 3D printed structures based on the new functionality. In several instances, however, the dancer's explorations suggested scaling back and removing newly implemented functionality. As an example, we implemented a way for the dancer to control the number of layers the printer would extrude based on gesture recognition. While we initially imaged that this expanded form of control would foster a greater degree of creative expression, in practice the reliance on fixed gestures constrained the dancer's creativity and led to unsatisfactory outcomes. These scale-backs resulted from software interactions getting in the way of conceptual and aesthetic goals—over-complicating the interaction paradigm and obscuring the connection between movement and 3D printing.

4.6.2 Material-Characterizing Software

Two of the artworks, Re:Forming and Kairos, featured experimental materials that aren't commonly used in fabrication. As such, during the creative workflow I conducted in-depth testing and characterization of the materials in order to define a design space for each. To gain a greater degree of precision and control over the characterization, I developed custom software that facilitated material testing rigs.

For Kairos, testing involved both the material properties themselves as well as the actuation method for phase-changing the eutectic alloys—moving between solid and liquid phases. Factors taken into consideration while testing included: strength of material, speed of phase change (in both directions), and impact of actuation method on both strength and phase-change speed. To characterize these material properties, I developed software to control the actuation methods—ambient heating via hot air wand, joule heating via embedded resistance wires, and induction heating via external coil—and to record and log sensing devices such as laser displacement and camera-based optical tracking.

In the case of Re:Forming, given that sodium acetate had not previously been used in 3D printing, testing the structural limits of the material for fabrication was essential for understanding what geometries are feasible for printing and how they can be controlled through software. In particular, it was important to understand how low-level material features, such as unsupported overhangs–a key feature and design affordance of sodium acetate–could be accounted for in the development of software constraints.

For both Kairos and Re:Forming, the scope of material characterization was partially constrained by aesthetic interests. For both of these projects, I was primarily concerned with the range of geometries that were feasible for fabrication. For instance, it was evident early on that sodium acetate too brittle a material for use in engineering applications. Therefore, after some brief formal tests to get a general sense of the material's strength, most of the strength characterization that followed was specific to particular geometries that I wished to use in the artwork.

4.6.3 Form-Describing Software

Three workflows, Re:Forming, Geometric Operations, and Natural Machine Landscapes, featured custom software that informed the design of an artifact. In the case of Re:Forming and Geometric Operations, software provided a bridge between aspects of human performance and 3D design features, while the software developed for Natural Machine Landscapes provided a way to generate form by mapping data from 2D to 3D.

Due to the experimental and novel nature of the material, fabrication system, and performance featured in Re:Forming, custom software was an essential part of producing 3D structures. Developing the software involved both aesthetic and functional decisions for translating the dancer's movement into fabrication instructions. On the functional side, software was developed to capture the dancer's movement via a laptop webcam, extract pose features, shuttle the feature data to the 3D printer control software, map the data to toolpath instructions, and send the instructions to the printer for fabrication.

These functional developments were often balanced by the aesthetic developments as the creative process progressed, sometimes resulting in tensions between artistic and engineering goals and needs. In the interaction method used in the final performance, where the toolpath of the 3D printer was controlled in real-time by mapping data from one point on the dancer's body to the task space of the robot arm, the dancer developed movement that would focus on groupings of the body that were spiritually and artistically meaningful. These focus areas included "Heart & Lungs", "Hyoid Bone", and "Jade Pillow". However, working within the framework of Tensorflow's PoseNet, extracted features of the pose were limited to a fixed set of joints such as "leftHip" or "rightElbow". As a result, an important part of the software development involved finding ways to modify the fixed aspects of functional tools (pose estimation) to serve the creative goals of the piece. In this case, an extra layer of data processing was added to estimate the locations of the desired body areas based on mathematical operations using PoseNet's list of joint features.

For Geometric Operations, developing form-describing software involved a negotiation between providing enough software-prescribed constraints to ensure the resulting structures maintained a unified aesthetic while leaving enough decision-making freedom to the artist to ensure a degree of creative variation between the structures. In practice this meant that a set of constraints governing geometric features—dictated by software encoded chance operations—were defined and auditioned by executing multiple sculpture performances in order to asses the aesthetics of the structures as a group.

An unintended consequence of this software development workflow was the high degree of practice and rehearsal that it necessitated. Each iteration of the sculpture performance lasted approximately 30 minutes and, to effectively evaluate a given set of software constraints, four sculptures needed to be produced. This meant that by the time the final set of software constraints were adopted, the performance itself was polished and ready for public exhibition.

4.7 Theme II: How Combined Human-Machine Control Creates Opportunities for Expression in Digital Fabrication

In the context of producing physical works of art, the method of fabrication typically falls into two categories: manual control and computer-numerical control (CNC). Manual control involves hands-on interactions with materials, such as woodcarving, shaping clay by hand, or 3D printing with handheld extruders. Fabrication via CNC involves the preparation of fabrication instructions which are sent to a machine, such as a 3D printer, CNC mill, or laser cutter, for fabrication. These fabrication instructions are often generated by designing digital models in software and exporting them to file formats that CNC machines can execute.

In the four artworks I discuss in this chapter, two projects (Kairos and Natural Machine Landscapes) fit neatly into these categories, while the remaining two projects (Re:Forming and Geometric Operations) occupy a space between manual control and CNC. The projects in between these categories of fabrication control draw on affordances of each and, through this combined-control, create expanded opportunities for artistic creation.

To better understand the artistic opportunities created through combined manual-CNC control, it is helpful to understand the affordances of each control type and how those affordances shape the artworks I discuss in this chapter.

4.7.1 Manual Control

Immediacy

Immediacy has been a recent focus of interactive digital fabrication. For example, [4] demonstrate how interactive digital fabrication systems with manual control offer the "the immediacy of the physical and the flexibility of the digital". With manual control, there is a direct and tangible connection between human actions and the resulting impact on the materials used in fabrication. Unlike CNC, there is no compilation process that abstracts a user's input to control the output. This immediacy allows for a nearly instantaneous feedback loop between human action and human perception of the action's results on the artifact. In the case of Kairos, I controlled the geometry of the sculpture by moving the materials with a handheld manipulator. This tangible connection allowed me to know at each moment the phase state of the eutectic alloy tubes (solid or liquid) so that I knew when it was possible to reconfigure them and when it was safe to release the tubes knowing they were cooled to the solid phase and would hold their shape.

Familiarity

Manual control often involves a hands-on interaction with the fabrication materials—such as sculpting with a carving tool or molding materials together by hand. As discussed in [10], these hands-on interactions draw on embodied and implicit knowledge gained from a lifetime using tools and interacting with the world mediated through our bodies. Relying on implicit knowledge in manual control facilitates a more direct path to expressive interactions. In Kairos, the manipulation tool used to reshape the sculpture resembled the use of eating utensils like chopsticks and forks. This familiarity, derived from the 'muscle-memory' gained through daily use of such utensils, made it easier for me and other participants to be expressive when interacting with Kairos.

Control of Time

Manual control facilitates a flexibility with the timing of actions in fabrication. As fabrication is not mediated by a software-controlled machine, actions and inputs are free from the need to be synchronize with a system clock. This freedom allows the artist to take as much or as little time as she wishes during the fabrication process. Given the previous discussion on immediacy, this means fabrication can occur as rapidly as the artist and materials are able to respond to one another. In manual control, since the fabrication process is not automated, the artist can also slow down fabrication in order to facilitate decision-making processes during production. Working at fast and slow timescales was important in my interactions with Kairos. At times, I wished to reconfigure the sculpture as close to the material's phase change as possible, while, at other times, I wished to take more time to observe the sculpture and plan my next steps.

4.7.2 Computer-Numerical Control

Complexity & Automation

CAD and CAM software enable design practices in which the effort of the human designer does not necessarily scale with the complexity of the geometry—allowing designers to create in ”smart, but lazy” ways[123]. To accommodate the complexity supported by CAD systems, software tools have been developed to access the fabrication viability of digital models by informing the user of issues with unsupported overhangs, material limitations, and machine tolerances[124]. In Natural Machine Landscapes, this automated accounting of manufacturability allowed me to spend more time designing and iterating complex 3D mappings of 2D elevation data by offloading the cognitive task of understanding how a model will be fabricated to the software. This resulted in a creative freedom during the design process in which I could generate models as complex as I desired and immediately verify if the resulting design was feasible for 3D printing.

Generativity & Novelty

While CNC fabrication often involves digital models and automated toolpathing software, CNC machines are agnostic to where the numerical control values originate from. Because of this, any stream of numbers (within the configuration space of the machine) are viable control values. As discussed by [26], this allows artists, designers, and architects to discover new structures and geometries by coupling generative algorithms with CNC toolpath commands. In particular, this creates an emergent quality to CNC fabrication as the artist can begin a fabrication process without knowing what the outcome of that process will be. Pairing this generative behavior with rapid fabrication methods, such as the liquid-crystal printer or CNC foam milling, creates an environment in which artists can fabricate generative 3D structures at timescales similar to those in computer graphics and other well-established artistic media.

Interchangeability

There is nothing inherent to the numerical values in CNC to dictate a certain type of fabrication method over another. As such, CNC fabrication is a relatively modular form of production. The same CNC sequence can create a foam-milled sculpture, ink-plotted drawing, or sand-deposited sculpture depending on the type of end-effector used. This modularity creates a rich platform of experimentation for artists. In early concept development of Natural Machine Landscapes, I generated a toolpath sequence for a 2D CNC plotter which allowed me to explore a variety of fabrication processes based on the same numerical control. This interchangeability of fabrication methods also means that artists can mix media, such as combining the liquid-crystal printer with the deposition of colored dyes, with a high degree fidelity between each medium as the underlying automated toolpath remains constant.

4.7.3 The Space Between Manual and Computer-Numerical Control

By combining different elements of CNC and manual control, artists can create fabrication scenarios in which particular features of both control methods support modes of expression that aren't feasible when using only one method. The work I discuss in this chapter features two distinct versions of combined control: machine-guided and human-guided. Machine-guided control, which is used in Geometric Operations, brings together CNC and manual control by creating a fabrication scenario in which custom software tools prompt and constrain design choices (CNC) that I fabricate by welding geometric structures from steel rods (manual control). My work on Geometric Operations surfaced

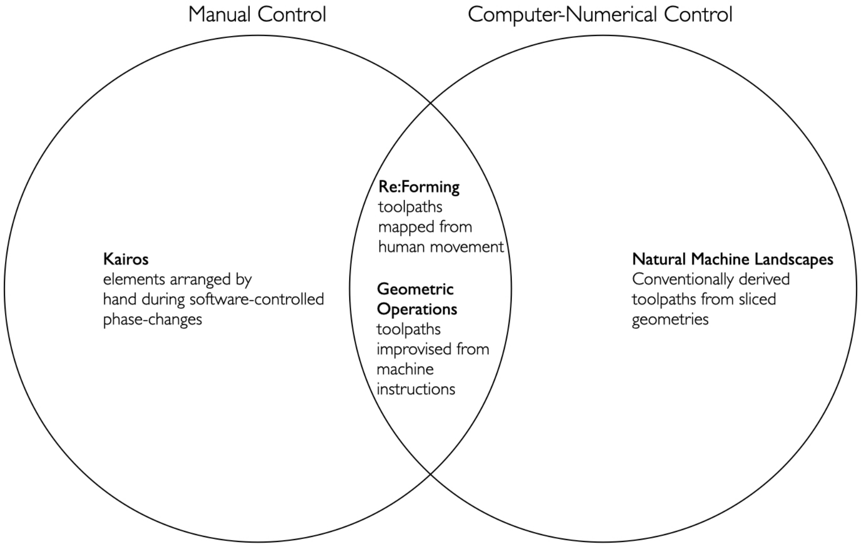


Figure 4.8: Two projects, *Geometric Operations* and *Re:Forming* explore the space between human-guided manual control and machine-guided Computer-Numerical Control.

two important opportunities of machine-guided combined control.

Pairing computational tools with human expression

The fabrication process I developed for Geometric Operations brought together the precision, complexity, and generativity of CNC with the immediacy, flexibility, and time control of manual control. The software tools provided guidance over the fabrication process, such as the type, quality, and number of geometric features to create, but left space for me to make real-time decisions about aspects of the assembly, such as the orientation and configuration of each geometric element. The resulting fabrication process was that of a guided improvisation. After each software prompt, I would improvise and explore different ways the prompt could be implemented through a fabrication action (welding). I was able to immediately assess the state of the structure after each action and, due to my control over the timescale, take as much or little time as I needed to carry out the next action.

Aesthetic coherence derived from machine constraints

By implementing parametric constraints in the custom software for Geometric Operations, I defined a finite design space for the geometric aspects of the sculpture. This helped to create a sense of aesthetic coherence by constraining all possible outcomes to geometric features within the design space. This machine-guided aesthetic coherence resulted in a heightened state of expressive freedom during the manually-controlled welding improvisation. While fabricating the structure, I knew that any variation I made during the improvisation would have aesthetic themes that trace back to the design space due to the initial software constraints. This allowed me to offload the cognitive burden of comparing different sculptures to each other during the fabrication process—effectively eliminating my ability to ”color outside of the lines”.

In contrast to machine-guided control, human-guided control inverts the causal relationship demonstrated in Geometric Operations. In this context, toolpaths are derived from an input featuring some form of human behavior. In the case of Re:Forming, brooke smiley’s dance movements (manual control) provided input to the liquid-crystal printer (CNC). The form of fabrication control used in Re:Forming highlights three important opportunities of human-guided combined control, all of which center around the idea of mapping human input to machine output.

Unconstrained exploration of input behavior through constrained mappings

To generate CNC output from human input, output data must be constrained to the task space of the fabrication machine, such as the build plate of a 3D printer. Once this output constraint is in place, the resulting range of input possibilities is no longer constrained by the system. This promotes experimentation with regards to the human behavior that generates the system's input. In Re:Forming, this constrained mapping allowed brooke to explore different types and qualities of movement with the knowledge that any gesture she made would be viable input for the fabrication system. This made it easy to test out new choreographic ideas and compare the resulting fabrication output by ensuring that all movements would generate executable toolpath instructions. From this unconstrained exploration, we were able to observe what input behaviors were aesthetically interesting and further tailor the input-output mappings to highlight that behavior.

Dynamic mappings support endless variation

In Re:Forming, the mapping between input and output were implemented through custom software. Varying these mappings became an important factor in the creative exploration and development of the piece. Creating dynamic mappings allowed us to use the same input (brooke's movement) to generate a high degree of variation in the fabrication system's output. A significant portion of the development of Re:Forming involved recording the stream of movement data and playing back that movement through different input-output mappings. Once we observed a mapping of interest, we presented it as a new interface prototype for brooke to explore–a process that led to further refinement and variation of the mappings.

CNC interchangeability facilitates dynamic inputs

The aforementioned interchangeability feature of CNC fabrication supported a key feature of the Re:Forming performance: variable input sources. From a conceptual standpoint, brooke was interested in the way data produced from the movement of different regions of the body resulted in different expressive outcomes. Given the input-agnostic quality of the CNC fabrication system, we were able to develop an interface that allowed us to freely change which part of the body was being tracked and used as input during the performance.

4.8 Theme III: How Time Influences Prototyping in Digital Fabrication Workflows for Art and Performance

Creating digital fabrication workflows for artworks and performances required prototyping in forms distinct from the kinds of prototyping that occur in digital fabrication for products or functional components. In particular, the time-based nature of interactive artworks and performance meant that prototypes were informed by and evaluated for their temporal qualities as much as their structural and aesthetic qualities. While conventional notions of prototyping physical artifacts—to serve as proofs of concept, validate deign goals, and verify fabrication feasibility—played a role in the artworks discussed in this chapter, the forms of prototyping that I engaged in during the production of the artworks that differ from conventional prototyping are:

1. *Prototyping Fabrication Materials*
2. *Prototyping Interfaces and Interaction Environments*

4.8.1 Prototyping Fabrication Materials

Three artworks (Re:Forming, Geometric Operations, Kairos) featured elements of interactivity or performance. The inherently time-based nature of this work meant that the materials used in fabrication needed to accommodate fabrication speeds that fit within the timescale of performance and real-time interaction.

For Re:Forming and Kairos, the nature of the performance was initially informed by material properties. In Re:Forming, the rapid crystallization of supercooled sodium acetate trihyrdrate suggested to me a form of rapid 3D printing. After arriving at this initial conceptual framework, I began a process of material prototyping in which I experimented with material attributes to optimize for print time, print resolution, and strength of the printed structure. In prototyping for print time, I systematically adjusted two features of the sodium acetate trihydrate solution: saturation and temperature. Supercooled sodium acetate, which is inherently unstable, is prone to spontaneous crystallization. The probability of that unwanted crystallization increase with higher ratios of sodium acetate to water as well as with lower temperatures. Conversely, lower concentrations of sodium acetate and higher temperatures result in slower crystallization velocities. The material prototyping phase involved experimentally finding an optimal solution in which crystallization velocities were relatively high but the chance of spontaneous crystallization was relatively low.

In Kairos, the phase-changing properties specific to eutectic alloys suggested to me an interaction scenario of continuously reshaping the structural elements of a sculpture. For eutectic alloys, the change between liquid and solid phases occurs instantaneously at a single temperature point (its *Eutectic Point*) without a plastic phase in between. This direct phase oscillation supports an interactive sculpting context in which I could move quickly between rigid and flexible structures. Eutectic alloys come in a number of compositions from an array of substances, each with a different eutectic point and structural properties. Alloys with lower temperature eutectic points require less energy to change phase but are also more brittle and less structurally sound. In Kairos, my prototyping process involved optimizing the material to be strong enough to create 3D structures with a eutectic point low enough to decrease the time required for the periods of heating and cooling while reshaping the sculpture.

Geometric Operations also involved material prototyping. In this case, unlike Re:Forming and Kairos where material properties informed the performance and interaction, the performance concept was developed first and prototyping was required to select a material that fit within that concept. In particular, the idea of welding geometric structures based on prompts from custom software led to a process of testing the performance of different stock steel materials and evaluating the resulting structure as well as the quality of the fabrication performance. To accommodate a sense of live performance, the welding process needed to occur quickly and directly—i.e. without setting up external structures to support each weld. This meant that the steel links needed to be lightweight enough to cut lengths with handheld tools and weld quickly. However, because welding for a live audience can be dangerous without proper protective equipment, the performance took the form of a virtual live-stream. As a result, the steel links needed to be sufficiently large enough to be clearly visible for a web audience in which image resolution could not be guaranteed. These constraints on welding and virtual performance led to a material prototyping process that involved performing the piece with an array of steel rods–to assess the fluidity of the performance flow–with a group of volunteers who accessed the live stream from an array of remote settings–to assess the aesthetic clarity of the fabricated structures.

4.8.2 Prototyping Interfaces and Interactions

For the performance and interaction oriented artworks I discuss in this chapter I created prototypes in the form of interfaces and interaction environments. For two of the projects (Re:Forming and Geometric Operations) this form of prototyping relates to my work developing performance-oriented custom software, while the third project (Kairos) relates to custom software for material characterization. During the software development for each, I created interface and interaction prototypes that were tested in performance and interactive settings to evaluate their range of creative opportunities and inform further development of the software.

Interfaces used in interactive artwork can differ in motivation and evaluation from interfaces used in other areas of HCI. For Kairos, developing a system for triggering the eutectic alloy's phase changes was a key component of the interactive sculpting experience. I implemented three prototypes for heating the alloy to move from the solid phase to liquid: joule, inductive, and ambient heating. Each method had strengths and limitations. The joule heating prototype was invisible", since the resistance wire was embedded within the tube of eutectic alloy; this embedded wire, however, also made the solid form of the alloy tube more likely to crack and lose shape in the sculpted structure. The inductive heating prototype was by far the fast method for heating the alloy but required a bulky coil to be placed around each alloy tube. For the ambient heating prototype I used a hot air wand at a distance of approximately 12cm to heat the alloy. While this prototype was slower than both the other two methods, it did not impact the strength of the material and didn't require additional hardware within the working space of the sculpture. My evaluation of these prototypes marks a departure from the form of evaluation these prototypes would undergo in a pure engineering context. Here, the aesthetic features of the prototype carry equal or more weight than aspects of efficiency and minimizing complexity. The ambient heating prototype was ultimately used in the final artwork as it offered the best compromise between a desire for clean sculptural elements as well as structural integrity of the sculpture.

When developing artworks for performance, factoring in the perspective and experience of an audience suggests interaction interfaces that might differ from those optimized from a systems engineering perspective. During the development of Re:Forming, we had to develop a number of interaction prototypes to explore different ways brooke's dancing could control the 3D printer's toolpaths. These prototypes explored different methods for selecting regions of the body to focus on in pose estimation, visualizing the status of the 3D printer for brooke, and the degree of synchronicity between brooke and the 3D printer. Given the remote nature of the performance, in which the brooke and the 3D printer were in different facilities, communicating the status of the 3D printer was crucial for providing visual feedback to brooke to inform her movement. Similarly, creating a method for brooke to change the part of her body being tracked was an important conceptual element of her choreography. While implementing the interaction prototypes we found that these two forms of agency (observing the 3D printer remotely and controlling the motion capture system) hindered the quality of the performance due to the cumbersome nature of interrupting the dance to interact with a computer interface. This resulted in a new interaction prototype in which my collaborators and I operated the interface–a strategy that required a greater degree of rehearsal and communication to ensure that we were effectively realizing brooke's choreographic and expressive goals. Synchronization between brooke and the 3D printer was a primary concern while developing interaction prototypes. The prototypes ranged from interactions in which the motion tracked region of brooke's body was directly linked to the toolpath of the 3D printer to interactions in which brooke's movements and gestures triggered more complex and autonomous 3D printing toolpaths that temporarily deviated from brooke's movement. Here, considerations for creating a successful performance outweighed our preferred interaction method. As a group we felt the more complex mappings between brooke and the 3D printer yielded the more geometrically interesting 3D printed structures. However, given that the audience had never experienced this form of 3D printing nor a performance incorporating 3D printing and dance, we found the direct, synchronous interaction prototype provided the most impactful experience for the audience as it gave a degree of clarity to the nature of the interactions between brooke and the 3D printer.

Artworks produced in the context of a performance support opportunities for instilling aspects of drama and stagecraft into the audience's experience of the piece. While developing Geometric Operations, I developed interface prototypes that suggested different types of agency and character traits to the software system that provided fabrication instructions. These prototypes included interfaces with a high degree of control—such as a MIDI controller through which I could alter an array of parametric settings for the software-generated fabrication instructions—as well as interfaces with highly constrained controls. In developing the latter, a single-button interface for prompting the next fabrication instruction, I found that limiting my ability to visibly change the software's behavior, I encouraged the audience to project a higher degree of autonomy and mystery on the part of the machine. This intentional constraint on expressive range is typically not be ideal in other interactive digital fabrication scenarios, where higher degrees of expression and control are often the goal, but in the context of performance this constraint was a key feature of the drama and aesthetic.

4.9 Discussion

In the previous sections I highlighted the findings of my autobiographical design methodology through a discussion of three themes: the impacts of custom software, the expressive opportunities that arise from a combination of human and machine controlled fabrication, and the relationship between time and prototyping in digital fabrication projects that feature aspects of performance and interactivity. In the discussion that follows, I contextualize my findings within the one of the primary benefits of autobiographical design outlined in section 4.1: identifying opportunities for new technology or advancements of current technology.

4.9.1 Opportunities for New Material Technologies

The choice of materials greatly impacts the expressive opportunities and outcomes of digital fabrication. The analysis of my autobiographical design projects demonstrated the way certain materials created opportunities for interactivity and enabled fabrication timescales that support live performance. The development and use of supercooled sodium acetate as a 3D printing material created opportunities to stream real-time data, such as the movement of a dancer, as input into the 3D printer's toolpath control. Additionally, the use of eutectic alloys supported an interactive sculpting scenario in which structures can be formed and reformed by oscillating between liquid and solid phases.

In both cases, the materials have important limitations. 3D printed structures of sodium acetate are quite fragile compared to engineering materials. As discussed in Chapter 5, tempering treatments can be applied to artifacts after fabrication to increase the strength of the structures, but structural failure was common during the printing process. This limitation suggests an opportunity for further research into the development of materials that support rapid fabrication as well as increased fracture strength. One path forward might be further refinement of sodium acetate. Material mixing, such as suspending small fibers within the solution, could provide extra structural support. Another path forward could include looking to other materials entirely, such as development of rapid photocurable polymers.

Material strength is also a limitation when working with eutectic alloys to create shape changing structures. In order for the phase changes to occur rapidly, the diameter of each alloy-injected tube needs to be small—less than 1 cm—to allow for efficient heating and cooling. The thin diameters of these tubes results in brittle structural elements. To increase strength and performance of these variable-stiffness structures, a combination of material research and improved methods for thermal actuation are needed.

4.9.2 Opportunities for New Software Technologies

The findings I discuss in Theme I demonstrate the way custom software supports expressive opportunities for interacting with digital fabrication machines. In creating the hybrid dance-3D printing performance with the LCP, I developed custom software to connect the dancer's movement data to the input of the 3D printing system. As part of this development, my collaborators and I discussed the tension in the way we mapped human movement to toolpath instructions. Mapping data from a tracked body part directly to a location on the build platform provided a degree of immediacy that worked well for performance, but also limited the expressive opportunities of the dancer to control the 3D printers output. Working at the level of real-time toolpath control made it difficult to imagine ways of creating more recognizable 3D structures and geometries from the dancer's movement. This presents an opportunity for future development into the way artists and designers can map real-time input data into high-level 3D features, such as geometry. New forms of mapping real-time data would be useful for both experimental additive digital fabrication, such as with the LCP, as well as the more established methods of fabricating 3D artifacts from streaming real-time data (discussed in chapter 2).

Our work developing custom software for Re:Forming surfaced another opportunity for new technologies: software tools that affirm indigenous and non-western identities. As my collaborators and I implementing software to track brooke's movements, we experienced a tension with the biases inherent to industry standard pose estimation tools. brooke, an indigenous artist and dancer, was interested in having the software track features of the human body that don't conform to the list of joint and body parts built into the pose estimation system. As a result, we implemented a second layer of software that attempts to derive indigenous and non-western conceptions of the body from the joint locations. This workaround, in addition to being imprecise, suggests an opportunity to develop computer vision tools that provide an array of options for how the system perceives and conceives of the human body that could affirm a greater number of cultures and identities.

My autobiographical design projects also highlight the way custom software can extend existing software tools. I developed custom software to support fabricating 3D structures from the 2D images produced by a neural network. Despite the creative opportunities that this custom software enables—such as the structures in Natural Machine Landscapes—using this software involves a degree of tedious manual interaction that constrains the number of 3D models that can feasibly be produced in a short period of time. These manual steps create bottlenecks in the workflow and suggest an opportunity for the development of new software tools. In particular, software tools that could support the creation of 3D models from a neural network that are viable for digital fabrication directly would allow the designer to act as curator of the automated design process. Additionally this would decrease the amount of manual labor needed to convert 2D images to 3D models and prepare (or repair) the models for printing.

Chapter 5

3D Printing via Deposition and Rapid Crystallization of Supercooled Solutions

One key finding from the analyses of digital fabrication workflows in Chapters 3 and 4 relates to the timescale of additive digital fabrication. Current forms of additive digital fabrication, such as FDM 3D printers, operate at timescales that are incompatible with the forms of real-time control and interaction used in other creative domains where digital tools are featured. The timescales are a result of material and machine constraints that limit the speed of fabrication. Chapter 5 presents a novel form of additive digital fabrication, based on the rapid deposition and crystallization of supercooled sodium acetate trihydrate, that supports fabrication timescales fast enough for real-time interaction and control. The results of this fabrication method offer one viable path forward for creating shorter timescales in additive digital fabrication.

5.1 Abstract

A new method is described for rapidly 3D printing structures via deposition and crystallization of supercooled solutions of sodium acetate trihydrate (NaCH3COO.3H2O) near room temperature. Crystallization of the supersaturated salt solution is nucleated upon initial deposition onto a seeded base substrate or via deposition onto crystallized printed structures during printing. The rapid solidification of the solution facilitates fast 3D printing of structures that can be formed using layer-by-layer deposition, similar to conventional deposition printing methods, or via direct extrusion. Deposition process parameters provide control over print resolution and speed, as theoretically predicted by liquid-droplet ballistics and crystallization kinetics. The method is capable of printing complex 3D structures, including high aspect ratio inclined, and unsupported, overhangs that do not deform, and are strong enough to stand against gravity. The strength of printed structures can be greatly augmented via mild heat tempering, while their optical properties may be altered through the addition of colored dyes or other reagents to the solution.

5.2 Introduction

This paper describes a method for three-dimensional (3D) printing based on the deposition and concurrent rapid crystallization of supercool sodium acetate trihydrate (SAT) solutions. 3D printing has received great interest during the last two decades, yielding new techniques involving a wide range of physical principles, processes, and materials [125]. Among the most common 3D printing techniques is fused deposition modeling (FDM), polyjet printing, stereolithography (SLA), and their variants [126]. These methods involve controlled transitions between solid and liquid or molten states of polymer

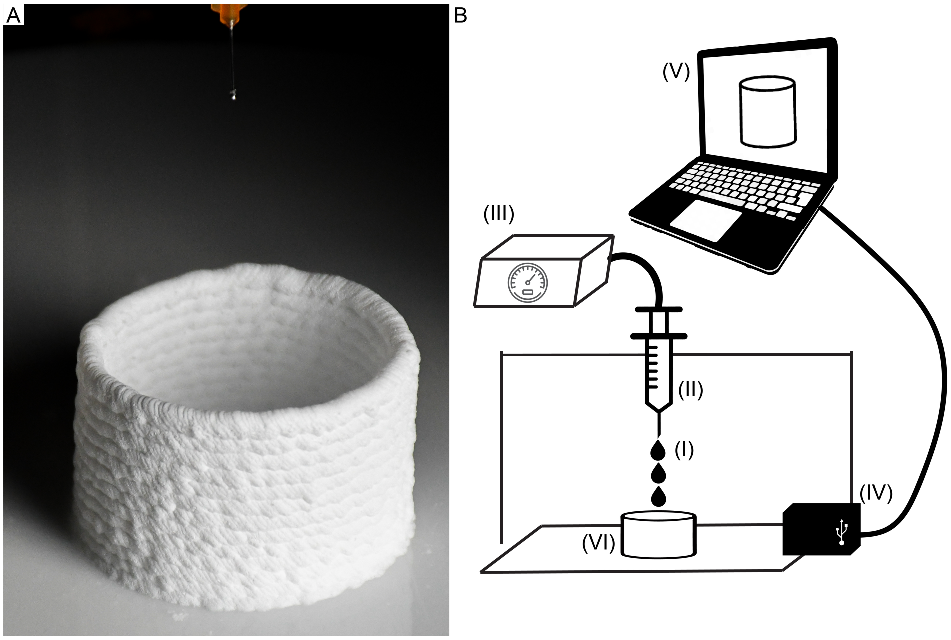


Figure 5.1: Overview of sodium acetate 3D printing system. (A) Cylindrical structure printed via layered deposition from sliced geometry (print time: 2m). (B) System Diagram: Supercooled sodium acetate solution (I) is deposited from a fine gauge syringe (II) at a controlled volumetric rate controlled by a pneumatic pump (III). The syringe is mounted to a commercial 3D fused deposition modeling printer (IV) controlled by toolpaths from the specified digital model (V). The printed structure is anchored to the build platform via a seeding of fine sodium acetate crystals (VI).

materials. FDM produces 3D forms via deposition of layers of molten polymer. SLA and related methods produce 3D forms by selectively curing a photosensitive liquid polymer resin layer-by-layer via light-induced cross-linking of monomers and oligomers. Polyjet printing creates 3D forms using layer-by-layer deposition of UV-cured liquid polymer resin. In each of these methods, additional support structures must often be printed to stabilize inclined or overhanging geometries. Removing these support structures, or removing uncured polymer, requires additional processing. Layer-by-layer 3D printing methods involve intrinsic compromises between resolution and printing time, arising from chemistry, mechatronics, and thermal effects, although recent advances have greatly accelerated these processes [23].

Here, we report a new method for 3D printing via deposition of an inorganic phase-change material — supercooled sodium acetate trihydrate (SAT). This 3D printing method addresses both the speed and geometric constraints of the aforementioned systems. Due to the instability of the supercooled SAT solution, the phase change occurs much more rapidly than the phase changes for both the molten polymer and photopolymer and does not require a catalyst or photo-stimulation. As we show, this rapid phase change allows for 3D printing in the FDM layer-by-layer paradigm at speeds up to 10 times faster than consumer grade FDM printers. The structural characteristics of SAT also allows for out of plane direct-extrusion which facilitates large structural overhangs that are strong enough to stand against gravity. The ability to print at such rates is important for industries including medicine [127] [128], food production [129] [130], and agriculture [131] [132].

5.3 Methods

Sodium acetate trihydrate (SAT) is a salt hydrate that is an attractive material for 3D printing due to its rapid crystallization rate, low-cost, and non-toxic properties [133]. Supercooling allows SAT to remain in a liquid state at temperatures below its solidifying temperature. Supercooling the aqueous solution renders the solution supersaturated without forming crystals. The supercooled, supersaturated SAT solution remains in a meta-stable state until nucleation initiates bulk crystallization, either through spontaneous primary nucleation of the liquid, or secondary nucleation via seed crystals it contacts [134]. Subsequently, rapid bulk crystallization occurs. This process is thermally and chemically governed, and can depend on the solution concentration, supercooling temperature, and interfacial geometry [135].

While such solutions have been used in chemistry education [136], and in energy storage applications [137], they have not been previously used in 3D printing, perhaps due to the several factors that must be regulated in order to realize a practical printing process. As we demonstrate, this is possible when the supercooled, suparsaturated SAT solution is stored in a sealed environment. Sealing the solution prevents unintended crystallization by allowing the solution to cool gradually after preparing the solution through a process of heating and dissolving solid crystals of SAT. Sealing also reduces the amount of foreign debris that could make contact with the liquid solution and initiate unintended nucleation [134].

5.4 Chemistry & Process

The sensitive dependency of primary nucleation on reagent purity, thermodynamics, and environmental factors makes it difficult to apply in controlled form [138]. Thus,

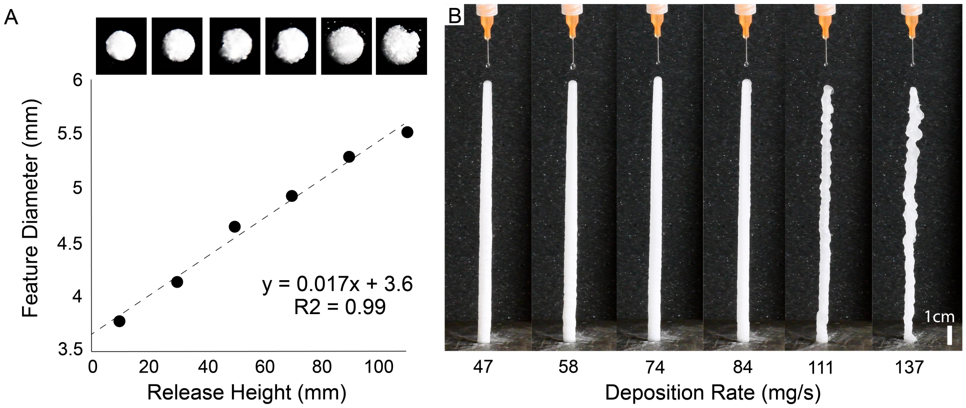


Figure 5.2: Deposition of sodium acetate. (A) Droplet diameter as a function of release height with the crystallized droplet shown. The boundary of the droplet becomes difficult to control at release heights greater than 4.5 mm where minimal artifacts were observed. (B) Columns formed by dripping solution. The shape of the column becomes difficult to control at deposition rates greater than 84 mg per second where minimal artifacts were observed. The nozzle was positioned at a constant height, therefore the columns formed a tapered shape.

our method is based on secondary nucleation via seed crystals applied to the printing surface or, during printing, the crystallized structure itself. Due to the exothermic nature of sodium acetate crystallization, the 3D printing speeds for our system are governed by the crystallization growth rate rather than the nucleation rate. The bulk rate of crystallization, called the crystallization velocity, is thermochemically regulated, and can depend upon the solution concentration, supercooling temperature, and the interfacial geometry [139].

5.5 Printing via Direct Extrusion

Figure 5.1 depicts the system for printing free standing structures via deposition and rapid crystallization of supercooled sodium acetate solution. The solution is deposited at a controlled volumetric rate R, which is determined by the pressure supplied by a pneumatic pump and the tip aperture of the printing head. The printing head is a fine gauge syringe mounted on a 3-axis computer-controlled translation stage sourced from a commercial 3D fused deposition modeling printer. During printing it follows a toolpath computed from the specified digital model.

The printed structure is anchored at the supporting substrate, which is seeded with fine crystals that facilitate initial nucleation for the crystallization (Figure 5.2). Deposition above a fixed planar location on the substrate produces extruded columns with very high aspect ratios. The height of these extruded columns sets an upper limit on the length of these vertical columns, which remain stable up to lengths greater than several centimeters. The cross-sectional widths of these columns, from 3 to 6 mm (Fig. 5.2A), are determined by three key factors: the droplet volume, the kinetics of crystallization, and the drop height. The column width increases with increasing drop height, consistent with qualitative predictions from the model accounting for droplet ballistics and crystallization kinetics [140] [141]. As the deposition rate is increased, the growth rate of such a vertical structure increases until the volume rate of deposition reaches the crystallization rate. At faster deposition rates, the supercooled liquid requires additional time in order to crystallize. These high deposition rates result in undulating patterns formed by the flow of portions of the liquid-phase solution beyond the location of deposition at the column tip.

Fabricating inclined structures results from the deposition of layers of material that are increasingly displaced in planar directions with increasing height. Narrow inclined columns like those shown in Figure 5.3B correspond to deposition along tool paths with constant translation velocities in directions that are inclined with respect to the substrate. The deposition nozzle is maintained at a fixed vertical height above the previously fabricated structure during this process. The fabrication process presented here is capable of producing high aspect ratio structures with severe inclines.

For example, the maximum length l and angle of inclination θ at which this method can print a stable leaning column of radius r is determined by the ultimate strength of the material σ_u, the modulus of elasticity E, and strength of adhesion at the base σ_a. The moments introduced by gravity W (weight of the column) and the force of the impacting droplet during deposition F (function of height and droplet size) are modeled as the superposition of axial compression and bending stresses as illustrated in Figure 5.3A.

For inclined columns without enlarged base features, and high surface adhesion, failure often occurs at the the base of the structure; consistent with the region of maximum stress of a cantilever beam. When the structure base provides sufficient adhesion support, a column of length l inclined at angle θ will fail according to the following criterion where $w = W/l$ is the weight per unit length of the column.

The column will fail in bending when the maximum stress, modeled as that of an angled cantilever beam, exceeds the ultimate strength σ_u of the material:

$$\sigma_u \leq \frac{4}{\pi r^3} \left[\frac{-lw\cos\theta}{2} - lF\cos\theta \right] \tag{5.1}$$

To facilitate even greater ultimate strength, and thus more severe lean angle θ, a tempering process like that described below can be used in order to increase resistance to fracture by fusing adjacent crystal domains within the bulk medium.

5.6 Printing via Layered Deposition

Figure 5.1A and Figure 5.4A depict structures printed via layered deposition of sodium acetate. Print instructions are prepared via conventional processes of slicing 3D geometry in software to generate CNC toolpaths. Layer height and texture can be modulated as a function of deposition rate, as in Figure 5.4B. Lower deposition rates produce irregular imbricated textures with less layer height, while higher deposition rates

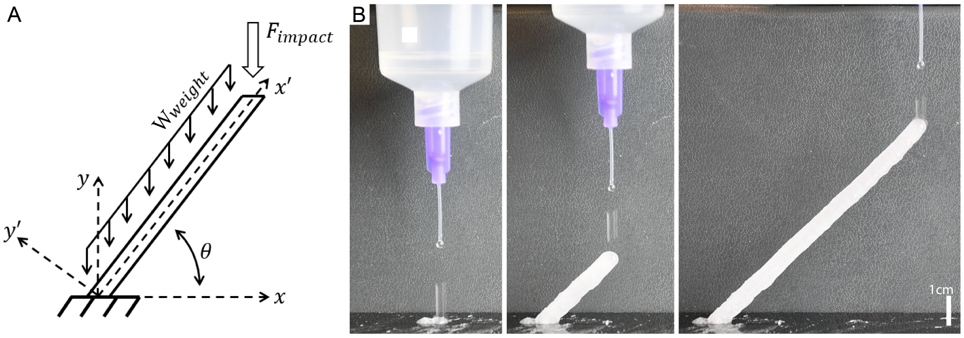


Figure 5.3: (A) Model of 3D printed inclined columns. The moments introduced by gravity W (weight of the column) and the force of the impacting droplet during deposition F (function of height and droplet size) are modeled as the superposition of axial compression and bending stresses. (B) Direct extrusion of freestanding inclined structures that are strong enough to stand against gravity. For a constant deposition rate, the angle of overhang is given as a function of speed in the x-y plane parallel to the print bed. In this example, the print nozzle is actuated along the z-axis to maintain a fixed release height of the liquid SAT droplets.

produce more a more uniform texture with greater layer heights.

5.7 Pre-Processing and Post-Processing

Additional steps can be applied in order to modify the mechanical or optical properties of the printed structures. After initial printing, following crystallization, residual water content from the supercooled solution yields coarse graining that impairs the strength of the structure (Figure 5.5A). Thermal tempering at temperatures lower than the melting temperature of solid SAT (60 C), can remove water content via dehydration and fuses boundaries between adjacent crystal domains (Figure 5.5B). After tempering for 30 minutes at 55 C, the fracture strength of printed samples, as measured via three-point testing, is increased by a factor of 1500%. In testing, we determined that longer tempering periods did not yield further increases in strength (Figure 5.5C).

Following crystallization, with or without tempering, printed SAT structures are translucent white in appearance. However, the color of the printed structure may be

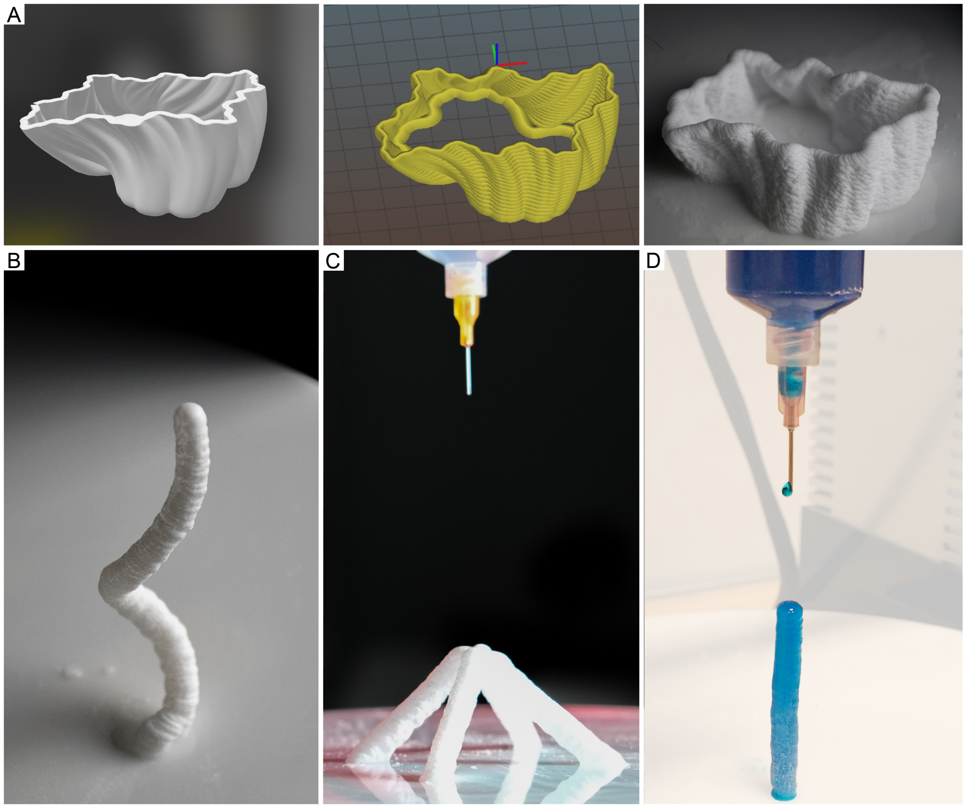


Figure 5.4: Example prints with sodium acetate. (A) Complex geometry printed in conventionally sliced, layer-by-layer modality based on digital model (print time: 4 m). (B) Freestanding helical structure printed in direct extrusion modality (print time: 30 s). (C) Freestanding wire-frame structure printed in direct extrusion modality (print time: 45 s). (D) 3D printing with colored dye mixed into sodium acetate trihydrate solution. Dye is mixed in during initial heating process to dissolve crystals and supercool the solution. The dye does not change nucleation and crystallization behavior for 3D printing.

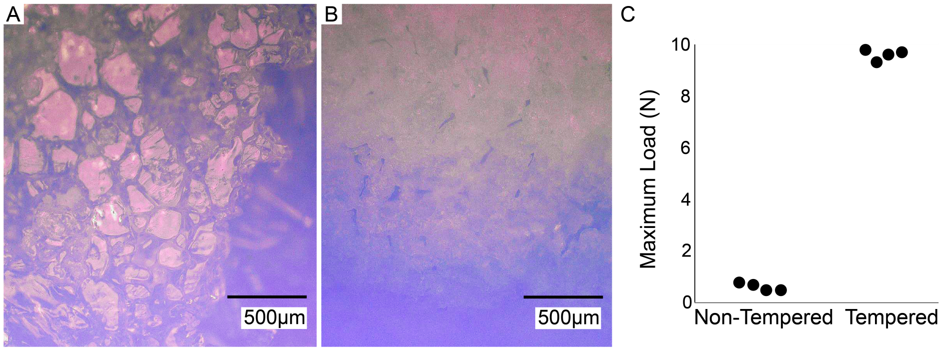


Figure 5.5: Post-Processing and Material Mixing. (A) Microscopic image of 3D printed sodium acetate trihydrate highlighting crystal domains. (B) Microscopic image the same 3D printed sodium acetate trihydrate sample after application of tempering treatment. Crystal domains are fused as a result. (C) Fracture strength of non-tempered and tempered samples of 3D printed SAT. Tempering for 30 minutes at 55 C increases fracture strength by a factor of 1500%.

easily altered through the addition of color additive dye, such as food coloring, to the SAT reagent prior to dissolution. Due to the rapidity of crystallization, this yields a uniform coloration of the printed structure, which is otherwise unmodified Figure 5.4D. The facile method with which color can be modified in printing via deposition of supercooled sodium acetate trihydrate may be compared with the difficulties encountered when printing via methods such as fused deposition modeling, for which different filaments must be acquired for each desired color.

5.8 Future Work

Improving the deposition method for 3D printing with SAT may be desirable for increased printing speed and resolution. In our system the droplet size of liquid SAT is governed by the droplets surface tension. Implementing a vibrating mechanism to the print head could reduce the droplet size and increase 3D printing resolution.

Further investigations into material mixing and encasing may be desirable for improving the strength of 3D printed SAT. For instance, embedding small fibers—that don't interfere with nucleation and crystallization—could scaffold the crystal structure and render the printed structures more resilient. Additionally, encasing the 3D printed structures with a chemically compatible epoxy or polymer could provide additional structural support.

Chapter 6

Discussion & Conclusion

6.1 Results

The introduction to this thesis proposed a vision for digital fabrication in which computational tools could be paired with highly interactive and engaging forms of making, like those observed in manual craft making. Such a form of digital fabrication could facilitate the types of expressive opportunities we see other digital media domains, including digital drawing, real-time audiovisual performances, and live electronic music. For this vision to be realized, an understanding of the implications of timescale in digital fabrication workflows needed to be investigated. Such an understanding could then inform research into new forms of digital fabrication that decrease fabrication times to support opportunities for interactive control and lead to creative scenarios in which the process of making is as important as the outcomes of making.

The preceding chapters investigated the nature of digital fabrication workflows, the role of time in digital fabrication, and the important role of materials in digital fabrication—such as supporting new forms of digital fabrication. The following sections highlight the primary results of these investigations.

6.1.1 Digital Fabrication Workflows

Chapters 3 and 4 featured analyzed the digital fabrication workflows featured in nine professionally designed products and four interactive artworks. These analyzes demonstrate that the way objects are made with digital fabrication tools is not a simple execution of a digital design, and that creative decisions are not made in CAD software alone. For both the products in Chapter 3 and the artworks in Chapter 4, access to low-level machine behavior and an understanding of material properties was a crucial component of the expressiveness in the digital design and digital fabrication process. Additionally, these chapters demonstrate that creativity and expressiveness is located in both the 3D design of geometry as well as the choice of materials and development of fabrication processes. In the case of the Chapter 3, materials and fabrication workflows evolved with the geometric design of the product and, in Chapter 4, the process of working with materials and machines was the artwork itself.

Chapters 3 and 4 also identify several cross-cutting themes in digital fabrication workflows. For the products discussed in Chapter 3, these themes include the way custom software development is informed by knowledge of materials and how professional designers often rely on incomplete physical or digital design representations. Additionally, these digital fabrication workflows demonstrate how expert knowledge of materials and machines enabled designers to anticipating product feasibility and how fabrication workflows were impacted by cost optimization, amounts of labor, and marketing strategies.

The analysis of artworks in Chapter 4 identified the crucial role of custom software in facilitating real-time interaction with fabrication machines as well as the way combining human and computer control of digital fabrication machines supports new forms of expressive opportunities. Additionally, the analysis of artworks in Chapter 4 highlights the way prototyping and developing fabrication workflows is impacted by the time constraints associated with interactive art.

6.1.2 Timescales in Digital Fabrication

The digital fabrication workflows discussed in this thesis highlight trade offs and opportunities that occur at different fabrication timescales. In digital fabrication workflows with longer timescales, the fidelity of fabricated artifacts to their respective digital design representations is high. This supports a greater degree of precision in the digital fabrication process and allows professional designers to faithfully translate their design knowledge of materials and machines into physical objects, as demonstrated by the professional digital fabrication workflows in Chapter 3. Shorter timescales, such as the digital fabrication system presented in Chapter 5, often decrease the degree of precision but increase the opportunities for interaction and direct manipulation of the fabrication process. These opportunities for interaction support forms of making that are more focused on the process of making—such as the hybrid dance-3D printing performance discussed in Chapter 5—rather than the outcomes of making.

The analyzes in Chapters 3 and 4 and the fabrication system discussed in Chapter 5 present digital fabrication workflows operating at a variety of timescales. The products created by professional designers in Chapter 3 highlight workflows that featured conventional fabrication timescales, ranging from hours to days. In contrast, the creative projects discussed in Chapter 4 and experimental 3D prints in Chapter 5 involved shorter timescales in order to foster greater degrees of interaction and direct manipulation during the fabrication process.

6.1.3 The Role of Materials in Digital Fabrication

Materials play a crucial role in digital fabrication workflows. The choice of material impacts design decisions, fabrication timescales, and product feasibility, as demonstrated by the important role deep material knowledge played in the digital fabrication workflows discussed in Chapter 3. Materials also play an important role in fostering new opportunities for creativity and expression. Chapter 4 and 5 presented digital fabrication workflows that focused primarily on materials. Chapter 5 introduced a novel, rapid additive digital fabrication system based on supercooled sodium acetate trihydrate and provided a characterization of the crystallization behavior. The forms of deposition supported by the rapid crystallization, direct extrusion and layered deposition, create structural opportunities and print speeds unique to this fabrication system. Chapter 5 also introduced methods for modifying the mechanical and optical properties of the sodium acetate printed structures. Chapter 4 demonstrated the expressive opportunities for interactive control of digital fabrication using sodium acetate in the form of a hybrid dance and 3D printing performance.

In addition to sodium acetate, Chapter 4 presented an implementation of eutectic alloys in an interactive artwork. This artwork demonstrated the opportunity to create 3D variable-stiffness structures which facilitate the shaping and re-shaping of the structure as an interactive sculpture. The discussion of this material included an overview of methods for inducing phase changes between solid and liquid states of the alloy as well as a custom method for encasing the alloy.

6.2 Opportunities for Future Work

6.2.1 Materials

In this dissertation I have demonstrated the important role of materials in digital fabrication workflows. In discussing my creative work and the development of the LCP, I demonstrate how material properties can lead to digital fabrication systems that reduce fabrication timescales and create expressive opportunities for interaction and control of digital fabrication machines. Despite the opportunities created by shorter digital fabrication timescales, the materials that support these timescales lacks the strength and durability of common engineering materials like PLA or ABS.

This trade off presents a material design problem for future work: how can we develop materials that are strong enough to create functional structures and also support rapid additive fabrication? One approach is to further develop sodium acetate as a 3D printing material. Two possible paths forward include post-processing and material-mixing. In chapter 5 I show how a tempering treatment of printed sodium acetate structures reduces water content and increases strength. Implementing a tempering treatment during the 3D printing process could increase the structural stability of the printed artifact and allow for larger and more complex structures to be fabricated. In chapter 5 I also show how materials can be mixed into the sodium acetate solution to produce changes in appearance. This approach could be applied to structural materials, such as small fibers, to increase the strength and functionality of the 3D printed artifact.

6.2.2 Interfaces

In this dissertation, the digital fabrication workflows featuring shortened timescales demonstrate the potential for including some of the computational tools and interaction paradigms frequently used in other forms of digital media. For instance, in Re:Forming, my collaborators and I developed a hybrid dance-3D printing performance in which movements from a dancer generates toolpaths for the 3D printer in real-time. These new opportunities for interaction suggest the need for new interfaces that create mappings between arbitrary inputs into the fabrication system and 3D features of the resulting fabricated artifact. This line of inquiry could extend and blend existing work in areas such as visual music, data visualization, and audiovisual art and performance.

6.2.3 Broader Implications of Digital Fabrication with Shorter Timescales

On a broader level, through the work presented in this dissertation, I point towards a speculative future in which digital fabrication workflows resemble other digital media workflows, such as real-time rendering in computer graphics and live performance in computer music. Developing digital fabrication technologies, materials, and interfaces that support short timescales could support the forms of interaction that have become commonplace in these other digital media environments—such as audio-reactive animation and musical compositions based on real-time data sonification. Future work that increases the feasibility and robustness of real-time, interactive digital fabrication could unlock new expressive paradigms for generating 3D artifacts and allow users of digital fabrication to engage in creative practices such as live performance.

Bibliography

[1] J. Jacobs, J. R. Brandt, R. Meundefinedh, and M. Resnick, *Dynamic brushes: Extending manual drawing practices with artist-centric programming tools*, in *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI EA '18, (New York, NY, USA), p. 1–4, Association for Computing Machinery, 2018.

[2] S. Chung, "drawing operations." `https://sougwen.com/project/drawingoperations-memory`, 2017.

[3] S. Mueller, P. Lopes, K. Kaefer, B. Kruck, and P. Baudisch, *Constructable: Interactive construction of functional mechanical devices*, in *ACM SIGGRAPH 2013 Talks*, SIGGRAPH '13, (New York, NY, USA), Association for Computing Machinery, 2013.

[4] K.-J. W. G. L. M. D. G. Karl D.D. Willis, Cheng Xu, *Interactive fabrication: new interfaces for digital fabrication*, *TEI '11: Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction.*

[5] A. Zoran and J. A. Paradiso, *Freed: A freehand digital sculpting tool*, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, (New York, NY, USA), p. 2613–2616, Association for Computing Machinery, 2013.

[6] L. Devendorf and K. Ryokai, *Being the machine: Reconfiguring agency and control in hybrid fabrication*, *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (2015).

[7] C. B. Julia Walter-Herrmann, *FabLab Of Machines, Makers and Inventors.* transcript Verlag, 2013.

[8] S.-B. N. P. N. Marjanović D., Štorga M., *A REVIEW OF MAKING IN THE CONTEXT OF DIGITAL FABRICATION TOOLS*, *DS 92: Proceedings of the DESIGN 2018 15th International Design Conference.*

[9] P. Blikstein, *Digital Fabrication and 'Making' in Education: The Democratization of Invention*, .

[10] M. McCullough, *Abstracting Craft : The Practiced Digital Hand.* MIT Press, 1996.

[11] J. Jacobs and L. Buechley, *Codeable Objects: Computational Design and Digital Fabrication for Novice Programmers*, p. 1589–1598. Association for Computing Machinery, New York, NY, USA, 2013.

[12] M. V. Mathews, *The digital computer as a musical instrument*, *Science* **142** (1963), no. 3592 553–557, [https://science.sciencemag.org/content/142/3592/553.full.pdf].

[13] P. Lechner, *Multimedia Programming Using Max/MSP and TouchDesigner.* Packt Publishing Ltd, 2014.

[14] C. Leider, *Digital audio workstation.* McGraw-Hill New York, 2004.

[15] A. Reuter, *Who let the daws out? the digital in a new generation of the digital audio workstation*, *Popular Music and Society* (2021) 1–16.

[16] W. Carlson.

[17] J. Peddie, *The History of Visual Magic in Computers: How Beautiful Images are Made in CAD, 3D, VR, and AR.* Springer Publishing Company, Incorporated, 2013.

[18] M. Laskujärvi, *Real-time interactive animated visualisations for music performances: comparing blender game engine and touchdesigner*, .

[19] F. Blum, *Digital Interactive Installations: Programming interactive installations using the software package Max/MSP/Jitter.* diplom. de, 2007.

[20] T. Koerselman, K. Ng, and O. Larkin, *The mav framework: working with 3d motion data in max msp/jitter*, *The MAV Framework* (2007) 1000–1006.

[21] M. Hirsch, J. Jacobs, and Y. Visell, “Sk3tch: Fast, interactive 3d printing via liquid crystallization.” `https://www.youtube.com/watch?v=cyG0Hq5Ga50&ab_channel=cmurobotics`, 2019.

[22] S. Mueller, *Interacting with Personal Fabrication Devices.* PhD thesis, University of Potsdam, 2016.

[23] I. Liashenko, J. Rosell-Llompart, and A. Cabot, *Ultrafast 3d printing with submicrometer features using electrostatic jet deflection*, .

[24] P. Robles Martinez, A. W. Basit, and S. Gaisford, *The history, developments and opportunities of stereolithography*, in *3D Printing of Pharmaceuticals* (A. W. Basit and S. Gaisford, eds.), pp. 55–79. Springer International Publishing.

[25] R. Kluszczynski, *Strategies of interactive art*, *Journal of Aesthetics & Culture* **2** (2010), no. 1 5525.

[26] P. Galanter, *What is generative art? complexity theory as a context for art theory*, in *In GA2003 – 6th Generative Art Conference*, 2003.

[27] E. OLIVERAS, *El grav, groupe de recherche d'art visuel*, .

[28] A. R. di CUTÒ.

[29] J. Rosenkrantz and J. Louis-Rosenberg, "floraform." `https://n-e-r-v-o-u-s.com/projects/sets/floraform/`, 2014.

[30] C. Reas, "path." `https://reas.com/path_p/`, 2001/2014.

[31] R. Baecker, "nowhere." `https://rlfbckr.io/work/nowhere/`, 2005.

[32] D. Bowen, "fly carving device." `https://www.dwbowen.com/fly-carving-device`, 2018.

[33] Y. Vishnevsky, "Silk." `http://weavesilk.com/`, 2011.

[34] F. Offert.

[35] C. Reas, *Making Pictures With Generative Adversarial Networks.* Anteism Books, 2019.

[36] W. McGregor, "living archive." `https://waynemcgregor.com/productions/living-archive/`, 2019.

[37] H. Peng, J. Briggs, C.-Y. Wang, K. Guo, J. Kider, S. Mueller, P. Baudisch, and F. Guimbretière, *RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer*, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2018.

[38] S. Kettley, *The foundations of craft: A suggested protocol for introducing craft to other disciplines*, *Craft Research* **3** (2012), no. 1 33–51.

[39] R. Tian, V. Saran, M. Kritzler, F. Michahelles, and E. Paulos, *Turn-by-wire: Computationally mediated physical fabrication*, in *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, UIST '19, (New York, NY, USA), p. 713–725, Association for Computing Machinery, 2019.

[40] S. Mueller, A. Seufert, H. Peng, R. Kovacs, K. Reuss, F. Guimbretière, and P. Baudisch, *Formfab: Continuous interactive fabrication*, in *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '19, (New York, NY, USA), p. 315–323, Association for Computing Machinery, 2019.

[41] L. Devendorf and K. Ryokai, *Redeform: Participatory 3d printing in public spaces*, in *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, (New York, NY, USA), p. 423–424, Association for Computing Machinery, 2015.

[42] D. Ilic, "roboaction." `http://www.draganilic.org/projects/2015/2015.html`, 2015.

[43] A. Pfeffer, "satisying drawing." `https://arnaudpfeffer.com/`.

[44] H. Twigg-Smith, J. T. O'Leary, and N. Peek, *Tools, Tricks, and Hacks: Exploring Novel Digital Fabrication Workflows on PlotterTwitter*. Association for Computing Machinery, New York, NY, USA, 2021.

[45] C. O. SILKwORMS, *silk pavilion: a case study in fibre-based digital fabrication*, .

[46] M. Kayser, S. Sharma, J. Duro-Royo, C. Bader, D. Kolb, and N. Oxman, "Synthetic apiary." `https://oxman.com/projects/synthetic-apiary`, 2016.

[47] S. Collective, "Mycocene." `https://somme-collective.net/#`, 2018.

[48] F. Design, *Materialized sketch*, 2005. `https://collections.vam.ac.uk/item/O1299501/materialized-sketch-chair-front-design/`, accessed Aug 2021.

[49] F. Design, *Sketch furniture by front*, 2007. `https://www.youtube.com/watch?v=8zP1em1dg5k` accessed July 2021.

[50] D. Dougherty, A. Conrad, and T. O'Reilly, *Free to Make: How the Maker Movement is Changing Our Schools, Our Jobs, and Our Minds*. North Atlantic Books, 2016.

[51] N. Gershenfeld, A. Gershenfeld, and J. Cutcher-Gershenfeld, *Designing Reality: How to Survive and Thrive in the Third Digital Revolution*. Basic Books, 2017.

[52] P. Blikstein and D. Krannich, *The makers' movement and fablabs in education: Experiences, technologies, and research*, in *Proceedings of the 12th International Conference on Interaction Design and Children*, IDC '13, (New York, NY, USA), p. 613–616, Association for Computing Machinery, 2013.

[53] S. Lindtner, G. D. Hertz, and P. Dourish, *Emerging sites of hci innovation: Hackerspaces, hardware startups & incubators*, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, (New York, NY, USA), p. 439–448, Association for Computing Machinery, 2014.

[54] E. Sells, S. Bailard, Z. Smith, A. Bowyer, and V. Olliver, *RepRap: The Replicating Rapid Prototyper: Maximizing Customizability by Breeding the Means of Production*, pp. 568–580. 2010.

[55] J. Lipton, R. Maccurdy, M. Boban, N. Chartrain, L. W. Iii, N. Gangjee, A. Nagai, J. Cohen, K. Sobhani, J. Liu, H. Qudsi, J. Kaufman, S. Mitra, A. Garcia, A. Mcnicoll, and H. Lipson, *Fab@home 3: A more robust, cost effective and accessible open hardware fabrication platform*, *Proceedings of the Twenty Third Annual International Solid Freeform Fabrication Symposium, An Additive Manufacturing Conference* (2012) 125–135.

[56] R. Schmidt and M. Ratto, *Design-to-fabricate: Maker hardware requires maker software*, *IEEE Computer Graphics and Applications* **33** (2013), no. 6 26–34.

[57] G. Saul, M. Lau, J. Mitani, and T. Igarashi, *Sketchchair: An all-in-one chair design system for end users*, in *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '11, (New York, NY, USA), p. 73–80, Association for Computing Machinery, 2010.

[58] N. Gershenfeld, *Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication.* Basic Books, 2005.

[59] C. Anderson, *Makers: The New Industrial Revolution.* Crown Business, 2014.

[60] M. Hofmann, G. Hann, S. E. Hudson, and J. Mankoff, *Greater than the Sum of Its PARTs: Expressing and Reusing Design Intent in 3D Models*, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2018.

[61] B. Lafreniere and T. Grossman, *Blocks-to-cad: A cross-application bridge from minecraft to 3d modeling*, in *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, (New York, NY, USA), p. 637–648, Association for Computing Machinery, 2018.

[62] R. Schmidt and K. Singh, *Meshmixer: An interface for rapid mesh composition*, in *ACM SIGGRAPH 2010 Talks*, SIGGRAPH '10, (New York, NY, USA), Association for Computing Machinery, 2010.

[63] C. Torres and E. Paulos, *Metamorphe: Designing expressive 3d models for digital fabrication*, in *Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition*, C&C '15, (New York, NY, USA), p. 73–82, Association for Computing Machinery, 2015.

[64] L. Oehlberg, W. Willett, and W. E. Mackay, *Patterns of Physical Design Remixing in Online Maker Communities*, p. 639–648. Association for Computing Machinery, New York, NY, USA, 2015.

[65] V. Savage, S. Follmer, J. Li, and B. Hartmann, *Makers' marks: Physical markup for designing and fabricating functional objects*, in *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, (New York, NY, USA), p. 103–108, Association for Computing Machinery, 2015.

[66] D. Ashbrook, S. S. Guo, and A. Lambie, *Towards augmented fabrication: Combining fabricated and existing objects*, in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '16, (New York, NY, USA), p. 1510–1518, Association for Computing Machinery, 2016.

[67] D. Leen, R. Ramakers, and K. Luyten, *Strutmodeling: A low-fidelity construction kit to iteratively model, test, and adapt 3d objects*, in *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, (New York, NY, USA), p. 471–479, Association for Computing Machinery, 2017.

[68] M. Larsson, H. Yoshida, N. Umetani, and T. Igarashi, *Tsugite: Interactive Design and Fabrication of Wood Joints*, p. 317–327. Association for Computing Machinery, New York, NY, USA, 2020.

[69] D. Leen, N. Peek, and R. Ramakers, *LamiFold: Fabricating Objects with Integrated Mechanisms Using a Laser Cutter Lamination Workflow*, p. 304–316. Association for Computing Machinery, New York, NY, USA, 2020.

[70] M. Gantt and B. A. Nardi, *Gardeners and gurus: Patterns of cooperation among cad users*, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '92, (New York, NY, USA), p. 107–117, Association for Computing Machinery, 1992.

[71] J. Li, S. Hashim, and J. Jacobs, *What we can learn from visual artists about software development*, in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, CHI '21, (New York, NY, USA), Association for Computing Machinery, 2021.

[72] A. Cheatle and S. J. Jackson, *Digital entanglements: Craft, computation and collaboration in fine art furniture production*, in *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing*, CSCW '15, (New York, NY, USA), p. 958–968, Association for Computing Machinery, 2015.

[73] K. N. Dew and D. K. Rosner, *Lessons from the Woodshop: Cultivating Design with Living Materials*, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2018.

[74] M. Annett, T. Grossman, D. Wigdor, and G. Fitzmaurice, *Exploring and understanding the role of workshop environments in personal fabrication processes*, *ACM Trans. Comput.-Hum. Interact.* **26** (Mar., 2019).

[75] N. Yildirim, J. McCann, and J. Zimmerman, *Digital Fabrication Tools at Work: Probing Professionals' Current Needs and Desired Futures*, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2020.

[76] E. Mark, M. Gross, and G. Goldschmidt, *A perspective on computer aided design after four decades*, *Proceedings of the 26th Education and research in Computer Aided Architectural Design in Europe Conference* (2008) 169–176.

[77] L. Devendorf, K. Arquilla, S. Wirtanen, A. Anderson, and S. Frost, *Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency*, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2020.

[78] J. Jacobs and A. Zoran, *Hybrid Practice in the Kalahari: Design Collaboration through Digital Tools and Hunter-Gatherer Craft*, p. 619–628. Association for Computing Machinery, New York, NY, USA, 2015.

[79] R. Wakkary, H. Lin, S. Mortimer, L. Low, A. Desjardins, K. Doyle, and P. Robbins, *Productive frictions: Moving from digital to material prototyping and low-volume production for design research*, in *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*, DIS '16, (New York, NY, USA), p. 1258–1269, Association for Computing Machinery, 2016.

[80] D. K. Rosner, M. Ikemiya, and T. Regan, *Resisting alignment: Code and clay*, in *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, (New York, NY, USA), p. 181–188, Association for Computing Machinery, 2015.

[81] D. Retelny and P. Hinds, *Embedding Intentions in Drawings: How Architects Craft and Curate Drawings to Achieve Their Goals*, in *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing*, (New York, NY, USA), pp. 1310–1322, ACM, 2016.

[82] D. F. Noble, *Forces of production: a social history of industrial automation.* Knopf, New York, 1st ed., 1984.

[83] E. Gulay and A. Lucero, *Integrated Workflows: Generating Feedback Between Digital and Physical Realms*, p. 1–15. Association for Computing Machinery, New York, NY, USA, 2019.

[84] J. Louis-Rosenberg, *Drowning in triangle soup: The quest for a better 3-d printing file format*, *XRDS* **22** (Apr., 2016) 58–62.

[85] N. Hudson, C. Alcock, and P. K. Chilana, *Understanding Newcomers to 3D Printing: Motivations, Workflows, and Barriers of Casual Makers*, p. 384–396. Association for Computing Machinery, New York, NY, USA, 2016.

[86] J. L. Meissner, P. Jarusriboonchai, J. McLaughlin, and P. Wright, *More than the Sum of Makers: The Complex Dynamics of Diverse Practices at Maker Faire*, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2019.

[87] T. Whelan, *We are not all makers: The paradox of plurality in the maker movement*, in *Proceedings of the 2018 ACM Conference Companion Publication on Designing Interactive Systems*, DIS '18 Companion, (New York, NY, USA), p. 75–80, Association for Computing Machinery, 2018.

[88] C. MacArthur, C. Wong, and M. Hancock, *Makers and quilters: Investigating opportunities for improving gender-imbalanced maker groups*, *Proc. ACM Hum.-Comput. Interact.* **3** (Nov., 2019).

[89] D. Roedl, S. Bardzell, and J. Bardzell, *Sustainable making? balancing optimism and criticism in hci discourse*, *ACM Trans. Comput.-Hum. Interact.* **22** (June, 2015).

[90] K. N. Dew and D. K. Rosner, *Designing with waste: A situated inquiry into the material excess of making*, in *Proceedings of the 2019 on Designing Interactive Systems Conference*, DIS '19, (New York, NY, USA), p. 1307–1319, Association for Computing Machinery, 2019.

[91] M. G. Ames, J. Bardzell, S. Bardzell, S. Lindtner, D. A. Mellis, and D. K. Rosner, *Making cultures: Empowerment, participation, and democracy - or not?*, in *CHI '14 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '14, (New York, NY, USA), p. 1087–1092, Association for Computing Machinery, 2014.

[92] S. Lindtner, S. Bardzell, and J. Bardzell, *Reconstituting the Utopian Vision of Making: HCI After Technosolutionism*, p. 1390–1402. Association for Computing Machinery, New York, NY, USA, 2016.

[93] J. Yao, D. M. Kaufman, Y. Gingold, and M. Agrawala, *Interactive design and stability analysis of decorative joinery for furniture*, *ACM Trans. Graph.* **36** (Mar., 2017).

[94] M. Lau, A. Ohgawara, J. Mitani, and T. Igarashi, *Converting 3d furniture models to fabricatable parts and connectors*, *ACM Trans. Graph.* **30** (July, 2011).

[95] D. Leen, T. Veuskens, K. Luyten, and R. Ramakers, *JigFab: Computational Fabrication of Constraints to Facilitate Woodworking with Power Tools*, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2019.

[96] C. Zheng, E. Y.-L. Do, and J. Budd, *Joinery: Parametric joint generation for laser cut assemblies*, in *Proceedings of the 2017 ACM SIGCHI Conference on Creativity and Cognition*, C&C '17, (New York, NY, USA), p. 63–74, Association for Computing Machinery, 2017.

[97] P. Baudisch, A. Silber, Y. Kommana, M. Gruner, L. Wall, K. Reuss, L. Heilman, R. Kovacs, D. Rechlitz, and T. Roumen, *Kyub: A 3D Editor for Modeling Sturdy Laser-Cut Objects*, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2019.

[98] T. Sethapakdi, D. Anderson, A. R. C. Sy, and S. Mueller, *Fabricaide: Fabrication-Aware Design for 2D Cutting Machines*. Association for Computing Machinery, New York, NY, USA, 2021.

[99] C. Torres, J. O'Leary, M. Nicholas, and E. Paulos, *Illumination Aesthetics: Light as a Creative Material within Computational Design*, p. 6111–6122. Association for Computing Machinery, New York, NY, USA, 2017.

[100] M. Shugrina, A. Shamir, and W. Matusik, *Fab forms: Customizable objects for fabrication with validity and geometry caching*, *ACM Trans. Graph.* **34** (July, 2015).

[101] A. Schulz, A. Shamir, D. I. W. Levin, P. Sitthi-amorn, and W. Matusik, *Design and fabrication by example*, *ACM Trans. Graph.* **33** (July, 2014).

[102] J. Coleman, C. Long, A. Manto, and T. Wastvedt, *Lots of parts, lots of formats, lots of headache*, *XRDS* **22** (Apr., 2016) 54–57.

[103] S. Mueller, B. Kruck, and P. Baudisch, *LaserOrigami: Laser-Cutting 3D Objects*, p. 2585–2592. Association for Computing Machinery, New York, NY, USA, 2013.

[104] J. Forman, M. D. Dogan, H. Forsythe, and H. Ishii, *Defextiles: 3d printing quasi-woven fabric via under-extrusion*, in *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, UIST '20, (New York, NY, USA), p. 1222–1233, Association for Computing Machinery, 2020.

[105] H. Takahashi and J. Kim, *3d printed fabric: Techniques for design and 3d weaving programmable textiles*, in *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, UIST '19, (New York, NY, USA), p. 43–51, Association for Computing Machinery, 2019.

[106] S. Mueller, S. Im, S. Gurevich, A. Teibrich, L. Pfisterer, F. Guimbretière, and P. Baudisch, *Wireprint: 3d printed previews for fast prototyping*, in *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*, UIST '14, (New York, NY, USA), p. 273–280, Association for Computing Machinery, 2014.

[107] D. Beyer, S. Gurevich, S. Mueller, H.-T. Chen, and P. Baudisch, *Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates*, p. 1799–1806. Association for Computing Machinery, New York, NY, USA, 2015.

[108] T. J. Roumen, W. Müller, and P. Baudisch, *Grafter: Remixing 3D-Printed Machines*, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2018.

[109] T. C. Yu and J. McCann, *Coupling programs and visualization for machine knitting*, in *Symposium on Computational Fabrication*, SCF '20, (New York, NY, USA), Association for Computing Machinery, 2020.

[110] C. Nandi, A. Caspi, D. Grossman, and Z. Tatlock, *Programming Language Tools and Techniques for 3D Printing*, in *2nd Summit on Advances in Programming Languages (SNAPL 2017)* (B. S. Lerner, R. Bodík, and S. Krishnamurthi, eds.), vol. 71 of *Leibniz International Proceedings in Informatics (LIPIcs)*, (Dagstuhl, Germany), pp. 10:1–10:12, Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, 2017.

[111] N. Peek, J. Coleman, I. Moyer, and N. Gershenfeld, *Cardboard Machine Kit: Modules for the Rapid Prototyping of Rapid Prototyping Machines*, p. 3657–3668. Association for Computing Machinery, New York, NY, USA, 2017.

[112] Kickstarter, *Kickstarter make 100*, 2021. `https://www.kickstarter.com/make-100`, accessed Aug 2021.

[113] I. Bennink, T. Carrigan, J. Arthur, J. Steiner, and N. Ierodiaconou, *Opendesk - furniture designed for inspiring workplaces*, 2013. `https://www.opendesk.cc/`, accessed Aug 2021.

[114] M. M. Maleki, R. F. Woodbury, and C. Neustaedter, *Liveness, localization and lookahead: Interaction elements for parametric design*, in *Proceedings of the 2014 Conference on Designing Interactive Systems*, DIS '14, (New York, NY, USA), p. 805–814, Association for Computing Machinery, 2014.

[115] J. Jacobs, D. Mellis, A. Zoran, C. Torres, J. Brandt, and T. J. Tanenbaum, *Digital craftsmanship: Hci takes on technology as an expressive medium*, in *Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems*, DIS '16 Companion, (New York, NY, USA), p. 57–60, Association for Computing Machinery, 2016.

[116] *A cultural economic analysis of craft*, 2019.

[117] A. Klamer, *Doing the Right Thing.* Saint Philip Street Press, Oct., 2020.

[118] C. Neustaedter and P. Sengers, *Autobiographical design in hci research: designing and learning through use-it-yourself*, in *DIS '12*, 2012.

[119] C. Frayling, *Research in art and design (royal college of art research papers, vol 1, no 1, 1993/4)*, .

[120] J. Zimmerman, J. Forlizzi, and S. Evenson, *Research through design as a method for interaction design research in hci*, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '07, (New York, NY, USA), p. 493–502, Association for Computing Machinery, 2007.

[121] A. Desjardins and A. Ball, *Revealing tensions in autobiographical design in hci*, in *proceedings of the 2018 designing interactive systems conference*, pp. 753–764, 2018.

[122] Merriam-Webster.

[123] F. Scheurer, *Materialising complexity*, *Architectural Design* **80** (2010), no. 4 86–93.

[124] P. Kyratsis, K. Kakoulis, and A. P. Markopoulos, *Advances in cad/cam/cae technologies*, 2020.

[125] J.-Y. Lee, J. An, and C. K. Chua, *Fundamentals and applications of 3d printing for novel materials*, *Applied materials today* **7** (2017) 120–133.

[126] N. Shahrubudin, T. C. Lee, and R. Ramlan, *An overview on 3d printing technology: Technological, materials, and applications*, *Procedia Manufacturing* **35** (2019) 1286–1296.

[127] C. L. Ventola, *Medical applications for 3d printing: current and projected uses*, *Pharmacy and Therapeutics* **39** (2014), no. 10 704.

[128] N. J. Mardis, *Emerging technology and applications of 3d printing in the medical field*, *Missouri medicine* **115** (2018), no. 4 368.

[129] R. Kumar, R. Kumar, *et. al.*, *3d printing of food materials: A state of art review and future applications*, *Materials Today: Proceedings* **33** (2020) 1463–1467.

[130] N. Nachal, J. Moses, P. Karthik, and C. Anandharamakrishnan, *Applications of 3d printing in food processing*, *Food Engineering Reviews* **11** (2019), no. 3 123–141.

[131] C. Maraveas, I. S. Bayer, and T. Bartzanas, *4d printing: Perspectives for the production of sustainable plastics for agriculture*, *Biotechnology Advances* (2021) 107785.

[132] M. De Clercq, A. Vats, and A. Biel, *Agriculture 4.0: The future of farming technology*, *Proceedings of the World Government Summit, Dubai, UAE* (2018) 11–13.

[133] H. Mohammadzadeh-Aghdash, Y. Sohrabi, A. Mohammadi, D. Shanehbandi, P. Dehghan, and J. E. N. Dolatabadi, *Safety assessment of sodium acetate, sodium diacetate and potassium sorbate food additives*, *Food chemistry* **257** (2018) 211–215.

[134] J. Mullin, *5 - nucleation*, in *Crystallization (Fourth Edition)* (J. Mullin, ed.), pp. 181–215. Butterworth-Heinemann, Oxford, fourth edition ed., 2001.

[135] J. Mullin, *2 - physical and thermal properties*, in *Crystallization (Fourth Edition)* (J. Mullin, ed.), pp. 32–85. Butterworth-Heinemann, Oxford, fourth edition ed., 2001.

[136] G. A. Hiegel, *Crystallization of sodium acetate*, *Journal of Chemical Education* **57** (1980), no. 2 152.

[137] Y. Wang, K. Yu, H. Peng, and X. Ling, *Preparation and thermal properties of sodium acetate trihydrate as a novel phase change material for energy storage*, *Energy* **167** (2019) 269–274.

[138] J. Mullin, *8 - industrial techniques and equipment*, in *Crystallization (Fourth Edition)* (J. Mullin, ed.), pp. 315–402. Butterworth-Heinemann, Oxford, fourth edition ed., 2001.

[139] P. L. Dietz, J. S. Brukner, and C. A. Hollingsworth, *Linear crystallization velocities of sodium acetate in supersaturated solutions*, *The Journal of Physical Chemistry* **61** (1957), no. 7 944–948, [https://doi.org/10.1021/j150553a023].

[140] V. Deshpande and S. Jape, *Isothermal crystallization kinetics of anhydrous sodium acetate nucleated poly (ethylene terephthalate)*, *Journal of applied polymer science* **116** (2010), no. 6 3541–3554.

[141] C. Miesse, *Ballistics of an evaporating droplet*, *Journal of Jet Propulsion* **24** (1954), no. 4 237–244.