Beyond Plastic Filament

An Exploration of 3D Printing as a Part of Creative Practices

by

Jennifer Weiler

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Graduate Supervisory Committee:

Todd Ingalls, Co-Chair
Stacey Kuznetsov, Co-Chair
Mary Bates Neubauer
Hye Yeon Nam

ARIZONA STATE UNIVERSITY

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ABSTRACT

The current push towards integrating new digital fabrication techniques into all parts of daily life has raised concerns about the changing role of the craftsperson in creative making. The goal of this dissertation is to gain insight into how new technologies can be incorporated into creative practices in a way that effectively supports the goals and workflows of practitioners. To do so, I explore three different cases in which 3D printing, a tool by which complex 3D objects are fabricated from digital designs, is used in tandem with traditional creative practices. Each project focuses on a different way to incorporate 3D printed objects, whether it be as a visualization for artists' processes, a substitute medium for finished artworks, or as a step toward a larger fabrication workflow. Through this research, I discover how the integration of 3D printing affects creative processes, explore how these changes influence how and why practitioners engage in artistic practices, and gain insight into directions for future technological innovations.

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CHAPTER 1

INTRODUCTION: PERSONAL CREATIVE PRACTICES IN THE AGE OF DIGITAL FABRICATION

In recent decades, emerging digital tools and techniques have begun to be incorporated into all aspects of daily life, including artistic and creative practices. These changes have affected not only how artworks are shared between creators and consumers, but also the actual making processes. One example of this trend is the several types of software that attempt to recreate the experience of artistic mediums, such as drawing and painting, entirely within a digital interface [41]. More recently, there has been a substantial increase in the popularity and availability of technology designed to translate digital creations into physical artifacts. Among these, the 3D printer is arguably the most recognizable and historically significant of the current push in personal fabrication, since it has the ability to accurately create complex 3D objects from digital designs [172]. The increasing affordability of 3D printers has allowed them to become widely incorporated in makerspaces and libraries, which positions them as a potential tool for many artists and makers. However, this push towards new fabrication techniques has raised concerns about the changing role of the craftsperson in creative making (e.g. [73, 171]).

While creative practices have always changed based on the types of materials and tools available, the integration of digital technology could potentially discourage both creative exploration and physical interaction. By limiting options to those offered through software, the user is restricted in their creative choices to the options given to them by the programmer [134]. Likewise, the fabrication possibilities offered by 3D printing may be undesirable to current artists and makers if they are implemented in a way that reduces, supplants, or excludes valued traditional elements of creative practices (e.g. [51, 108]). Within this current context, this dissertation will examine how 3D printing systems can be integrated into existing arts practices.

This dissertation presents findings related to the use of 3D printing based on collaborative research from the last 5 years. The research presented includes a combination of prototypes, workshops with creative practitioners from a variety of fields, as well as hands on experimentation with several creative practices. Chapter 2 serves as an overview of related literature in the fields of fine arts, anthropology, and human-computer interaction that have influenced the work presented in this dissertation, and each of the following three chapters detail a project that relates to the incorporation of 3D printing into different aspects of creative practices. Chapter 3 explores ways of translating traditional pencil drawings into computer-generated visualizations of the making process. Chapter 4 describes my work creating a software system, physical kit, and workflow designed to translate a traditional artistic technique (ceramic lithophanes) into a hybrid digital-physical fabrication process. Chapter 5 discusses how designs produced by standard plastic-filament 3D printers can be incorporated into different creative practices, including specialized fine arts methods (metal casting), experimental maker materials (mycelium), and widely-accessible creative making (food preparation). Through this research, we are able to better understand how digital technology and emerging fabrication approaches can be successfully integrated into artistic practices in a way that supports, rather than supplants, the goals and workflows of creative practitioners.

CHAPTER 2

RELATED LITERATURE

This chapter serves as a summary of the related literature that has influenced the work presented in this dissertation, which draws from the domains of fine arts, anthropology, and human-computer interaction. Section 2.1 begins with working definitions of terms which are later expanded upon through the research of various authors. Each perspective focuses on a different aspect of creative making that offers insight into how technology can be incorporated into creative practices. Section 2.2 describes current research in regards to the hybridization of craft with digital technology, either as a means to augment the creative or art viewing process. Additional related literature is included in subsequent chapters.

2.1 Descriptions of Creative Processes

While words like “craft” and “technology” can be easily used and understood in common conversations, they describe such a wide range of potential activities and objects that they are difficult to specify. Therefore, in order to assist in the clarity of this paper, this section states basic working definitions of key terms, summarized from the related literature.

Art: Aesthetic or creative works produced through some combination of human skill, imagination, or intellect. While art is generally expected to elicit an emotional or aesthetic response, what is considered art is culturally dependent [1,5, 16, 25, 72, 91].

Technology: The objects, tools, and machines created to solve problems or serve purposes. Technology can be viewed as both freeing and inhibiting. Technology can be used to make the difficult easy and the impractical possible. However, technology is inherently about reducing things to their function, which can result in the disengagement of individuals from the material aspect of creative practices and making [50, 72, 171].

Craft: A process or activity in which skill is used to produce a creative work. Generally, the skill is developed through repeated engagement in the crafting activity. Therefore, craft itself may be viewed as a process, rather than a result [1, 73, 74,108, 127, 139].

Design: The intellectual labor involved in the creation of an object. The design of an object can be partially or fully completed before the construction of the physical object begins, or the design can emerge through the physical interaction of the maker and the material [127, 139].

Making: The physical labor involved in the creation of an object. Making can be similar to crafting, though making can describe both skilled and unskilled physical activity [74, 139].

2.2.1 The Interplay of Art and Craft

Within his book *Thinking through Craft*, Glenn Adamson describes the differences between craft and art when viewed through the lens of fine arts. Adamson describes art, within current cultural context, as being perceived as autonomous and oriented toward optic effects, whereas craft is largely perceived as supplemental, focused on material experience, and embodies skill [1]. When describing art as autonomous, Adamson points to the fact that art is often encouraged to exist for its own sake. He cites the painting as an example of this in practice: paintings are “rectangles of presence that cut themselves off from the surrounding world” and are meant to be visually observed, rather than physically interacted with (Adamson, 39).

In contrast, while craft is seen as necessary to the creation of works of art, it is not viewed as having clear intrinsic value. Crafting activities are not undertaken for their own sake, but in the service of making something else. In addition, rather than being a stagnant object, craft exists in motion, as it is the culmination of skills developed through habitual action. Based on this definition of craft, Adamson categorizes those who engage in craft into two ideological frameworks, the pastoral and the amateur [1]. The *pastoral* approach to craft is characterized by a nostalgic desire to remove oneself from the stress and demands of everyday life. With the advent of modern technology, the pastoral also connotes a return to traditional making practices, and the cultural traditions that surround them. In contrast, the *amateur* can be described as one who creates for self-gratification rather than for critical analysis or financial necessity.

In *The Principles of Art,* R. G. Collingwood lays out what he believes to be the main distinctions between craft and art. In his description, craft relates to the planned activities by which raw material is transformed into a finished object [25]. In contrast, artistic work is the result that can occur through creative engagement, rather than pre-planned execution:

“What he wants to say is not present to him as an end towards which mean have to be devised; it becomes clear to him only as the poem takes shape in his mind, or the clay in his fingers.” (Collingwood, 29)

Through their analyses, Adamson and Collingwood present largely similar descriptions of the distinctions between art and craft, though Collingwood elaborates further on the role of craft within the context of cultural needs. As one of his distinctions between art and craft, Collingwood notes a hierarchical relation between crafts, in which the materials, means, or parts that are the end product of one craft often serve as the raw material for another. For example, fabricated wooden planks could be used to help miners produce ore, which could then be shaped into horse shoes, which allow for the ploughing and cultivation of fields [25]. In this way, the traditional crafts could be seen as something akin to a pre-industrial fabrication pipeline. Notably, while Adamson’s description of the *pastoral* and *amateur* denotes a view of craft that is undertaken for the mental or emotional benefit of the creative practitioner, Collingwood views craft mainly as a means to an end.

2.1.2 The Role of Technology in Creative Practices

In recent decades, many researchers have explored how the inclusion of technology may affect creative practices. While art itself could be seen as a type of technology [50], the focus of this analysis will center on the use of modern mechanical and digital technology, as opposed to all border definitions of technology. In *What Things Do: Philosophical Reflections on Technology, Agency, and Design*, Verbeek describes how technology "promises enrichment but delivers impoverishment" [171]. In his view, the promises of increased leisure and personal time that automation could have enabled have failed to materialize. Instead, the average person is being increasingly exhausted and overworked [171]. When discussing the role of craft in relation to modern life, Adamson asserts that craft is sometimes used as "a Utopian prop, a story we tell to assuage our anxieties in an increasingly fluid, technological society" [1]. He states that, in contrast to the automation of modern technology, craft is viewed as an escape from the anxieties, pressure, and conformity of modern day. In the forward to *Radical Lace & Subversive Knitting* [109], David Revere McFadden expresses similar views about the value of craft and manual labor as a response to the alienation caused by technology:

"In a world where the clinical and impersonal nature of digital technologies may perplex and discourage us (and where we daily confront what often seems like homogenous anonymity in the global village), what can restore our connection to community, to our history, and to our shared aspirations is the ease of hand-i.e., of making something from start to finish by manual labor." (McFadden, 8)

This stance can result in an overall negative view of modern technology, and sets up the relationship between technology and craft to be an opposing one. However, technology and craft can also be viewed as existing on a spectrum of fabrication approaches. In "The Textility of Making," Tim Ingold argues that while craft and technology are distinct, they both emerged from foundational aspects of making practices – with technology as an extension of technical processes, while craft is an extension of tactile interactions [74], both of which can be utilized within creative practices.

2.1.3 Workmanship of Risk

In David Pye's seminal work, *The Nature and Art of Workmanship* [127], Pye focuses on human involvement in fabrication through his analysis of workmanship, which he defines as "the application of technique to making, by the exercise of care, judgement, and dexterity." Pye describes workmanship as being either 'workmanship of risk' or 'workmanship of certainty,' in which 'risk' is categorized by the agency and ability of the craftsperson to influence the outcome during the fabrication process [127]. One example of workmanship of risk would be writing with a pen, versus the workmanship of certainty of the printing press. However, Pye also discusses how multiple stages of production, including the fabrication of tools, are necessary in order to produce the final object. He describes these early stages of production as ‘preparatory workmanship,’ the skilled labor required to create the tools needed for workmanship of certainty. One example of preparatory workmanship in digital technology might be a computer program which, while capable of generating an output without any human intervention, was originally created by a skilled individual.

In his description of skill as an aspect of craft, Adamson references and praises Pye’s distinction between workmanship of risk and workmanship of certainty, which he felt better described the dichotomy of making than distinction between craft and industry [1, 127]. However, Adamson argued that Pye’s attempt to define what was ‘good workmanship’ through any sort of observation of the quality of works lacked an awareness of cultural contexts, and would therefore be inadequate means of determining the value of crafted works. Pye’s apparent lack of cultural critique stems from the fact that he believed that good and bad workmanship could be objectively observed, based on their soundness and comeliness. In his description of these attributes, Pye views soundness as relating to the ability to transmit and resist force, and comeliness as relating to desired aesthetic appeal. Notably, Pye felt that the success or failure of soundness and comeliness in the workmanship should be perceived based on the original intentions of the designer, rather than abstract ideals or cultural standards. However, he also suggested that since designs are often based on precise forms (such as geometric objects and perfectly fit joints), workmanship that comes close to but does not achieve these forms is generally perceived as sub-par, since the viewer can clearly perceive both the ideal design (the geometric form) and the workmanship's failure to achieve it [127]. In his critique, Adamson disagrees with Pye's assumption that the viewer would have any such sense of perfect geometric forms, instead arguing that these views are culturally based [1].

Overall, Pye's approach valued, but did not exalt, the presence of spontaneous creative exploration as a part of the making process. Unlike many of his contemporaries in the field of fine arts who exalted 'hand-made' items, he envisioned an approach to fabrication in which increasingly precise technology could be used alongside more established tools and techniques. As such, his view of creative practices can be helpful in outlining the inclusion of digital technology, including 3D printing, as part of creative workflows. However, the usefulness and applicability of these tools should likely be viewed through the context of the specific goals and creative workflows of the people who will be utilizing them.

2.1.4 Non-Hylomorphism in Making

When looking at creative practices through the context of workmanship of risk, the creation of the object is seen as a process that can either improve upon or subtract from the original design. However, creative processes can also be viewed as a type of itinerate wayfinding, in which the artist improvises the design during the making process [31, 74].

Tim Ingold describes this type of process as ‘non-hylomorphic,’ in which the finished object emerges from the maker’s engagement and interplay with materials [72, 73, 74]. He contrasts this view of fabrication with the ‘hylomorphic’ approach, where objects are created as a result of a designer enforcing their vision onto materials [74]. For Ingold, an example of non-hylomorphic fabrication would be the freehand drawing of a line on paper, whereas hylomorphic fabrication would be pulling a line straight with the use of a straightedge or ruler. Because of this distinction, non-hylomorphic making gives greater focus to the importance of the dynamic and temporal aspects of creative process, while hylomorphic making focuses on the end product. As such, non-hylomorphic making is more in-line of Adamson’s concept of craft, which is also heavily characterized by action, rather than result.

2.1.5 Digital Technology as a Crafting Medium

In his book *Abstracting Craft*, Malcolm McCullough explores craftsmanship specifically in the context of digital fabrication [108]. By framing the computer as a medium rather than an assortment of tools, he draws parallels between traditional craft and digital form-giving process and argues that, despite the lack of physicality, digital designs are nevertheless products of the mind, eyes, and hands. With his framing of computer as a medium, he tries to establish digital crafts in physical human agency and to develop non-pervasive and transparent digital interfaces for designers by following the ideals of traditional craftsmanship. This broader definition of what is a ‘material’ seeks to expand the definition of craft beyond what Adamson, Pye, and Ingold had described. However, in doing so, McCullough refocuses the central character of craft on the skills acquired from repeated making, and reaffirms the importance of action as a characteristic of craft. This concentration on action encourages an approach to the design of technological systems in which the individual and the machine collaborate in the creative process. When designing systems for the integration of traditional and emerging techniques, these theoretical approaches ground the research presented in this dissertation on craft and the making processes within creative practices, rather than on the appearance of finished art objects.

2.2 Hybrid Crafting Processes

In recent years, there has been a growing body of work which focuses on the design and creation of new technologically-integrated crafting workflows. Currently, digital systems and fabrication tools are increasingly being used alongside traditional practices in fine arts domains to create hybrid crafting processes [32, 36, 40, 53], many of which seek to support traditional practices while allowing for added digital features. In particular, recent research has explored how the incorporation of technology may alter more than just the medium or materials of the fabricated objects. Rather, emerging 'hybrid' crafting processes may result in the emergence of entirely novel creative practices [10, 20, 55, 79].

2.2.1 Avoiding the Physical-Digital Dichotomy

When processes are described as either physical or digital, they are being categorized in terms of technology, which does not necessarily reflect the iterative and often hybrid practices of artists. As noted by literature surrounding hybrid crafting, in order to better understand creative processes, research also needs to focus on the factors that affect how people are fabricating items, not just the technology being used [24, 73, 127, 148]. This engagement with process and display of skill during careful manipulation of material characterize craft, which has been increasingly explored as a vital aspect of hybrid fabrication [1, 10, 73, 170]. For example, the works of Torres et. al [158, 159, 161], have focused on the design of creative environments that allow for the integration of digital features while prioritizing craft-oriented making practices.

2.2.2 Emerging Technology and Creative Practices in Human-Computer Interaction (HCI)

Human-computer interaction (abbreviated as HCI) is the study of the design of computer technology with the specific focus on the interaction between humans and computers [69]. Within HCI literature, there is a long history of incorporating digital tools into creative practices in order to design new fabrication experiences [38, 76, 135, 169], with an increasing focus on the importance of iteration in creative endeavors [26, 52, 68, 89, 96, 180]. For example, Rosner et al. have developed digital records to attach additional meaning to the traditional arts activity of needle-crafting [132], while abstract installations with integrated digital tools have explored the meaning of interactive space from an artistic perspective, such as in the work of Anna Vallgårda [168, 169]. In addition, Clarke et al. have suggested that current arts practices can be used to provide insights into the role of digital technology in contemporary social issues [24]. Current HCI literature has also been influenced by research in creative processes. For example, Ingold's notion of non-hylomorphism making has been applied to interaction design is the work of Devendorf et. al, who designed a system in which the user is able to act as a 3D printer while still retaining creative control during the fabrication process [33].

2.2.3 Using Digital Tools to Study Traditional Craft Processes

Within research communities focused on human-computer interaction (HCI), there is a well-established interest and respect for traditional artistic mediums, with recent papers focusing on the importance of traditional crafting and modes of encouraging creative people to try their hand at making art [32, 93], and incorporating arts in interaction design [13, 57, 58, 122, 123, 144]. At the same time, there has also been research into how digital factors and hybrid fabrication can be integrated with new digital and physical materials and thereby change the creative practices of artists [9, 34, 36, 51, 78, 92, 128, 181]. New technology is also allowing novel features, such as interaction and data storage, to augment traditional materials [35, 60, 148]. Through this growing body of work, the field of HCI is making strides towards understanding the nuances of process that exist within craft practices.

Even beyond the growing field of HCI, scientific inquiries into the processes behind art making have a long history within many academic disciplines. In psychological and cognitive science, a series of work done by Tversky et. al described the order of compilation of a drawing as a key element of an artist's drawing style as it reveals the mental construction and conceptual organization of the drawing inside the artist's brain [163, 164, 165]. In the related field of computer graphics, a set of prior work explored computational methods to mathematically generate simulations of the sequential order of drawings [47, 100]. However, instead of displaying an authentic drawing process, these works mainly focus on generating visually pleasing video renderings based on heuristic approaches with little or no involvement from actual artists. A number of prior works, including Miall and Tchalenko's in-depth investigation of a professional painter, can be found tracking eye and hand movements of artists by attaching motion sensing equipment to drawing utensils [54, 113, 151]. A similar recent work [21] has used a Cintiq tablet to record the hand movements of artists. As technology continues to become more affordable and available, digital tools will be increasingly incorporated into creative processes, and digital fabrication methods can be used to create and display different creative aspects of artistic works.

2.2.4 Facilitating Novel Art Sharing Experiences

Much of the appreciation for craft processes centers around the display of skill needed to create the finished artwork [1, 50, 127]. As such, several avenues of research have explored the perceptions of art viewers tracked through recordable tangible interactions, the possibilities of portraying “static” art forms such as painting as an active performance, and the artist-viewer dynamics of group engagement through participatory live-action art [101, 141, 153, 156]. This focus on art as action could tie into the performative elements of many traditional artistic processes, which can represent unique aspects of the artistic process including skill, technique, artistic apprehension, and mood [30]. For example, Hook et al. recently explored how digital technology might support documentation of participatory arts experiences [67]. However, the sharing of creative practices through digital technology also opens up new questions about what kinds of works will be shared, and who will have curation control over how art is viewed and disseminated.

2.2.5 The Curation of Data Collected from Artistic Practices

A growing body of research has explored the importance of curation in the age of digital sharing, as well as what effect curation has on the curators and those viewing the curated information [140, 142, 173, 178]. Experimental machines, such as slow technology, have been designed to curate when and how viewers see information in order to provoke contemplative reactions rather than serve an immediate function [119, 120]. Additionally, many researchers have investigated how individuals build and share their digital collections and personas, and how the visibility of that data needs to evolve as individuals go through different life experiences [2, 42, 44, 64, 106, 107, 166, 182]. When displaying information, especially data that an individual feels a strong personal connection to, it seems imperative that the person who created it, or others who can act on their behalf, have some lasting control over how the information is presented and contextualized. As digital technology becomes universal, the curation and sharing of information may in itself become a new type of creative practice.

2.3 Conclusion

Drawing from the fields of fine arts, anthropology, and human-computer interaction, this chapter reviewed the breadth of literature related to the interrelated roles of craft, art, and technology. We have looked at craft as it compares to art and technology, and reflected on several different perspectives on creative making and how the incursion of technology can serve as both an expanding and limiting force. We then summarized many of the trends within hybrid craft research, including creative practices within human-computer interaction, the use of digital tools to study traditional craft processes, and the facilitation of novel art sharing experiences. Within this context, the next three chapters describe novel research which adds to the current body of knowledge surrounding the integration of new technology into creative practices. Chapter 3 explores how digital technology can be used to record and catalog the movements of artists during creative processes, in which we are influenced by current work within the field of HCI. Chapter 4 investigates what kinds of constraints arise from translating techniques from fine arts domains into new workflows that incorporate 3D printing, and we analyze participant's interactions through the perspectives on creative making described by Pye, Ingold, and McCullough. Chapter 5 explores how 3D printing with different materials can support fine arts, biofabrication, and everyday craft practices. Through this research, we gain greater insight into the challenges and opportunities for integrating 3D printing with creative practices.

CHAPTER 3

USING DIGITAL TECHNOLOGY TO RECORD, DISPLAY, AND FABRICATE ASPECTS OF THE FREEHAND DRAWING PROCESS

This chapter explores a case study in which 3D printing and digital technology are incorporated into the freehand drawing process in order to strengthen the connection between artist, artwork, and art viewer. The system we developed accomplishes this without interfering with the traditional workflows of artists, since it does not require the artist to switch from the traditional pencil-on-paper drawing approach. In order to accomplish this, we created an easel which unobtrusively tracks and visualizes the movement and pressure of the artist's pencil while still allowing the artist to use traditional pencil-on-paper drawing techniques. From the collected data, we were able to display some aspects of the creative process through computer-generated animations and 3D prints. Through sessions with artists and art viewers, we were able to gain insight into how the representations of process could be used to complement viewers' appreciation for the finished artwork. Sections of this chapter were taken from Fernando, Weiler, and Kuznetsov [46].

3.1 The Freehand Drawing Process

From viewing a 20th century expressionist artist doing a live action painting to watching a timelapse video of a pencil drawing on YouTube, seeing the process of making an art

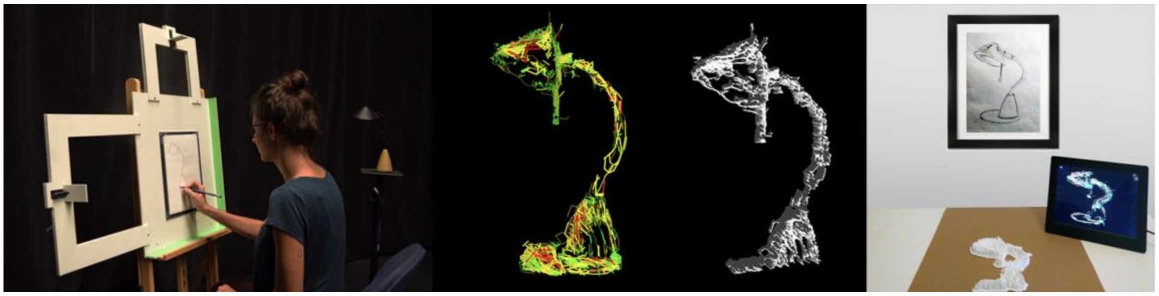

Figure 3.1 Pencil tracking system. Our system unobtrusively capturing process data during freehand drawing (left), video rendering and 3D bas-relief model representations of an artist's freehand drawing process (middle), and gallery exhibit of drawings and system-generated process representations (right).

piece has been valued as an integral part of the art viewing experience [131]. This general interest in process reflects viewers' fascination with the skill and creativity involved in the movement of the artist's hand. The dynamic elements of the drawing process, including the order of compilation, lengths of strokes, speed of the movement, and the pressure applied on the drawing surface can reveal unique aspects of the artistic process including skill, technique, artistic apprehension, and the artist's mood [30]. A multitude of previous work have used computational technologies (i.e. hand and eye movement tracking) to capture elements of the drawing process [54, 113]. Complementary to this research, our work explores how representations of the artistic process influence both the art drawing and art viewing experience. More specifically, we ask: How can digital technologies reveal aspects of fine arts practice, and how does this information influence the artist's process? How do digital and physical representations of the art making process shape the experience of viewing the final artifact? And finally, what are the social implications of sensing, sharing, and curating the intimate aspects of artistic process with different audiences?

We investigate the above research questions by iteratively implementing and studying a research probe consisting of an interactive drawing system that unobtrusively tracks the freehand pencil drawing process on a traditional easel. Through the use of two cameras and acoustic sensing [61], the easel tracks pencil movements and the pressure exerted on the drawing surface without disrupting the traditional freehand drawing practice. From the captured data, we generate two representations, a video rendering and a bas-relief (low-depth) sculpture, which reveal the sequential order of stroke compilation, pencil speed, and pressure at each point of the drawing process (fig. 3.1). We chose to focus on analog pencil drawing because it is considered to be one of the most quintessential art mediums, and there are unique advantages to drawing on paper as opposed to using digital drawing tools such as tablets. These include the tactile pressure feedback of traditional materials, direct hand-eye-surface interaction, accessibility and, for many artists, established familiarity.

We used our research probe and the resulting drawn artifacts to elicit broader discussions related to our research goals in three iterative focus group studies. First, we conducted a study with six experienced artists whereby each of them individually created multiple pencil drawings using our setup. Afterwards, we held a critique-style group discussion where all the artists were presented with each other's finished drawings, the resultant video renderings, and 3D printed bas-relief sculptures. During this study, artists discussed how the visualizations reflected their artistic process and revealed hidden elements in each other's work. Second, in a different focus group session, five informed art viewers were shown the original pencil drawings and the visualizations from the first study and engaged in a semi-structured discussion. Third, we exhibited the pencil drawings along with videos and 3D printed outputs from our first study to a general audience at a gallery opening and received survey feedback from visitors.

Our studies reveal that artists, expert art viewers, and general audiences are able to infer a timeline of the drawing process (order of compilation) and individual artistic styles from our system, and this new information enables participants to learn from and connect with the artists. We then discuss potential directions for further research, including unobtrusively capturing elements of creative processes, representations of latent but critical process information, and platforms for sharing and curating the creative process.

3.2 Sensing and Visualizing Drawing Processes

To understand the implications of sensing and sharing aspects of freehand drawing and creative practices more generally, we designed our research probe [48] in three iterations, working closely with art practitioners from multiple domains. In the first version we used a Leap Motion device to track the hand movement of three industrial designers while they sketched on a regular easel. Based on their feedback, in the second iteration we improved the sensing mechanism to track the movement of the tip of the pencil (location and speed) using two cameras mounted on the easel. We tested this system with 6 practitioners working in fine art domains, industrial design, and landscape design. While the resultant animations clearly visualized the unique features of each artist's drawing style, almost all the artists suggested that the system could be improved with pencil pressure sensing, which was added in the next iteration. Thus, the third and final iteration of our system includes a traditional drawing easel, inconspicuously augmented with two independently functioning subsystems: the pencil tracking system and the pencil pressure sensing system. Below we describe the implementation of this final iteration, which was used as a research probe in our main focus group studies.

3.2.1 Pencil Tracking

We used two cameras to track the drawing pencil, mounted on the top and left sides of the easel. Images captured at 20 fps from these cameras are processed by a Matlab-based custom implemented image processing program in order to determine the vertical and horizontal positions of the drawing pencil. To increase the accuracy of the tracking mechanism, we covered the majority of the drawing pencil in blue ink to improve the camera recognition. In addition, we mounted two green colored background strips along the bottom and right edges, each of which faces the camera mounted on the opposite side (fig. 3.1). The horizontal and vertical position of the drawing pencil is determined by locating the blue color blob created by the pencil against the green background. The system was calibrated by placing a grid marked in millimeters on the drawing surface in order to map the pencil's pixel locations to the physical coordinates of the drawing surface. Since the cameras were permanently fixed to the easel, this calibration process was only required once.

3.2.2 Pressure Sensing

Our pencil pressure sensing system is based on an acoustic sensing technique [61]. We experimentally observed that the intensity of the sound waves created by friction between the drawing surface and the tip of the pencil can be used as a close approximation for pencil pressure. Even though this relationship is not entirely sensitive to very subtle variations in pressure, we found it is sufficient for detecting the major changes. In implementing this system, we designed an acoustic sensing module which contains a Teensy 3.2 micro-controller and an Adafruit electret microphone module with built-in amplifier. We placed 12 of these modules in a 3 X 4 grid on the back side of the easel. Each of these modules were programmed to read the digital output of the microphones 20 times per second in sync with the two cameras of the pencil tracking system. Weighted averages (Pw) of the three sensors closest to the pencil (based on the pencil position determined by the camera tracking system and microphone) are used to approximate the pencil pressure exerted on the drawing surface at each frame of the video.

3.2.3 Representing Aspects of the Drawing Process

In order to visually represent the pencil location and pressure data captured by our system, we implemented a Processing 3.0-based application, which renders the pencil speed and the pressure exerted on the drawing surface as an animation. Here, the pencil

Figure 3.2 Bas-relief 3D prints generated from artist's data

speed is determined by calculating the Cartesian distance(d) between two adjacent data points. The pencil strokes which were drawn in slow (< 10mm/s), medium (>= 10mm/s and <50mm/s), or high (>= 50mm/s) speeds are represented distinctly in the visualization using green, yellow, and red colors respectively. By analyzing the pencil pressure data collected from our study, we observed the practical range of Pw as 0 -170 (audio signal ranged from 0 to 2.5Vrms with 50x gain). The different pressure levels are depicted using different line thicknesses (Low 1px, Medium 2px and High 3px) based on the Pw.

We implemented another Processing 3.0 program to generate 3D bas-relief models displaying the drawing data from each artist. Bas-relief is a type of sculpture that consists of a projected image with little overall depth, such as Egyptian hieroglyphs or coins, and has been used as a means of visualizing data in a tactile form [86, 129]. Our model takes the form of a slate with raised ridges corresponding to where lines were drawn. Figure 3.2 shows an example of one of the generated 3D models. Here the thickness(t) of the ridges is based on the speed of the drawing, while the height(h) of the ridges is based on the pressure of the drawing stroke. The height of the ridge can be compounded if several lines are drawn over the same area. The 3D models from all artists were printed using a Makerbot, and ranged in size from 4 to 5 cubic inches in width and height, with depth ranging between 0.5 to 1.0 cubic inch.

3.3 Methods and Study Design

This study was designed with the goal of better understanding how artists and art viewers may perceive representations of the artistic process that are created through digitally recording certain aspects creative interactions. Below, the methods and the design of the studies are described, including data collection, analysis, and limitations.

3.3.1 Individual Artistic Sessions and Group Discussion

To find artist participants willing to create drawings using our probe, we reached out to university art-related departments and local artist groups through emails to recruit six participants (four female, ages early twenties to late thirties) who had at least two years of drawing experience. We refer to these six participants as “artists” or “artist participants” in this paper. Over the course of a week, we held individual drawing sessions with all six artists, each lasting roughly one hour. In the beginning of each session, the artists were asked about their art practices and mediums, how they gained their skills, and how they shared their work with others. Then, the artists created three sketches using our system, each taking approximately ten minutes. For the first two sketches, each artist was asked to draw the same objects located in the room: a table lamp and a flower pot. For the final sketch, they were asked to draw whatever they wanted. At the end of each drawing, artists viewed the system-generated representations of their drawings and engaged in a semi-structured interview.

After all of the artists had completed their individual drawing session, they were invited back for a group critique and discussion. At the beginning of the discussion, they compared, contrasted, and collectively critiqued the pencil drawings created during the individual sessions. Then, they were shown the video renderings and 3D-printed bas-reliefs of their drawings, and participated in a group discussion about how the different visualizations represented different aspects of the original sketch and what could be discerned about the artist's process and intent from the visualizations. Artists were compensated $15 per hour for their time.

3.3.2 Discussion with Informed Art Viewers

In order to explore how digital and physical representations of the art making process shape the experience of viewing the final artifact, we also reached out to experts from a variety of related fields and invited them to join us for an hour-long art viewing and discussion. We recruited five individuals (three female, ages mid-twenties to mid-fifties), all of whom were professionals in fine arts or design related fields. At the beginning, the art viewer participants were shown the pencil drawings from our individual drawing sessions and were asked to discuss how they inferred information about the drawing process from the finished pieces. After that, we explained how our system captures the artist's data while the work is being created, and showed them the resulting video renderings and bas-relief sculptures for each pencil drawing. The art viewers then reflected on how these representations engaged them with the artistic process behind each piece. They also discussed additional information they wanted to know about the process, the implications of sharing and curating this data, and issues around artistic authorship of the digital renderings.

3.3.3 Data Collection and Analysis

All interviews and discussions were audio recorded, transcribed, and analyzed using open coding. Data was coded independently by two members of the research team, the results of which were then compared to resolve any discrepancies. During data synthesis meetings, the researchers used affinity diagramming to organize the codes around our research questions, and then discussed unexpected connections between themes in the data. In our findings, we reference data owing to the artists as A1-A6, and informed art viewers as R1-R5.

3.3.4 Exhibits and Public Survey

In addition to insights from artists and expert art viewers, we also wanted to see how a general audience would react to our process visualizations of the artistic works. We showcased the drawings, video renderings, and bas-relief sculptures in a public art exhibition. During the exhibit, roughly thirty-five members of the general public viewed the artworks, of which fifteen filled out a survey about their reactions to the data visualizations and whether they were interested in learning more about the artistic process. This survey consisted of 9 questions with a typical 7-point Likert scale responses on agreement. This part of the research was not intended as a rigorous survey to evaluate our system, but was meant to serve as supplementary feedback in order to gain insights into how general audience viewers interacted with our system.

3.3.5 Limitations

Our study is prone to self-selection bias, as all of our artist participants chose to be involved because they were interested in freehand drawing and wanted to learn more about our probe. In addition, the public exhibits likely attracted people with prior interest in analogue and digital arts, and the small survey size is meant to only supplement our qualitative data.

3.4 About the Artist Participants

The six artist participants that were recruited for our study included two female MFA students, two male cartoonists, one female primary school art teacher, and a female independent fine artist, all of whom had several years of experience of drawing with traditional art materials. Discussions with our participants revealed further insights into the importance of traditional mediums and how artistic skills are acquired. The five expert art viewers we recruited came from a wide range of art related fields, including ceramics, visual communication, and design research. They shared our artist participants' preferences for traditional drawing mediums and understanding of artistic practices, so we are reporting findings from both groups in this section.

3.4.1 Reasons for Preferring Paper-Based Drawing

While the participants in this study were selected based on their familiarity with traditional drawing techniques, some (A3, A4, R2) also had experience drawing with digital tablets. However, those participants still viewed analogue drawing as a preferable sensory experience based on the tactile interactions and auditory feedback that results from the meeting of pencil and paper.

Tactile Interactions

For the artists we spoke to, one key difference between using a digital tablet and traditional paper is the tactile feedback. One art viewer in the group critique, R2, described using a tablet as "*completely different, and I don't like it. The tactile quality of a pencil moving on paper is so much more fulfilling than this anonymous plastic tip gliding on glass.*" Furthermore, participants disliked having to look at the screen to see how the force they were exerting with a digital pencil was affecting the drawing, rather than physically feeling the canvas or paper bend or warp in response to their movements.

Auditory Feedback

In addition to the physical differences between digital and paper-based drawing mediums, our participants discussed sound as an integral part of the drawing process. Each "*scratch of the nib on the paper"* [A4] produces a distinct sound as each stroke is created. R1 elaborates on why the auditory feedback may be beneficial to the mood of the artist and increases their engagement in and desire to draw: "*The sound of a pencil on paper has something really nice, that maybe takes us back to our childhoods and calms us down.*" In short, while some participants perceived digital tablets as being able to capture most of the sensitivity and precision of the artist's movements, participants noted that current digital technologies do not provide the artist with the tactile and auditory feedback that artists highly value when working on paper.

To summarize, all of our participants had either extensive drawing experience or a professional background in visual design. Overall, they preferred traditional drawing tools for their tactile and auditory feedback and importantly, the artists mentioned that their natural pencil drawing styles were not disturbed by our system because of its unobtrusive nature and the utilization of familiar traditional tools.

3.5 Findings

We present the findings that emerged from this research under 3 key themes: how the representations of digitally sensed process information helped artists and viewers to reflect on the finished art piece, why this creative process information was valued by both artists and art viewers, and motivations and barriers for sharing information about the creative process.

3.5.1 Reflecting on Aspects of the Drawing Process

There were many instances throughout our studies where both the artist and art viewer participants expressed excitement about being able see the pencil's movements and pressure as a visual rendering. While our participants felt that the final pencil drawings alone could show some of the process information, they used the two additional representations generated from our system to reflect on several key factors of the finished piece, including the order of compilation of the strokes, drawing technique and, in some cases, even the emotions and feelings of the artists. This offered them more insights into their own and each other's styles and triggered suggestions for additional types of data that might be useful in revealing process information further.

Order of Compilation, Time, and Effort

Most participants stated that through viewing the video renderings of the drawing process, they were able to reflect on the order in which the drawing was compiled. The artists considered the visualization of the sequential order of drawing as a 'timeline' that reveals important temporal aspects of their own and each other's drawing processes. In critique sessions, both the artists and informed art viewers pointed out how differently each artist progressed with his or her drawing from others based on their video renderings. A4 attributed these dissimilarities in stroke progressions to the differences in the thought processes of the artists: "*I enjoy seeing the thought process of where someone started and ended. That is not something you can tell by just looking at the drawing*."

As we observed during the drawing sessions, the act of drawing does not consist of a smaller, independent set of repetitive actions performed at a constant speed. Instead, as A1 best put it, "*drawing is a combination of carefully and slowly rendered details and fast and loosely drawn gestural strokes*." In that regard, the artists reflected on the value of seeing variations of an artist's time and effort spent rendering different parts of a drawing, as visualized by our probe. For instance, A3 noted that: "*In historical art pieces, I've seen the faces are more beautifully rendered than the rest of the parts [...] the reason is they put lot*

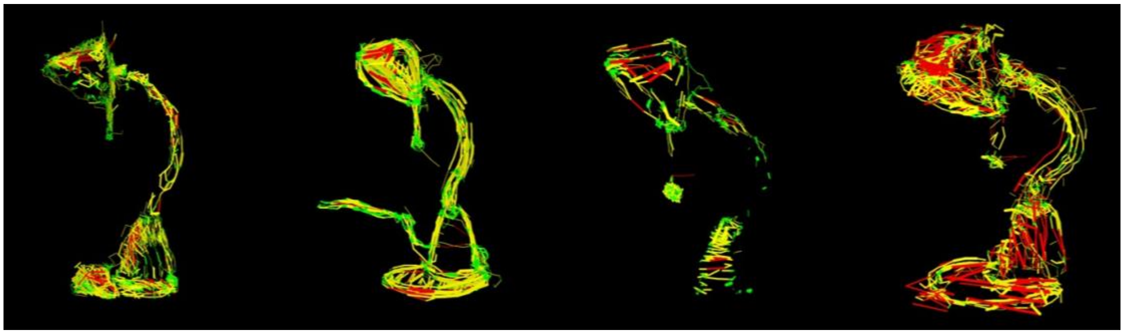

Figure 3.3. Video renderings corresponding to the pencil drawings of 4 different artists

of time to draw faces [...] if you have a timeline, something similar to this [video rendering], you can see the time and energy that an artist will put to draw certain parts of the drawing." This ability to reflect on the way an artwork was compiled was also valued by the general audience public exhibit. All 15 survey respondents from the exhibit of the work agreed (with an average of 6.4 on the 7-point Likert scale) that the video rendering helped them understand the order in which different parts of the sketch were drawn by the artist. In addition, most of them agreed that video rendering helped them understand the time (87% with an average of 5.6) and effort (80% with an average of 5.4) that the artists applied to different parts of the drawing.

Unique Drawing Styles

When viewing the static pieces, participants (unprompted) tried to infer the techniques and drawing styles of different artists (e.g., gestural drawing vs slow detailed drawing). However, after seeing the digital outcomes from our system, they mentioned that the video rendering provided additional information that they felt unable to discern from the static pieces. Both the artists and the art viewers reflected on the process information presented by our probe as a means of providing insight into distinct characteristics of individual drawing styles (fig. 3.3). For example, the participants were able to distinguish video renderings of more classically trained artists from those who had never gone through formal training based on the differences of colors (speed) and line thicknesses (pressure). For instance, A6, a cartoonist, noted the unique features of his pencil strokes by referring to the distinct characteristics of his video rendering: "*My video shows a lot of low-pressure lines [...] The reason is, I'm not so committed with my strokes. Mostly, I like to have the luxury of wiping off my strokes [...] I think this rendering reflects my typical drawing style.*"

Self-Reflections on Emotions During the Drawing Process

Apart from seeing the drawing styles and techniques, some artists reflected on video renderings as a medium that potentially depicted their own feelings and emotions during their drawing process. While the final art piece could provide some insights about the creator's emotions and feelings, our artist participants discussed how the video rendering showed additional information presented gradually to correspond with each moment of art making. A1 articulated her thoughts on this: "*You can see when I feel little bit nervous. My lines are getting little bit constrained [...] When I'm feeling confident my drawings are going much faster [...] I think [the rendering] provides the viewers more of a window to the artist.*" However, these insights were discussed only when participants inter- acted with video renderings of their own process; 90% of the viewers who took our survey felt unable to discern any of the artist's feeling or emotions from the information presented though video renderings.

Wanting to See Additional Process Data to Deepen Engagement

In addition to reflecting on the drawing process based on the sensing and output modalities of our current system, the artists and art viewers had suggestions for additional data-gathering that could deepen their engagement with the artistic process. They were interested in knowing more about the artist's unique drawing techniques and styles by seeing how they hold pencils or other drawing utensils and gestural details such as palm and elbow movements in different parts of the drawing. Moreover, they suggested using additional sensors to track physical changes in the artist as they sketch, such as eye tracking, pupil dilation, and heart rate. By including this information, participants hoped to see how the process of drawing manifested in the human body. In particular, it was suggested that either heart rate data or recorded sound of the pencil scratching on the paper could be used to create an auditory component of our data visualization, thereby allowing the viewer to become more enveloped in the drawing process.

In summary, our system served as a probe to prompt artists and art viewers to reflect on a range of latent information related to the drawing process as shown by our visualizations. Participants also suggested collecting new types of data, including biometrics of the artists, to deepen engagement with the creative process behind finished artwork.

3.5.2 The Importance of Process Information

In addition to their fascination with seeing the hidden “layers” [A1] of drawing process behind a static art piece, there were deeper reasons why participants expressed their interest in our process renderings. Based on their sense of having gained insight into their artistic processes by seeing the visualizations created by our system, our participants suggested several future application areas where our system would be beneficial, including providing feedback to artists and enhancing the art viewing experience.

Providing Feedback

For many of the artists who took part in our drawing sessions, this was their first time seeing their drawing process without being actively engaged in it. They perceived the process information generated by our system as a means of getting feedback on their drawing processes. A2: “*When I look at this [rendering], I look at my process of drawing. It allows me to go back and see myself as a third person.*” Most of the participants valued this feedback as a means of identifying the areas where they could improve their techniques. A3’s comment reflects the ideas expressed by most of the other participants: “*The consistency of the pressure and speed is probably something I can work on my drawing [...] This gives some feedback on that [...] For the style of drawing I do, it would be helpful to be more consistent[...] Getting feedback on what is actually happening when you draw is really helpful.”*

A1 also commented on how she could reflect on the changes of her drawing style over a period of time, especially after developing an injury, by looking at the video rendering of her drawing: "*I think this is kind of important for me as a reflection [...] A few years ago, I was an extremely controlled drawer [...] since I started grad school I developed Tendonitis, and I don't have the control as I used to [...] Now, my work has become very fast and gestural because of that [...] I think it would be neat seeing the progression of my hands changing and my mark changing*."

Enhancing the Art Viewing Experience

In our discussions with participants, we leveraged our system as a probe to examine how digital technologies can provide novel art viewing experiences. On one hand, the process information was perceived as a way to more deeply understand the work. For instance, R2 noted that: "*I, personally, like to have more information about visual pieces. These pieces [digital renderings] give way more information about them than the final products [...] I'm excited to have all these clues about the process [...] It is more information, information would lead you to greater understanding [of the work]*." On the other hand, participants considered process information as a resource that helps them understand the creator behind an art piece. For instance, R1 noted that: "*Everyone has a different way of going about making the same drawing, I think it does link together with what kind of artists they are, the speed of their lines speaks about them [...] sometimes the artist gets removed from the art piece [...] As a viewer, for me, this information is important to understand the person behind the art piece.*" However, it was not clear what exactly participants meant by "*greater understanding of an art piece*" or by "*understanding the artist behind the art piece*". Even though we pressed participants to tell us why they perceived the renderings to be so interesting, they were unable to provide any clear answers. Perhaps, in the same way that the process of making or viewing art contains a level of enjoyment that cannot be easily defined, the visualizations generated by our research probe may also contain some implicit enigmatic value.

In addition to using our probe to reflect on aspects of the free-hand drawing process, many participants also discussed both the video renderings and the 3D bas-relief models as a novel medium of art. For instance, R2 expressed his thoughts on the artistic merit of these renderings. "*In the end it is like an aesthetic thing, more like a data driven aesthetic [...] It would be really beautiful if they [artists] have a knowledge of what sort of thing would come out of it. It will make an interesting piece of art in the end.*" Similarly, A4 articulated her view that the 3D bas-relief models were art pieces that could provide new ways of experiencing 2D artwork: "*I really like that tactile quality, I can't put it into words [...] Something that's subconscious [...] I think it is an interesting art piece, something that you can feel from the original drawing."* Likewise, more than 80% of the survey respondents from our general audience exhibit agreed that being able to touch the 3D bas-relief models provided them with a novel way of experiencing a 2D drawing and made them feel more connected to the original pencil drawing.

In summary, our findings suggest that exposing the process information which is otherwise hidden in a finished art piece can be valuable for both artists and art viewers. As our participants pointed out, in addition to prompting them to reflect on artists' processes, this information also provided novel process-aware art viewing experiences to the audience.

3.5.3 Motivations and Barriers for Sharing Process Information

All of the artists who took part in our drawing study mentioned that they often share their final pieces with audiences through exhibitions, art sales, or over social media. In addition, many of them pointed out instances where they shared process information such as rough sketches, images of ongoing work, or short time lapse videos. Below, we describe how participants' interactions with our probe revealed ways in which process information might enhance viewer engagement with artists and their work. At the same time, participants also discussed concerns related to sharing personal and intimate aspects of process information with different audiences.

Motivations for Sharing Aspects of the Process

For our participating artists, their motivations to share their process information with the public varied from getting feedback to personal satisfaction to attracting potential buyers. Some of them (A1, A2) specifically mentioned that they usually share their rough sketches or preliminary work with the public because they find that people are curious to know how an artwork is progressing. A2 was also very clear on how she uses process images as a business tactic in selling art pieces: “*Most of my pieces are commissioned. The buyers [get] excited seeing how the piece progressed when I show them the images of different stages of the drawing. From a business perspective, when more people get excited by seeing how the work progressed, more people ask for their own [commissioned artwork] to be created as well. It is more of a business tactic.”*

Not surprisingly, the artists reflected on how engagement with art audiences could be enhanced through digital outputs during the creative process, such as those presented by our probe. They suggested that seeing the sequential order of strokes and the pressure variations could enable deeper engagement with the underlying art making processes as well as understanding the unique drawing styles of the artist. The participants stated that, by seeing how each subtle pencil stroke contributed to the final piece, the audience would be more aware of and appreciate the time and effort the artist spent to create the work. For instance, A4 expressed that: “*It helps people to understand the time and effort I put into things, and to understand my process, too [...] It helps them see the value of different styles and appreciate them*.” Interestingly, perspectives of the general audience viewers from our public exhibit also aligned with these ideas. 87% of the attendees of our public exhibit who filled out our survey agreed (with an average of 5.7 out of 7 on the Likert scale) that knowing more about the drawing process helps them appreciate the artist’s work. Furthermore, 90% (with an average of 5.5 out of 7 on the Likert scale) have shown a strong interest in seeing the different iterations and adjustments made by the artists, including mistakes.

Deterrents for Sharing Aspects of the Creative Process

During the group discussion, artists expressed two key reasons why they sometimes become hesitant to share aspects of their creative process. First, participants had general concerns over privacy and did not want process sharing to intrude on their practice. These concerns mainly revolved around their need to maintain their peace of mind in order to engage with the art piece as they are making it. All of them mentioned having their own art studio spaces being highly customized to their needs. They considered these physical and emotional personal spaces to be an integral part of their art practices. In that regard, A2 expressed how the sense of being watched during art making would deter her ability to engage with her work: "*There has to be a distance. You have to have a personal engagement with the piece you are making [...] If you have six eyes watching your all the time, it isn't going to work."*

Second, they had broader concerns about the work not meeting certain standards and not being ready to share. As many of the participants (A1, A2, A3) mentioned, even for skilled artists, not every work meets their personal bar for excellence, and there is always a risk that the end piece will not reach their standard. To this end, A2 mentioned that she wouldn't like to share the process information until she is confident about the quality of end result. "*I have a standard for myself, I know to what level I can paint to, if a piece* *doesn't meet my standard or technique, I wouldn't share the process images with public."* While our survey results suggest that the viewers are interested in seeing the adjustments and mistakes done by an artist, some of the artists, especially A1, mentioned that she would try to mask her mistakes from the final piece to prevent viewers from seeing them: "*There are these moments of confidence, moments of vulnerability, moments of intimidation [...] That is something I don't want to see in a final piece [...] I try to mask them by putting more shading or erasing them completely."*

Amidst all the advantages of sharing process information that were discussed by our participants, these sentiments of the artists illustrate a desire to keep some distance between themselves and the audience, and in some way curate what others see of them and their work.

3.6 Discussion and Implications

By using our research probe in a series of studies with experienced artists and art viewers, we have identified a number of areas where digitally captured information of art processes could be useful for both groups. In addition, the artists who took part in our study mentioned their motivations to share process information as well as their concerns over making it publicly available. Together, these findings reveal 3 concrete opportunities for future research: 1) systems for unobtrusively capturing dynamic elements of creative processes; 2) designing new ‘process-aware’ art viewing experiences; and 3) platforms for curating and sharing the creative process.

3.6.1 Unobtrusively Capturing Elements of the Creative Process

While interacting with our probe, both the artists and art viewers reflected on the value of being able to see additional information about the artistic process. They also felt that it was crucial for any recording system to be unobtrusive in nature and utilize familiar, traditional tools in order to allow the artists to not deviate from their natural style. Moreover, despite some of the advantages of digital drawing interfaces, all of the participants expressed their preference for pencil and paper because of the unique auditory and tactile cues these materials provide during drawing. Overall, our findings suggest sensing and visualizing aspects of fine arts practice as an effective approach for engaging viewers with how the work was created—i.e., by showing aspects of the process that are not visible in the final static piece. This brings us to the broader question, “How can we design systems that capture important but latent elements of creative processes without altering their authentic traditional qualities?”

First, specifically in regards to pencil drawing, our participants’ feedback suggested several other modalities that could be sensed in addition to the pencil movement and pressure captured by our system. Many of the participants expressed interest in seeing artists’ hand and palm positions in order to see how they hold drawing utensils while applying different drawing techniques. While future implementations of these ideas can be grounded in the existing knowledge of non-invasive hand gesture recognition methods [105], further research can develop precise sensing mechanisms that are robust enough to capture subtle differences of artists' hand gestures. Moreover, both the artists and viewers have shown great interest in biometric information such as the artists' heart rate, eye movement, and pupil dilation while they are drawing. Even though capturing such information was beyond the scope of this probe, there are opportunities for incorporating existing biosensing methods [3, 62, 133] into the system in order to study the implications of tracking such data about the artist. Related research has also shown a growing interest in the technical and social aspects of sensing human biometric data [22, 27, 28, 112].

Furthermore, based on our findings, we see opportunities to engage audiences with process information across other artistic mediums such as painting, sculpture, and performing arts (e.g., dancing [93]). From tracking the movement of a paint brush to perceiving the pressure applied to clay by a sculptor to sensing the subtle motions of a dancer, there are opportunities to utilize digital technologies to capture latent elements of a vast array of artistic practices. However, the design of our probe highlighted the importance of implementing digital sensing mechanisms that do not intrude on the personal spaces of the artists or hinder the authentic qualities of their processes. These considerations may raise new technical challenges. For instance, how might new systems seamlessly integrate pressure sensors into the sculptor's palm or fingers without interfering with his or her natural practice? How might future technologies augment a paint brush with motion sensors in a way that would not cause the artist to alter their painting style? Importantly, addressing these challenges will open up new opportunities to merge fine arts with research domains such as ubiquitous computing [23, 66], wearable technologies and embodied sensing [80, 117, 126], and interactive performance [141].

3.6.2 Designing New ‘Process-Aware’ Art Viewing Experiences

In our work, two visualization modalities–video renderings and 3D bas-relief models–were used to present the captured process information and were viewed not only as forms of data representation which can be useful for self-reflection during the drawing process but also considered as new forms of digitally-mediated art. This suggests new directions for designing ‘process-aware’ art viewing experiences.

For many viewers, understanding artistic process is an intrinsic part of art appreciation [91]. While artistic works can be viewed solely for their finished properties, numerous artists and art curators have also chosen to present descriptions of process alongside the art objects [157]. In our research, the process information presented in the video renderings and the 3D bas-relief models provided our participants with a novel art viewing experience, which leads us to see these visualizations as novel ‘information art’. In recent years, information art has emerged as a domain of interaction design where artistic content has been generated by computers based on the processing of digital data [14, 43, 65, 90]. These artworks show that information art can be used as a creative way to visualize monotonous digital information by presenting it as an artistic expression. In this light, we believe that collected art process data can be displayed as information art pieces integrated with the original static artworks (e.g., pencil drawings, sculpture). In turn, these collective digital-physical art forms could provide dynamic, multi-sensory and process-aware art viewing experiences. For example, the final result of a wheel thrown ceramic piece can be presented with a series of 3D prints, which show the different stages of its formation process. This would give viewers a visual and tactile experience to see and feel how the form of the piece changed with time. Likewise, the gradual change of a blob of glass during a glass blowing process could be shown as an animation together with finished glassware, and the amount of air blown at different stages could be mapped into an audio output that could be played in the background. However, these new creative explorations must involve artists in the design process to remain synergistic with the innate artistic qualities and intentions of the original pieces.

3.6.3 Platforms for Creating and Sharing Process Information

The artists we interviewed had mixed reactions about the idea of sharing aspects of their creative process. Many participants were willing to show the process for some of their work, but disliked the idea of sharing their complete process for all pieces including unsuccessful attempts. The artists' desire to control what work is shown is in tension with what we found to be the audience's interest in seeing the entirety of the artistic process, including iterations, mistakes, and adjustments. This tension is further complicated by the fact that professional artists may be financially encouraged to share their work, as A2 points out: "*From a business perspective, other people get excited by seeing the work progress*."

These concerns lead us to ask how future sharing platforms could support open dialogue between the audience and artist, while at the same time taking into account concerns about privacy and observation. While each creator will feel differently about what parts of their process they are willing to share, especially when it comes to perceived mistakes and adjustments, it is clear that any method of publicly sharing process data will need to include some means of self-curation. Digitally, this could be done through assigning metadata, such as timestamps, descriptions, or related work, that would be viewed with visualizations in order to process representation. Research is already examining a range of mechanisms for and challenges inherent in curation of digital content, including approaches for slowing down digital consumption, ways to focus and clarify digital presence, and better understanding why and in what circumstances individuals are willing to share personal information [8, 11, 56, 118, 119, 120, 136, 155]. Future platforms for sharing process information could explore the tradeoffs between showing large amounts of data that could potentially overwhelm the viewer and revealing only carefully curated information. In addition, sharing on social platforms could allow artists to curate not only what information they share, but also which groups, such as close friends, students, customers, or the general public, would be allowed to see their process. For instance, a future sharing platform may allow artists to select certain moments or aspects of their drawing process to be shared, while enabling them to curate mistakes. Such systems might also allow the viewers to comment and provide feedback or encouragement during parts of the process. This could enable dialogues between artist and viewer, support new forms of critique, and perhaps lead to new communities who want to learn and share process.

Interestingly, while the artists we spoke to wanted to curate and limit how their process information was shared, they were also enthusiastic about sensing new, more intimate aspects of their drawing process. Their suggestions included biometric data, such as heart rate, eye tracking, and pupil dilation. This leads us to ask what it would mean to share biometric data, which goes beyond sharing a person's finished creation, or even crafting processes, to displaying the innate physical, physiological, and psychological processes of a human organism during creative practice. How might sharing intimate aspects of the drawing process, such as biometric data, tactfully support greater understanding of and feelings of connectedness with the artistic process? Given the current trends in biosensing and personal informatics, future research can engage with this question from technical, social, and philosophical perspectives.

3.7 Conclusion

This chapter explored how digital sensing, visualizing, and sharing of dynamic elements of traditional drawing processes might shape the art making and art viewing experience. Our probe is a system that tracks the pencil movement and pressure of the freehand drawing process on a traditional easel and then visualizes the captured information as video renderings and 3D bas-reliefs. We used this probe in a series of studies with artists, expert art viewers and general public to investigate how digital sensing, visualizing, and sharing of previously concealed aspects of the artistic process can influence both art making and art viewing. The research probe revealed latent information—the order of compilation, speed, length, and pressure of strokes—as a way of engaging artists and viewers with the techniques, processes, and emotions during fine arts practice.

Our findings suggest that capturing and showing latent information behind traditional art processes can support artists' reflections on their own creative practices, as well as enable art viewers to more deeply engage with finished works by understanding aspects of the process, including the time and skill involved in creating the final piece. By making process visible and tangible, our work begins to blur the line between artistic process and finished art product and demonstrates ways in which 3D printing can be used in tandem with traditional materials and approaches. In the next chapter, we explore how creative practices could be translated into the domain of 3D printing, and investigate the constraints and challenges which may arise when digital technology is integrated into preexisting workflows.

CHAPTER 4

LITHOBOX: TRANSLATING FINE ARTS TECHNIQUES INTO 3D PRINTING WORKFLOWS

After observing how digital technology can be used to record and catalog the movements of artists during creative processes, we explored what kinds of constraints arise from translating techniques from fine arts domains into new workflows that incorporate digital technology and modern fabrication tools. In addition, we examined how the integration of digital fabrication into craft processes could affect the creative practices of artists. The goal of this work was to gain insight into how the different constraints manifested in creative processes can affect artists' agency in design and making.

This chapter details the implementation of a research probe to explore how hybrid materials, tools, and processes shape creative fine arts practice. Inspired by the traditional lithophane technique whereby designs are molded in porcelain and visible only when backlit, Lithobox is a software system, physical kit, and workflow for easily creating illuminated 3D-printed lithophanes. In worksessions with nine artists, Lithobox was implemented as a research probe to explore the effects of digitally-augmented crafting on creative practice. The findings reveal how factors such as creative expression, constraints, iteration, and expertise shape the participants' current work, and are shaped by the use of Lithobox. These insights allow us to better understand how productive constraints relate to agency in digital and physical aspects of creative making, and theorize how emerging technology and fabrication approaches could be incorporated to support rather than supplant craft amongst communities of practice. Sections of the chapter were taken from Weiler, Fernando, Ingalls, and Kuznetsov [176].

4.1 Lithophanes

Lithophanes were first invented in the early 18th century in Europe and were originally made by carving an image into clay and then firing it in a kiln [99, 175]. These early lithophanes were traditionally plaques resembling a bas-relief, in which a sculptural image was depicted with little overall depth. However, when back-lit, the thinner parts of the lithophane allow light to shine through while the thicker part of it do not, thereby creating a luminescent image. Later, as lithophanes became a popular commercial product, designs were also mass-produced. This was done by carving the original design into wax, which was then used to make a plaster mold. The mold was used as a template to make multiple copies of the original design [99, 175]. Because they needed to be evenly backlit during the carving process, ceramic lithophanes were generally created as flat tablet, though there were some rare cases of lithophanes molded into three dimensional shapes, such as orbs [99].

4.1.1 Translating Creative Practice between Mediums

Because the images depicted in lithophanes are created by varying the thickness of the material, rather than through the use of color or ink, they can be effectively created using single-color 3D printing filament. The concept of lithophanes has recently been explored in 3D printing [115, 146] with several online programs and tutorials allowing users to turn their images into 3D printable lithophanes on flat plaques or cylinders [29, 45, 71]. However, considering the potential complexity that can be achieved by 3D printing, we contend that the available designs do not take full advantage of the options presented with 3D printing technology.

In our work, we utilize 3D fabrication, which is becoming widely available in fablabs and design studios alongside new methods and approaches for making 3D models, many of which are designed to make specific types of models with relative ease. Intuitive interfaces and programmatic construction of 3D models have been used to create 3D prints that visualize large amounts of data or embody prescribed shape-changing behavior [19, 75, 130]. Other interfaces have focused on making the construction of 3D modeling easier by allowing users to generate or animate 3D shapes using drawing metaphors [81, 82, 83, 86, 98]. There has also been an increased interest in understanding what attracts amateurs to craft activities and how to make learning and engaging with new fabrication techniques and digital interfaces more accessible [33, 110, 116, 150, 184]. In our design of Lithobox, our goal was to support greater variety and individual design in the overall shape of the lithophane, as well as its outer and inner textures. In addition, we also designed a kit for illuminating the lithophanes created with Lithobox, such that the resulting artifacts are displayed on a rotating platform, allowing the details of the illuminated image to reveal themselves gradually to the observer.

Light Art and Digitally-Augmented Craft

Our work is inspired by effects made possible through backlighting lithophanes, and we are interested in exploring new possibilities afforded by interaction design of light-based experiences. In addition, we draw inspiration from the growing body of work focused on fabricating objects with unique qualities based on lighting and perspective. While the use of lights as indicators or accessories has been prevalent in interaction design for a long time, more recently the tradition of light art has inspired the use of light as a primary creative medium in design research [37, 137, 160, 179]. In addition, recent works have focused on optical manipulation and incorporation of lights as a part of technology-augmented crafting [20, 35, 97, 183].

4.2 Lithobox

We set out to explore digitally-mediated workflows for fabricating lithophanes because the established method of hand-crafted ceramics requires specialized equipment and has limited design possibilities in terms of the complexity of the produced forms. Through a year-long partnership and series of discussions with local ceramicists, we explored design possibilities for digital fabrication of lithophanes. Our goal was to design a system and workflow for creating lithophanes as 3D printed artifacts with complex extruded shapes that can depict detailed images when back-lit. We designed our system as a probe to explore

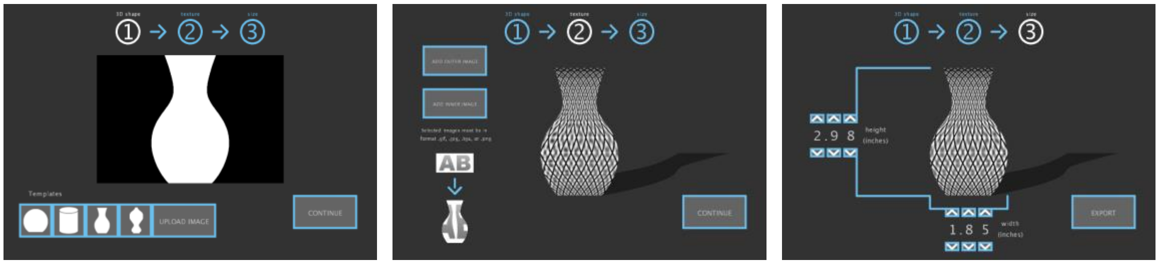

Figure 4.1 Lithobox digital workflow. From left to right: user draws outer shape of lithophane; user chooses images to be extruded along the surface of the 3D shape; user selects size of lithophane.

how artists enact values through hybrid processes and materials while crafting [10, 12, 170].

We iterated on early versions of the Lithobox software and workflow in several informal sessions with artists and designers. In these iterations, we improved visual aspects of the interface, added written prompts, and implemented several additional features that allowed for iteration on the lithophane design. The final version consists of software for easily generating 3D print files for complex lithophanes, a physical kit that can be 3D printed or laser-cut to rotate and illuminate each artifact, and electronic components.

4.2.1 Software Interface

The 3D model lithophanes are generated within Lithobox, a downloadable application created with Processing that outputs the finished models as OBJ files. Lithobox is composed of three separate preview screens (fig. 4.1) during which the user creates the shape for the lithophane, selects which images will be displayed on the surface of the lithophane, and chooses the print size of the lithophane. The process of creating a lithophane is implemented as a series of steps, each with its own page in the interface, and users can skip to or return to any step throughout the workflow.

During the first step, the user designs the outer shape of the lithophane. While traditional porcelain lithophanes are generally created from geometric shapes (e.g. rectangular frescos), 3D printing allows for more complex forms that are harder to create by hand. As such, we designed the system so that the user can create any radially symmetrical form. We made this choice because it allows for a wide variety of forms, which are extremely difficult to create by hand in mediums such as ceramics. Radially-symmetric shapes also allow for new aesthetic possibilities that can be observed on a rotating platform that comes with our physical kit. The interface supports iterative drawing of the shape's 2D outline, which is mirrored symmetrically, while ensuring that the minimum thickness of the model is compatible with our physical kit for illuminating the 3D printed artifact (description below). In addition to drawing from scratch, users can also select a shape from several pre-existing options (a cylinder, an orb, and generic vase shape), or upload other images of shapes that they had saved.

In the second step, users choose 2D images to be mapped to and extruded on the outer and inner sides of the lithophane. Uploaded images are mapped along the 3D shape, by stretching each horizontal line of pixels in the image to the corresponding thickness of that section of the 3D model. The mapped images are extruded from the surface of the model based on the darkness of the color in each pixel (maximum additional depth is 3mm, which we determined through several early trials). In the software preview, the lithophane model is automatically rotating so that the viewer can see how the finished 3D design will look from all angles. The preview for the inner images are slightly blurred, to reflect the fact that in the finished 3D printed model images on the inside of the print tend to have a slightly translucent appearance compared to the images placed on the outside of the lithophane. Once 3D printed, the outer image extrusion is visible to observers even when there is no light inside the lithophane, while inner images are only become visible when the lithophane is illuminated from the inside.

In the final step, the user chooses the size of the exported 3D model. Our system scales the 3D model to the desired size (the Ultimaker we used to print the models had a maximum build size of 8.26in^3 (210mm^3)), while still keeping the thickness of the material at .04in (1mm) for translucence. When the user resizes the model, the bottom of the print is resized to maintain a diameter of 1.25in (31.75mm), so that the bottom fits other parts of our kit during the physical assembly. The exported model is saved as an OBJ file which can be printed using a variety of commercially available 3D printers. Lithobox also saves the images representing the shape outline, inner and outer bas-relief, and scale that was used to generate the model to support future alterations, whereby previous designs can be reloaded into the Lithobox software to continue iterating.

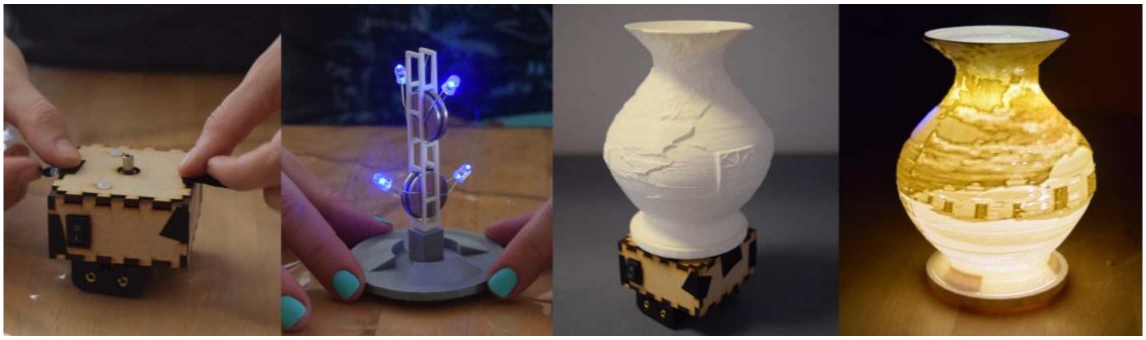

Figure 4.2 Lithobox physical assembly from left to right: makercase box containing rotator, 3D-printed platform and tower with lights, and examples of rotating, illuminated 3D printed lithophanes

4.2.2 Physical Kit and Assembly

We designed an easy physical assembly process to allow the finished 3D printed lithophane to be lit from the inside and displayed on a rotating platform. The rotation allows the displayed part of the lithophane to change over time, adding an interesting perspective for observing the mapped and illuminated images. Beyond the 3D printed lithophane, the materials required to make this finished assembly include additional 3D printed or laser-cut parts consisting of a base, a light support tower, and sides of a makercase box (fig. 4.2). The electronic components include a 6 RPM servo, switch, battery pack, batteries, and LEDs.

LEDs and coin cell lithium batteries are inserted in slots along a vertical tower at the center of the rotating platform. After the lights are assembled, the 3D printed lithophane is placed over the light tower and latched into notches on the base. The rotator is made by attaching the wires of the servo to the battery pack and switch, and then putting all the materials inside of the assembled box. The spinning end of the servo, which sticks out through a hole in the makercase box, can then be fitted to the bottom of the support platform, allowing the 3D printed lithophane to rotate.

4.3 Methods and Study Design

We developed Lithobox as a research probe to explore how hybrid materials and tools shape and are shaped by artistic practice. In a two-part study, we conducted worksessions whereby we observed the creative processes of artists using Lithobox. Semi-structured discussions throughout the sessions allowed us to explore our research themes related to material affordances and constraints, iterative process, and workmanship of risk. Below, we describe the worksessions and study structure in more detail.

4.3.1 Worksessions with Artists

Before the study, we briefed participants (by phone or email) on what traditional lithophanes are, and asked them to bring several image files that they would like to see displayed on a lithophane. During the first worksession, which was conducted individually with each participant, participants discussed their artistic background, materials, and processes, and engaged in a brainstorming session during which they generated ideas for lithophanes either through sketching on paper or molding them with playdough. They then used Lithobox to design a 3D lithophane form and experiment with their own images and the images the researchers had on hand as the inner and outer extrusions on the lithophane. If participants were unsatisfied with their chosen design or wanted to continue to iterate, they had the option to download the Lithobox program to their computer and email their design to the researcher later. After each participant decided on a design, it was 3D printed by a Ultimaker. The participants were then invited back for a second session during which they worked with their 3D-printed model to physically assemble the lighting and rotating platform for the finished lithophane setup. At the end of the session, participants kept their lithophanes and were offered a copy of the Lithobox software for future projects. Again, throughout this session, we prompted participants into semi-structured discussions to reflect on our research themes. Participants were offered basic compensation ($10 for attending the first session and $15 for attending the second).

4.3.2 Data Collection and Analysis

All worksessions and interviews were audio recorded, reviewed by researchers, and relevant discussions were transcribed (e.g., we did not transcribe small talk or casual conversations between researchers and participants that were not related to the use of Lithobox or our research questions). Each transcription was coded and affinity diagramed separately by two different researchers, and the resulting categories were then discussed, compared, and synthesized to reveal findings along our research themes.

4.3.3 Limitations

Our system serves as a research probe to explore the intersection of digital-physical fabrication and fine arts through a case study of lithophanes, and our findings may not be universally applicable to other fabrication processes. All of our participants were interested in learning about the possibilities of 3D printing within the context of fine arts. Because of this, we cannot be sure to what extent their opinions on digital fabrication techniques are representative of the perspectives of people from similar creative backgrounds due to possible self-selection bias. In addition, participants' feedback is based on their experience making a few complete lithophanes. It is possible that extensive and repeated interaction with the system may produce different results.

4.3.4 About the Participants

To recruit participants interested in creating works with Lithobox, we reached out to the arts communities on our university campus. Nine people (five female, ages late 20s to mid 50s) from a variety of creative backgrounds agreed to participate. All participants were active art practitioners with between five and twenty years of experience in traditional and/or digital arts domains. Three had a primary focus in mixed-media sculpture (e.g., metal casting, found materials) (P2, P4, P8) and two in new media (e.g., sound installation) (P3, P5). Other participants had backgrounds in dance (P1), ceramics (P6), engineering (P7), and traditional 2D media (P9). Of our participants, only two (P4, P7) had experience

Figure 4.3 Examples of lithophanes created by participants with Lithobox. Custom images were mapped and extruded along the lithophanes' inner and outer surfaces, and each lithophane displays a unique image when lit from within

with basic 3D printing. Only one participant (P6) had previously tried making ceramic lithophanes by hand, though at the time of the study has not yet finished the project.

4.4 Findings

During our interviews with participants, we identified certain factors to be especially motivating and influential towards shaping their artistic practices. We then explored how these facets of their creative practice were influenced by working with Lithobox to understand how artists could utilize digital fabrication techniques, as well as to explore the contrasting approaches and benefits of digital and physical crafting. Our findings cover 4 themes: creative expression, productive constraints, iteration, and expertise, and for each category we present how participants' experiences with Lithobox related to these aspects of their creative process. The final section of our findings summarizes participants' perceptions of integrating digital technologies with craft techniques more generally.

4.4.1 Creative Expression and Curiosity

While the individual approaches and materials being worked with differed across participants, all of them viewed their artistic practices as an outlet for creativity that is driven by their curiosity.

P9: *"I'm just lucky that I went through an education system that kept me curious, I didn't have to search for [creative outlets] at first. And from then out just kind of jump on any opportunities that I find interesting to me."*

P9's quote above reflects other participants' emphasis on pursuing personal interests and curiosities through their work. For many, the ability to pursue their own creative interests was also a cornerstone of the enjoyment of their craft and helped them to overcome the nervousness they would feel about displaying their work publicly.

Exploring Creative Practice through Lithobox

The importance of creativity and curiosity was reflected in participants' initial approaches to working with Lithobox. Prior to the study, we asked participants to bring images to be used as textured extrusions in the design of their lithophane. When choosing which images to work with, most participants took the opportunity to use images related to their creative work, allowing them to display their artistic practice in a new medium. For instance, P4 brought in images of metal casting, an activity central to her creative practice. In addition to sharing her artistic process in a different medium, she was also interested in creating a thematic connection between the bright light of molten metal and the illuminated lithophane.

P4: "*A couple of them [images] are from the foundry process and just thinking about that bright light, and the rest are about – just also thinking about stories- you know, so like foundry, the imagery is from specific places I've gone before, so there's a story with that but also a story within the history of casting."*

Similarly, one of the images P3 chose for his 3D lithophane design was a photo he used in other art projects, and he was excited to see how it would visually change when stretched over the lithophane.

P3: "*I like this photo a lot, and I've used it for several different things, it's actually a textural basis for different projects or for website and image design and it's actually very cool to see it, even though it's now - I mean, it's expressed in a very different mode, to see it differently like this – it's absolutely connected to my own engagement with the photo*."

Thus, while designing their lithophanes using our system, participants chose to experiment with pictures that they found creatively engaging, which served both as a means to further explore their current work and connect it with the Lithobox project.

4.4.2 Constraints and Affordances of Physical and Digital Materials

All of the participants have worked extensively with physical materials in their own practices. For many, the ability to directly manipulate the materials and the tactile feedback they would receive were their main motivations to continue working primarily in a physical medium (e.g., ceramics). For example, P2 felt that she was better able to perceive the qualities of an object when holding it, rather than viewing it.

P2: "*There's something about touching stuff that makes you know things in a different way. Especially the textures, I think I saw that in the image but it never- it's much more apparent in the actual object.*"

In contrast, while digital tools were perceived as being potentially useful, the lack of immediate tactile interaction beyond the traditional mouse/keyboard interface was seen as a detriment for integrating these into current practices.

P6: "*It just was not real to me. It wasn't real enough… the machine can do things that I can't, but when it comes to developing an idea for form, I think my hands work more intuitively than my fingers on a keyboard or a mouse.*"

Above, P6 acknowledges the potential benefits of digital (computer-based) crafting, but he describes the process of using digital tools as 'unreal' compared to working with physical materials. When working in their chosen mediums (e.g., ceramics or metal), participants valued the natural constraints presented by the materials themselves, the available tools, and their environment. Additionally, when trying to improve a specific skill to generate a particular type of work, participants would temporarily focus their attention on one technique, which would serve as a productive constraint in furthering their craft. P8 described purposely limiting himself by focusing on particular techniques when learning woodworking:

P8: "*You can learn something much more in depth by focusing on just it for a while. My most recent example of that is learning woodworking in a more focused way*."

At the same time, participants described contexts where they were presented with too many options at once, causing them to become less productive. 3D modeling software (e.g., SolidWorks) was cited as a common example of this, in which participants felt overwhelmed by an array of tools and options. Thus, essential to participants' current practices were the constraints and affordances of the physical materials being worked with, which is consistent with related literature [e.g., 73, 74, 108, 127].

"Sculptural" Constraints within Lithobox

While Lithobox generates lithophanes using a digital interface, our participants reflected on several ways in which the system afforded physical-like interactions. For example, when P1 touched and interacted with the 3D print of her lithophane, it led her to reflect on whether she considered the object to be something she had 'sculpted' in the computer.

P1: “*I have this embedded idea of sculpting being something I am generating or doing with my physical body, so it is hard to say that the moments in which I was creating on the computer were sculpting, but because they manifested as something that I am now holding in my hand I feel like they became sculpting.”*

At the same time, aspects of the digital interface served as a constraint which led some participants to reflect on the challenges of limited (or lacking) tactile feedback. For example, P4 reflected on the limitations of sketching with digital software because she had to adapt to “*movements it [the software] likes and doesn’t like.*” As illustrated by this case, the digital aspects of the system were harder to translate to the physical world, though we suspect these could be alleviated with more tactile forms of drawing (e.g., a tablet interface).

Despite the limitations of drawing digitally, participants appreciated the productive constraints in the Lithobox workflow, which supports making one type of 3D model (radially symmetrical lithophanes):

P5: “*[When] you know what shape you want, what cylinder or cone or whatever, and then you know what texture you want, to be able to take those two skills and put them together and suddenly I now have a 3D model that I can assumedly take and just plug in to the printer, that is really remarkable to me, because I feel like you just erased all of the learning curve that has been preventing me from 3D printing something. Obviously it [the software function] is limiting, but it feels really approachable.”*

P5's quote above reflects other discussions with participants who felt that while too many constraints can stifle creativity, overall, design constraints that focus the artist on achieving a specific technique or effect can be very beneficial. This same sentiment was described when participants used the physical kit to assemble the lights and rotating platform for their lithophane. Because of the limited choices that could be made in the assembly, the kit was described as "*more like a puzzle and maybe less like craft*" (P5), but because it involved "*using hands to put [the materials] together in a certain physical configuration*," the process was considered "*physical sculpting*" (P1). Thus, while the constraints of the kit limited creative choices, participants felt engaged with the physical crafting process and were able to create a specific result.

To summarize, participants valued productive constraints both in their interactions with physical materials as well as their experiences with digital tools such as Lithobox.

4.4.3 Time and Iteration

In addition to the affordances and constraints of physical materials, all of our participants discussed how time considerations shaped their creative practice, both in terms of what materials they chose to work with and how much time they would spend on each project, which could range from days to years. Our participants described craft as an iterative creative process, and as such, it could potentially translate to other fabrication approaches regardless of the technology involved. P7's quote best summarizes this point:

P7: "*You work on a craft. You iterate on it… It's not so much about the ontological end status, it's about whether you're continually working on it."*

When describing why and how they allocated their time and effort to their work, participants emphasized the value of iterating on projects, both during the conceptual ideation as well as during the physical crafting phases of their work. Determining how much time and iteration to spend on projects was a question several participants grappled with, as described below by P3:

P3: "*I have to ask myself 'should I really be spending this much time and attention on getting this thing done well or is it actually okay if this doesn't look as cool and it just works, right?' … Probably not, but maybe. Maybe it's worth it, too… it's always a question of whether it's worth the time*."

Time was also often cited as a reason for not working with certain materials and technologies altogether. For instance, participants discussed instances where they shied away from using unfamiliar technology if learning its features would require a large time investment. This was especially true if they didn't see the new material or technique as being essential for their creative practice.

Reflections of Time and Iteration through the Use of Lithobox

Observing how participants used Lithobox as a form of creative practice furthered our understanding of the importance of time and iteration in physical-digital creative practice. On one hand, everyone appreciated the speed with which they were able to design and generate 3D models. For instance, P5, who had struggled to make 3D-printable models in the past using traditional modeling software (Maya, 123D Make), valued being able to create something without having to invest much time into learning the process.

P5: "*People who don't have the background knowledge in 3D modeling and sculpting… have the capability to go and make something physical exist in the physical world*."

However, as highlighted by our discussions, being able to produce work quickly is not always the primary goal of creating works of art. Some of our participants saw the time invested in work as a way of reflecting on the progress of the piece and as a means of increasing their own personal attachment to the work. Despite finding the speed of creating a 3D model "*really satisfying*," P2 felt less attached to the finished object because of the lack of time investment (e.g., "*this was really satisfying because it was quick but I feel less connected to it because of the time*").

In this way, participants' work with Lithobox offered an interesting point of comparison for how digital fabrication with 3D printing influences iterative practices. On one hand, when creating their lithophanes in the Lithobox software, participants were able to iterate on their design choices by altering the 3D shapes of the lithophanes and their choice of displayed images. They were also able to quickly experiment with different images on the outside or the inside of the lithophane.

While these forms of digital iterations were highly valued by participants, there was a disconnect between this digital phase and the perceived 'finality' of the 3D printed artifact. The change from digital preview to physical object took some of the participants by surprise, as exemplified by the following comment by P4:

P4: "*I think I didn't expect it [the final 3D print] to be this. Like, seeing it in the computer I couldn't – even though I had seen 3D prints before – I couldn't imagine it 3D printed.*"

While most of the surprise at seeing the 3D print design was positive, our participant's reactions implied they felt limited possibilities for further iteration on the physical 3D print.

P3: "*There's also the kind of finality of a 3D print, there's also that kind of thing where you commit to it, I'm not very good at committing to these processes*."

P3's quote above reflects others participants' sentiments: to iterate on their lithophanes, participants felt that they would need to redesign and reprint the model, rather than physically alter the 3D print. Given that our participants were used to manipulating physical materials, this reticence to physically alter the 3D print was unexpected, but perhaps could be explained by the participant's unfamiliarity with plastic materials and their view of the print as a finished object.

To summarize, our explorations with Lithobox suggest a tension between offering artists tools to quickly produce artifacts, while also having mechanisms for longer-term iterations on projects to support more connection to the work. In addition, while artists appreciated the creative exploration offered by the digital interface, the perceived unalterable characteristics of the 3D print meant that iteration in the design was limited in certain parts of the craft process.

4.4.4 Scaffolding Expertise through Creative Workflows

Participants' experiences with Lithobox led them to think about how materials and workflows attracted them to their respective domains, and in some cases deterred them from working with certain processes. Each of our participants had an extensive background in their chosen medium(s), with some participants having upwards of two decades of experience in their field. Yet, when discussing what drew them to their area of work, participants described the value of being able to explore and experiment with simple tasks. P6, who practices and teaches ceramics, stressed the importance of starting with basic, approachable techniques, from which individuals can develop a large toolkit of approaches and skills that could be applied to tackle more advanced projects.

P6: "*Even though some of these techniques seem very basic, and you may have done it before, you never know when you are going to use it*."

At the same time, perceived lack of expertise was also a deterrent for working with certain materials and tools. Some participants expressed fear of feeling discouraged and devalued if they tried something and were unsuccessful, while others avoided using specialized tools or equipment if it would require extensive help from others.

P1: "*If I were to attempt to do something that I don't understand or am not good at, I would feel devalued.*"

P4: "*It was like 'ok, what's the path of least resistance?' to accomplishing this, and there's this learning curve and there's also – so there's time, right?*"

As noted by both P1 and P4 above, participants often preferred to start their projects by applying familiar techniques rather than investing additional time in learning new skills at the beginning of the project. In short, participants valued basic, approachable techniques, both as foundational knowledge within their area of expertise, as well as a means to gain understanding of unfamiliar tools and processes. Without such background knowledge, it was considered difficult to effectively engage in the exploratory creative process that led to increased expertise at later stages of their work.

Accessible Workflows in Lithobox

We designed Lithobox to make the complex process of designing and creating lithophanes more accessible. When using Lithobox, participants who had no digital 3D design experience and participants who had previously given up on learning modeling software were quickly able to grasp how the program worked and what it was able to do.

While participants still had to learn the specifics of Lithobox's setup, the overall program allowed them to design a complex 3D printable model with relative ease. In this case, the workflow supported by Lithobox led participants to quickly begin engaging in the crafting process, as P3 describes:

P3: "*For a beginner like me, having some ramp into the process… I would be a lot more likely to actually go through the whole process than I would if I just had a complete open sandbox… That would be too intimidating and would take too much time for me to get something that is like actually printable.*"

Moreover, participants also reflected on how our system allowed them to begin engaging in 3D fabrication more generally. For many of our participants who had struggled with or avoided 3D modeling software in the past, the ability to quickly generate a finished model was seen as a substantial accomplishment and led to further interest in 3D modeling. By increasing their familiarity with the medium, participants appeared more optimistic in their ability to eventually cultivate expertise.

4.4.5 Broader Reflections on Digital-Physical Crafting

In this section, we present participants' broader reflections on the integration of digital technology with existing craft traditions in ways that serve, rather than stifle or eliminate creative aspects of the craft process. Below, we show how participants on one hand wanted to preserve craft skill and tradition, while at the same time wanting to apply technology to enable new creative outcomes.

Preserving Traditional Craft Skills

Because of their diverse backgrounds, our participants had differing views on how to define craft. However, it was generally agreed that crafting involved repeated engagement with and exploration of a specific medium. For this reason, some participants felt that their creative community was hesitant to integrate digital tools into creative processes. For instance, when reflecting on why artists and craft enthusiasts that she knew were hesitant to use new fabrication methods, P2 suggested that individuals who had cultivated skills over many years did not want to feel replicated or replaced by digital machinery.

P2: "*The people in those areas [ceramics, painting, fibers] are really devoted and take a lot of pride in the craft – like the time they spent to learn the skills to craft an object, and so I think they are a little skeptical of 'Oh wait, now I can just print it?' and so there's an insecurity that happens and I think is part of maybe why people in those areas have not embraced the 3D printers. They still want that time and all of those years they've spent developing this skill to matter."*

In P2's example, which reflects opinions of other participants, the perceived ease of digital fabrication is put in tension with traditional, skilled craft practices. This underlines the importance of designing and implementing technology in a way that enables, rather than supersedes, workmanship of risk.

Enabling New Creative Processes

At the same time, participants also acknowledged the potentially freeing aspects of technology. When describing their own creative practices, participants described being limited by the medium they are using and/or their own skills. P1 suggested that the availability of new tools and techniques could provide alternative ways of manifesting ideas.

P1: "*If, say, for instance, I'm someone who is not good with my hands, this offers me an outlet to do something that I wouldn't necessarily otherwise be able to do … It allows you to sculpt without the same limitations that we find when sculpting or working with traditional materials*."

Similarly, P4 reflected on a common belief among participants: that there was potential for new technologies to enable different kinds of fabrication within craft traditions.

P4: "*I am interested in how we can… push these technologies and then also how these technologies relate to traditional craft and technique and how they can – I don't like saying the word "replace" – but how it can stand in a place of these more traditional techniques that have been used in the past*."

Participants described each craft medium as having its own limitations based on the tools and materials used, and were optimistic about the possibilities of tech-based approaches that focus on novel fabrication possibilities (rather than methods that to recreate and potentially replace traditional approaches). With the assistance of emerging technology, participants hoped to explore new mediums for crafting and widen the scope of the artifacts they are able to make.

4.5 Discussion

Our iterative design of Lithobox was inspired by the works of Ingold, Pye, and McCullough, which provide insight into the nature of craft in the digital age [73, 74, 108, 127]. We used Lithobox as a research probe in a study with nine artists to explore how factors such as iteration, material interaction, and productive constraints shape creative digital-physical crafting. Below, we more generally reflect on participants' experiences with the digital and physical fabrication of 3D lithophane artifacts using Lithobox, and relate our findings to concepts from our earlier discussion of craft in the digital age.

4.5.1 Non-Hylomorphic Crafting Processes

When describing their experiences with Lithobox, participants talked about the workflow in ways that reflect Ingold's characterization of non-hylomorphic process, in which the art objects result from engagement and interplay between artist and material [73, 74]. While many of their projects began with a design goal, participants viewed the artistic process as an expression of creativity and curiosity, in which their interactions with materials often led to unexpected results. In addition, participants' work was shaped by the time they spent crafting an artistic artifact or learning new tools. This was especially highlighted in their work with Lithobox, where, while they appreciated the quick and easy workflow of the software, they also mentioned that had they spent more time they would feel a stronger emotional connection with the produced artifact. These experiences point to a non-hylomorphic approach, where the iterative interactions and the time invested into crafting an artifact are essential to the practice.

The non-hylomorphic approach to fabrication was also seen in the participants' dislike of the perceived 'finality' of the 3D print. Being able to continually iterate, change, and evolve the art object is vital to non-hylomorphic craft, and participants felt constricted by being unable to perform such iterations on their 3D print, even if they did have an overall positive impression of the design.

4.5.2 Workmanship of Risk

While working with Lithobox, participants described factors that influenced their creative practice that reflect Pye's characterization of workmanship of risk [127]. During workmanship of risk, the artist has the ability to affect the outcome of the work throughout the creation process. In their descriptions of working with their chosen media, participants emphasized the importance of being able to effectively act upon, experiment with, and respond to changes in their work. However, when participants designed their lithophanes using the Lithobox software and discussed potential integrations of digital fabrication tools, they also expressed satisfaction in engaging with preparatory workmanship, in which their creative interactions were then translated into the manufacturing of items, such as 3D prints. Participants were also receptive to using the workmanship of certainty epitomized by high-tech fabrication methods, as long as they were also able to continue to iterate and creatively interact with their projects throughout the crafting process.

4.5.3 Digital Form-Giving

In describing the computer as a medium rather than a series of tools, McCullough validates digital processes as a type of craft [108]. Our participants also were interested in using the computer as a creative medium, and compared their experiences with physical materials and digital interfaces. When manipulating physical materials, participants described valuing the productive constraints presented in traditional physical mediums as opposed to some digital interfaces that 'intimidate' the users with an overwhelming number of functions and tools. To this end, they viewed the focused workflow of Lithobox software as a productive constraint that helped them to immediately start creating artifacts, whereby they used the software as part of a cohesive creative approach, rather than as a series of unrelated tools and commands.

4.6 Supporting Digital-Physical Crafting

In the remainder of this chapter, we discuss several specific approaches to support integrated arts practices alongside modern fabrication methods: 1) selective automation of tasks to allow for more focused or creative iteration; 2) productive constraints to scaffold creative workflows; and 3) supporting materially-oriented interactions throughout the physical and digital design process.

4.6.1 Selective Automation of Tasks in Creative Practice

What is considered an essential part of creative practice has often changed based on technological innovation. Before the mid-1800s, the practice of painting included grinding pigments and mixing them with binders to create paint. However, with the invention of the paint tube in 1841, artists were able acquire pre-made paints and, as a result, could spend more time creatively applying paint to canvas, rather than carefully pre-fabricating their colors [15, 91]. Today, painters can still choose to make their own paints, but the majority tend to opt for the convenience of paint tubes.

Drawing on our work with Lithobox, we can begin to speculate on how today's emerging techniques and technologies could selectively automate mundane aspects of creative processes. Such automation could allow artists to spend more time creatively iterating on aspects of their projects that interest them or allow them to develop valued skills. Because each individual takes enjoyment from different parts of their craft process, ideal automation would be tailored to the desired design practices of the artist.

4.6.2 Productive Constraints to Scaffold Creative Workflows

Often, tools, programs, and processes are designed with the stated goal of giving the user as much agency and freedom of choice as possible. However, as we learned from our study participants, this could have the downside of complex, overwhelming systems not clearly conveying what they can contribute to an artist's pre-existing creative practice. As we observed with the design and use of Lithobox, interfaces designed with productive constraints and options tailored towards specific workflows and goals can help direct creative practice. This can be seen in our study, where users responded enthusiastically to being able to generate complex 3D models that are specific to lithophanes, even if it meant having some limits in design choices. In cases of more complex software, this could be achieved by starting with a simple pipeline and allowing more complex options to become available over time or as the user becomes more experienced.

In parallel, through digital interfaces and fabrication techniques, technology has the ability to make specialized workflows, such as sculpting, more accessible to people of various backgrounds and skill levels. This could allow not only for novices to experiment with unfamiliar processes and materials, but also to allow artists to actualize design ideas across a broad range of mediums. Future work could explore new workflows for enabling engagement with a diverse range of making materials, tools, and processes. For instance, 3D prints could be used as molds for modeling ceramics or casting metal, allowing artists to translate their design ideas from one medium into different materials. Through this application of technology, digital appurtenances would be able to serve as a gateway to traditional crafting techniques that were previously inaccessible.

4.6.3 Designing for Materially-Oriented Interactions

Material interactions are a key way in which humans perceive and engage with the world and are vital to the creative practices of many artists as we saw from our research. This suggests opportunities to design technology and emerging fabrication techniques lie in the support of material interactions, as is being explored by a growing body of related work [32, 33, 36, 55, 60, 63, 70, 132, 184]. Future work could focus on making the results of digital processes physically malleable to overcome the perceived finality of 3D prints expressed by our participants, who valued having longer term engagement with their creative projects. Current research has begun to explore the possibilities of 3D printers adding material to existing 3D prints [18]. This process could allow for physical iteration on already existing 3D prints, during which users could break and reassemble 3D printed objects into new forms. The malleability of 3D prints could also be encouraged by using alternative, flexible 3D printed material, including deformable plastics or traditional materials such as clay or biomaterials. If 3D prints could be easily physically manipulated and altered into new forms, 3D printing could serve as an iterative creative process in addition to its current application of fabricating finalized physical objects.

4.7 Conclusion

This chapter explored how digital-physical hybrid materials, tools, and processes shape the creative practices of artists. Lithobox is a software program, physical kit, and workflow inspired by the traditional arts technique of lithophanes. The system was implemented as a research probe in worksessions with nine artists from a variety of creative backgrounds. Our findings present insights into factors, including iteration, constraints and affordances of physical materials, and creative workmanship, that influence participants' artistic practice. This work points to ways in which digital fabrication techniques could be incorporated with traditional crafting so as to support existing craft practices through selective automation, productive constraints, and materially-oriented interactions. However, while feedback from participants for Lithobox was positive, the design approach of the system was limited to creating objects with 3D printed plastic filament. The next chapter will explore possibilities for incorporating accessible 3D printing tools into preexisting artistic practices with various materials, with the goal of allowing creative practitioners to leverage the benefits of 3D printing designs without having to forgo traditional material interactions.

CHAPTER 5

EXPLORING HOW 3D PRINTING WITH DIFFERENT MATERIALS CAN SUPPORT FINE ARTS, BIOFABRICATION, AND EVERYDAY CRAFT PRACTICES

In the previous chapter, we explored what kinds of opportunities and constraints arise from translating techniques from traditional fine arts domains into workflows that incorporate digital technology and fabrication tools. In this chapter, we investigate the possibilities of using 3D fabrication technology to create items in a diverse set of materials beyond plastic filament. Although 3D printers that print with custom materials such as metal or food are becoming available, they have not yet been widely adopted in art studios, design labs, or makerspaces. To explore the implications of these tools without investing in specialized 3D printers, we developed a software and workflow for incorporating plastic-filament 3D printing into a range of creative practices with different materials: fine arts methods, biofabrication techniques, and widely-accessible craft practices. Through personal exploration and workshops with creative practitioners, we gained insight into how 3D printing can be integrated into creative practices to support rather than supplant skilled crafting.

5.1 Integrating 3D Printing with Traditional Creative Practices

In recent decades, emerging digital tools have become incorporated into all aspects of daily life, including individual creative practices and making processes. The 3D printer in particular offers many opportunities for creativity and innovation, since it has the ability to accurately manifest complex 3D objects from digital designs and is becoming increasingly affordable and accessible for individual artists and makers [124]. However, the popularization of new fabrication techniques has also raised concerns about the role of physical crafting in creative making, since the integration of digital technology could potentially exclude certain types of skilled creative exploration (e.g., [51]).

As an alternative approach, we seek to engage with existing making processes and examine how 3D printing systems can be integrated in a way that does not reduce, supplant, or exclude valued traditional elements of creative practices. This chapter explores how designs produced by standard plastic-filament 3D printers can be incorporated into fine arts work with metal-casting, biofabrication with mycelium, and everyday craft with food. The techniques we present can serve as a template for how 3D printing can be integrated with other materials and creative practices, and we hope our research inspires future multidisciplinary, collaborative approaches to digital-physical fabrication.

5.2 System and Process

To explore the integration of plastic 3D printing with other materials, we created a software system and physical workflow to allow people without previous 3D modeling experience to create complex, detailed 3D prints.

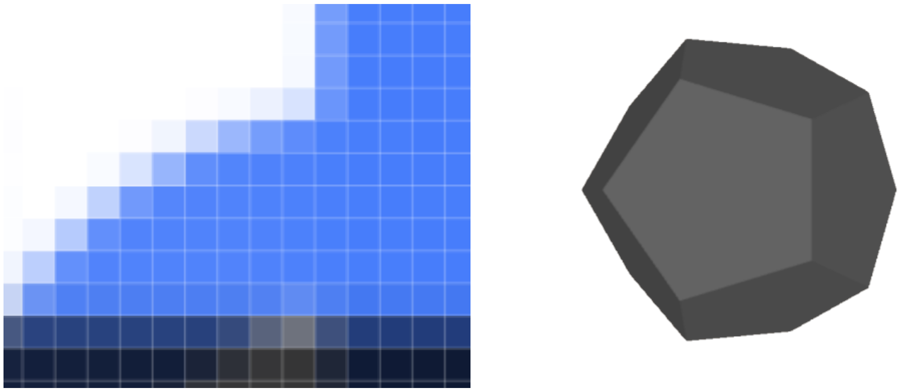

Figure 5.1 Data organization in different file formats. Left: 2D raster image composed of a series of pixels containing different colors. Right: 3D model composed of x-y-z points (vertices) connected by flat 2D surfaces (faces).

5.2.1 Software System

For our workflow, the 3D designs were created and printed with standard plastic filament 3D printers before being translated into other materials. In order to generate models for 3D printing, we created an easy to use program in Processing that takes grayscale 2D images and extrudes them into 3D prints. Through this approach, users can easily create detailed 3D models from drawings or photographs without needing experience in 3D modeling.

Within the Processing program we created, the 3D model is created by generating an .obj file from the original 2D raster image (fig. 5.1). 2D raster images are composed of pixels, which contain the red, green and blue color data corresponding to each x-y coordinate point in the image. In contrast, .obj files store information about 3D models. Each obj file has information about vertices (the individual x-y-z coordinate points that make up the 3D model) and faces (the 2D surfaces that connect specific vertices in order

Figure 5.2 Workflow for generating 3D models from 2D images. From left to right: Source image; generated 3D model; 3D print.

to generate the complex 3D model form). In order to generate 3D models from 2D images, the x-y position of each vertex in the 3D model is based on the position of a corresponding pixel in the 2D image. The z (depth) of each vertex is determined by the color data within the pixel.

In our program, we increased the depth (z) value of each vertex in the 3D model based on the value (average lightness of the red, green, and blue values) of the corresponding pixel in the 2D image. The extruded depth of the 3D model is based on a single variable (a number that the user types into the program), which makes it is easy to change how thick the resulting model will be. This allowed us to quickly generate several different 3D models from each 2D design in order to decide what thickness we preferred. The majority of our models were printed with an image depth of 1.0-1.5 inches, with the width and length of the models being between 3.5-4.0 inches.

After creating the original program, we iterated on additional features that would allow the user to create more complex shapes. We created a version of the program that uses a color signifier (in this case, red) to exclude part of the 2D image from the generated 3D model (fig. 5.2). Additionally, we explored several features that supported the programmatic shaping and warping of the models. For example, the model could be morphed into a simple 3D form, such as a sphere, or twisted based on mathematical formulas (fig. 5.3, fig. 5.4).

5.2.2 Translating Designs with Silicone Molds

To translate 3D prints into other materials, we explored the well-established approach of mold-making, and in our work, we specifically sought to utilize a molding material that was easy to use, affordable, and resulted in models that could be flexible while accurately capturing the details of the 3D print. We tested several materials for making molds, including rubber and plaster, before deciding that silicone molds were the most effective means of translating 3D-printed designs to other materials. The type of silicone we use is Silicone Plastique, a two-part putty solution that can be mixed together to take the form of whatever shape it is pressed into. After the putty solution sets, the finished mold holds its new shape while still maintaining flexibility [102]. After a mold is made from the original 3D print, it can be integrated into many different crafting practices to shape different types of materials.

5.2.3 Exploring Applicability with Different Creative Practices

We explored the versatility of our system and approach by utilizing it with several craft materials. When deciding which materials to investigate, we chose to focus on different creative practices that touch on several current craft approaches – fine arts (metal casting), biofabrication (mycelium-the fibrous part of fungus), and everyday craft activities (food). Through our research, we found that our approach could be successfully implemented with all three materials, and through these investigations we were able to gain greater insight into the nuanced differences and similarities between fabrication approaches with different materials. The next section describes our experiences fabricating objects using metal, mycelium, and food, as well as the interviews and workshops we held with practitioners with experience in these creative areas.

5.3 Case Studies

As part of our exploration in translating digital designs beyond plastic filament, we designed and fabricated objects in metal, mycelium, and food. Creating these objects provided us with firsthand experience and knowledge of the advantages and challenges that exist with current workflows. In addition, while exploring potential applications for our fabrication process, we held several workshops and interviews with creative practitioners in addition to engaging in personal creative explorations. In order to further explore with the possibilities of integrating of 3D printing into metal casting practices, we held a group session with experienced metal casters who had used 3D printing as part of their creative practices. To learn more about the opportunities and potential applications of biofabrication, we held a workshop with members of a local makerspace, during which they were able to design and create their own mycelium objects using silicone molds. As part of our exploration of how 3D printing can be integrated into everyday culinary practices, we held studies with a group of experienced culinary practitioners who designed and created their own silicone molds and cooked dishes. Through these workshops, we were able to gain greater insight into how 3D printing could be effectively integrated into different creative practices.

5.3.1 Metal Casting

While metal 3D printers are becoming commercially available, they are still extremely costly. Moreover, there is pushback against the adoption of such technologies because they might replace aspects of traditional metalwork. To explore how 3D printing might support rather than supplant existing metal casting practices, the lead author partnered with a local foundry over the course of one year, becoming fully embedded in this community through various metal casting projects and collaborations. During this time, we cast several bronze sculptures from 3D prints created with makerbot plastic-filament printers.

Figure 5.3 Process for creating a metal sculpture from 3D models. From left to right: 3D models; cast pieces; finished sculpture in which metal rods connect several 3D printed designs.

Through earlier phases of this work [177], we explored using silicone molds made from 3D prints as part of a metal-casting process. In that case, the original 3D prints were used to make wax replicas, which were then shelled and cast into metal. The shelling process involves repeatedly dipping the wax replica in a silica slurry and coating it with sand, which then hardens, forming a shell [17]. The shell is then cut open and heated, allowing the wax to be melted and drained out. Heated metal can then be cast into the empty shell (fig. 5.3).

However, that process restricted the types of designs that can be created, since the 3D-printed models and wax duplicates need to be removable from the mold without damaging either of them. After some iteration, this chapter presents our later projects that directly shell the 3D models. After the shelling process is complete, the 3D-printed plastic can be melted out of the shell. One downside to directly casting the 3D print is that it makes the process of replicating a design more difficult, since each 3D print can only be used once. In terms of time and cost, it is more efficient to create several wax replicas from a mold

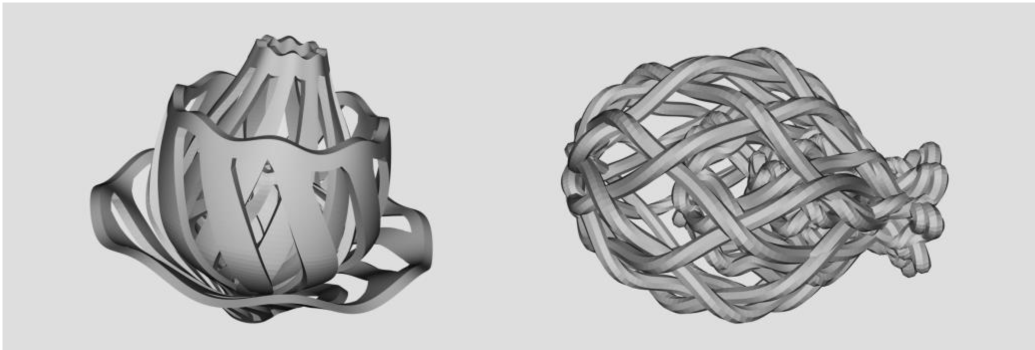

Figure 5.4 Complex 3D model designs for metal casting

rather than 3D printing several copies of the model. However, for complex interwoven models like the ones we created during this exploration, direct casting is the only option.

As part of our work with metal casting, we experimented with complex 3D-printed forms. Figure 5.4 (right) contains one of the more elaborate designs based on the same software we developed previously. In this case, the flat model generated from the 2D image is warped into a cylindrical shape using the software we developed. Several versions of the model warped in different ways are then layered on top of each other in order to create an increasingly complex form.

Casting these complex 3D-printed designs presents unique challenges. Both of the designs featured in Figure 5.4 are composed of several long narrow passages, which may prevent the poured bronze from spreading into all of the details before it hardens. As a result, parts of the finished sculpture would be missing. In order to prevent this as much as possible, centrifugal casting was used during the bronze pour. Centrifugal casting is a metal casting approach in which the shelled mold is spun as the liquid metal is poured into it. The

Figure 5.5 Bronze sculptures cast from 3D-printed designs. Left: detail of defect caused by metal casting process. Right: finished bronze sculptures with patinas

technique is most commonly used when making metal pipes, though it can also be used to ensure that detail is captured in complex sculptures [121].

For our models, the finished cast sculptures captured small details, including the marks of the filament layers from the 3D print. However, one of our casts also showed a small defect (fig. 5.5), where the metal did not completely fill out the shell. This was caused by either the 3D-printed plastic not being completely drained out of the shell, or the centrifugal casting not being fast enough to push the liquid bronze into the small cracks. Defects such as these could be perceived as a downside of using traditional casting techniques as opposed to metal 3D printing. However, for many artists who work with metal, the anomalies that occur during the casting process are part of what makes each work unique and are seen as a valued part of their creative practice.

To create the final version of our sculptures (fig. 5.5), we also added a patina, which is a discoloration of the metal caused by exposure to chemicals. The addition of a patina works to 1) give the sculpture a unique character and aesthetic appearance based on the color of patina chosen (we chose red and turquoise for our sculptures), and 2) prevent the natural patina and discoloration that would occur over time due to the metal coming in contact with chemicals in the air. Like the metal casting process, the application of patinas to metal is both an art and a science.

As we explored the possibilities of using 3D-printed designs to create metal sculptures, we found that the use of new technology allowed for the creation of complex alternative sculpture designs, while still allowing for the incorporation of many traditional metal casting processes, such as the metal pour and application of patinas.

Metal Casting Session

As part of our investigation into how 3D printing with different materials might support fine arts practices, we held a group session with experienced metal casters during which they discussed their experiences using 3D printing as part of their creative practices and how they think metal casting techniques may continue to evolve in the future. To recruit participants, we reached out to local foundries and artists on our university campus. The three participants who agreed to take part in our group session were artists with experience metal casting who had used 3D printing or 3D modeling technology as part of their metal casting projects. During the group session, participants discussed their artistic background, previous projects, and processes, and theorized about future work and technology that they would be interested in using. Throughout this session, we prompted participants into semi-structured discussions to reflect on our research themes.

5.3.2 Biofabrication with Mycelium

Our second exploration focuses on how 3D printing can be applied in biofabrication to support workflows with mycelium, the white fibrous part of fungus. Unlike prevailing rapid prototyping materials such as plastic or acrylic, mycelium is both biodegradable and sustainable. Mycelium is already being integrated into a range of sustainable bioart and product design projects [94, 149, 154]. Building on this work, we set out to explore how 3D printing could be used in conjunction with mycelium for sustainable and creative biofabrication.

In our research, we used Ecovative mycelium mixture [39], in which the mycelium spores are provided within an organic substrate. The steps for biofabrication utilizing mycelium are as follows: First, a mixture of flour and water is added to a bag of mycelium, which allows the mycelium fungi to begin growing. After 3-4 days of growing within the bag, the mycelium is mixed with additional flour and water, and can then be shaped by hand or by using molds. The mycelium objects are then left alone to continue growing for a period of 5-7 days. During this time, the mycelium fibers weave through the organic

Figure 5.6 Biofabrication with mycelium. Left: mycelium spores mixed into an organic substrate. Right: mycelium objects shaped using silicone molds.

substrate, binding it together as a solid object. The finished objects are then heated in an oven, which dries out and hardens the mycelium into a finished static artifact.

Similar to our work with metal casting, we created 3D prints and then silicone molds that the mycelium objects were grown inside of. Throughout our research, we explored the textures and aesthetics that could be achieved by mycelium. Figure 5.6 shows a comparison of 2 mycelium artifacts grown in the same silicone plastique mold. The model on the left was given 5 days to grow, while the model on the right was given 10 days. In the model on the left, the mycelium grew just enough to hold the organic substrate together, whereas on the right, the mycelium grew into every crevice in the silicone mold, allowing the details of the 3D-printed design to be evident in the final model.

During our work with mycelium, we also explored the possibilities of creating multi-part designs with our 3D print-based silicone molds. From an aesthetic perspective, this allowed us to create designs that took advantage of the variety of visual texture we could create with mycelium objects. In addition, the multi-part designs enabled us to create larger artifacts, since we were no longer limited by the size of our makerbot 3D printer.

Through our work with mycelium, we found that detailed mycelium objects could be successfully shaped and grown inside of silicone molds, which opens new opportunities in translating 3D-printed designs into organic objects.

Workshop at Makerspace

As part of our exploration in biofabrication, we ran a workshop at a local makerspace, during which participants were able to design and grow their own interactive objects. After receiving the approval of the makerspace's staff to hold our workshop at their location, we recruited members of the local making community for the event by posting about the event on the makerspace's website and events calendar. During the workshop, 20 individuals were given a brief introduction to the mycelium fabrication process, and were then invited to create their own mycelium molds using the Ecovative mycelium mixture and available silicone and plastic molds. Once the mycelium molds were created, they were stored inside a cabinet at the makerspace for 5-7 days to allow the mycelium to grow. Afterwards, participants returned to retrieve their finished mycelium objects. We also left additional mycelium mixture at the makerspace, which allowed some makers to experiment further with the material. They shared their results with us through email.

5.3.3 Everyday Craft Activities with 3D-Printed Designs

Finally, as part of our research on how our 3D modeling software and workflow might support creative practices with different materials, we set out to explore food preparation as a common and accessible creative outlet. There are now 3D printers that can print using specific edible materials, such as chocolate [4, 59, 87, 88, 174]. However, current printers limit the ability of the user to experiment with different recipes, since the 3D printer requires printed material of a specific and uniform consistency and melting temperature. There is some preliminary research being done with 3D printing materials based on vegetables, but that requires the materials to be evenly blended into something that can be smoothly squirted through the nozzle of a 3D printer [84].

Beyond 3D printing, there has also been research in applying other emerging fabrication methods to food. Mizrahi et al. have discussed the possibility of using laser cutting to slice vegetables, allowing for more precise and intricate designs than the human hand is capable of producing [114]. Recent work by Lee et al. has also explored use of deformation in their construction of Korean dumplings [95]. Rather than building the food using advanced machinery, they explore DIY options and simple tools for hand-shaping food. Likewise, in our explorations with making multiple dishes, we focused on accessible, readily available approaches.

Since we were working with edible materials, we wanted to guarantee that nothing about our process would make the final objects unfit for human consumption. Because the silicone molds were used to shape food, there was not any direct contact between the 3D printed material and the finished food product [49, 104, 111, 138, 143]. To insure additional food safety for the food dishes we created, the 3D prints were created using PLA (polylactic acid) filament that is food safe, and the 3D printers used stainless steel hot end extruders, as other types, specifically brass, may contain trace amounts of lead [6, 125]. The type of silicone we used was silicone plastique, a two-part putty solution that is mixed together and pressed onto the 3D prints in order to form the molds. Once created, the silicone molds are food safe up to 450° F (232° C), making it possible to bake food items in them, giving the food preparer a wide range of food and food processes to experiment with [102, 103].

Culinary Study

We examined how 3D printing might support everyday craft practices by exploring our process in the context of food preparation with culinary enthusiasts. In our study, we collaborated with eight culinary enthusiasts from a local dining group, two of whom have degrees in culinary science while the other six are lifelong culinary enthusiasts. After meeting to discuss their personal food experiences and culinary approaches, participants used photos and drawings to design their own 3D prints using our software. They made their own silicone molds from the prints and used them to shape different culinary dishes. By cooking with molds created from plastic 3D prints, our method allows for flexible 3D

Figure 5.7 Examples of different foods shaped using silicone models. Left to right: egg yolk, melted chocolate, gelatin agar mix, frozen popsicle, wonton skins with a vegetable filling

fabrication with different foods rather than using a specialized 3D printer for each ingredient.

Participants shaped many different types of food using their custom silicone molds, including shortbread, omelets, and flan (fig. 5.7). During the study, the use of different foods had a huge effect on how accurate the images were. While some materials (such as wraps) were not able to capture a lot of fine details, chocolate and other viscous materials (such as raw eggs) were able to accurately replicate details from the original photograph. In addition, some participants chose to create multiple silicone molds from an individual 3D print and bake several finished baked goods with the same design simultaneously. This provides an advantage over food-based 3D printers, which would have to 3D print each food item one at a time.

	Metal Casting Study	Mycelium Study	Culinary Study
Number of participants	3	20	8
About participants	Metal casters who had used 3D printing in their creative practice	Members of a local makerspace	Culinary enthusiasts
Age Range of Participants	Mid-20s to mid-30s	Late teens to mid-60s	Mid-20s to mid-50s
Study Format	Group interview	Group workshop	Group interview and individual exploration
Length of Study	1 hour	1 hour	1 hour (interview) 4-6 weeks (exploration)
Data Collected	Audio	Notes, photography	Audio, photography

Table 1: Information about study participants and data collection

5.3.4 Data Collection and Analysis

The interviews and group discussions from the metal and culinary workshops were audio recorded, reviewed by researchers, and relevant discussions were transcribed (e.g., we did not transcribe small talk, casual conversations unrelated to the creative practices being investigated or our research questions). The transcriptions were then coded and affinity diagramed, and the resulting categories were then discussed in data synthesis meetings among members of the research team in order to ascertain findings related to our research themes. When quoted, participants from the metal casting session are referred to as M1-M3, and participants from the culinary workshop are referred to as C1-C8. Due to the location and large number of participants attending the mycelium workshop, audio could not be clearly recorded. As an alternative, data was collected through photography and the researchers' notes.

5.3.5 Limitations

All of our participants chose to be involved because they were interested in the possibility of incorporating 3D printing and mold making techniques into creative practices, which makes the study prone to the possibility of self-selection bias. Participants' feedback is based on their experience of several creative explorations (the culinary study) or during an hour-long session (the mycelium makerspace workshop), and as such it is possible that more extensive interaction with the system may produce different results. In addition, our findings may not be applicable to creative practices beyond the ones we investigated during this study.

5.4 Findings

From our explorations in translating 3D-printed designs into metal, mycelium, and food, as well as the workshops and interviews we held with creative practitioners, we have identified several areas that contribute to the successful integration of 3D printing with traditional fabrication approaches. We present findings on how the versatility of tools can expand the scope of 3D printing, which sheds lights on the potential applicability of new fabrication tools and techniques. In addition, we look at how creative practitioners leverage previous knowledge within new approaches, which helps us to discern how to support current craft practices while integrating digital technology. Lastly, we gain insight into how creative processes are visualized with finished artifacts, which opens possibilities for unique fabrication-based aesthetics.

5.4.1 Expanding the Scope of 3D Printing through Versatile Tools

Through our work and the feedback of creative practitioners we spoke to, we found that our system and approach were versatile enough to be successfully integrated with several different materials and creative processes. In both metal casting and mycelium, we were able to consistently produce multiple copies of highly detailed, complex designs from a single 3D-printed design and silicone mold. Furthermore, the physical flexibility of the molds allowed them to be used with a wide variety of foods that were prepared at different temperatures - including eggs, popsicles, vegetable wraps, and flan. The combined results of our personal explorations with metal, mycelium, and food as well as the experiences of the participants of our culinary and mycelium workshops demonstrate that this approach can work with multiple materials. In addition, from our discussions with creative practitioners, we also found that our approach benefitted from incorporating relatively available technology. These insights help us to understand how new fabrication tools can be applied to current approaches.

Incorporating Available Technology

Part of the versatility of our approach is based on the accessibility of the components. The materials we use are 1) free-access software that can be run on any type of computer,

2) standard makerbot 3D printers that are increasingly affordable or accessible through community areas such as makerspaces, and 3) silicone plastique, versions of which are available at most craft stores. Because of this, several of the creative practitioners we interviewed were already familiar with some of the tools and techniques that we used as part of our process.

In all of our studies, we found that many participants were familiar with or had experience with the tools that we used as part of our system and approach. For example, C2 had not used 3D printers as part of his culinary work, but had become familiar with them through his purchase and use of a 3D printer to create small objects, either toys or tools, from designs he found online.

C2: *"I have a 3D printer at home… I mostly find 3D models on the internet, and sometimes I modify them here or there."*

Because C3 was already familiar with 3D printing in a different context, he was able to imagine ways to easily incorporate our approach into culinary practices beyond the scope of our study. In a similar manner, the participants at our makerspace workshop had access to and were familiar with the 3D printers present at the makerspace, and therefore were able to brainstorm future projects that combined mycelium with 3D-printed designs.

Several participants also had previous experience with commonly available mold-making techniques. C3 had experience using store bought silicone putty in the past in order to create custom molds from shapes that he fabricated by hand.

C3: *"I took just an outline of somebody's face, for a birthday, and I made an emblem for a chocolate cake… I just used the silicone food safe mold you can get from [local craft store]."*

During our interviews, we found that many participants were already familiar with and had access to the tools and technologies that were part of our fabrication approach. This, in turn, made it more likely that they would be able to use our system outside of the context of the study.

Flexibility in Integration Approaches

In addition to being able to shape multiple materials, our approach could be integrated with many different types of preexisting craft processes because the system could be implemented in parts, rather than as a fixed fabrication pipeline. This flexibility was beneficial to many of the creative practitioners we interviewed. For example, while creating custom silicone molds during the culinary study, C5 created silicone molds from plastic figurines she owned as well as her custom 3D printed designs. During the mycelium workshop, participants explored the process of using molds to shape mycelium without designing their own 3D models. In addition, in our own explorations with metal, we deviated from our original approach by casting 3D prints both using the silicone molds and directly from 3D models. This variety of experiences and approaches indicate the flexibility and applicability of our system, and the diverse creative explorations that can result.

5.4.2 Leveraging New Approaches to Build on Current Practices

Throughout our creative practice as well as the work of creative practitioners we spoke to, there is a strong focus on utilizing preexisting knowledge as part of learning new tools and techniques. Rather than viewing each new tool or approach as an isolated skill, new tools were seen as an expansion or outgrowth of existing creative practices. In our personal fabrication experiences, we began to view each successive material as additional options in an already established fabrication approach, which caused them to be easier to integrate into our existing skillset. For example, we originally chose to use silicone models as part of our exploration with food, but after creating several silicone prototypes, we found that the resulting molds were flexible and highly detailed. After this realization, we contemplated how this approach could be incorporated to other craft domains and made the decision to investigate other creative approaches, resulting in our explorations with metal casting and mycelium.

We also observed several creative practitioners attempt to incorporate their existing area of expertise when presented with new materials or techniques. When working with mycelium for the first time, participants at the makerspace who had experience with electronics sought to embed wires and Arduino components into mycelium in order to see if the mycelium objects could be used as part of electronic projects. They also brainstormed potential applications for mycelium within their current makerspace projects, such as utilizing it as insulation or building material. In this way, they were taking an unfamiliar material and process and integrating it into their existing creative focus, which, in turn, encouraged them to learn more about mycelium.

During our group session with metal casters, we found that, while all three participants currently used integrated digital-physical approaches, they had different experiences that led them to their current creative practices. M2 and M3 both began with metal casting techniques, and then incorporated 3D printing and digital modeling as part of their metal process. In contrast, M1 started out with digital fabrication before adding metal casting. Below, she describes how she was hesitant to integrate different approaches because she viewed it as being outside of her area of focus, but chose to continue exploring metal casting because she viewed the addition of new creative processes as a valuable tool:

M1: *"It felt like I was cheating by doing a traditional process and not doing a digital process…. But I recognized it as a tool, and I thought 'well, I'll just fight and keep doing this stuff, I'm not going to stop'."*

Because she viewed metal casting as one new tool amongst many in her creative practice, M1 chose to incorporate a new technique into her approach. M3, who first gained experience in metal casting before integrating digital technology, also described his desire to learn new techniques as a means of expanding his current creative practice. In addition, he described the integration of digital technology being actively encouraged from professors in his sculpture department.

M3: *"At my previous school, it seemed to be more the graduate students that were doing [digital fabrication approaches as part of metal casting], but there were still professors that were pushing it… kind of like the new frontier in a certain sense."*

By viewing digital fabrication techniques as a 'new frontier' in metal casting, emerging metal artists can be encouraged to integrate digital technology into their current craft practices without feeling that new techniques might supplant, replace, or 'cheat' their creative process.

5.4.3 Visualizing Process through Finished Artifacts

Most fabrication processes result in objects with unique marks or attributes that indicate how they were produced. These marks can create unique aesthetic effects or allow viewers greater insight into fabrication processes, and several of the creative practitioners we spoke to commented on how the presence or absence of process marks on finished artifacts changed how they interacted with the work. During our group session with metal casters, several individuals discussed the presence of 'print lines' on metal sculptures created from 3D-printed designs. Print lines are the ridges visible in 3D-printed objects, and are caused by the resolution and speed of the 3D printer [145]. As they discussed their experiences

Figure 5.8 Print lines in objects created from 3D-printed designs. From left to right: cast bronze sculpture; mycelium object grown in silicone mold; silicone mold.

creating metal sculptures from 3D-printed objects, metal casting participants described how the presence of print lines were perceived in finished metal sculptures.

M1: *"People would get down and look at [the print lines] ... I think it made other people curious… Usually I keep the print lines in my work, because I think it's neat to show tool processes."*

As M1 describes it, the physical record of the 3D printing process made the finished objects more interesting for the audience at art shows. However, M2 stated that she had seen several artists request to not have print lines on their finished pieces.

M2: *"When I was working at [professional foundry], we would use 3D printing in there, but all the artists who want their pieces cast do not want them with print lines. I think it's just a matter of if you want to show the process of it or not. So like some people consider it very sloppy to leave them. I personally leave them. I don't mind it."*

As M2 further explained, in order to remove print lines from the finished sculpture, each line has to be sanded down and polished. This process requires a significant amount of time and labor, and, as a result, sculptures that lack print lines are significantly more expensive than sculptures that have them. While M2 could not say for certain why artists requested not to have print lines visible in their final sculptures, she theorized that they may have 1) preferred the aesthetic appearance of a smooth form; 2) wanted the final sculpture to visually mimic their original clay or digital design as closely as possible; or 3) wanted to hide or obscure any visible marks on the finished sculpture that would indicate the creative process that was used to make it. In contrast, M1 and M2 both stated that they preferred having print lines shown in their finished works, since it provided a unique texture not often seen in metal sculptures and gave audience members insight into the creation process.

The Effect of Print Lines on Subsequent Making Processes

In our fabrication process, in which 3D-printed designs are used to create silicone molds with can then be used to shape other materials, the silicone molds accurately reproduce the details of the 3D-print, including print lines. During our work with both food and mycelium, the presence of the print lines affected both our process and results. This serves as an example of how multi-stage fabrication processes are often interdependent, and indicates how translating between digital and physical fabrication processes may have unforeseen challenges and complexities.

When creating culinary dishes using the silicone molds, both the participants in our culinary study as well as our own experiments with food revealed that certain foods and cooking processes recorded different levels of detail from the mold. In general, frozen items, such as ice or popsicle, were able to record print lines, whereas cooked items, such as eggs and wraps, smoothed over fine details in the mold. However, even in cases where the print lines were not visible in the finished food object, they affected our cooking process. In cases of baking (for example, pancake or egg), pieces of the food would be left in the print lines and other small details of the silicone mold after the cooking process. Through cleaning with soap and water, the food particles could be removed. However, because of the small size and relative depth of the details in the silicone molds, the task of cleaning was notably longer than it would have been with a smoother surface. As such, the process of using silicone molds for culinary activities become slightly more difficult when the molds are based on 3D-printed designs.

However, while the presence of print lines may have made some of our work with food more difficult, it also encouraged new avenues of exploration while working with mycelium. As part of our fabrication experiences with mycelium, we compared the results of different mycelium growing conditions by how well the finished mycelium models were capturing fine details in the silicone mold (fig. 5.8). As such, the addition of print lines allowed for detailed visual results in the mycelium objects.

From these examples, we can see how the details in fabrication processes can have significant effects on why individuals might choose to incorporate certain approaches into their creative practices, and how unforeseen challenges and opportunities can arise from these novel combinations of fabrication approaches.

5.5 Discussion

We created a versatile approach to making 3D printed designs in multiple materials through the use of a fabrication pipeline composed of free-access software, standard makerbot 3D printers, and commonly available silicone modeling material. Based on the findings gathered from our own fabrication experiences as well as the workshops and sessions we held with creative practitioners in a variety of fields, we were able to gain insight into how 3D printing is being used alongside established creative practices. In this section, we discuss key takeaways from the findings that are applicable to future research: 1) investigating applicability of new fabrication tools and methods; 2) supporting current practices while integrating digital technology; and 3) designing for unique fabrication-based aesthetics.

5.5.1 Investigating Applicability of New Fabrication Tools and Methods

As technology continues to progress, we are continuously seeing new tools and methods becoming available. From our explorations in translating 3D-printed designs into different materials, as well as the workshops and interviews we held with creative practitioners, we were able to study how a new system and workflow could be integrated into existing creative processes. We found that our approach, which combined a straightforward 3D-modling software, plastic filament 3D printing, and custom silicone molds, could be versatilely implemented with multiple materials as well as different creative workflows.

From the results of our work, we are able to envision directions for future 3D printing technology. Currently, specialized 3D printers are becoming available that can print using alternative material filaments, including chocolate and metal [7, 85, 167]. Future work could explore augmenting such machines with devices that allow users to manually guide the movements of the 3D printer [36] or alter pre-existing items [152]. For example, a metal 3D printer could be used to augment existing metal sculptures with additional designs. This would allow users the option to iterate using mixed fabrication techniques, since 3D printing technology could modify objects made using traditional processes.

5.5.2 Supporting Current Practices While Integrating Digital Technology

By incorporating 3D printers into existing fine arts and maker practices, our goal was to expand upon, rather than eliminate, current creative practices. In the group workshops and our own explorations, we engaged with many crafting techniques that would not have been possible if the finished object was directly 3D printed. These include exploring the limits of centrifugal casting to create metal sculptures, incorporating electronic and magnetic objects into mycelium artifacts, and baking multiple copies of a food dish at once using several silicone molds. In addition, because of the flexibility of our process, participants were also able to utilize parts of our system with their existing fabrication approaches, which allowed them to more effectively integrate new techniques.

Future work could explore how other digital technologies can be incorporated into existing creative practices. For example, researchers could explore how 3D printing technology could serve the artistic goals of time-based creative mediums, such as animation or dance. By working closely with artists and makers engaged in iterative fabrication approaches, designers could gain a better understanding of their unique goals, needs, and current limitations. From these interactions, current or emerging digital technologies could be built to support and expand fabrication processes.

5.5.3 Embracing Aesthetics that Reveal Process Information

Throughout our interviews with creative practitioners and our personal fabrication experiences, we found that the print lines left behind by 3D printing affected both process and outcomes. When describing their current fabrication approaches, the metal artists discussed several reasons to show or remove print lines in finished metal sculptures. In the culinary study, we found that the existence of print lines in our silicone molds added extra challenges to cleaning the molds. During the mycelium study, the print lines served as a useful marker that allowed us to judge the success of the mycelium growth. These examples further emphasize to us the importance of approach and process in the creation of finished works.

Previously in Chapter 3, we explored the importance of process information as a means of capturing and sharing data about creative practices. In that project, the information being recorded was the pencil movements of artists, the data from which was then displayed in the form of 3D prints. Our findings in this chapter also explore aspects of process that become visible through recording process. However, in this instance, the process we are observing is the creation of the 3D print and the nuances in form that result from that fabrication method.

Building upon existing process-focused research [10, 36, 170], future work could explore how different emerging fabrication processes affect the objects built with them, and how the resulting properties of these objects change how they are perceived and used. For example, many accessible technologies are currently utilized to create tools for additional fabrication, such as laser cutters which are used to create parts for DIY 3D printers. Emerging research could investigate how laser-cutting fabrication techniques affect the visual and functional attributes of the resulting 3D printer. Likewise, within creative arts communities, research could explore how the telltale signs of different fabrication methods affect the aesthetic properties of and audience reactions to finished pieces. This could encourage greater understanding of and appreciation for the nuances and varying results of specific fabrication processes, and raise questions about how different processes can be creatively combined in the future.

5.6 Conclusion

This chapter investigated the possibilities of using 3D fabrication technology as part of creative fabrication process with materials beyond plastic filament. We sought to explore how 3D printed designs could be translated into other materials and, through the use of custom silicone molds, were able to create custom objects in metal, mycelium, and food. In addition, we held several interviews and workshops with creative practitioners in order to better understand how digital fabrication processes may alter or expand current craft practices. From this work, we gained insight into the existing versatility and applicability of existing fabrication tools and approaches, as well as how integrated craft practices may develop in the future. In the following chapter, we summarize key takeaways and conclude with avenues for future research.

CHAPTER 6

CONCLUSION AND FUTURE WORK

We are at a time in history where digital fabrication techniques are being integrated into all aspects of daily life, including artistic practices. While these new tools have the potential to be beneficial, it is possible that digital approaches may be difficult to blend into or completely supplant existing craft practices. Within this context, this dissertation has examined several examples of 3D printing systems being integrated into existing arts practices. In Chapter 3, we explored how digital technology can be used to record artists' pencil movements and display that data as information art. Chapter 4 described our work translating the traditional ceramic technique of lithophanes into 3D printing and worksessions with artists in which we gained insight into how the change of medium affects current artistic constraints and affordances in design and making. Chapter 5 examined possible workflows and creative implications of translating 3D printed designs into other materials, including metal, mycelium, and food. In all these projects, we explored how 3D printing could be amalgamated into artistic practices, and gained valuable insights into the future of creative work.

For each of the projects discussed in this dissertation, we were able to investigate how different aspects of 3D printing could serve existing creative practices based on the affordances of the materials within that practice. When looking at pencil drawings, the 3D prints were not part of the physical drawing process. Instead, they were utilized as a means to complement and provide additional information and insight about an existing craft. With

Lithobox, the 3D prints served as finished art objects in place of traditional ceramic lithophanes. This was possible because of the physical properties shared by both plastic filament 3D prints and ceramics: both can be used to create complex 3D forms and, when thin enough, have translucent surfaces. When creating finished 3D-printed designs in metal, mycelium, and food, the 3D prints were used to produce molds that shaped the finished objects. In this case, the 3D print is not part of the final art piece, but rather serves as a part of the larger fabrication process. These approaches — whether they be 1) utilizing 3D prints as a visual aid to traditional processes; 2) using 3D printed objects in place of a traditional making material; or 3) employing 3D printing as part of a fabrication pipeline — were successfully implemented because they could be integrated with the specific material affordances we were exploring. These material affordances, which are unique to each medium and process, have a large impact on how new tools can be integrated into existing creative practices. Future research could explore such touchpoints across different creative mediums while focusing on how emerging technology can serve existing needs. For example, the time-based aspect of 3D printing could be incorporated with performing arts. The movements of a 3D printer could be used to mimic the gesticulations of a dancer in real time to create interactive prints and sculptures that are a physical record of the performance. Alternatively, 3D printers could be used to fabricate custom tools for existing craft practices. Using the unique additional fabrication process of 3D printing, specialty tools could be created to spread or shape materials such as paint or clay as part of novel craft approaches.

A final question hinted at by the work of this dissertation is whether digital technology can have a more active or even collaborative role in creative processes. As we continue to find new ways to integrate technology into creative practices, it may become feasible for digital approaches to serve as a creative collaborator. Throughout our studies, participants would occasionally mention the machine as a collaborator, though they were unsure if it was the machine they were working with, or the person who designed the software they were using. For the most part, the software and 3D printers were viewed as tools. However, the potential of computers and digital fabrication approaches to express unique design acumen hint at a possible future in which digital technologies are valued for their aesthetic, rather than computational or mechanical, contributions to art.

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