# Productive Frictions: Moving from Digital to Material Prototyping and Low-Volume Production for Design Research

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## ABSTRACT

In this paper we discuss the low-volume production of an interaction design research product known as the tilting bowl. The form of the tilting bowl was designed with 3D modeling tools and utilized digital fabrication for rapid prototyping. The final form was produced in a small number of glazed ceramic forms with embedded electronics and actuators. We focus on the lessons we learned from the challenges and design opportunities that arose in moving from digital processes to ceramic processes. We reflected on these lessons and developed thematic notions we refer to as *frictions*. These include shifting constraints, naïve expertise, manual automation, and dynamic materiality. The contributions of this paper are new design insights into the combination of digital and material processes for studio based prototyping and low-volume production and adds to the emerging relevance of digital fabrication, physical fabrication, and physical materials to interaction design and HCI research.

## Author Keywords

Prototyping, materials, fabrication, rapid prototyping, ceramics, design research, slip-casting, research product.

## INTRODUCTION

Until recently, volume manufacturing and production have largely been industrialized [16]. Within the last decade, computer-aided manufacturing and prototyping tools like 3D printing and CNC machining have become accessible to DIY makers, designers, researchers and others through hacker spaces, design studios, and academic research labs. In addition, there has been significant progress with materials in digital fabrication tools resulting in capabilities to fabricate with polymers, ceramics, wax, paper, and various metals [27]. Further, there has been exploratory research into fabrication with unconventional materials such as soft fibres, food, wood and other materials (e.g. [11,16,21,31,32]). While these results and innovations are not generally accessible some have been made available in limited size, quality and quantity from online services and service shops (e.g. [16,31]).

These transitions in manufacturing and production have led some to refer to a "democratization of manufacturing" and a rise of personal fabrication [10]. As a consequence, hyped (we can make anything!) or ease-of-use (just push a button!) narratives of digital fabrication have arisen that are as uncritical as they are popular. For example, Shapeway$^{TM}$[31], a company that offers online printing and additive manufacturing services, largely focuses on the end product as its goal. The service allows customers to pick online any material for any form and have it delivered to them days later. Despite the innovations in materials and fabrication processes these narratives and online services hide the particularities of practice, craft, and materiality that are inherent to any form of making. Ironically, this has the reverse effect of minimizing rather than enabling materiality and practice in making. We believe that aspects of making are being reconfigured in ways that need to be visible and understood as matters of criticality and agency in the shaping of emergent types of products, processes, and practices.

These are broad issues, our particular position or purchase on these matters originates with and concerns design research in HCI. Design research gives prominence to the system or artifact in question and its making as a concern of its own or enabler of a phenomenon for study [18]. Digital fabrication and rapid prototyping have vastly increased design researchers' abilities to produce artifacts of quality, complexity, and volume. However, artifact production in design research is typically low-volume and single run or one-time as opposed to the continual mass production of industrial manufacturing. Design researchers typically function as a small but multi-disciplinary team that is reflexively focused on the experimental and novel in terms of outcomes and modes of design production. Hence, design research in HCI affords a highly insightful, first-

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hand and reflexive view of the practices of making products and the reconfiguration of these practices in light of new digital and material fabrication processes and tools. This understanding is echoed by Lindtner et al. who argue that HCI can be a site of innovation with respect to digital fabrication, positioned for critical reflection and guidance in relations to materials, tools, and design methods [13].

In this paper we offer a critical reflection on the role of digital and material prototyping and low-volume production in HCI research. We do this as design researchers who bring forward insights based on our first-hand and in-depth experience in the material processes of making a single design research project. In our account, we pay attention to the particularities of practice, especially the emergent relations and configurations that result in digital and material prototyping for design research.

There is much that is unpredictable and surprising in the negotiation of digital and material prototyping or in almost any form of making. As such, we highlight what we refer to as *frictions* that are thematic notions distilled from our experiences of making. We believe the frictions are unique characterizations in that they are counter-intuitive with respect to the typical norms of practice or they amplify effects to a greater degree than usual. In either case, *frictions* signal a change or reconfiguration of practices that result from combining digital and material forms of production. They offer new design challenges and opportunities for designers. Like real-world frictions, they are neither inherently positive nor negative.

Our paper contributes a detailed case study and analysis of the form making processes of a design research project we refer to as the *tilting bowl*. The *tilting bowl* is a ceramic bowl that tilts three to four times each day. We produced six multiples of the artifact for long-term deployments in people's homes (see Figure 1). The research aim of the *tilting bowl* is to investigate the nature and type of computational artifacts that can be shaped and given meaning by people as a matter of living with and performing everyday practices over time.

Our paper is organized as follows. We firstly provide an introduction to our design case, the *tilting bowl*. We provide background and related literature to digital fabrication and materials research. We provide an overview of the prototyping and production phases of our form making and then provide a detailed analysis of the four frictions that arose from the process. We conclude with a discussion of our reflections and insights including future improvements to the process.

**Figure 1 The tilting bowl**

Our paper makes two main contributions: 1) a detailed case study and analysis of the process by which we designed, prototyped, and fabricated a form for design research moving from digital to material prototyping and production; 2) the enabling of new design sensibilities via a description of four *frictions* including shifting constraints, naïve expertise, manual automation, and dynamic materiality.

Our primary audience for this paper are design researchers engaged in digital and material fabrication of artifacts for research. More generally, this paper is relevant to practitioners or researchers who are engaged with digital fabrication and the underlying reconfigurations of practice in the making artifacts.

## BACKGROUND: TILTING BOWL

The *tilting bowl* is a design research project that aims to investigate how computational artifacts can consciously and unconsciously become a meaningful resource in the practices of everyday life over time [28]. We refer to the idea as *things of practice* in which we want to understand how the interweaving of shape, materials, interface features, software, and electronics come together in digital artifacts to enable adoption within practices. As a consequence, the specifications for the *tilting bowl* are that it be a desirable artifact for the home and that it seamlessly fits and functions with other everyday objects for several months [19]. In large part, this drove the design decisions of the *tilting bowl*.

The form of the tilting bowl was designed and prototyped utilizing a 3D CAD modeling software (Rhino), a digital fabrication support software (Autodesk's 123D Make), and laser-cutting. We fabricated the form in ceramic earthenware that was slip cast, bisque and glaze fired. We utilized the analogue fabrication process of slip cast ceramic for reasons of quality, size, and control of the process. As a result, our case study offers an in depth account of the interweaving of digital and analogue practices and pays particular attention to the role of materiality.

Our account of the tilting bowl focuses on the move from digital to material prototyping and low-volume production of the form of the artifact in a studio production context. Our attention to forming technologies and processes means we focus less on the electronics prototyping and builds, as well as finishing techniques employed like glazing. The emphasis on a studio context mirrors the typical production of forms and artifacts in either a design studio, a research lab, and in our case a ceramics studio.

## BACKGROUND / LITERATURE REVIEW

In what follows, we present related works within HCI research that address advances in digital fabrication including computer-aided design, rapid prototyping, and hybrid manufacturing, and HCI's recent concern and interest for materiality in interaction design.

### Digital fabrication research

In the last years, there has been innovative work in research and in the industry towards creating more accessible, cheaper, and more customizable tools for digital fabrication. In addition to applying these innovations in the fields of design and design research, the application of digital fabrication has been proposed to include fields such as engineering, science, and art [12].

Amongst many aspects of digital fabrication, we focus on two that are most relevant to our work: the digital crafting of a shape via computer-aided design (CAD), and the rapid prototyping necessary to make this digital model translate to a physical thing. Computer-aided design is a process by which two or three dimensional computer drawings of artifacts are generated using specialized computer software, whereas rapid prototyping is an overarching term encompassing a variety of processes and methods for the accelerated making of physical prototypes using drawings generated through computer-aided design. Examples of computer-aided design software include 2D drawing and editing tools Autodesk AutoCAD, Adobe Illustrator and CorelDraw [2], as well as 3D modeling tools such as Robert McNeel & Associates Rhinoceros 3D (also referred to as Rhino), and Dassault Systèmes SolidWorks. A common approach to translating CAD digital data to physical models is by slicing or faceting 3D models into 2D representations that can more easily be produced and assembled. Prominent examples of commercial software that have these features include AutoDesk 123D Make [33] and Paperkura [34]. Recent research in HCI has focused on creating algorithms and software that tackle additive manufacturing process issues such as strength enhancement [15], model partition [29], balance [22], and slicing optimization [5]. In addition, HCI researchers have also investigated the opportunities of using new and unconventional materials for rapid prototyping (e.g. [6,11,16,21,31,32]).

While there has been a lot of research pushing the technical and material boundaries of digital fabrication, HCI researchers recently started to reflect on the meaning and the function of things that are produced [3,20]. Pushing the reflection even further, researchers propose to look at the performance and the experience of the act of making, referring to "the meaning of actions from which those object emerged" [3:555]. In this sense, actions are considered the "primary product of fabrication activity" [3:555]. In support of this view, it has also been put forward that "designing for qualities of experience" could prove to be advantageous in facilitating meaningful making experiences [4:2477].

Another area of interest in the field of HCI has been human-computer hybrid manufacturing. This "synergistic cooperation between human and machine" [30:433] has benefits in that the machine component helps to ensure accuracy while the human component "[preserves] the expressiveness of manual practice" [30:433]. This concept is evident in the work of several researchers, who have created fabrication tools that are hybrid in nature. Mueller et al., for instance, created an "interactive fabrication version" of a rapid prototyping system, LaserOrigami, whereby human input and machine fabrication alternate [17]. Zoran et al, have also experimented with hybrid manufacturing through the creation of FreeD V2, a tool for carving, which encompasses new techniques for the fabrication of static as well as dynamic models [30]. Finally, Devendorf et al. explored a productive shift in authority by reversing the roles of the human and the machine [3,4]. This research on human-computer hybrid manufacturing is particularly relevant to our work in the sense that it investigates the separate but complementary roles between what the machine can do and what humans can do.

### Materiality research

Materiality has become a topic of interest in the field of HCI [7,24]. Robles et al. have argued that when designing with computational form, it is also critical to consider the physical properties of materials [23]. This work has brought to light the use of texture as an aesthetic lens, appropriate when designing with physical and digital materials. Reflecting on existing research, Giaccardi et al. looked into how materiality has the ability to influence ways of doing and practice [8]. Lastly, within HCI research, past work has offered rich and detailed examples of how materiality can support tacit knowledge and collaborative practices in hobby and everyday activities (e.g., the practice of gardening and bookbinding [9,25]). More closely related to our project, Rosner et al. [26], similarly to us, investigated the intersections of the digital and the material in a series of ceramic explorations. They particularly focused on the potential to explore expressivity, value and skill in their interweaving of clay and code.

In digital fabrication, there is often a more important focus on the shape or the form of a product than the material it will be produced in (often eclipsing the cultural significance of materiality). We gave the example of Shapeway$^{TM}$[31] in our introduction (see Introduction), a company that offers online printing and manufacturing services, arguing that it focuses on the end product of digital processes inadvertently hiding the underlying practices and materiality with respect to making. In this paper, one of our goals is to consider how materiality influences the making process, and to examine the tensions between digital and

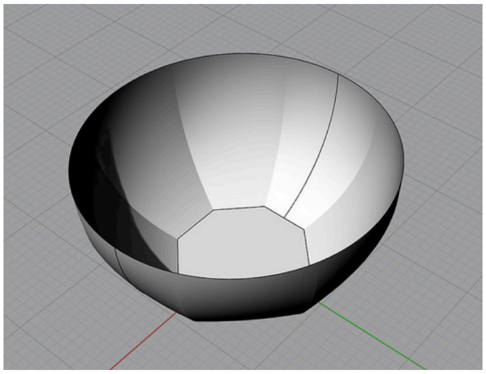

**Figure 4 CAD model of a half-spherical form of the tilting bowl.**

physical fabrication processes. The work we present in this paper aims at contributing to both areas of related works..

## PROTOTYPING AND FABRICATION

The making of the form of the bowl can be divided into two phases: 1) prototyping and 2) fabrication. In what follows, we provide an overview of each phase.

### Prototyping phase

We started the prototyping phase of the tilting bowl with digital tools. Our conceptual idea of a tilting bowl was relatively clear, but we needed to go through an iterative prototyping phase to investigate the scale and shape of the bowl, the frequency and amplitude of its movement, and the mechanical and electronic aspects that would make the bowl tilt, and the material of the final form.

Conceptually, we started with the idea of a half-sphere bowl with a false half bottom. We 3D modeled this concept quickly in Rhino to discuss the idea amongst the team members (see Figure 4). However, in order to rapidly create a bowl that we could manipulate, refine, and iterate upon, we decided to utilize digital fabrication software (123D Make) with the aim of creating a 2D pattern of our form that could be reconstructed into 3D forms with cardboard and laser cut MDF (Medium-Density Fiberboard) (see Figure 2). 123D Make is specifically aimed at generating 2D patterns to be cut and assembled into a 3D form much like a 3D puzzle. The program converts a 3D CAD model into 2D shapes (called 3D model flattening) that can be adjusted and allows for multiple build techniques. In our case, our bowl alternatives were each generated as a series of triangular facets that when assembled formed the bowl structure.

**Figure 2 Examples of some of the many alternative forms produced with *123D Make* in cardboard and MDF.**

We explored a variety and number of facets in 123D Make (more facets means a better resolution but will take much more time to assemble). Once we found a balance, we reimported the object into Rhino to clean the model and to generate the pattern to laser cut (using the ‘unrollsurface’ function). This function generated a long flat surface where all the pieces are attached to each other. However, this does not account for pieces that might overlap. By hand, we repositioned the sections that were overlapping.

We started our material exploration by laser cutting thin brown cardboard to make the bowl. This allowed us to fold the pieces into form and to attach the remaining pieces with transparent tape. This step allowed us to create multiple bowls with a variety of size of facets and different scales. However, the bowls were still very flexible and we could not start our exploration with the actuators with this material. And so we repeated the same process with 1/8 inch MDF. We laser cut the pieces and attached them with transparent tape. Once a bowl was complete, we turned it upside down and applied wood glue to all the edges and let it dry for a few hours. Once dry, the bowl proved to be rigid enough to contain many things and it was rigid enough to start our experimentations and iterations with electronics and actuators to see how we would make the bowl tilt (see Figure 3). At this point, we also started to imagine how a false bottom would be necessary to hide the electronics in the bowl. We returned to Rhino and scaled in one dimension only (height) the existing bowl. With this new

**Figure 3 MDF prototype for iterating the electronics, actuators, and movement of the bowl while bearing weight.**

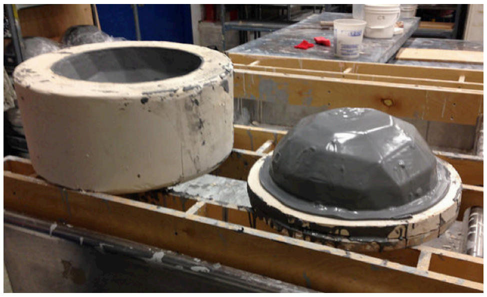

**Figure 5 The successful two-part slip-cast mould**

shallower bowl, we followed the same steps to create an MDF version of it and placed it inside the larger bowl. The MDF prototypes were robust enough allowed us to do experience prototyping deployments with embedded electronics and actuation in which members of the team lived with a functioning prototype.

At this stage, we decided that the final form would be in ceramic since we conceptually limited our material choices for our *thing of practice* (see Background: Tilting Bowl) to everyday materials found in the home and we reasoned as designers that the emerging aesthetic of our form would best be realized in ceramic. Given this, we proceeded with the ceramic fabrication process discussed in the next section.

### Fabrication phase

To achieve fidelity with the prototyped *tilting bowl*, we used the MDF prototype as the pattern form as a starting point for the ceramic slip-casting process. Briefly, slip-casting is a ceramic production method that uses a combination of a plaster mould, or form and liquefied clay called "slip" to produce a series of identical ceramic objects.

Shifting the *tilting bowl* to the analogue process of ceramics from a largely digital process proved more challenging than originally expected. For example, the making of the slip-casting mould involved multiple failed attempts in its design and execution of the mould. The difficulties faced arose from following aspects of the bowl's form: its relatively large size, the complexity associated with a double-walled slip-cast form and the faceted surface. Further challenges were encountered when calculating and accounting for clay shrinkage and variations in the cast wall thickness. All factors that affect the dimensions of the interior cavity of the double-walled bowl where adequate tolerances were required to accommodate the installation of the electronics, actuators, and battery.

Three attempts were made to design the mould, two of which failed, and one finally succeeded. The first attempt involved designing a mould translating the final form to a Rhino file to model a complex four-part mould design. The Rhino CAD model was 3D printed in a gypsum plaster based 3D print medium. This first attempt at the mould failed at the printing stage, due to technical issues with the printer and the relative to size and scale of the mould. The second attempt involved creating a similar, but less complex, four-part double-walled mould by hand. This attempt failed at the slip-casting stage due to the compounding complexities created by the design of the multi-part mould partition lines that caused irregular thin wall sections and partial tearing when attempting to demould the slip-cast clay parts.

For our final and successful attempt to design the mould, we chose to cast the inner and outer bowl separately and assemble the pieces by hand, after casting, thereby eliminating some of the complexity associated with the double-walled mould design. This resulted in a comparatively simple design that took the form of two separate one-part moulds and was fairly traditional in terms of manufacturing technique (see Figure 5).

Once the mould design was finalized, the mould parts were processed, cast in moulding plaster, and dried in a heated chamber for 7 days in order to cure and remove all moisture from the respective parts. When the mould was dry and ready for casting, we tested a variety of slips, looking for the material properties that best suited the challenges associated with the *tilting bowl* and mould design.

It is important to note, that the scale of the mould was unusually large and it was anticipated that this unusual design was going to be problematic at the slip-casting stage, requiring variations from typical studio techniques. We discovered from testing that a particular slip (WhiteStar cone 04) was the ideal clay to compensate for the problematic design of the mould due to its very elastic material properties and minimal *memory* (its inherent

| **Table 1: Fabrication steps once the mould is complete** |
|---|
| Slip is poured into the mould; then, allowed it sit in its cast for 45 minutes to congeal the ceramic material. |
| Excess slip is poured out and the resultant moulded part is let to dry for 24 hours while remaining in the mould. |
| The set-slip or "leather-hard" clay pieces are de-moulded and any excess soft clay flashing is trimmed off. |
| The separate form parts are then slipped and scored at the union of the two parts (inner and outer bowl) and assembled into a single double-walled bowl. |
| The leather-hard forms are dried slowly to avoid cracking requiring 7 days to become bone dry, this is often referred to as *greenware*. |
| The greenware forms are biscuit fired to Cone 05 (1045 Celsius). |
| After bisque firing the forms are sanded by hand to remove any minor surface imperfections. |
| Glazing and testing - looking for ideal aesthetic characteristics regarding colour and sheen. |
| *Satin Stone* Cone 04 glaze is applied with HVLP spray gun and the forms are ready for final glaze firing. |
| Final Glaze fire to Cone 04 (1060 Celsius) |

materiality). The remainder of the workflow to produce 6 identical slip-cast forms is detailed in Table 1.

In this section we provided an overview of the prototyping and fabrication process. In the next section we discuss our insights and reflections of the process characterized as frictions.

## FRICTIONS IN MOVING FROM DIGITAL TO MATERIAL

We are mostly aware of the differences between our virtual and physical worlds. Each world comes with its own clear constraints and limits that affect the possibilities and procedures in working either virtually or physically. In moving from digital to material prototyping and fabrication, the contexts shift, meaning the tools, techniques, methods and materials change, while the design concept remains constant or at least aims to remain constant. The general awareness of these differences is clearly nothing new, however, as is often the case in design it is the particularities that are of concern.

We aim here to present the insightful particularities of our process as *frictions*. Frictions signal a change in practices given the shifts between digital/physical design and fabrication contexts. The frictions we discuss below are: shifting constraints, naïve expertise, manual automation, and dynamic materiality.

The thematic notions of frictions arose from post-mortem meetings, written reflections by each team member, and annotated photo-documentation. The noteworthy observations were refined, sorted and synthesized in a series of affinity diagram meetings. Post-mortem sessions typically follow the end of a design process and focus on observations and reflections of the process. This process was by no means exhaustive. We chose those frictions in which many observations could support and were agreed upon by the team as unique and insightful with respect to our past experiences.

### The friction of shifting constraints

The characteristics of 3D modeling are in the main algorithmic, parametric, and virtual. This creates a wide range of possible transformations of form virtually with varying degrees and types of automation. Further, the speed and range of possible transformations of forms allows for a very wide and fast exploration of the design space through the quick generation of many alternatives. However, these of course occur virtually in bits and pixels. Shifting constraints from the digital to the material means that producing these alternatives materially is exponentially more time consuming and resource intensive.

In terms of rapid prototyping, output from 3D modeling typically utilizes additive or subtractive fabrication methods like 3D printing or CNC. While quick by traditional standards, either approach would be too slow or costly for our needs to iterate and explore the form physically. We needed the ability to explore the design space physically, functionally, and to scale (not just virtually) to allow us to experience prototype the movement of the bowl and to live with a functional alternative ourselves for periods of time.

As we discussed earlier (see Prototyping phase) the 3D model flattening approach afforded by 123D Make helped us negotiate the shifting constraints of moving from 3D modeling to material output in the prototyping phase. This allowed us to quickly experiment with different faceted shapes for the form of the bowl that led to our cardboard and MDF prototypes (see Figure 2). As a result, the *tilting bowl* became a faceted form.

While we navigated the complexities of the physical world, in part through 3D model flattening in our iterative prototyping, our move to the ceramic process for fabrication was more challenging of which we hinted at earlier (see Fabrication phase). The differences and increased complexity between the virtual and physical worlds became even more evident. In many respects, there was no greater shift in constraints than moving our conceptual form from a virtual world of no physical laws to the material world of the physical laws. The law of gravity and dynamics of water and air were especially manifest in the ceramics making process.

The slip-casting process of ceramics relies on a process of deflocculation that keeps the clay particles evenly distributed and suspended in the liquid clay and allows for a balanced absorption of water from the slip by the plaster mould. The sheer materiality of the clay, the plaster, and the water made evident the mass and volume of our undertaking that our digital processes did not at all prepare us for. As previously discussed (see Fabrication phase), the size and complexity of our form was quite ambitious for ceramics. This was evident in the multiple attempts and different strategies in the design and making of the plaster moulds. In addition, the moulds were very large and heavy. One of the plaster moulds in particular weighed well over 45 kilograms or over 100 pounds. The mould was very difficult to lift and move, requiring more than one person to manipulate each part, causing difficulty, inefficiency and

**Figure 6 Due to the weight and size of the mould it required at least two people to lift and maneuver.**

delay in the slip casting process (see Figure 6).

In another example of the friction of shifting constraints, the structural integrity of the laser cut and MDF prototypes were sufficient for experience prototyping however as a pattern for the mould, the part that is utilized for the direct impression, it could not handle the weight and water dynamics of the plaster mould material. During the mould making process, the MDF form "blew apart" in places partly distorting the geometry of the mould.

The friction led to inventiveness in the form of the bowl and inventions and challenges in its making. It signaled that the effect of material practices and constraints of the fabrication material, in our case ceramic, is already manifested in the decisions of the digital process. As soon as we decided to fabricate our form in ceramics, the material characteristics, its constraints and qualities impose themselves retrospectively on our decisions in the digital process. Conversely, the effect of digital practices and constraints are continually resonant and persistent throughout the material fabrication process. The digital qualities literally continued to shape, challenge, and invent in an ongoing dialogue with the material and its process long after we left the digital processes behind. In summary, our digital processes took on material qualities retrospectively in a type of "feed-backward" action while digital qualities persisted throughout the material processes in a type of "feed-forward" action.

### The friction of naïve expertise

In the design approach of the tilting bowl we had not decided on a material to use for the form of the bowl at the outset. The idea of working in ceramics was one of many options at the concept and prototyping stages and was not decided upon until the laser-cut MDF forms were done. This meant that the complete interdisciplinary team that included the ceramicists and materials researchers was not together until midway through the project. While in some respects this was not ideal, it was planned as we wanted the decision on which material and techniques to use to emerge from the design and prototyping processes.

This approach created the friction in which one half of the team fluidly applied expertise in digital form making, prototyping, electronics, 3D CAD modeling, and interaction design with a naïve understanding of ceramics. This resulted in the materials and ceramics researchers stretching past their known approaches and techniques to solve problems and create outcomes that would not typically be considered in ceramics practice.

In essence, part of our team members' fluidity with digital tools–model flattening, laser cutting and assembly–led to naïve form making for ceramics that created unexpectedly complicated forms and fabrication processes. As we stated earlier, the size, structure, and faceted sides of the tilting bowl made it a very ambitious and difficult project from the perspective of ceramics. This was unbeknownst to the designers of the form in the earlier stage and yet embraced by the team, especially the ceramicists involved, despite the challenges.

While our naïve expertise friction was unwitting, it is a common strategy among creative practitioners to attempt to do what is unknown or previously unthinkable. In a sense, knowingly embark on "naïve" projects in order to experiment or push the boundaries of one's own practice– and fully accepting the risk of failure.

It is important to state here that expertise in creative practices is both intellectual and in the main tacit and embodied. This equally applies to areas of expertise in interaction design and HCI yet is even more evident in ceramics. Physical materials like clay embody unique and nuanced physical characteristics–each type of clay is different. Understanding and creatively working with these characteristics are acquired through hands-on experience and time with materials and material techniques. Knowing the boundaries and complexities of ceramics is based in this type of expertise yet expertise in this sense can also be a limiter to creativity, unless one willingly explores past the limits or accepts the unknowing challenges, like our team with the *tilting bowl*. The friction created here called for transgressing beyond current bounds of expertise in ceramics, especially mould making for slip casting to address the naïveté of our form design and ambitions.

The resulting productive friction led to experimentation with digital and multiple analogue approaches to the mould making that mostly failed but did result in the design of a very complex mould system that far exceeded anyone's 'analogue' mould making abilities. The resulting form is especially striking for ceramics. The friction pushed the limits of mould making and de-moulding techniques and resulted in a ceramic form that is nearly impossible to produce within traditional ceramic practices of design and fabrication. In summary, the friction reveals the inherent and unique potential in the shift from digital to material to push the creative bounds of practice, materials, and form giving.

### The friction of manual automation

Digital fabrication and slip casting are largely viewed as automated processes that quicken, scale, perfect, and ease the fabrication process. In an industrial context, this is largely true. However, in the context of studio low-volume production, the move from digital to material often requires direct manual or hand input. These instances of manual interventions were required either to augment or repair aspects of the fabrication process in ways that attempted to mimic or maintain the integrity of the automated processes.

A clear example of a manual intervention of an automated process was in our use of 123D Make. We often had to make manual fixes in Rhino, our 3D solid modeling tool, to adjust for odd patterns and gaps that were generatively created by the software. We expected this to be the case,

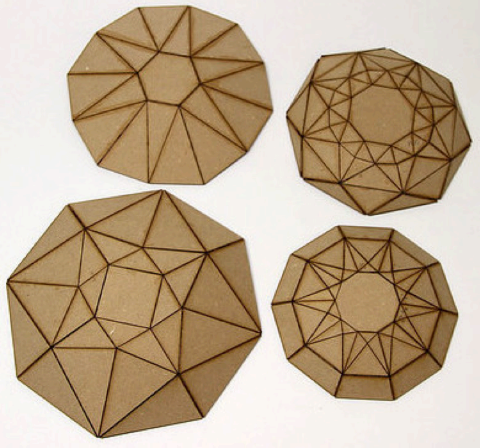

Figure 7 examples of the "manually" made forms designed in Rhino that mimicked the generated facets.

especially as we experimented with the form and manipulated both the number and placements of the facets of the bowl. For our final design, the form generatively created with 123D Make was correct on one half of the bowl while the other side had odd patterns. To fix this, we brought the model back in Rhino, cut it in half, deleted the 'bad' half, mirrored the 'good' half and recreated some of the facets at the junction of the two halves to stitch them back together aesthetically.

The digital automated processes strongly influenced our manual augmentations or repairs. This manifested in the pattern that our manual interventions aiming to mimic digital processes or outcomes. For example, in the prototyping phase of the project we experimented with multiple different faceted shapes for the bottom of the bowl to explore the impact of the form on its movement (see Figure 7). These faceted forms were not produced in 123D Make generatively but were directly produced in Rhino. This was a "fix" in a way since we could not sufficiently control the output of 123D Make for our purposes. Yet we followed the faceted form technique that is generated by 123D Make, however we created symmetrical shapes, something that cannot be made in 123D Make.

In some sense this makes sense since ultimately we planned for these bottoms to fit with the rest of the faceted form of the bowl, and, equally importantly, because we knew these bowl bottoms would be prototyped using the same laser cutting technique as the rest of the bowl. However, in hindsight, we see this design move as the first of many steps in which the faceted form of the prototype, produced in this manner for expediency, became the desired aesthetic goal of the form. We explore this further in our discussion section (see Lost and Found in Translation).

Another form of the mimicking of the digital "by hand" was in terms of outcome rather than process as the previous example illustrates. 3D CAD models appear realistic and even more so appear "perfect". The unencumbered mathematics and geometry provide ideal roundness, angles, and surfaces. This translated reasonably well in our laser cut and MDF prototypes despite our gluing and sanding of the joints. In the ceramic process, this proved to be more of a struggle. It is important to note, that pursuing fidelity of the "perfect" virtual representation of the *tilting bowl* was not a stated goal, rather it was consciously or unconsciously assumed by members of the team as the desired outcome.

Figure 8 The plaster mould being manually "fixed" to sharpen the angles to recover fidelity of the CAD model and laser cut prototype.

This assumption manifested in efforts to counter the softening of the angles and edges that are inherent to the slip-casting process and the inherent materiality of clay and plaster, due in large part to the fluid state of these materials. As a result, there was continual manual effort to rework the clay pieces to re-sharpen the edges in attempts to "return to" the fidelity of the digital (See Figure 8).

The friction signals a shift from the norms of craft and practice in which manual or handwork is typically seen to serve individual or human expression rather than qualities of automation. The persistence of digital qualities in the material form can be said to take on an expression of its own. In this sense, digital, manual, and automated processes can be seen to work together as mediators of different qualities and types of expression.

### The friction of dynamic materiality

The dynamic and unpredictable nature of clay and ceramics is unchangeable and in stark contrast to the inert nature of materiality in digital form. For example, when firing ceramics in a kiln, there are many different negative outcomes as a consequence of the materiality of the process that can occur that are very difficult to predict. These include undetected air pockets that under heating cycles can expand causing cavities or holes in the ceramics, airborne particulate can collect and fall onto the clay form and fuse together, and there are inherent challenges with thermal consistencies at high temperatures that result in over liquefaction of glazes or slumping of the clay form [35].

Kiln firing and other aspects of the dynamics of the materiality are nearly impossible to take into account in the digital making of the form. Industrial processes minimize these issues by reducing the variables as much as possible but this approach does not apply to the creative process of

**Figure 9 Trimming the opening of the bottom of the bowl after the form has dried.**

design research in which experimentation and iteration of forms, materials, and processes are desirable or unavoidable.

In our experience, there were two inherent dynamics to the materiality of ceramics that illustrate the friction. One is a propensity for ceramics to have a plastic memory due to its physical composition and structure. The plastic memory in clay is the is a characteristic of a clay-water interaction in which once a force is removed it may return to its shape [1]. As a result, clay has the tendency to remember both intentional an unintentional changes to its structure. For example, the clay physically 'remembers' accidental bumps and mishandling, even once the shape has been corrected. This plastic memory releases during thermal change in the biscuit and glaze firing process that may result in the ceramic unexpectedly deforming or cracking. Furthermore, each clay body has its own degree of plastic memory [1].

A second dynamic is the loss of water from the clay causing shrinkage. There are many types of clay and different clay bodies shrink at different rates with shrinkage varying from as little as 4%, to as much as 15% from the liquid state green state. Even still, the exact percentage for any particular clay also is difficult to predict precisely due to the factors which affect at which a clay shrinks is complex. Clay shrinks differently at the various stages that lead up to final firing and complete vitrification of the clay body.

In the case of the *tilting bowl*, we require a hexagonal opening at the bottom of the bowl for the electronics and actuators that are attached to a plate that fits the opening. We used a physical template in the hexagonal shape to carve and trim the opening after the drying process (see Figure 9). Due to the uniqueness of the shrinkage for each bowl, the openings of each bowl differed up to 3 millimeters from one to the next requiring a custom fit for each plate to each bowl.

This friction displaces the general notion that digital qualities are dynamic and material qualities are static. Further, the dynamic materials qualities are too complex to model or predict in a digital context further underscoring the necessary dialogue and emergence between the digital and the material.

## DISCUSSION

Our account highlights the need for designers and design researchers to articulate the particularities of new practices and to share them as theoretical and practical knowledge. Given this, in this section we extend our findings of the frictions by discussing the relations among the frictions and their potential contribution to design research.

### Lost and Found in Translation

The frictions we discussed earlier are clearly interrelated and directly influenced how each manifests. The interplay of direct and manual creative interventions and automated processes plays out in ways that can be seen as beneficial discoveries of the translations between processes and modes, and the immoveable characteristics of the materiality of clay.

One way to consider the moves from digital to material fabrication is as a series of translations. For example translating the CAD model into material form or translating the form making process from 3D model flattening to ceramic slip casting. As we have discussed in the frictions, these translations can be a matter of context as we did in the prototyping phase of opting for assembly of laser-cut 2D forms rather than 3D printing or CNC fabrication (see The friction of shifting constraints); subject to expertise for example digital prototyping resulting in naïve choices in ceramics fabrication (see The friction of naïve expertise), and the need or assumed need to manually "fix" or "repair" analogue processes to maintain fidelity to digital processes and outcomes (see The friction of manual automation). In each of these examples of translations, we often focused on what was lost or we discussed how we could "fix" aspects manually to recover lost fidelity such as sharpening and changing the angles of the facets in the plaster mould. Overall, it is clear that some aspects are lost in translation.

However, it is also clear that many aspects that came to characterize the *tilting bowl* were gained (or found) through series of translations. For example, the glazing process in ceramics in the end softened the details even further despite our efforts to sharpen angles whenever possible. Nevertheless, this created engaging light patterns in the way light reflected and was absorbed by the surfaces (see Figure 1). This made for an ideal tension between the mass and solidity of the bowl and more ephemeral and dynamic qualities of its form. In many respects this is what we wanted out of fabricating in ceramics.

Even more fundamental to the form of the bowl, its faceted shape can be seen to be a gain through translations from digital to material. In short, the faceted shape of the bowl was a product of expediency for prototyping that led to the desired aesthetic goal or outcome of the form in ceramics (see Prototyping and The friction of shifting constraints). This acceptance of the faceted form as an aesthetic decision can be traced back to the decision to manually produce alternatives for the bottom of the bowl that were faceted, as we discussed earlier (see The friction of manual automation). Additionally, we discussed how we attempted to maintain the fidelity of the digital faceted form throughout the analogue process of ceramics through a series of manual interventions clearly marking the point in which faceted form became the aesthetic ideal (see The friction of manual automation). Others in the ceramic studio, not part of the team commented on its unique form and aesthetics, and as we discussed in the friction naïve expertise, it is a form that would not be considered achievable in a typical ceramic design and fabrication process.

The benefit of the faceted form is a result of a series of frictions and translations. In many respects, a creative process often looks to the specific aesthetics and characteristics to emerge from the process rather than *a priori* or *a posteriori* in which aesthetic results is independent of the process. This leads to the desirable transparency in the making of artifacts that as we can see equally applies in translations from the digital to the material.

### Practice and Craft

Our *tilting bowl* was made in a “studio space”, not an industrial ceramic or technology production facility. The studio space serves as an ideal platform for discovery and knowledge creation. It affords a close relationship to the making at hand and facilitates experimentation in ways that makes evident the relations of craft and the practice of that craft.

In viewing our frictions in light of the evolution of the practice of a given craft we could view the digital as a new craft but ultimately the general translation issues, what we described as frictions would be similar for example to those in moving between the crafts of illustration to a material prototyping in plastic, or paper pattern-making to a finished garment in fabric. Our account cannot definitively answer this question but if it is the case it offers interesting insights nevertheless.

Practically, we argue that the particularities of the move from digital to ceramics are important to articulate since it is at the level of the particular that practices are formed. In our view it is centrally important that the particularities of new digital to material practices are articulated and shared.

On a theoretical level, the very consideration of the digital as another practice or material is a substantive reconfiguration on its own. For example, Löwgren and Stolterman have argued that the digital is a “material without qualities” [14] yet the frictions begin to describe how material qualities for digital processes may manifest. Further, if the frictions articulate digital processes at the same general level as other craft practices we can begin to view how other practices, namely their strategies and tactics can be applied to digital fabrication.

An opposing view of frictions in light of practice and craft is that the digital and its relations to material practices are unique and not like other translations of practice from one craft to another. For example, the friction of shifting constraints illuminates a retrospective manifestation of material qualities in the digital processes in what we referred to as a “feed-backward” action alongside a “feed-forward” action in which the digital process persists to shape and constrain the material and material practices. This occurred in ways different and greater than a paper pattern imposing itself on the making of a fabric garment. The frictions also reveal counter-intuitive formulations of practice such as manual interventions to express automated and digital qualities. The uniqueness of the digital to the material opens up distinct qualities of the digital, human, and automated that can co-exist in a form.

As mentioned previously, this account cannot offer a definitive answer of the relations of our frictions to practice and craft but it is clear that the frictions make contributions in either formulation. Ultimately, we aim for this paper to encourage and even inspire further research through design reflections of the materiality and fabrication.

## CONCLUSION AND NEXT STEPS

In a future project, we would benefit from more time being invested by the full design team made up of the design researchers, designers, and fabricators (ceramists) during ideation and iterative phases of the product development. This would allow us to better conceptualize the possible material qualities in the practice of the digital process and enable us to utilize our frictions as a step toward shaping our design sensibilities for the shift from digital to material processes.

In this paper, we presented a case study of the form making processes of a design research project we refer to as the *tilting bowl*. In this case, we investigated the role of digital and material prototyping and low-volume production in HCI research through a reflexive, low-level, and in-depth analysis of our project. We reported on four *frictions* resulting from our prototyping and fabrication processes including shifting constraints, naïve expertise, manual automation, and dynamic materiality. Our account highlights the need for designers and design researchers to attend to the details and particularities of digital and material production opportunities, and to share their own accounts as a form of material and practical knowledge.

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