WeaveSlicer: Expanding the Range of Printable Geometries in Clay

Camila Friedman-Gerlicz
friedmangerlicz99@unm.edu
Department of Computer Science
University of New Mexico
Albuquerque, New Mexico, USA

Deanna Gelosi
dege9758@colorado.edu
ATLAS Institute
University of Colorado, Boulder
Boulder, Colorado, USA

Fiona Bell
fbell1@unm.edu
Department of Computer Science
University of New Mexico
Albuquerque, New Mexico, USA

Leah Buechley
buechley@unm.edu
Department of Computer Science
University of New Mexico
Albuquerque, New Mexico, USA

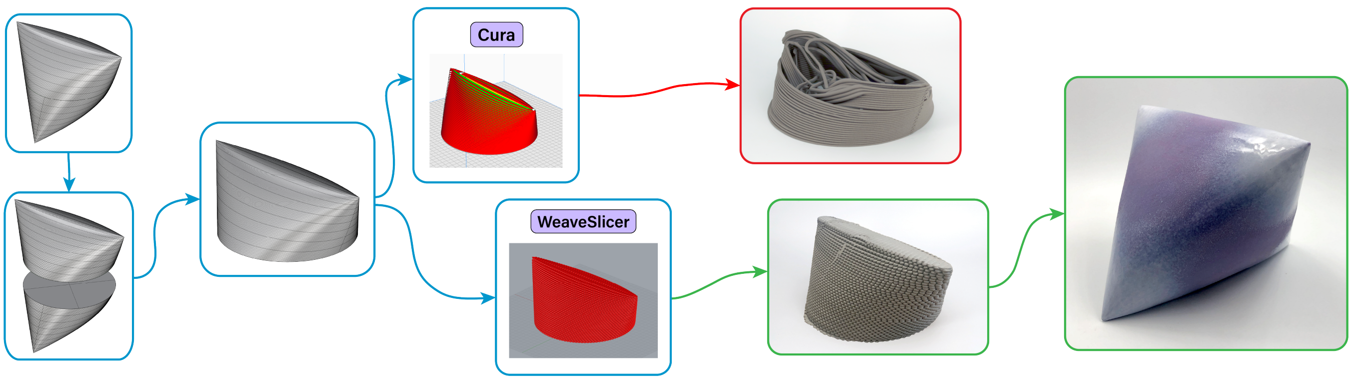


Figure 1: WeaveSlicer is a slicer that expands the range of 3D printable geometries in clay by implementing an oscillating toolpath that keeps the wall thickness of prints constant. Above: an example of a form that fails when sliced by Cura (top) but prints successfully when sliced by WeaveSlicer (bottom). The image on the far right shows the final glazed version of the WeaveSlicer-generated form.

ABSTRACT

Clay 3D printing is a relatively new technology and only a narrow range of geometries is 3D printable if one is employing commercially available slicing software. We experienced these limitations in an artist residency program where artists discovered that many desired geometries failed to print successfully. This motivated us to develop *WeaveSlicer*, a slicer optimized for 3D printing in clay that maintains constant wall thickness throughout the form. We achieve constant wall thickness by generating an oscillating path where the amplitude of the oscillation is determined by the form's overhang angle. We demonstrate the effectiveness of our approach by comparing a range of successful prints, sliced by WeaveSlicer, to failed prints of the same forms sliced by Cura, a widely used slicing software. We then showcase a collection of complex artifacts designed by artists in residence that were constructed with WeaveSlicer.

CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**; • **Applied computing** → **Computer-aided design**.

KEYWORDS

Clay 3D Printing, Digital Fabrication, Slicing Software, Toolpath Generation, Ceramics, Artist Residency

ACM Reference Format:
Camila Friedman-Gerlicz, Deanna Gelosi, Fiona Bell, and Leah Buechley. 2024. WeaveSlicer: Expanding the Range of Printable Geometries in Clay. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA*. ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3613904.3642622

CHI '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0330-0/24/05
https://doi.org/10.1145/3613904.3642622

1 INTRODUCTION

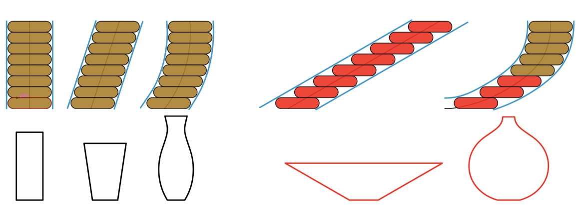
With the relatively recent introduction of consumer-grade clay 3D printers, a broadening group of artists, designers, and fabrication researchers are exploring digital fabrication in ceramics [24, 37, 49]. While conceptually similar to the Fused Filament Fabrication (FFF) of plastic materials like PLA, clay 3D printing is a distinct and very different process due to the material differences between clay and thermoplastics.

Melted plastic extruded by FFF printers hardens as soon as it leaves the nozzle. In contrast, clay remains soft and malleable during the printing process. Clay hardens slowly and gradually as it dries—a process that takes place after printing and typically requires several days or even weeks. Clay is also much heavier and denser than traditional print materials. Clay structures are not only softer than traditional prints while they are printing, they also have to bear more weight.

Compounding these challenges, many clay 3D printers extrude a continuous bead of material; they lack the ability to stop and restart extrusion [2]. This means that the ideal toolpaths for clay printers are continuous; they contain no travel paths. A travel path is a movement of the print head during which no extrusion occurs. Travel paths are ubiquitous in toolpaths generated by traditional slicing software like Cura [64] and Simplify 3D [57]. Current slicing software–which converts geometry into 3D printer toolpaths–was developed specifically for FFF machines and their toolpaths are optimized for thermoplastics, not clay.

Perhaps the most important difference between clay and thermoplastic is that solid forms cannot be printed in clay. Clay shrinks significantly during drying and firing–from 10-15% for stoneware clays to up to 30% for porcelains [52]. A clay form must be dried and fired evenly to avoid cracking. If the outside of a form dries or fires before the inside, cracks develop. In general, forms thicker than 2 inches (50 mm) tend to crack or explode during firing. Clay, whether 3D printed or formed using a traditional ceramic technique, is typically used to make hollow forms.

This collection of features profoundly limits the geometries that have been printable in clay. Clay prints are much more prone to collapse than traditional FFF prints. Significant overhangs, in which layers are less vertically stacked are particularly challenging to print. In general, when using traditional slicers, clay printers are well suited to printing tall narrow vessels. Shapes with dramatic overhangs or underhangs are unprintable without supports, Figure 2.



(a) Printable (b) Not printable

Figure 2: (a) 3D printable clay forms vs (b) typically unprintable clay forms.

Previous research has been conducted to improve the range of 3D printable geometries in clay by optimizing support generation [34]. However, supports in clay prints are awkward and undesirable. They must be printed in clay and then either carved away from or broken off of completed prints—a process that is time-consuming, labor-intensive, and prone to failure since clay forms are very delicate until they are fired.

In this paper, we expand the range of printable geometries with *WeaveSlicer*, a slicer designed to support clay's unique material characteristics. WeaveSlicer generates continuous unsupported toolpaths optimized for clay. The central insight of our development is that clay forms are *hollow*, not solid, and should have *walls of a consistent thickness*. Through a careful analysis of the character of 3D printing toolpaths, we realized that a traditional "vase mode" 3D printing approach—in which layers of consistent thickness are stacked up vertically—vessel wall thickness changes as a function of the wall's overhang or underhang angle. As the angle away from vertical increases, layers spread out horizontally and walls become thinner, Figure 3-left.

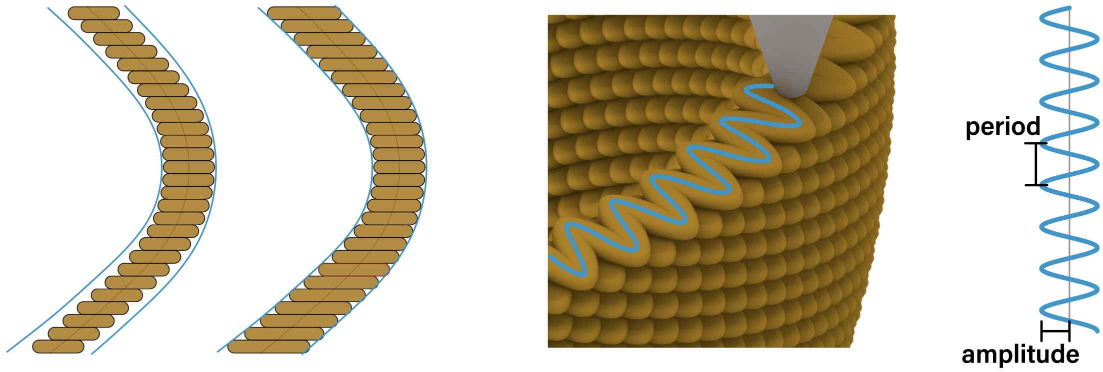
WeaveSlicer addresses this problem by generating a toolpath in which the wall thickness is kept constant, Figure 3 center-left. Note the critical distinction between *layer thickness* and *wall thickness*. We achieve a constant wall thickness by generating an oscillating path for each layer where the amplitude of the oscillation, and thus the path width, is determined by the wall angle. Figure 3 shows a cross-sectional view of a vessel wall with a traditional toolpath on the left and a toolpath generated by WeaveSlicer in the middle. The image on the right shows a more complete view of a WeaveSlicer print. The oscillating path is offset by half a period every other layer, resulting in the woven-like appearance that gives the software its name.

This paper introduces WeaveSlicer, a slicer that expands the range of 3D printable geometries for clay. We discuss the development of the software in the context of an artist residency program in which HCI researchers collaborated with ceramic artists. We demonstrate WeaveSlicer's effectiveness by comparing prints generated by WeaveSlicer to prints with traditional 3D printing toolpaths and testing a range of overhang angles and forms. We then employ WeaveSlicer in artists' practices to create pieces of theirs that previously failed to print with traditional toolpaths. Lastly, we discuss the technical limitations of WeaveSlicer; we highlight WeaveSlicer's versatility, noting how it can be widely implemented by other artists and researchers; we address some of the aesthetic and technical aspects of "woven" clay; and we reflect on artist residency programs in HCI as a context for fostering technical and artistic innovation.

2 RELATED WORK

2.1 Ceramics Research and Clay 3D Printing

Ceramics have gained increasing interest within the HCI community, with ceramics research ranging widely from studying relationships between humans and ceramic technologies [44, 65, 66], to designing interactive ceramic interfaces [6, 68], to creating sustainable clay-like materials [5, 7, 12, 53]. Several research efforts have been focused on developing new technologies for clay fabrication. Notably, Horn et al, introduced a software for slab-based ceramics



Traditional Path: constant *layer thickness*
WeaveSlicer: constant *wall thickness*
WeaveSlicer Toolpath
Sinusoidal Curve

Figure 3: Cross-sectional views of a 3D printed vessel with a traditional 3D printing toolpath in which the width of each layer is constant (Left) and a toolpath generated by WeaveSlicer in which the width of the vessel wall is constant (Center-Left). A view of a WeaveSlicer vessel print (Center-Right). A sinusoidal curve with period and amplitude shown (Right)

[35], Devendorf explored a collaborative human-machine clay fabrication process [23], and Rivers et al. leveraged video projections to assist in creating precise ceramic sculptures [54]. Along similar lines, Dick et al. used laser cutters to introduce cracks into glazed ceramics, resulting in controlled textures and patterns [24], while Arredondo et al. used digitally controlled scoring tools to create patterns on wet clay that promote shape-change [6].

One of the significant methods for computational clay fabrication is clay 3D printing [15], which has been adopted by both ceramic artist and HCI researchers alike. Within the ceramic art community, artists such as Jolie Ngo [45], Bryan Cera [14], and Slip Rabbit Studio [58] have integrated clay 3D printing into their respective artistic practices. Within HCI, researchers have used clay 3D printing to tangibilize sound and vibration data into ceramic objects [17, 18, 55] as well as restore ceramic objects [71]. Most relevant to our work, Buechley created a Python library for g-code generation for clay 3D printing based on Turtle geometry [11] and Bourgault et al., developed a software tool to parameterize tool path generation for 3D printing non-cylindrical shapes in clay [9]. We build on these past works by developing of a new, craft-inspired software tool called WeaveSlicer that expands the range of forms that can be 3D printed with clay.

2.2 Craft-Inspired Fabrication

We found inspiration for this project in traditional craft practices and in existing intersectional craft and fabrication research. The perspectives, processes, and practices derived from "craft coproductions" [22] inform HCI practitioners on employing material-oriented craft methods in research [10]. HCI researchers have found inspiration in artists' use of tools, forming the basis for hybrid or augmented tool design [28, 36, 56, 70]. Human-machine collaborations are another area of work in which artists offer real-time and immediate influence over fabrication workflows [23, 43, 47, 67]. We're inspired by HCI practitioners who worked closely with craftspeople on software interventions related to their craft, resulting in tools like AdaCAD [31] and CoilCAM [9], which were designed in collaboration with weavers and potters, respectively.

In this work, we draw from the craft practice of ceramics, using 3D printers to support artistic creation with clay. We build on similar modes of hybrid craft, to bridge the gap between traditional craft practices from trained ceramic artists and digital fabrication techniques. As such, we contribute new software that allows us to print expanded geometric forms that previously have only been achieved through hand building. We note that collaborating with artists was instrumental in arriving at our new technique for 3D printing.

2.3 Art and Artist Residencies in HCI

Artist-researcher collaborations within HCI have become increasingly common [8, 38, 41] and range across a variety of artistic practices including, but not limited to, weaving [4, 13, 21], knitting [3, 39], needle punch embroidery [16, 40], leatherworking [62], stained glass making [32], glassblowing [50], kirigami [69], wood joinery [43, 60], wood carving [46], silversmithing [61], drawing [33, 59], and dance [26]. These works highlight the knowledge and new technologies that can be generated through engaging with traditional art and craft practices in HCI.

Artist residencies hosted within HCI labs provide an increasingly popular structure for supporting these artist-researcher collaborations. Devendorf et al. showcased the advantages of incorporating craft-based approaches into engineering research through an "Experimental Weaving" residency program [19], a model that has also fostered multiple partnerships between ceramic artists and HCI researchers. Zheng et al. collaborated with artist Hans Tan to create interactive ceramic pieces through a traditional resist sandblasting technique used for glazing [68]. Bourgault et al. worked alongside artists Pilar Wiley and Avi Farver to develop an action-oriented toolpath programming system for 3D printing non-cylindrical forms [9]. Rosner et al. collaborated with Helen Martino to design a ceramic bowl that represents an audio message [55]. Desjardins found a mutual interest in capturing data stories in porcelain with artist

Timea Tihanyi in cups [17] and sculptural objects [18]. In all these works, the concept of *mutual benefit* [20] for both the researcher and the artist is emphasized. We similarly present the work that stemmed out of our lab's artist residency program, aiming to benefit the work of our artists in residence while contributing HCI research outcomes. In this paper, we detail the technical aspect of our resulting slicer software and also discuss how the artists in our lab inspired the work and helped lead and shape the course of the research.

3 METHODOLOGY AND MOTIVATION

3.1 Research Team

Our multidisciplinary team brought together different skills and values to design this software tool. Author 1 is a ceramic artist whose work involves making mathematical forms out of physical materials. She has over twenty years of experience working with clay and has made work using the methods of wheel throwing, coil building, slab building, and slip casting. She also has a graduate degree in mathematics and extensive experience with digital fabrication. Author 2 is a Ph.D. student and HCI researcher who creates computational systems for art and fabrication applications. She has degrees in Physics and Computer Science along with extensive experience in design and fabrication. Author 3 is a postdoctoral researcher whose background is in HCI, design, and materials engineering. Author 4 is a professor in HCI and computer science who led the artist residency program that provided the platform for our research.

3.2 Process Overview

Our work takes place in the context of a ceramic artist residency program hosted in an HCI research lab. In the summer of 2022, our lab hosted two artists in residence through this program, including Author 1 who created the pieces in Figure 4. Our aim was to develop new ceramic work along with new tools and techniques for ceramic 3D printing. Over the course of the three-month residency, the visiting artists each made a body of work employing clay 3D printers. During this residency, Author 1 faced challenges and did a lot of problem solving when making her work, which serves as a primary motivation for WeaveSlicer, developed over the subsequent summer.

In the summer of 2023, Author 1 returned to our lab as a visiting researcher. In this role, she focused on developing new tools and applications—that are grounded in her artistic practice—for a research context and audience. Authors 1 and 2 worked together to develop WeaveSlicer, while Authors 3 and 4 provided ongoing feedback and support during this process.

3.3 Author 1's Work

Author 1's ceramic work is centered around making the theoretical physical by using mathematical ideas to generate form [29]. She is interested in thinking about space mathematically while also experiencing it with the whole body. She uses formulas and algorithms that create beautiful forms and interesting paths in space. These forms could be visualized using a computer, but she instead renders them out of physical material so that she can touch the math and make a direct connection between her brain and her body.

Figure 4: 3D printed ceramic sculptures created by Author 1 during the 2022 residency. The forms are quite large, ranging from 1 foot to 2 feet in their largest dimension.

During the summer 2022 residency, she created a series of clay sculptures of algebraic surfaces defined by equations in three variables (x, y, and z). Author 1 has spent many years building a digital library of algebraic surfaces that she found through research, play, and discovery [27, 63]. As can be seen in Figure 4, the forms have complex geometry that include dramatic overhang and underhang angles and saddle points. Following the workflow for 3D printing a form in Figure 5, Author 1 modeled the forms in Rhino and Grasshopper and then "broke" each sculpture into multiple pieces (in software). Joints were chosen to maximize printing success. Depending on the printability of the form and its pieces, sculptures could require many prints. For instance, the forms shown in Figure 4 required between two to eight pieces. Once individual pieces were printed they were joined using traditional pottery joinery techniques. Author 1 then smoothed the outside of the forms. The sculptures are representations of mathematically smooth surfaces, so she wanted the clay surface to mimic this mathematical property.

3.4 Summer 2022 Residency Challenges

In summer 2022, Author 1 tested various slicing and printing methods for her sculptures. The conventional method to craft a hollow form using slicing software is the "vase mode," where a solid object, not a hollow one, is provided. This mode produces walls of one horizontal layer thickness, adjustable via the extrusion rate.

Traditional slicers could potentially create clay forms with specific wall thicknesses by modeling the hollow form and slicing in "normal mode". However, as the design complexity rises, modeling a hollow form with consistent wall thickness becomes computationally challenging [42, 48]. It requires creating a non-intersecting

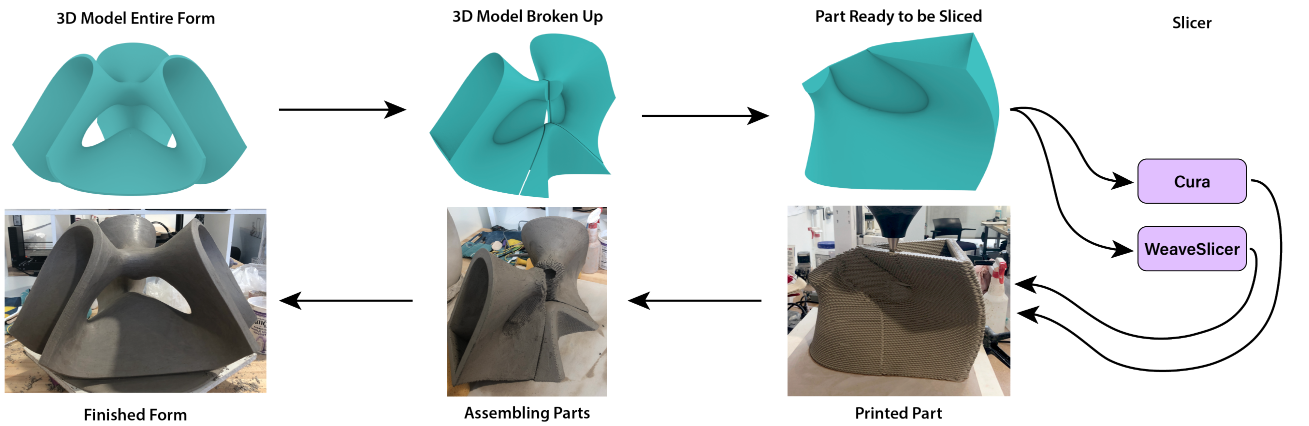


Figure 5: Author 1's workflow. The same process was used in 2022 and 2023 except Cura was used for slicing in 2022 and WeaveSlicer was used in 2023.

offset surface, which is difficult to achieve for intricate geometries. Rhino (the tool we were using) can only generate approximate offset surfaces for a limited class of forms. Ultimately, Author 1 chose to use Cura to generate toolpaths for solid models, using multiple walls and infill for support.

Challenges were not limited to slicing, as issues also arose during printing. For instance, Cura's toolpaths incorporated travel moves, which on the PotterBot Super [2] led to inconsistencies in the extrusion rate. The necessity for infill meant excessive clay usage. Although the surplus infill clay was recyclable, it consumed time and resources. Often, large prints required more clay than the print tube could hold, which required resizing or mid-print refills. Furthermore, printed sculptures regularly cracked post-firing, with cracks appearing along print lines. This process is illustrated in Figure 18. We theorize that the infill printing process hindered proper layer adhesion, exacerbating drying and adhesion issues. Our journey in summer 2023 began with a determination to address and rectify these issues and build a slicer that could expand the types of geometries that could be printed with clay.

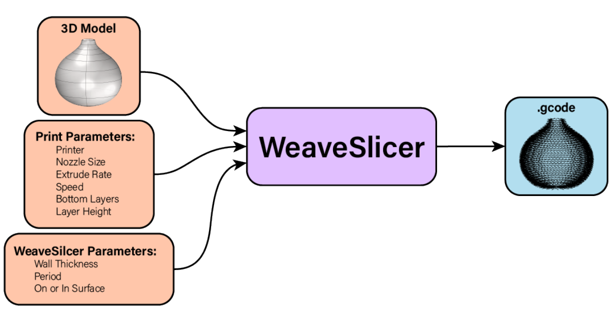


Figure 6: Overview of workflow with Weave Slicer in Grasshopper/Rhino.

4 SOFTWARE

Over the course of the summer of 2023, we developed WeaveSlicer, an open-source software library that can be used in the Grasshopper Rhino environment [1]. This library is public and can be downloaded [30] and used in Grasshopper.

4.1 Overview

WeaveSlicer takes a solid form as an input and generates a toolpath in the form of a 3D printable .gcode file. The continuous toolpath creates a shell of the input form with walls of a consistent thickness. Layers are made of alternating sinusoidal oscillations. The amplitude of the oscillation changes based on the wall angle of the form.

WeaveSlicer has a similar workflow to a traditional slicing software. As shown in Figure 6, the user imports a 3D model into the Rhino and Grasshopper file. They then chose and adjust the parameters relevant to the machine and form they are printing. The adjustable parameters fall into two categories: standard print parameters and WeaveSlicer-specific parameters.

- *Print Parameters*: WeaveSlicer currently supports three different clay printers (3D Potter Super, 3D Potter Micro, and Eazao Zero). A user chooses a printer, a nozzle diameter, extrude rate, and speed. The user also chooses the number of bottom layers for their print and a layer height.
- *WeaveSlicer Parameters:* The user chooses the desired wall thickness and the distance between oscillations (the period of the sinusoidal curve). They can also specify if they want their tool path to be centered on the surface of the form or lie entirely inside the form, a feature motivated by our desire for mathematical precision, see Figure 10 (a).

After all the parameters are adjusted to the user's preference, the toolpath is visualized in Rhino and the user can export the .gcode and send it to the printer.

4.2 Continuous Toolpath with Constant Width

As we discussed in the introduction, in a traditional toolpath for a hollow form—generated by using "vase mode" in a slicer—as the

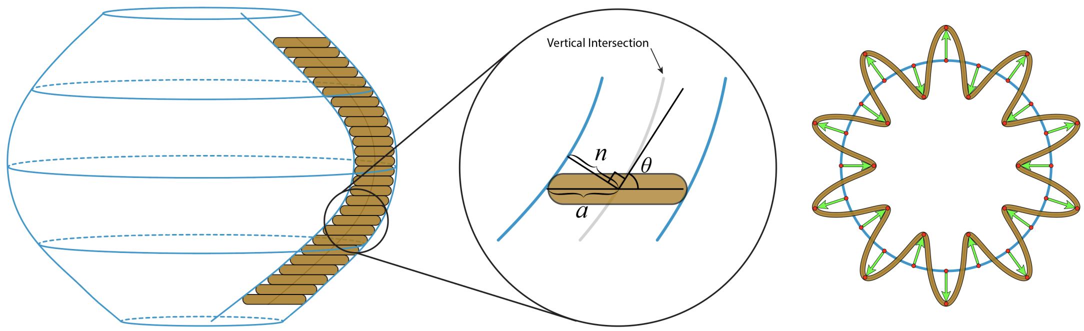


Figure 7: Left: Cross section of a wall with a constant width, generated by WeaveSlicer. Middle: Calculation of variable amplitude used in WeaveSlicer. Right: A top down view of how the sinusoidal toolpath is constructed.

angle of the wall becomes less vertical, each vertical layer sifts horizontally to accommodate the angle (Figure 2). Eventually, these layers shift so much that they are insufficiently supported by the layers below, causing a print to collapse. Early in our development process, we created a parametric visualization to generate cross-sectional views of different print paths like the ones in Figures 2, 3, and 7. This visualization tool helped us identify the fact that areas with shifted layers also have very thin walls.

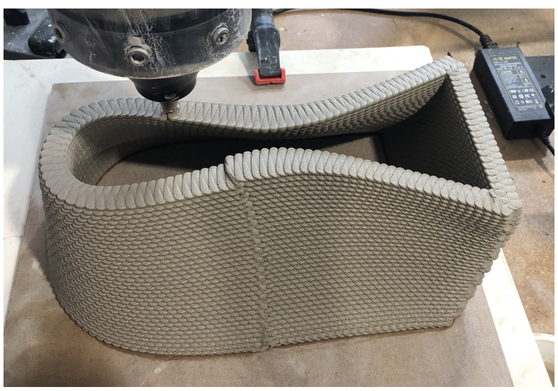


Figure 8: Demonstration of the adaptive amplitudes generated by WeaveSlicer to ensure uniform wall thickness. Note the different amplitudes that are present in a single layer; amplitudes are larger where the form has a steep wall angle (in the middle of the form) and smaller where the form is more vertical (on the right side of the form).

Our software significantly improves print quality by generating a continuous toolpath where wall thickness is kept constant. The software first finds contours of the form to be printed at the specified layer height. It then splits each curve into a number of equidistant points, where the distance between points is half of the period set by the user. The points are then moved in and out in a alternating pattern to create a sinusoidal/zigzagging path, as seen in Figure 7 right. The distance each point is moved (the amplitude of the sinusoidal curve, Figure 3-right) increases as a function of wall angle. To calculate the amplitude for a given wall thickness (or normal distance), n, the software first finds the wall angle, θ, at each point along the toolpath. To do this, it takes a vertical intersection of the form near the point, as seen in the middle of Figure 7. It then finds the angle between the tangent line of this curve and a horizontal line, θ. Finally, the software calculates the amplitude, a, with Equation 1:

$$a = \frac{n}{\sin(\theta)} \tag{1}$$

This results in a wall that has a uniform normal thickness as seen in Figure 7-left. This path is naturally continuous, as opposed to a wall that is made up from multiple horizontal layers. This helps maintain the structural stability of our form, eliminates travel movements, and helps with vertical layer adhesion. Note that for complex forms, the amplitude may take many different values in a given layer, since the wall angle may have different values for different points in the layer, see Figure 8.

By offsetting each vertical layer by half a period, we give prints a distinctive woven like surface texture. We believe that this approach may help strengthen our forms, similar to the way a woven structure imparts strength to textiles. Though our prints do not have a vertical warp, like fabric does, our oscillating layers form a similar interlocking structure, as soft extruded clay settles into the supporting layer below.

4.3 Other Considerations and Features

4.3.1 Density of Oscillations. Our default setting keeps the distance per oscillation (d/o) constant. This insures that layers are of consistent density. The distance between oscillations significantly impacts the amount of clay that is deposited; as d/o decreases, more clay is deposited per mm of path length traveled. For high values of d/o, oscillations are distinct and the texture is pronounced, Figure 9-left. With a very small d/o, oscillations can become so tightly packed that layers become thick and solid and the texture becomes less visible, Figure 9-right. We have found the most useful range for d/o to be 100% of nozzle size - 200% of nozzle size for a given printer.

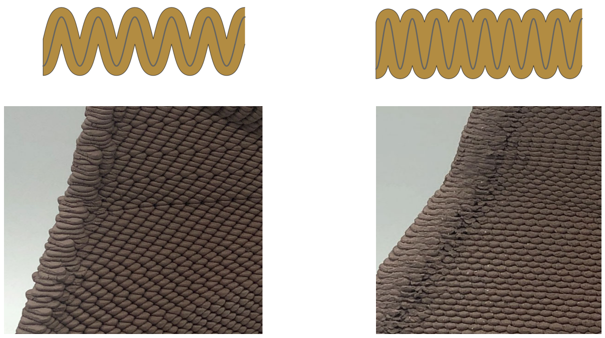


Figure 9: Difference in surface texture of a larger distance between oscillations (left) and smaller distance between oscillations (right)

It is also worth noting that when we keep d/o constant, the number of oscillations present in a layer is a function of the path length of the layer, modulo the d/o. This means that oscillations on different layers may not always align, resulting in prints with an uneven weave structure, Figure 11 (b).

4.3.2 Toolpath Location and Overlaps. A user of WeaveSlicer can specify if they want their tool path to be centered on the surface of the form or lie entirely inside the form, Figure 10 (a). This feature was motivated by our desire for mathematical precision. We wanted to insure that a printed form could have the exact dimensions of the input geometry.

When we are printing with the toolpath generated inside of the form, parts of the sinusiodal curve can reside outside of the surface if there is a sharp angle, Figure 10 (b) top. In these instances, WeaveSlicer adjusts the path by taking the points outside the form and mapping them to their closest points on the surface of the form. This keeps the toolpath on the inside of the surface, Figure 10 (b) bottom.

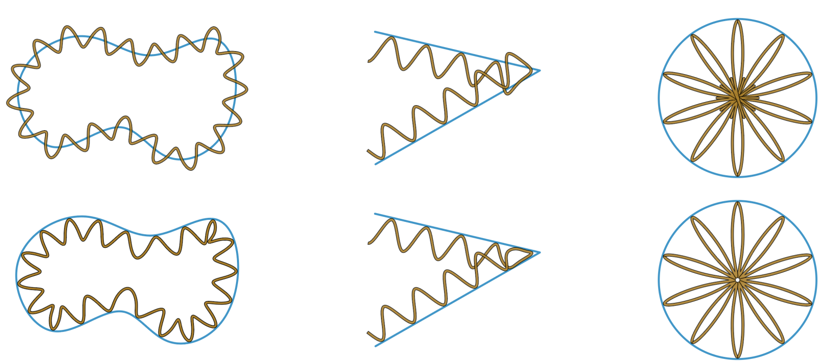
Our software also accounts for other moments when the toolpath might overlap itself and cause an over extrusion of clay. When closing a form, if the amplitude of a sinusoidal curve is larger than the distance from the current point to the center of the final contour curve, this causes overlap in the tool path, Figure 10 (c) top. WeaveSlicer detects these moments, and shortens the toolpath, so it still covers the required area, but does not over extrude, Figure 10 (c) bottom. The toolpath is shortened so that it reaches the center of the closed form, but does not move past it. These considerations and features ensure a more accurate and cleaner-looking print.

(a) Weave pattern near the start of each layer

(b) Weave pattern away from the start of each layer

Figure 11: The weave pattern depends on the distance from the start of each layer. Near the start, the sinusoidal toolpaths are offset so each layer nests into the the previous, (a). Since the d/o is kept constant, there might be a different number of oscillations for each layer, resulting in a weave pattern that does not nest on part of the object, (b).

4.3.3 Bottom Layers. WeaveSlicer also optimizes the bottom layers of a print, automatically picking the direction and order of the bottom layers to maintain a continuous print path. Bottom layers are printed concentrically, either from the inside of a form to the outside or vice versa. If the user specifies an odd number of bottom layers, the slicer will start in the inside of the first bottom layer and print out. The second bottom layer will then print from the outside in, and so on. WeaveSlicer ensures that the last bottom layer will finish printing on the outside of the layer, so it can transition to the wall layers without any excess travel.



(a) (b) (c)

Figure 10: (a) Printing with the toolpath centered on the surface, or inside of the surface. (b) Adjusting a toolpath to keep it inside a surface on a sharp angle. (c) Adjusting a toolpath to minimize overlap and over extrusion.

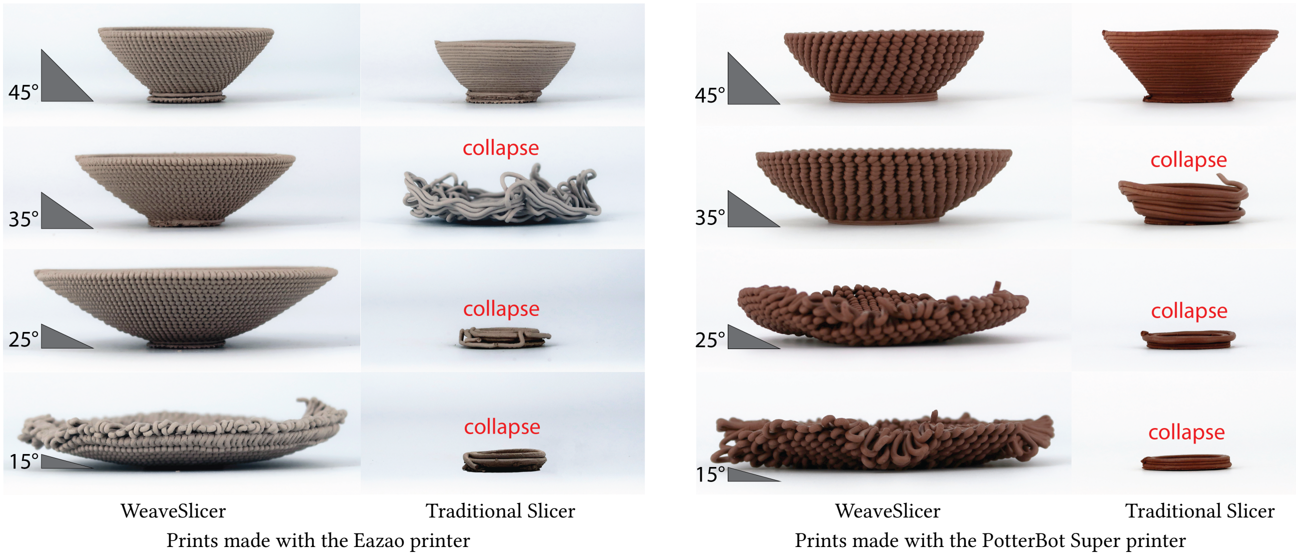


Figure 12: A comparison of prints made with a WeaveSlicer path, and a traditional single-walled path. The two columns on the left were printed with the Eazao Zero, and the two on the right were printed with the PotterBot Super. N=3 for each condition.

5 TESTING

5.1 Machines and Materials

We used two different clay printers for testing, a 3D PotterBot 10 PRO [2] (Figure 13 left) and an Eazao Zero [25] (Figure 13 right). The PotterBot has a print volume of 415 x 405 x 500 mm^3 and a clay tube that can hold up to 2000 mL. The Eazao has a print volume of 150 x 150 x 240 mm^3 and a clay tube can hold up to 500 mL. Both machines can use a variety of nozzles. We employ a nozzle with a 1.5 mm width on the Eazao and one with a 3 mm width on the PotterBot. To match the different sizes of these printers, we tested forms at two different scales, guided by nozzle size. The forms we printed on the PotterBot are twice as large dimensionally as the forms we printed on the Eazao.

We also worked with two types of clay. We printed a red cone 04 (low-fire) earthenware on the PotterBot and a white cone 6 (mid-range) stoneware on the Eazao. The Eazao is a small printer built from motors with relatively small amounts of torque. This necessitates softening clay considerably before loading and printing. The Eazao's extruder includes an auger mechanism that mixes the clay immediately before it exits the nozzle, thus removing air bubbles. For this machine, we used a kitchen stand mixer to introduce water into the clay and evenly mix it. We used a penetrometer to measure the material's hardness, adding water until we reached a hardness of 0.6 kg/cm^2.

The PotterBot is a larger machine with more powerful motors that can work with firmer clay. However, this machine does not include an auger, which means that all air bubbles must be carefully removed from the clay before loading the machine since trapped air bubbles result in small explosions that can damage a form during printing. To prepare clay for this printer, we wedged clay—a method used in traditional ceramics [51]—to soften it and remove air bubbles. Clay was mixed to a hardness of 1.3 kg/cm^2.

5.2 Comparison Testing: Bowls

We tested WeaveSlicer for its effectiveness in printing an expanded number of geometries in clay. We use simple bowl shapes with different overhang angles and compared toolpaths generated with WeaveSlicer to traditional toolpaths with single walls, Figure 12. We printed bowls with wall angles of 45°, 35°, 25°, and 15° with respect to horizontal. We generated three identical prints for each condition to ensure our results were consistent and repeatable.

On the Eazao printer, the only print with traditional toolpaths that was successful was at 45°, as seen in Figure 12. All other traditional-toolpath prints collapsed. With WeaveSlicer, overhang angles were successful through 25°, and the 15° angle vessel warped while not completely collapsing.

On the Potterbot printer, we achieved similar results. The 45° bowl was the only successful traditional-toolpath print, as can be seen in Figure 12. With WeaveSlicer, overhang angles 45° and 35° were successful, and both 25° and 15° tests experienced warping but not full collapse.

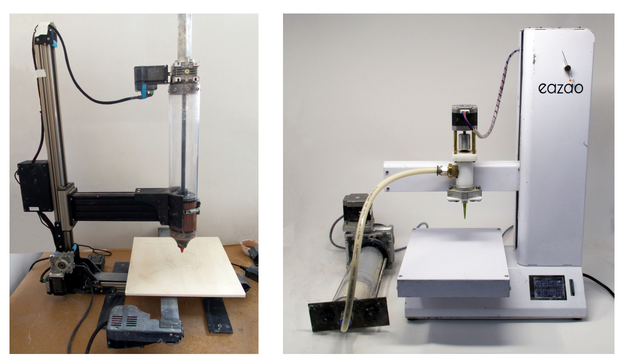
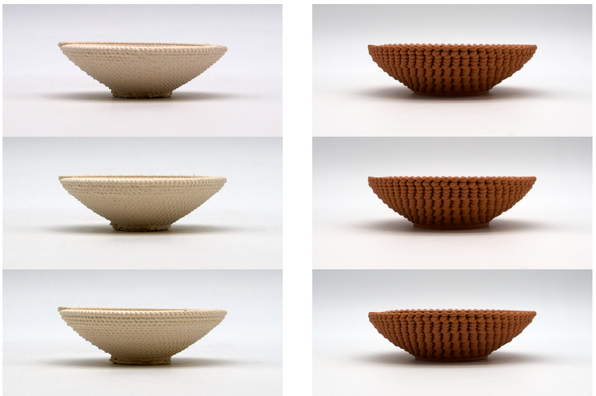


Figure 13: The 3D Potter 10 PRO (left) and Eazao Zero (right).



Fired prints made with the Eazao Zero printer

Fired prints made with the PotterBot Super printer

Figure 14: Repeated 35° overhang tests printed with WeaveSlicer and fired. The column on the left was printed with the Eazao Zero, and the one on the right with the 3D PotterBot Super.

We attribute the differences between machines to the difference in the consistency of clay. Since the clay we used in the Eazao was so much wetter, it was not as plastic (elastic) as the clay we used in the Potterbot. This meant the clay in the Eazao did not need to be as compressed as it was while printing in the PotterBot. This pressure caused the 25° test to collapse more on the PotterBot. These tests demonstrate that WeaveSlicer does expand the range of printable geometries in clay since we are able to print vessels with a more dramatic overhang angle using our generated toolpaths.

After printing, all of the test prints were fired. Figure 14 shows three fired bowls–three identical prints from the Eazao Zero (left) and 3D PotterBot (right) with a 35° overhang angle. All of the WeaveSlicer test prints fired successfully. Using WeaveSlicer did not negatively impact the quality of the fired ceramic artifacts.

5.3 Comparison Testing: Half Sphere

We also tested WeaveSlicer on a form with overhang angles that change throughout the print by creating a series of half spheres. A half sphere requires printing at angles that steadily change from 90° with respect to horizontal, at the bottom of the form, to 0° at the top. We compared the performance of WeaveSlicer to traditional single and double wall prints, Figure 15, printing three copies for each condition to ensure the reliability of our tests. We also used both the Eazao printer as well as the Potterbot, which allowed us to print the same form but at a different scale. The results of these tests were very similar on both printers.

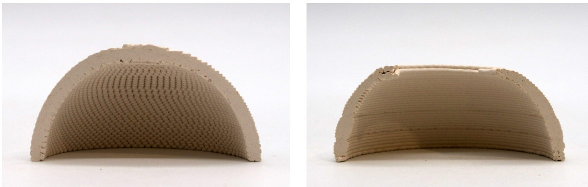
The half spheres printed with WeaveSlicer, shown in Figure 15 (a), remained completely stable throughout the print. They never appeared to sag and the final profile curves were convex. The half spheres printed with a double wall, Figure 15 (b), remained stable until around layer 40, where they began to sag and immediately collapsed into themselves. The weight of the inner wall layer pulled the remaining layers down. The half spheres printed with a single non-oscillating wall were stable until around layer 30, where separation in the layers can be seen in Figure 15 (c). After this point, while the print continued and the layers adhered to the previous ones, the form was unstable and the wall began to undulate. It finally collapsed fully around the 50th layer.

The toolpaths created with WeaveSlicer were able to print the half sphere completely where traditional toolpaths failed. We also cut some of the forms in half to examine the wall thickness and see if our initial visualizations (Figure 3-left) matched up with the physical objects. The half spheres printed with WeaveSlicer had uniform wall thickness throughout the form, Figure 16 (a). It can also be seen in Figure 16 (b) that in addition to the collapsed roof on the half sphere printed with the traditional double wall toolpaths, the wall gets thinner as the overhang angle becomes more dramatic.

(a) WeaveSlicer (b) Double Wall (c) Single Wall

Figure 15: Fired half Spheres printed with (a) WeaveSlicer, (b) double wall, and (c) single wall toolpaths, $N = 3$. The top row was printed with the Eazao printer and the half spheres have a 7.5cm diameter. The bottom row was printed with the 3DPotter printer and the half spheres have a 15cm diameter.

All of these test prints were also fired successfully. The positive outcomes of these tests encouraged us to use WeaveSlicer to try to print even more complex forms.



(a) WeaveSlicer (b) Double Wall

Figure 16: Cross-sections of a half sphere printed with WeaveSlicer (left), and a traditional toolpath with double wall thickness (right). The thickness of the wall of the half sphere printed with WeaveSlicer is uniform throughout the piece, whereas the wall thickness of the double wall print gets noticeably thinner as the overhang angle increases.

6 WEAVESLICER IN PRACTICE

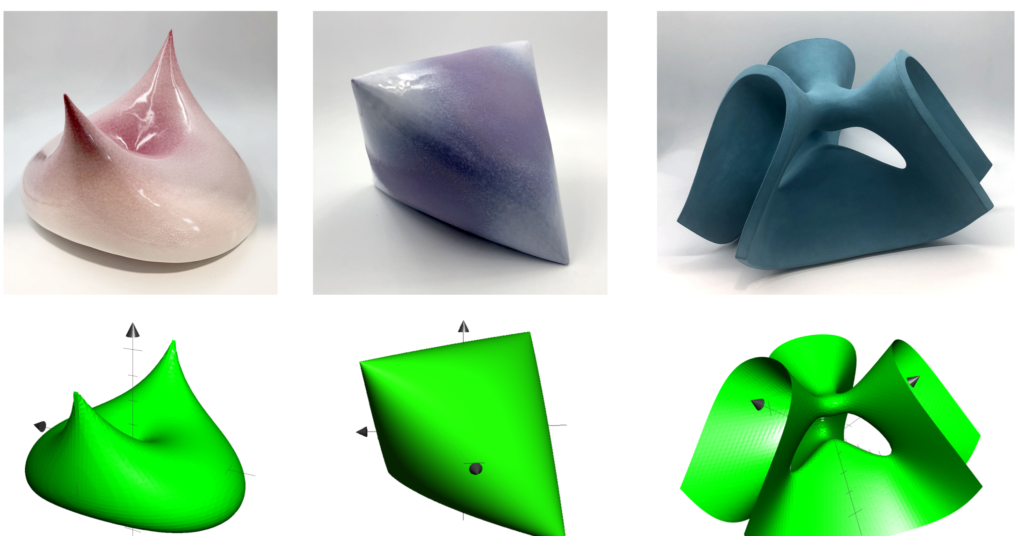
To verify that WeaveSlicer was a useful tool in practice as well as in theory, we employed it to fabricate three artist's work. First, Author 1 used WeaveSlicer to remake two of the forms that she struggled to build in 2022. She also created a new piece using WeaveSlicer. We also collaborated with the 2023 ceramic resident artists in our lab, using WeaveSlicer to generate and print forms of theirs that collapsed or were unsatisfactory when printed using a traditional slicer and workflow.

6.1 Author 1's Work with WeaveSlicer

We used WeaveSlicer to reprint and make two of the forms that Author 1 made in the summer of 2022, the *Horned Torus* form and the *Envelope Surface*. We also used it to print one new form Author 1 has been working on, the *Clebsch Diagonal Cubic*. All of these forms have steep overhangs, and the first two are closed off at the top as modeled in Figure 17-bottom.

To print the *Horned Torus* in 2022, Author 1 split the 3D model into four large sections. The model was split up into sections that she knew would print successfully with just a double wall and infill as discussed in Section 3.3 and seen in Figure 18-top. In the summer of 2023, Author 1 split up the main body of the form into just two sections, Figure 18-bottom. Since both sides of the form are rounded, it was necessary to split up the body so that it had a flat base to begin the print. The small pointy horns were printed separately to retain their detail. One of the body sections was 283mm x 184mm x 361mm and the other was 131mm x 145mm x 330mm. The bigger part was significantly larger than what Author 1 was able to print last summer and both forms were printed with WeaveSlicer without any infill. They were both stable throughout the print and there was no noticeable slumping or collapsing. The lack of infill and few parts made assembly easier and more streamed-lined.

The *Envelope Surface* has an even more dramatic overhang than the *Horned Torus*. Author 1 split it into two sections for printing in 2022, but used significant infill to ensure that it did not collapse. In 2023, Author 1 split the form in two pieces with no infill. These



Horned Torus
$x^4 + x^2(2y^2 - z^2 - 1) +$
$y^4 + y^2(z(z+2) - 1) +$
$z^2((z-2)z+2) = 0$

Envelope Surface
$(z - xy)^2 = (1 - x^2)(1 - y^2)$

Clebsch Diagonal Cubic
$81(x^3 + y^3 + z^3) - 9(x^2 + y^2 + z^2) -$
$189(x^2y + x^2z + xy^2 + xz^2 + y^2z + yz^2) +$
$54xyz - 9(x + y + z) + 126(xy + xz + yz) - 1 = 0$

Figure 17: Top: Finished images of the three mathematical surfaces printed with WeaveSlicer. Bottom: Models and equations of the three mathematical surfaces

Figure 18: Top: Workflow of *Horned Torus* build from summer 2022 residency from left to right. One piece with infill of a four-part sculpture immediately after printing. Infill is removed from each piece. The pieces are smoothed and joined together to create one half of the final piece. Multiple cracks developed along print lines after firing. Bottom: Workflow of Horned Torus build from summer 2023 residency from left to right. Large part of the body of the sculpture without any infill. Smaller part of the body of the sculpture without any infill. The two pieces are smoothed and joined together. No cracks appeared after firing.

forms also printed without slumping or collapse. Even with infill, this piece somewhat collapsed when printed in the summer of 2022. Author 1 not only spent a lot of time carving away all the infill, but she also had to rebuild the parts that collapsed. In 2023, the parts printed with WeaveSlicer were strong and had uniform thickness. The process of assembling and finishing the piece was significantly easier.

The *Clebsch Diagonal Cubic* piece was different from the other two because the final piece was meant to be an open surface. The model was split up into four pieces in Rhino, and each piece was altered so that it was a closed form that the WeaveSlicer could slice, see Figure 5. Similar to the previous two forms the parts printed well without any slumping. Author 1 then smoothed and assembled the pieces. There were some walls that were necessary for a successful print that were then cut away in the final piece. The open nature of the *Clebsch Diagonal Cubic* demonstrate that the walls of the form have a uniform thickness, which was the main contribution of WeaveSlicer.

For all three of these forms, after the parts were printed and dried until a leather hard state, Author 1 smoothed the texture that resulted from the print, and assembled the parts. Having fewer parts made the smoothing and assembly much quicker and more efficient. This part of the process required a lot of handling and touching of the pieces. Author 1 noticed that she could feel the uniformity of the wall thickness, and the forms felt very strong. Weave slicer allowed Author 1 to make her work with a more efficient and streamlined workflow. The forms she created with WeaveSlicer were also less prone to cracking in the kiln. There were fewer parts to assemble, which meant there were fewer seams that can be sources of cracking. Author 1 also noticed that the pieces did not crack along any of the print layers as was happening when she used Cura to slice the forms. As a final step, Author 1 glazed and fired her pieces one more time to achieve their final look, Figure 17 top.

WeaveSlicer allowed Author 1 to successfully print and fabricate forms that she could not have before. Using WeaveSlicer did not eliminate all ceramic post-processing, but streamlined it and made the post-processing easier and more effective. Author 1 still made forms with multiple parts, but WeaveSlicer allowed her to split her forms into fewer and larger parts, where each part could each be printed with one tube of clay. Post-processing like smoothing, carving, attaching, and piercing is very common when making objects out of clay. WeaveSlicer does not seek to eliminate all of this post-processing, but it facilitates and makes these post-processing techniques more possible. It can print an expanded set of geometries that have even walls and are less likely to crack when fired.

6.2 Summer 2023 Residents

We also applied WeaveSlicer to print forms designed by the artists participating in the Summer 2023 residency in the lab. We tested out 3D forms that were unprintable with traditional slicing methods to compare the results with WeaveSlicer as well as forms specifically made for WeaveSlicer.

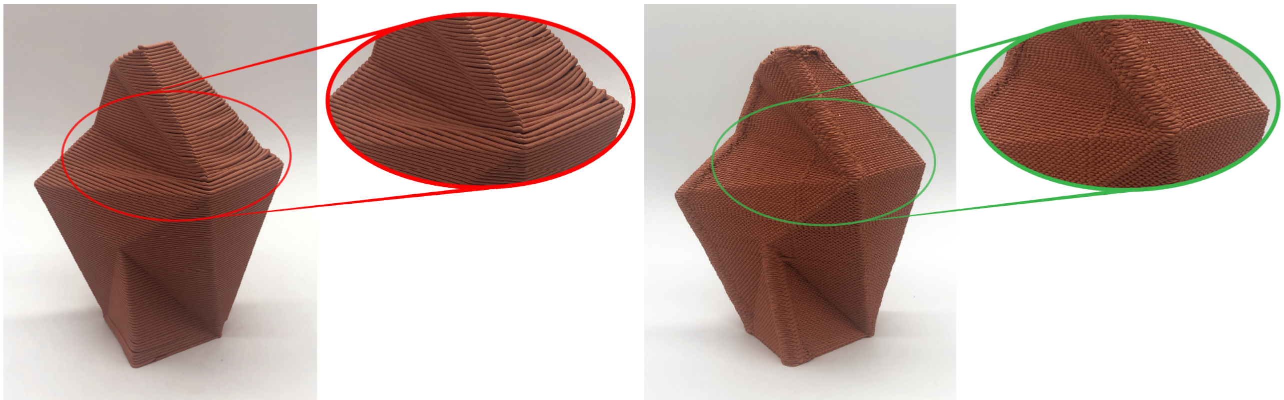


Figure 19: Images of *Sunfish* piece made by Resident 1 sliced with Simplify3D on the left and WeaveSlicer on the right. The zoomed in area on the left shows the slumping and delaminating of layers when printed with a traditional slicer. The same area on the one sliced by WeaveSlicer is highlighted on the right.

Resident 1 is a Native American potter and multimedia artist. He is a member of Cochiti Pueblo and received a Bachelor's degree in Architecture. His work blends contemporary approaches with indigenous pottery traditions, featuring striking geometric shapes and surfaces painted in the traditional Cochiti style. Early in the residency, Resident 1 attempted to print a piece titled *Sunfish*, a closed geometric form with faces of varying degrees of overhang. The single spiral toolpath created using Simplify3D [57] resulted in slumping, Figure 19-left. When printed with WeaveSlicer, the adaptive amplitude successfully printed all of the overhang walls without any slumping, Figure 19-right.

Resident 2 is a Native American potter and jeweler. She is a member of San Felipe Pueblo and has a Bachelor's degree in Fine Arts. She uses digital fabrication and her extensive knowledge as a jeweler to make multimedia art. Resident 2 was very interested in the texture produced by WeaveSlicer as a result of printing an oscillating toolpath, while also struggling to print successfully with Cura [64] and Simplify3D [57]. She used the properties of WeaveSlicer as both a structural and decorative element of her piece called *Anfractuous Transmutation*, and created a form with protruding ribs which she later smoothed, leaving recessed parts unaltered, Figure 20. This form was printed from naturally harvested "wild" clay and pit fired using traditional Pueblo pottery techniques. This provides further evidence of WeaveSlicer's applicability to different clay bodies and firing processes.

7 DISCUSSION

7.1 Limitations and Future Directions for WeaveSlicer

Currently, WeaveSlicer works only for solid forms without holes or multiple contours in one layer. Both of these instances require the implementation of travel paths as each layer could have curves that are not connected. Depending on how many curves per layer and how they are nested in each other, the problem of organizing and figuring out optimal travel paths becomes nontrivial. We chose to focus on making the slicer work optimally for a smaller subset of geometries. As discussed in Section 6, Author 1 split up her forms into multiple sections in Rhino before printing to ensure that their geometry would work well with WeaveSlicer. While we have not yet implemented full slicing capabilities, *we hope to continue to build on the software to be able to slice and print more complex topologies.* We are also hopeful that our software and conceptual contribution can be used and integrated into other custom slicing software.

We note that even with WeaveSlicer the 15° tests in the overhang tests depicted in Figure 12 were not successful. We attribute this failure to both the movement of the print nozzle and the forces of gravity. At 15°, the amplitude is at its greatest and puts greater force on the clay moving in and out, causing rippling motions in the printed clay. As with all prints, the clay is fighting against gravity, and the dramatic overhang of 15° means there's more surface area and weight to pull the clay downward. While our adaptive layer thickness wavered or failed at our most dramatic wall angles, we note that there are other parameters that we can potentially modify to successfully print the 15° overhang. For instance, decreasing the layer height could compress the clay more, thus resulting in a

Figure 20: *Anfractuous Transmutation* made by Resident 2 and sliced with WeaveSlicer. It is unfired on the left, and finished by pitfiring on the right. Resident 2 smoothed certain areas of the pot and left the texture of the WeaveSlicer toolpath in others.

Figure 21: Additional artifacts printed using WeaveSlicer. Top: Porcelain vases printed on the Eazao Zero printer with a nozzle width of 1.5mm. Bottom (left to right): Earthenware sculpture printed in two parts using WeaveSlicer, earthenware vessel printed with WeaveSlicer on the 3D PotterBot 10 PRO with a 3mm nozzle, earthenware vessel printed with WeaveSlicer on the 3D PotterBot 10 PRO with a 3mm nozzle, porcelain teapot printed on the Eazao Zero printer with a nozzle width of 1.5mm, stoneware vessel printed on the Eazao Zero printer with a nozzle width of 1.5mm

more stable form. Another potential solution might be to print on a non-planar base.

7.2 Versatility of WeaveSlicer

The simplicity of WeaveSlicer's geometry (e.g., Equation 1) allows us to apply our technique to all different types of clays, 3D printers, and programming/CAD environments. We demonstrate the flexibility of WeaveSlicer in this paper through two different testing setups: (1) an Eazao Zero [25] that printed a white stoneware clay via a Python library that can be used in the Grasshopper environment and (2) a 3D PotterBot 10 PRO [2] that printed a red earthenware clay via solely the Grasshopper environment. We envision WeaveSlicer being used with a variety of printers, environments, and clay materials. We also note that WeaveSlicer does not impact other clay processes such as firing—we successfully fired prints in both a kiln (Author 1) and a pit (Residents 1 and 2).We used WeaveSlicer to make artifacts ranging from 2mm to 20mm thick that were made with natural wild clay, commercial earthenware, a sculpture clay body, and porcelain. Drying and firing times needed to be adjusted depending on their thicknesses. The amplitude of the sinusoidal toolpath and the consistency of the extruded clay ensured that we were not introducing air bubbles into the walls. All of the artifacts were fired, and none of them exploded or cracked, Figure 21. Through these artifacts, we ultimately demonstrate how versatile WeaveSlicer can be and envision WeaveSlicer benefiting other ceramics artists, as well as makers, designers, and HCI researchers who want to work with clay 3D printing. By creating geometries that were once, impossible, WeaveSlicer opens up an easy-to-implement way to print new forms that were not previously possible with clay.

7.3 Aesthetics of "Woven" Clay

In conducting our tests of WeaveSlicer (Section 5) and demonstrating it through our final applications (Section 6), we noticed qualities in the prints that were unexpected, but also visually compelling. Ceramic 3D printing is instantly recognizable by the clearly defined horizontal extrusion lines that are created in the printing process. Our forms had a radically different texture, one that was reminiscent of textiles, making them look almost like woven baskets (Figure 22-left), *which ultimately inspired the name WeaveSlicer*. While this "woven" texture has been previously explored by artists such as Ron Rael [49] and Timeya [58], our texture is significantly emphasized due to the nestling sinusoidal layers forming what looked like bumps on the surface. The clay filament was wavy like yarn as it furled up around the vessel, thus introducing us to a new aesthetic quality of clay. The materiality of "woven" clay makes us consider possibilities in combining textile and ceramic craft practices like developing weave patterns. This metaphor of weaving and textiles carried into the collapsed structures which appeared to unravel as shown in Figure 22-center and right.

Author 1 removed the texture created by WeaveSlicer because she wanted her final pieces to be smooth. However, Resident 2 embraced the texture that results from WeaveSlicer, using it as a decorative element in her final piece. She chose to smooth and burnish the ribs of the vase and left the woven texture in the more recessed places. When asked why she made this decision, she said, "In pueblo pottery, there is a phenomenon of touching the vessel to feel the imprints of the artists hands, especially on the interior surface. This is seen as a way to test the authenticity of the vessel

Figure 22: Left: Vase with a woven texture. Center and Right: Examples of unraveled 15° wall angle test prints.

and a way of seeing the Trace[1] of the maker's hands in the clay. Thinking of this, I chose to leave the recessed areas with the texture from the print as a way of showing the Trace left from the 3D printer." This demonstrated that the sinusoidal curve was not only a useful shape for facilitating variable amplitudes and creating a continuous toolpath, but it was also an opportunity for decoration and surface on a final piece.

7.4 Reflecting on Artist-Researcher Collaborations in the Context of HCI Residency Programs

The collaboration between artists and researchers during the summer residencies was instrumental in the development of WeaveSlicer. The software addresses challenges that arose from Author 1's practice, with the central insight behind the software being anchored to her deep understanding of clay and traditional ceramics practice. That being said, the software was developed collaboratively with the other researchers in the lab, leveraging their collective expertise in ceramics, mathematics, and software development. Finally, a new resident cohort was able to help evaluate the software, verifying its applicability to a range of clay forms and its utility outside the context of Author 1's practice.

Residencies are beginning to emerge as a significant research methodology in HCI. As Devendorf et al. have discussed and this work makes clear, artists can serve as important *technical collaborators* in research [19]. Author 1's technical knowledge about the material as well as the field of ceramics made her able to see more ambitious and aspirational possibilities for what could be made with a 3D printer. Before the summer of 2022, the researchers in the lab had not considered using the 3D printer to make large-scale sculptures that did not resemble a vessel. Author 1 was accustomed to building large sculptures in parts using many different ceramic techniques, so when she began using the 3D clay printers, it felt natural to try to integrate the 3D printer into these familiar techniques. It was this new perspective paired with personal motivation to print objects with different geometries and scales that drove the development of WeaveSlicer.

We also highlight how our residency was *mutually beneficial* [20] for both the artists and the researchers. WeaveSlicer directly supports both Author 1's creative practice, as well as our lab's research objectives for developing new creative tools and technologies. The long-term nature of our collaboration is also significant. This work was made possible by the in-depth and sustained time we have been able to spend together, working side by side in the lab. Through this multi-year process, researchers have developed a much richer and nuanced understanding of clay and artists have explored new digital fabrication technologies. Collaboratively, we have been able to develop new technical and artistic approaches to digital fabrication in clay. We believe that it is unlikely any one of us would have developed a tool like WeaveSlicer if we were working in isolation.

8 CONCLUSION

In this work, we introduce *WeaveSlicer*, a craft-inspired computational tool for slicing 3D forms with dramatic angles into printable objects. Through WeaveSlicer we demonstrate a wider possibility of 3D-printed ceramic forms that were previously impossible to print with traditional "normal" slicers. The motivation to print at more varied geometries was introduced through the 2022 artist residency by Author 1, who returned to the lab one year later as a researcher and co-created WeaveSlicer. We evaluated WeaveSlicer by printing bowls of varying overhang angles as well as half spheres, then utilized WeaveSlicer to print large sculptures designed by Author 1 as well as various objects designed by our labs' artists in residence in 2023. Ultimately, we see WeaveSlicer as the result of a *mutually beneficial collaboration* between artists and researchers that we envision being widely adopted by both groups to print a wider range of geometries in clay.

ACKNOWLEDGMENTS

This work is supported by National Science Foundation (NSF) Grant No. 2026218. We would like to thank Jared Tso, Jeff Suina, Monica Silva Lovato, Alyshia Bustos, Jaime Gould, Erin McClure, and Alyssa Johnson - team members of the Hand and Machine lab.

REFERENCES

[1] Rhinocerous 3D. 2023. Rhinoceros 3D. https://www.rhino3d.com/
[2] 3D Potter. 2022. 3D Potter - Real Clay 3D Ceramic Printers. https://3dpotter.com
[3] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference*

[1] Resident 2 describes Trace as, "Trace; the deposits of identity, culture, and history left behind by previous generations, multigenerational knowledge and ancestral connections."

on Human Factors in Computing Systems (CHI '19). Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300414

[4] Lea Albaugh, James McCann, Lining Yao, and Scott E. Hudson. 2021. Enabling Personal Computational Handweaving with a Low-Cost Jacquard Loom. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3411764.3445750 event-place: <conf-loc>, <city>Yokohama</city>, <country>Japan</country>, </conf-loc>.

[5] Fernanda Andreola, Alessandro Borghi, Simone Pedrazzi, Giulio Allesina, Paolo Tartarini, Isabella Lancellotti, and Luisa Barbieri. 2019. Spent Coffee Grounds in the Production of Lightweight Clay Ceramic Aggregates in View of Urban and Agricultural Sustainable Development. *Materials* 12, 21 (Jan. 2019), 3581. https://doi.org/10.3390/ma12213581 Number: 21 Publisher: Multidisciplinary Digital Publishing Institute.

[6] Rachel Ann Arredondo, Ofri Dar, Kylon Chiang, Arielle Blonder, and Lining Yao. 2022. Blue Ceramics: Co-designing Morphing Ceramics for Seagrass Meadow Restoration. In *Proceedings of the 14th Conference on Creativity and Cognition (C&C '22)*. Association for Computing Machinery, New York, NY, USA, 392–405. https://doi.org/10.1145/3527927.3531453 event-place: Venice, Italy.

[7] Fiona Bell, Netta Ofer, and Mirela Alistar. 2022. ReClaym our Compost: Biodegradable Clay for Intimate Making. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3491102.3517711

[8] Steve Benford, Chris Greenhalgh, Bob Anderson, Rachel Jacobs, Mike Golembewski, Marina Jirotka, Bernd Carsten Stahl, Job Timmermans, Gabriella Giannachi, Matt Adams, Ju Row Farr, Nick Tandavanitj, and Kirsty Jennings. 2015. The Ethical Implications of HCI's Turn to the Cultural. *ACM Transactions on Computer-Human Interaction* 22, 5 (Sept. 2015), 1–37. https://doi.org/10.1145/2775107

[9] Samuelle Bourgault, Pilar Wiley, Avi Farber, and Jennifer Jacobs. 2023. CoilCAM: Enabling Parametric Design for Clay 3D Printing Through an Action-Oriented Toolpath Programming System. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–16. https://doi.org/10.1145/3544548.3580745

[10] Leah Buechley and Hannah Perner-Wilson. 2012. Crafting technology: Reimagining the processes, materials, and cultures of electronics. *ACM Trans. Comput.-Hum. Interact.* 19, 3 (Oct. 2012), 21:1–21:21. https://doi.org/10.1145/2362364.2362369

[11] Leah Buechley and Franklin Pezutti-Dyer. 2022. Extruder Turtle. https://handandmachine.org/projects/extruder_turtle_rhino/

[12] Leah Buechley and Ruby Ta. 2023. 3D Printable Play-Dough: New Biodegradable Materials and Creative Possibilities for Digital Fabrication. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–15. https://doi.org/10.1145/3544548.3580813

[13] Alice Buso, Holly McQuillan, Milou Voorwinden, and Elvin Karana. 2023. Weaving Textile-form Interfaces: A Material-Driven Design Journey. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23)*. Association for Computing Machinery, New York, NY, USA, 608–622. https://doi.org/10.1145/3563657.3596086 event-place: <conf-loc>, <city>Pittsburgh</city>, <state>PA</state>, <country>USA</country>, </conf-loc>.

[14] Bryan Cera. 2023. Bryan Cera. https://www.bryancera.com/

[15] Zhangwei Chen, Ziyong Li, Junjie Li, Chengbo Liu, Changshi Lao, Yuelong Fu, Changyong Liu, Yang Li, Pei Wang, and Yi He. 2019. 3D printing of ceramics: A review. *Journal of the European Ceramic Society* 39, 4 (April 2019), 661–687. https://doi.org/10.1016/j.jeurceramsoc.2018.11.013

[16] Ashley Del Valle, Mert Toka, Alejandro Aponte, and Jennifer Jacobs. 2023. PunchPrint: Creating Composite Fiber-Filament Craft Artifacts by Integrating Punch Needle Embroidery and 3D Printing. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3581298

[17] Audrey Desjardins and Timea Tihanyi. 2019. ListeningCups: A Case of Data Tactility and Data Stories. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 147–160. https://doi.org/10.1145/3322276.3323694

[18] Audrey Desjardins, Timea Tihanyi, Freesoul El Shabazz-Thompson, Brock Craft, and Julia Saimo. 2023. THE INNER EAR: CAPTURING AND PHYSICALIZING HOME VIBRATIONS. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23)*. Association for Computing Machinery, New York, NY, USA, 594–607. https://doi.org/10.1145/3563657.3596070

[19] Laura Devendorf, Katya Arquilla, Sandra Wirtanen, Allison Anderson, and Steven Frost. 2020. Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–13. https://doi.org/10.1145/3313831.3376820

[20] Laura Devendorf, Leah Buechley, Noura Howell, Jennifer Jacobs, Cindy Hsin-Liu Kao, Martin Murer, Daniela Rosner, Nica Ross, Robert Soden, Jared Tso, and Clement Zheng. 2023. Towards Mutual Benefit: Reflecting on Artist Residencies as a Method for Collaboration in DIS. In *Designing Interactive Systems Conference*. ACM, Pittsburgh PA USA, 124–126. https://doi.org/10.1145/3563703.3591452

[21] Laura Devendorf, Sasha de Koninck, and Etta Sandry. 2022. An Introduction to Weave Structure for HCI: A How-to and Reflection on Modes of Exchange. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22)*. Association for Computing Machinery, New York, NY, USA, 629–642. https://doi.org/10.1145/3532106.3534567

[22] Laura Devendorf and Daniela K. Rosner. 2017. Beyond Hybrids: Metaphors and Margins in Design. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17)*. Association for Computing Machinery, New York, NY, USA, 995–1000. https://doi.org/10.1145/3064663.3064705

[23] Laura Devendorf and Kimiko Ryokai. 2015. Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, Seoul Republic of Korea, 2477–2486. https://doi.org/10.1145/2702123.2702547

[24] Nir Dick, Naama Glauber, Adi Yehezkeli, Moran Mizrahi, Shani Reches, Maiayn Ben-Yona, Anna Carmi, and Amit Zoran. 2018. Design with Minimal Intervention: Drawing with Light and Cracks. In *Proceedings of the 2018 Designing Interactive Systems Conference (DIS '18)*. Association for Computing Machinery, New York, NY, USA, 1107–1120. https://doi.org/10.1145/3196709.3196814

[25] Eazao. 2022. Eazao Zero - Eazao. https://www.eazao.com/product/eazao-zero/

[26] Sarah Fdili Alaoui. 2019. Making an Interactive Dance Piece: Tensions in Integrating Technology in Art. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 1195–1208. https://doi.org/10.1145/3322276.3322289 event-place: San Diego, CA, USA.

[27] Gerd Fisher. 1986. *Mathematical Models: From the Collections of Universities and Museums-Photograph Volume and Commentary* (2nd ed.). Springer-Spektrum, Weisbaden, Germany. https://doi.org/10.1007/978-3-658-18865-8

[28] Matthew Flagg and James M. Rehg. 2006. Projector-guided painting. In *Proceedings of the 19th annual ACM symposium on User interface software and technology (UIST '06)*. Association for Computing Machinery, New York, NY, USA, 235–244. https://doi.org/10.1145/1166253.1166290

[29] Camila Friedman-Gerlicz. 2023. Camila Friedman-Gerlicz. https://camilafg.com/

[30] Camila Friedman-Gerlicz. 2024. WeaveSlicer. https://github.com/Hand-and-Machine/WeaveSlicer

[31] Mikhaila Friske, Shanel Wu, and Laura Devendorf. 2019. AdaCAD: Crafting Software For Smart Textiles Design. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300575

[32] Daniel Gagnon-King, Lee Jones, and Sara Nabil. 2023. Interactive Stained-Glass: Exploring a new design space of traditional hybrid crafts for novel fabrication methods. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3569009.3572796

[33] Mafalda Gamboa. 2022. Conversations with Myself: Sketching Workshop Experiences in Design Epistemology. In *Proceedings of the 14th Conference on Creativity and Cognition (C&C '22)*. Association for Computing Machinery, New York, NY, USA, 71–82. https://doi.org/10.1145/3527927.3531450

[34] Jean Hergel, Kevin Hinz, Sylvain Lefebvre, and Bernhard Thomaszewski. 2019. Extrusion-based ceramics printing with strictly-continuous deposition. *ACM Transactions on Graphics* 38, 6 (Nov. 2019), 194:1–194:11. https://doi.org/10.1145/3355089.3356509

[35] Melody Horn, Amy Traylor, and Leah Buechley. 2022. Slabforge: Design Software for Slab-Based Ceramics. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3491102.3517663

[36] Jennifer Jacobs, Joel Brandt, Radomír Mech, and Mitchel Resnick. 2018. Extending Manual Drawing Practices with Artist-Centric Programming Tools. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174164

[37] Jennifer Jacobs and Leah Buechley. 2013. Codeable objects: computational design and digital fabrication for novice programmers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. Association for Computing Machinery, New York, NY, USA, 1589–1598. https://doi.org/10.1145/2470654.2466211

[38] Rachel Jacobs, Steve Benford, and Ewa Luger. 2015. Behind The Scenes at HCI's Turn to the Arts. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, Seoul Republic of Korea, 567–578. https://doi.org/10.1145/2702613.2732513

[39] Lee Jones, Greta Grip, and Sara Nabil. 2023. Wear Your Heart on Your Sleeve: Using Digital Knitting Machines to Craft Wearable Biodata Portraits. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23)*. Association for Computing Machinery, New York, NY, USA, 547–563. https://doi.org/10.1145/3563657.3596007

[40] Lee Jones, Miriam Sturdee, Sara Nabil, and Audrey Girouard. 2021. Punch-Sketching E-textiles: Exploring Punch Needle as a Technique for Sustainable, Accessible, and Iterative Physical Prototyping with E-textiles. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied*

Interaction (TEI '21). Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3430524.3440640
[41] Makayla Lewis, Miriam Sturdee, Thuong Hoang, Sarah Fdili Alaoui, Angelika Strohmayer, and Mafalda Gamboa. 2023. Futuring (CHI)Art: Building a Collective Common Future. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–5. https://doi.org/10.1145/3544549.3573791
[42] Takashi Maekawa. 1999. An overview of offset curves and surfaces. *Computer-Aided Design* 31, 3 (March 1999), 165–173. https://doi.org/10.1016/S0010-4485(99)00013-5
[43] Shiran Magrisso, Moran Mizrahi, and Amit Zoran. 2018. Digital Joinery For Hybrid Carpentry. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3173574.3173741
[44] Hedieh Moradi, Long N Nguyen, Quyen-Anh Valentina Nguyen, and Cesar Torres. 2022. Glaze Epochs: Understanding Lifelong Material Relationships within Ceramics Studios. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3490149.3501310
[45] Jolie Ngo. 2023. Jolie Ngo. https://ngojolie.net/
[46] Charlotte Nordmoen and Andrew P. McPherson. 2022. Making space for material entanglements: A diffractive analysis of woodwork and the practice of making an interactive system. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22)*. Association for Computing Machinery, New York, NY, USA, 415–423. https://doi.org/10.1145/3532106.3533572
[47] Huaishu Peng, Rundong Wu, Steve Marschner, and François Guimbretière. 2016. On-The-Fly Print: Incremental Printing While Modelling. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 887–896. https://doi.org/10.1145/2858036.2858106
[48] B. Pham. 1992. Offset curves and surfaces: a brief survey. *Computer-Aided Design* 24, 4 (April 1992), 223–229. https://doi.org/10.1016/0010-4485(92)90059-J
[49] Ron Rael and Virginia San Fratello. 2022. Bad Ombres v.2 | Emerging Objects. http://emergingobjects.com/project/bad-ombres-v-2/
[50] Mohammad Abu Nasir Rakib, Jeremy Scidmore, Justin Ginsberg, and Cesar Torres. 2023. Thermoplastic Kilnforms: Extending Glass Kilnforming Techniques to Thermoplastic Materials using Ontology-Driven Design. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. ACM, Pittsburgh PA USA, 263–281. https://doi.org/10.1145/3563657.3596027
[51] A. Reijnders. 2005. *The Ceramic Process: A Manual and Source of Inspiration for Ceramic Art and Design*. University of Pennsylvania Press, Incorporated. https://books.google.com/books?id=qWy9DAAAQBAJ
[52] D. Rhodes. 2015. *Clay and Glazes for the Potter*. Ravenio Books. https://books.google.com/books?id=9ed8CwAAQBAJ
[53] Michael L. Rivera, S. Sandra Bae, and Scott E. Hudson. 2023. Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23)*. Association for Computing Machinery, New York, NY, USA, 294–311. https://doi.org/10.1145/3563657.3595983
[54] Alec Rivers, Andrew Adams, and Frédo Durand. 2012. Sculpting by numbers. *ACM Transactions on Graphics (TOG)* 31, 6 (2012), 1–7. Publisher: ACM New York, NY, USA.
[55] Daniela K. Rosner, Miwa Ikemiya, and Tim Regan. 2015. Resisting Alignment: Code and Clay. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15)*. Association for Computing Machinery, New York, NY, USA, 181–188. https://doi.org/10.1145/2677199.2680587
[56] Roy Shilkrot, Pattie Maes, Joseph A. Paradiso, and Amit Zoran. 2015. Augmented Airbrush for Computer Aided Painting (CAP). *ACM Transactions on Graphics* 34, 2 (March 2015), 19:1–19:11. https://doi.org/10.1145/2699649
[57] Simplify3D. 2024. Simplify3D. https://www.simplify3d.com/
[58] Slip Rabbit Studios. 2023. Slip Rabbit Studios. https://www.sliprabbit.org
[59] Miriam Sturdee and Joseph Lindley. 2019. Sketching & Drawing as Future Inquiry in HCI. In *Proceedings of the Halfway to the Future Symposium 2019 (HTTF 2019)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3363384.3363402
[60] Rundong Tian, Sarah Sterman, Ethan Chiou, Jeremy Warner, and Eric Paulos. 2018. MatchSticks: Woodworking through Improvisational Digital Fabrication. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173723
[61] Vasiliki Tsaknaki, Ylva Fernaeus, Emma Rapp, and Jordi Solsona Belenguer. 2017. Articulating Challenges of Hybrid Crafting for the Case of Interactive Silversmith Practice. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17)*. Association for Computing Machinery, New York, NY, USA, 1187–1200. https://doi.org/10.1145/3064663.3064718
[62] Vasiliki Tsaknaki, Ylva Fernaeus, and Mischa Schaub. 2014. Leather as a material for crafting interactive and physical artifacts. In *Proceedings of the 2014 conference on Designing interactive systems*. ACM, Vancouver BC Canada, 5–14. https://doi.org/10.1145/2598510.2598574
[63] Robert Tubbs. 2014. *Mathematics in 20th –Century Literature and Art: Content, Form, and Meaning*. Johns Hopkins University Press, Baltimore, MD. https://doi.org/10.1007/978-3-658-18865-8
[64] Ultimaker. 2024. Ultimaker Cura. https://ultimaker.com/software/ultimaker-cura/
[65] Ron Wakkary, Doenja Oogjes, Sabrina Hauser, Henry Lin, Cheng Cao, Leo Ma, and Tijs Duel. 2017. Morse Things: A Design Inquiry into the Gap Between Things and Us. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17)*. Association for Computing Machinery, New York, NY, USA, 503–514. https://doi.org/10.1145/3064663.3064734
[66] Ron Wakkary, Doenja Oogjes, Henry W. J. Lin, and Sabrina Hauser. 2018. Philosophers Living with the Tilting Bowl. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–12. https://doi.org/10.1145/3173574.3173668
[67] Karl D.D. Willis, Cheng Xu, Kuan-Ju Wu, Golan Levin, and Mark D. Gross. 2010. Interactive fabrication: new interfaces for digital fabrication. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction (TEI '11)*. Association for Computing Machinery, New York, NY, USA, 69–72. https://doi.org/10.1145/1935701.1935716
[68] Clement Zheng, Bo Han, Xin Liu, Laura Devendorf, Hans Tan, and Ching Chiuan Yen. 2023. Crafting Interactive Circuits on Glazed Ceramic Ware. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–18. https://doi.org/10.1145/3544548.3580836
[69] Clement Zheng, HyunJoo Oh, Laura Devendorf, and Ellen Yi-Luen Do. 2019. Sensing Kirigami. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 921–934. https://doi.org/10.1145/3322276.3323689
[70] Amit Zoran and Joseph A. Paradiso. 2013. FreeD: a freehand digital sculpting tool. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Paris France, 2613–2616. https://doi.org/10.1145/2470654.2481361
[71] Amit Zoran, Roy Shilkrot, Suranga Nanyakkara, and Joseph Paradiso. 2014. The Hybrid Artisans: A Case Study in Smart Tools. *ACM Transactions on Computer-Human Interaction* 21, 3 (June 2014), 15:1–15:29. https://doi.org/10.1145/2617570