SketchPath: Using Digital Drawing to Integrate the Gestural Qualities of Craft in CAM-Based Clay 3D Printing

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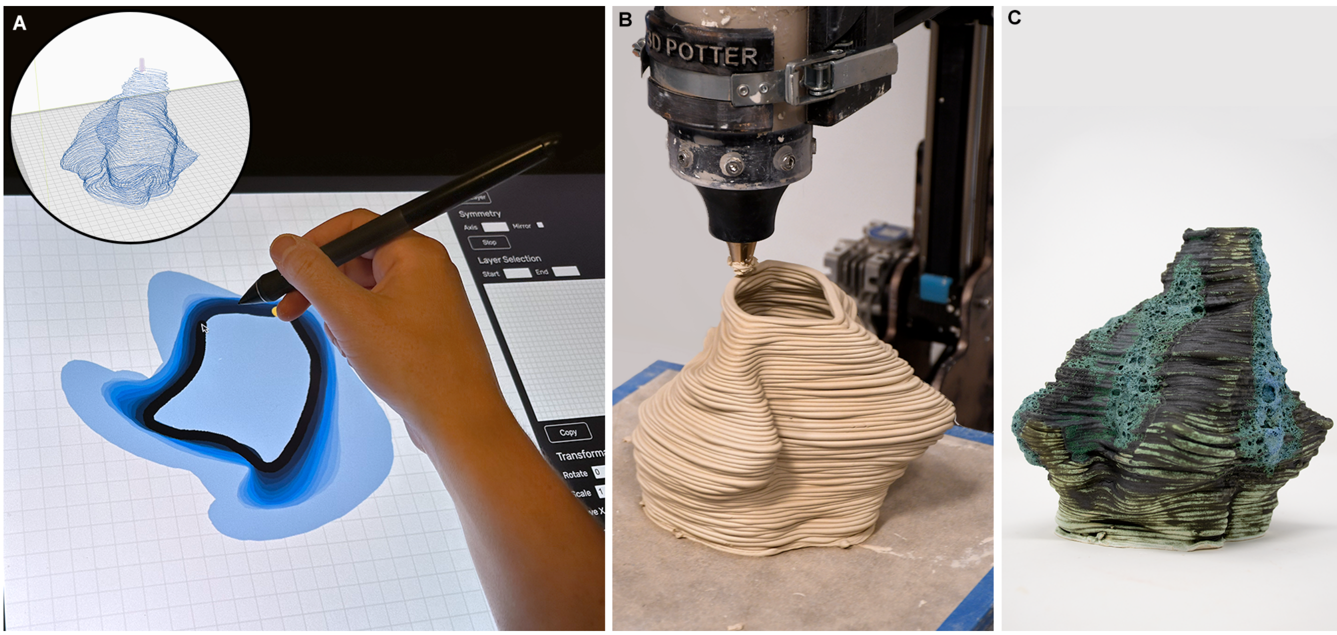

Figure 1: SketchPath is a system for clay 3D printing design that employs drawing layers as the primary creation modality. Here we show the process of an organic form designed in SketchPath. A) Drawing layer 70 of form on the SketchPath canvas with final 3D toolpath render. B) Clay 3D printing of form in progress. C) Final glazed form demonstrating the organic shape and hand-drawn textures of the toolpath.

ABSTRACT

This paper presents the design and outcomes of SketchPath, a system that uses hand-drawn toolpaths to design for clay 3D printing. Drawing, as a direct manipulation technique, allows artists to design with the expressiveness of CAM-based tools without needing to work with a numerical system or constrained system. SketchPath works to provide artists with direct control over the outcomes of their form by not abstracting away machine operations or constraining the kinds of artifacts that can be produced. Artifacts produced with SketchPath emerge at a unique intersection of manual qualities and machine precision, creating works that blend handmade and machine aesthetics. In interactions with our system, ceramicists without a background in CAD/CAM were able to produce more complex forms with limited training, suggesting the future of CAM-based fabrication design can take on a wider range of modalities.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

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1 INTRODUCTION

Over the past two decades, 3D printers have gained popularity as a way to bring the machine precision typically associated with industrial manufacturing into homes, studios, and schools. This technology has allowed individuals to explore the production of their own highly customized and precise objects [3, 16]. Researchers and developers have created tools that enable different methods of designing custom objects for 3D printing, including modeling [2, 34, 41], scanning physical forms [40], and generating numerical representations [15, 29, 42]. Although these approaches aim to reduce the labor of 3D printing, the process of accurately matching digital design qualities with machine constraints still involves a laborious and time-consuming iterative process. To achieve machine precision commonly associated with 3D printing, one has to be dedicated to thoroughly understanding their machine tuning [39] and digital representation, as well as being willing to engage with the complex relationship present when translating from digital to physical. This investment of labor is worthwhile to maximize the potential of 3D printing, but often, software aimed at novices tries to simplify the 3D printing process by obscuring machine complexity and capabilities [19]. We argue that the abstraction of machine functionality disadvantages newcomers to 3D printing, limiting their technical understanding of the process and reducing their capacity to maximize the opportunities available through digital fabrication. Specifically, artists with rich technical mastery in physical form creation, but who are new to 3D printing, encounter limits in creating desirable aesthetic qualities due to the obfuscation of machine capacities.

Clay 3D printing is a compelling case for examining the tensions between the artistic opportunities of 3D printing and the limitations of software abstraction aimed at supporting ease of use. Clay 3D printing allows ceramicists to explore new modes of expression, such as creating unique surface textures or customizing the production process through precision form reproduction. Clay 3D printing practitioners frequently use *CAM-based design techniques* [4, 10, 37]. In this process, the artist uses computer-aided manufacturing (CAM) to directly specify the operations and toolpath the machine will follow to print forms. CAM-based design methods allow for direct control over not just what gets made but how it gets made. In contrast, modeling geometry in computer-aided design (CAD) software and creating toolpaths using slicers significantly reduces the opportunity for low-level control in digital fabrication. Slicers automate the toolpath creation for the user but lack consideration of how the path affects material outcomes.

The primary approach to CAM-based design for clay 3D printing involves using symbolic tools wherein creators control printer behavior by programming numeric expressions. Such tools are powerful in the hands of experienced computer programmers, but they require different skills from manual craft. Further, the CAM-based design modalities are fundamentally misaligned with physical ceramic practices. Numerical representation centers the form-creation process on altering symbolic characters to create digital toolpaths, eliminating the opportunity for the creative physicality that ceramicists generally employ while making forms. Traditional ceramic practices are deeply embedded in the embodied and visual space [18]. Building forms is inherently a physical process with consideration to the visual outcomes. An artist's process to produce forms partially depends on embodied physical capabilities, strength for handling clay, and manual dexterity. Thus, traditional ceramic practices allow individuals to create without symbolic abstraction disrupting the creative flow from mind to body [24].

The gap between current CAM-based design modalities and the embodied processes of physically designing and creating forms presents an opportunity to develop new modalities of designing for clay fabrication. We set out to explore an alternate modality of designing forms for clay 3D printing that preserves the direct control of CAM-based design while lowering the barrier to access and aligning the design process with the manual coiling practices. We created a system, *SketchPath*, that uses drawing as the primary design modality, giving artists CAM control over their toolpaths as they build the form layer by layer. We provide precision operators to support hand-drawn form generation, including drawing with rotational symmetry, layer copying and transformation, and precision layer stacking. We explore alternate printing expectations, outcomes, and relationships with computational design by creating a system that enables toolpath design grounded in direct manipulation and manual skill. While existing CAM-based design tools focus on low-level symbolic manipulation and slicers provide high-level manipulation of toolpaths, we support low-level toolpath control through direct manipulation of graphical specifications (e.g. drawing).

SketchPath was developed as a collaboration between two HCI researchers and two professional ceramic artists during a 10-week craft and computational fabrication residency. Both ceramicists used SketchPath as part of their practice during the residency, producing over 40 printed pieces. We used this process to evaluate the design opportunities of our system by conducting a series of structured discussions between the authors on the aesthetic qualities of SketchPath artifacts and the experience of using the SketchPath system. Our contributions include:

- A drawing system for CAM-based design in clay 3D printing. Our method supports the precision and iterative repetition found in symbolic CAM-based design approaches through a direct manipulation interface.
- A collaborative design process that demonstrates how drawing for CAM-based design can enable skilled manual artists to intuitively develop toolpaths for clay 3D printing.
- A series of artifacts produced in collaboration with professional ceramicists that show the expressive variety possible with SketchPath. In particular, these artifacts show how our system supports the expression of individuals' manual drawing style in 3D-printed clay forms.

2 BACKGROUND

Our work builds on prior research and arts practices in CAM-based design for fabrication, alternate fabrication modalities, and digital clay fabrication practices.

2.1 CAM-Based Fabrication

Digital fabrication design practices have evolved out of engineering traditions in industrial production. Before the industrial incorporation of CNC machines, fabrication depended on machine operators with highly developed manual skills and material knowledge. A managerial push to computationally driven machines shifted the power of machine control from manually skilled workers to specialized engineers [31]. This industrial shift has trickled down into home fabrication, resulting in machines and design processes that reinforce structural imbalances between manually and digitally skilled fabricators. As a result, home machines designed to be accessible and usable without intensive industrial training still present high barriers to use for those with manual and material knowledge, requiring an extensive time investment in learning digital software that is ultimately designed for engineering purposes

We use the term **CAD-based design** to refer to design operations that pertain to digital non-machine specific geometry [28]. We use the term **CAM-based design** to refer to design operations that describe machine-specific toolpaths [8, 27]. HCI researchers have attempted to bridge the gap between manual fabrication knowledge and digital design by focusing on material properties in specific applications of CAM-based design methods such as carpentry [26], textiles [14], and plastic printing [33, 38].

We distinguish between **direct manipulation design tools** and **symbolic design tools**. In symbolic tools, the designer edits a description of the work, often in the form of a textual or visual programming language [44]. In direct manipulation, the designer edits the geometry directly by selecting and manipulating a graphic depiction of the design, receiving immediate visual feedback on the results of their actions[28, 36]. Prior CAM-based design methods, like the ones cited above, primarily rely on symbolic tools. To our knowledge, SketchPath is the first direct manipulation CAM-based design tool for additive fabrication.

2.2 Alternate Fabrication Modalities

Many researchers and artists have explored non-conventional approaches to fabrication that break down digital design paradigms and create new relationships to the fabrication process. Devendorf’s Being the Machine puts a human in the role of a digital fabrication machine by prompting them to assemble 3D forms from found objects by following a point-by-point toolpath [13]. This direct form of assembly encourages creators to engage with manual control and human imperfection, creating a state where they can “relinquish control” and “enter a creative state of mind” when working with their hands. Researchers have also developed workflows that play on material properties and low-level machine parameters to support exploratory form generation [1, 33, 38]. Others have modified fabrication machines to support new material fabrication processes [21].

Sketching has also been investigated as an alternate method to symbolic practices for digital modeling and design. Goel discussed how sketching aligns with the process of designing and human systems of internal representation [17]. Drawing plays a natural role in the design process which has resulted in research on exploring converting 2D drawings into 3D models [22]. Other researchers have investigated drawing in 3D space as a form of modeling [47]. These techniques focus on sketching as an approachable modality of form generation but produce models that still need to be prepared for machining, easing the CAD process but not the CAM process. Spatial Sketch [45] and Sketch Chair [35] both explore an end-to-end sketch-based process from drawing to fabrication but focus specifically on laser cutting planar pieces for assembly. Kim et al. use drawing as one of many real-time physical design interactions for a custom FDM printing setup [25]. Despite capitalizing on the expressiveness of drawing, many sketch-based CAD tools remove unique hand-drawn variations in the translation into fabricatable 3D models. Sketch Furniture is a system from Front Design that captures furniture forms drawn mid-air uniquely preserving the sketched strokes of the forms, but they are then processed for stereolithography printing, thus still focusing on form design rather than toolpath control [9]. Opportunities for sketching as a CAM-based design system have not been thoroughly developed.

2.3 Clay HCI Research

Clay 3D printing technologies emerged in 2009 from Unfold Design Studios [43]. Recently, clay 3D printers have become a topic for HCI fabrication research due to the unique material properties of clay and the exciting design space clay 3D printers offer. Artists and researchers alike are capitalizing on the capabilities of numerical representation and machine precision to specify unique toolpaths that would be laborious to reproduce by hand (Fig. 2). Horn et al. created Slabforge, a system for creating slab-building patterns [20]. Zheng et al. inlaid conductive ink into ceramic surfaces to create circuited ceramic objects [48]. Bryan Czibesz makes a variety of complex organic and geometric forms [5](Fig. 2C). Audrey Desjardins, an HCI researcher, and Timea Tihanyi, a ceramic artist, teamed up to create Listening Cups from sound data [10](Fig. 2F). Keith Simpson specifies toolpathing that builds up forms through compressed dollops of clay [37]. CoilCAM is a Grasshopper library built to create mathematically manipulated parametric vessels [4]. Understandably, ceramicists want to explore clay 3D printing as a new tool but must traverse the gap between manual fabrication expertise and digital CAD/CAM form generation knowledge. Our work aims to explore new modalities of form design by capitalizing on the existing manual skills of ceramicists while maintaining toolpath level control. We theorized that doing so would allow artists to create toolpaths that emulate and diverge from stylistic norms in clay 3D printing.

3 METHODOLOGY

SketchPath was developed during the Expressive Computation Lab’s two-year computational ceramics research residency at the University of California, Santa Barbara. We hosted two professional ceramicists, Raina Lee and Eun-Ha Paek, in the lab for eleven weeks. During the residency, the residents and researchers exchanged knowledge from their respective expertise to generate artifacts and software at the intersection of manual ceramic production and

Figure 2: Notable work in the clay 3D printing field that exemplifies common textural and design elements. A) Researcher Sam Bourgault creates mathematically defined cups where the toolpath extends past the vertical edge of the form to create unsupported drooping loops [4]. B) Artist Jolie Ngo prints multiple vertically extruded forms and hand assembles them into complete works [30]. C) Artist Bryan Czibesz creates geometrically evolving surface textures via unique toolpathing [5]. D) Artist Eun-Ha Paek hand builds forms that she scans and re-prints [32]. E) Researcher Leah Beuchley creates irregular surface patterns by excessively increasing the z height between layers [6]. F) Researcher, Audrey Desjardins, and artist, Timea Tihanyi, teamed up to encode audio data in the toolpath of ceramic cups. [10].

clay 3D printing technologies. The SketchPath development was conducted during the second year of the residency. This allowed us to inform the design of SketchPath from the experiences and feedback of residents in the first year. SketchPath was inspired by prior resident and ceramic coiling expert Pilar Wiley's closing interviews where she discussed the limitations of clay 3D printing with respect to her work. Coming from her coiling practice, Pilar felt that her time was better spent manually producing ceramic work than investing in learning the CAD/CAM skills necessary to capitalize on clay 3D printing technologies. We developed SketchPath to provide our second round of residents with an alternate modality of designing for clay 3D printing that requires lower software learning investment to produce varied printable pieces.

3.1 Collaboration in a Residency Model

Each author brought valuable insights and skills to the research process. Devon is a Ph.D. student and HCI researcher working on designing systems for art and fabrication. Raina is a Los Angeles-based ceramic artist and glazing expert. She creates functional and decorative vessels (Fig. 3 D, E, F). Raina is highly skilled in throwing and coiling but had no experience with clay 3D printing or digital form generation methodologies before the residency. Eun-Ha is a Brooklyn-based ceramic artist and animator who creates stylized figurative works through manual and 3D-printed methods. She has designed for clay 3D printing by scanning hand-built forms and by modeling in Blender (Fig. 3 A, B, C). Jennifer is a professor whose research focuses on digital fabrication and creativity support.

Our methods build on established HCI techniques for technical development through artist collaboration [4, 10, 48]. HCI researchers have used the residency model to meaningfully exchange knowledge with artists and to establish recognition of the technical expertise of artists [11]. There has been broader interest in developing HCI and arts residency models that support extended artistic inquiry and mutual benefit for researchers and artists [12]. We draw from this model in our work, and like prior works, we include our artist collaborators as co-authors because this accurately reflects the critical insights and labor they brought to the work. Further, by conducting this research collaboratively, we developed deeper insights over the eleven-week collaboration which would not have been possible in a short-term user study.

We found the residency model is an effective choice for working with ceramic practitioners because of the time-consuming nature of producing finished ceramic works. Creating with clay necessitates long drying times, bisque firings, glazing, and final firing of all pieces. We were also able to gather long-term feedback about the system and interactions. Although a user study with more participants could have provided broader insights into the versatility of the interactions, working with two ceramic artists for a longer time provided more depth and opportunities for iterative refinement. HCI researchers have raised concerns that the residency model can instrumentalize arts [7]. Devon and Jennifer addressed this by developing personal relationships with the artists, actively facilitating the use of machines and software, and working to align goals across researchers and participants. The residents were also paid at the postdoctoral rate, reflecting the expertise they brought to the research.

3.2 Research Phases

We began development on SketchPath one month before the start of Raina and Eun-Ha's residency. Drawing from the experiences and output of past resident Pilar Wiley, we developed a working prototype before the residents' arrival and introduced it to Raina and Eun-Ha in the second week of the residency. We introduced SketchPath with an overview of Rhino/Grasshopper and pre-configured Grasshopper CAM files designed for plug-and-play use. We provided equal support for each form generation method to help residents harness different tools to support their goals. Devon and Jennifer also presented Raina and Eun-Ha with other options for form generation, including clay 3D printing specific parametric systems, slicing models, scanning forms, or downloading models. At all phases of the residency, the residents had the discretion to use whatever tools they preferred for their work. At regular intervals Devon and other lab members worked to address any questions Raina and Eun-Ha had about SketchPath or other software tools.

The residents also shared their ceramics expertise with us, contributing to our general knowledge of clay practices and the overall efficacy of our clay 3D printing practice. Raina conducted a thorough glaze mixing demo, generating over 30 glaze variations that all lab members used in glazing final works (Fig. 1C, Fig. 9, Fig. 10). Eun-Ha conducted a Blender modeling demonstration, introducing us to one of her typical approaches for creating forms for 3D printing. In addition to specific demonstrations, daily knowledge of form drying, firing, and other clay practices was invaluable for producing artifacts and technologies.

Devon took continual feedback about the system's interactions, printed products, and functionality during residency. Devon continued system development throughout the residency, providing bug fixes, usability improvements, and feature integration derived from resident experiences and feedback. We had two discussions around the system that were recorded and transcribed for evaluation. In our first discussion, the system was introduced and we explored basic functionality. In our second discussion, we conducted a collaborative evaluation of SketchPath and the artifacts produced by Raina, Eun-Ha, and Devon. We discussed the opportunities presented by SketchPath in the context of the software options explored during the residency and its implication for the broader ceramics community's engagement with clay 3D printing.

4 SYSTEM

SketchPath is a *direct-manipulation CAM-based design* system for drawing clay 3D printing toolpaths. We theorized that toolpath drawing can enable artists to execute a CAM-based design process, similar to the clay hand-coiling design process, by allowing them to realize the structure of the form through skilled hand movements and layer-by-layer development. By drawing toolpaths, we seek to narrow the gap to machine control through the artist's manual movements.

SketchPath is a **direct modeling system**, meaning that design operations are unconstrained and constitute destructive edits. We contrast direct modeling with **parametric systems**, in which design operations are constrained by the model parameters [46]. SketchPath is designed to support continuous sketching, letting an artist rapidly build up a form with each layer connecting to the next layer. To avoid interrupting the sketching workflow by requiring artists to specify constraints explicitly, we did not include parametric functionality within the system. The system contains additional layer manipulation features that enable artists to automate aspects of layer creation with precise geometry if desired; however, we do not maintain a parametric representation of these operations.

4.1 Drawing Interface and Controls

We developed SketchPath as a web application to reduce barriers to installation and usability. Upon opening SketchPath, the artist is prompted to select a clay 3D printer profile, nozzle width, and layer height for their print. They then continue to the primary interface, where the artist is presented with a canvas representing a top-down view of the printer bed (Fig. 4A). The canvas has a background grid that is sized according to the chosen printer profile's bed size, with each grid square being equivalent to 1cm on the physical printer bed. The pen stroke width corresponds with the nozzle size and will draw lines of proportional size to the extruded coils while printing. By drawing a 2D line, the artist specifies the print path for a given layer. Artists can progress to the next layer by selecting the next layer button or closing the illustrated layer at the yellow start/end point (Fig. 4G). By enabling drawing through the start/end point, forms can rapidly be built up with a single continuous line. We facilitate gradual layer variation by adapting the onion skinning technique from animation tools, showing the top 13 layers on the canvas as a progressively lightening gradient. Any layers below the 13th from the top are a single light color to give a sense of the periphery of the form while allowing the artist to focus on the immediate form progression they are drawing. We also provide a secondary 3D toolpath representation (Fig. 4D) as an additional general form proportioning and development aid. Artists can refer to this 3D perspective in conjunction with the top-down drawing view.

4.2 Drawing Manipulation Features and Precision

We focus SketchPath on the design of free-form toolpaths; however, to maintain the option of computationally driven precision, we augmented our system with three tools for precision operations: numerical transformations of layers, radial symmetry, and zones of locking successive layers to previous ones. These tools are compatible with free-form manual sketching and allow artists to include aesthetics derived from machine precision when desired. While these modifications are computational iterations on drawn layers, these are non-parametric changes that cannot be modified later without clearing the existing layers.

Figure 3: Prior work of residents. A) Eun-Ha's hand-built chair. B) Eun-Ha's hand-built sculpture. C) Eun-Ha's hand-assembled figurative sculpture comprised of 3D printed components. D) Raina's 30cm moon jar with multicolored glazes over the textured surface. E) Raina's collection of small hand-coiled vessels. F) Raina's small hand-coiled pot with bright glazing and organic surface texture.

4.2.1 Transformations. The Transformation tools allow artists to procedurally duplicate and geometrically transform one or more hand-drawn layers (Fig. 5). First, the artist selects a range of existing layers to be duplicated using the Layer Selection tool panel (Fig 5B). The selected layers are rendered as a light blue copy on the canvas (Fig. 5D). Using the Transformations tool panel (Fig. 5C), an artist can dynamically rotate, scale, or move the layers copy. The light blue layers preview on the canvas will dynamically render transformation changes (Fig. 5D). Any transformation can be applied equally to all selected layers or propagated to each of the selected layers incrementally. For example, if the artist selects four layers and enters a rotation value of one degree, all four layers can be collectively rotated to one degree. Alternately, if the Propagate box is checked, each layer gets an additional one degree of rotation so that the top layer would have 4 degrees of total rotation. Selected layers can also have multiple copies made simultaneously with transforms either applied consistently across all copies or propagated among the copies, creating progressively more extreme transformations on each repetition (Fig. 5E). Once the artist is satisfied with their transformations, they can select the Bake button in the Transformations tool panel (Fig 5C), which will render the new layers as part of the form on the canvas (Fig 5E) and toolpath preview (Fig 5F). This allows artists to generate forms rapidly and create repeating structures or textures (Fig. 5G).

4.2.2 Locking. Locking mode allows precise vertical stacking of specific zones of sequential hand-drawn layers (Fig. 6). First, an artist enters locking mode by selecting 'Start Lock' (Fig. 6A). This allows them to trace zones of the prior layer in light purple (Fig. 6C). Once the artist has traced their desired locked zones in purple, they can end Locking mode (Fig. 6A), and orange entry points will be generated for all locked zones (Fig. 6C). When drawing the following layer, artists can freely draw in any non-locked areas, but once they have entered a locked zone start point, the system will constrain their drawing to directly on top of the prior layer (Fig. 6D). If the artist strays from the locked zone too far, their line will not be rendered. We do this to avoid ambiguity in the artists' drawing intent. Once they have traced one continuous locked zone, they can free draw again until entering another locked zone (Fig. 6D). The artist can draw as many new layers as desired when in Locking mode. When the artist wants to remove the locked zones, they can select the 'Delete' button in the Locking tool panel (Fig. 6A, E). By creating layers that are stacked perfectly on top of each other, artists can control surface texture in these regions and create precise vertical walls (Fig. 6G).

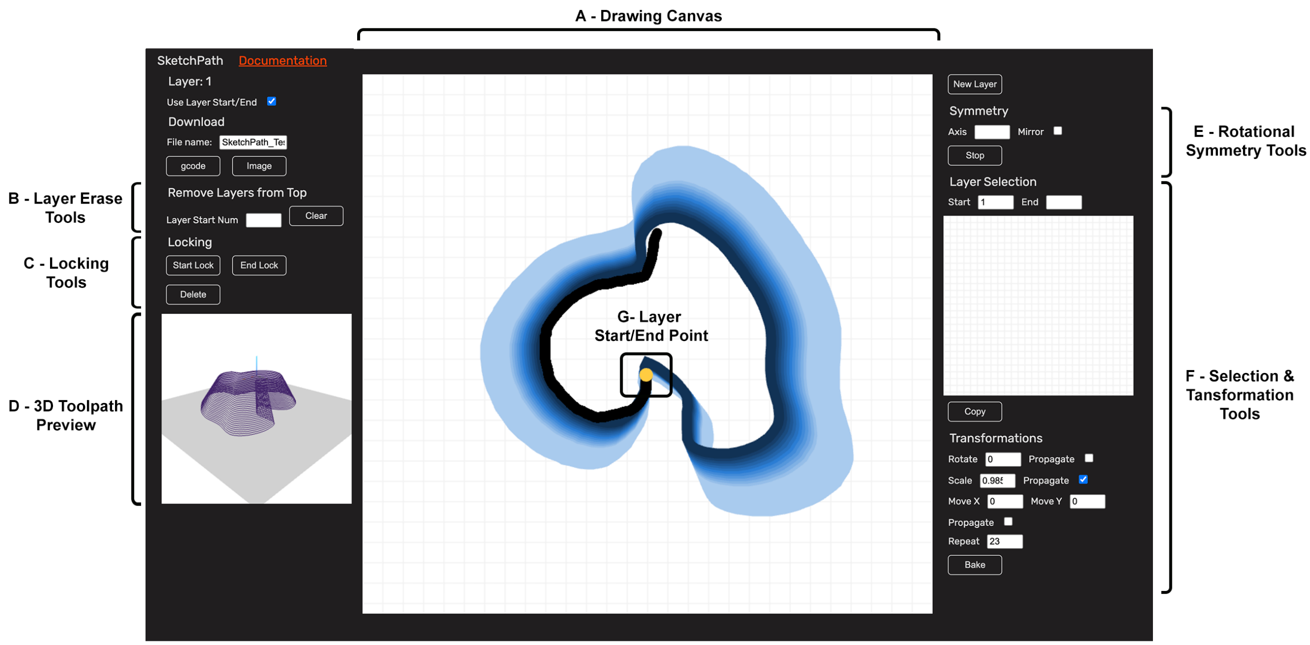

Figure 4: SketchPath web interface. A) drawing canvas, current layer drawings are always a black line with prior layers colored lighter blues. B) Layer Erase Tool - layers can be removed from the top down, leaving 'Layer Start Num' as the new top layer. C) Locking Tools - allows the artist to lock zones of the prior layer to create direct stacking when drawing subsequent layers. D) 3D Toolpath Preview - shows a 3D line render of the toolpath the extruder will follow when printing. E) Rotational Symmetry Tools - allows the artist to draw rotationally symmetric forms. F) Selection and Transform Tools - allows the artist to select groupings of layers to copy and perform rotation, X/Y movement, and scaling transformations on. G) Layer Start/End Point - a yellow dot marking the start/end of each layer allows the artist to start and end each layer automatically while continuing to draw.

4.2.3 Symmetry. Symmetry can be used to create radially symmetric forms and textures reminiscent of radial vessels produced in throwing or hand-building clay traditions. To use symmetry in SketchPath, the artist first selects the number of rotational symmetry axes (n) desired in the Symmetry tool panel (Fig. 7A, E). This will render a light grey circle with a $n/360$ degrees slice at the top (Fig. 7B, F). As an artist draws on the canvas, the system will instantly propagate the specified degree of symmetric lines on the canvas (Fig. 7B, G). The artist can also toggle mirrored symmetry mode (Fig. 7E). This will result in rendering a $2n/360$ degrees slice and mirroring the lines in each n axis-symmetric propagation zone (Fig. 7F). Start/end points are rendered on either side of the drawing slice, allowing for rapid layer completion and form build-up.

4.3 Limitations

SketchPath is a prototype software system developed by a small team over six weeks. As a result, some non-research features are limited compared to software created over more extended development periods and with more significant resources. This is common in systems development research. Our residents noted some feature limitations. SketchPath does not have built-in exporting and importing of in-progress drawing functionality, which requires artists to draw their entire form in a single session. SketchPath has browser compatibility limits and screen size limits. Drawing detailed forms is most effective on a 32-inch Wacom, but we found laptops and iPads also work.

4.4 Summary

By combining a drawing-based interface and a series of optional computational manipulation features, we allow artists to engage in toolpath-level control for clay 3D printing. Drawing-based toolpathing provides low-level machine control while avoiding symbolic numeric specification. Manipulation tools for transformations, locking, and symmetry allow the merging of organic hand-drawn forms and computational precision to develop forms and textures.

5 ARTISTIC PRODUCTION WITH SKETCHPATH

By working with professional ceramicists for an extended period, we were able to observe the long-term use of SketchPath for the production of many objects. Raina printed and fired 35 objects, five of which are reprints of the same cup as part of a series (Fig. 9 B). The largest piece produced was 24.9cm tall and the smallest was 5cm tall. Eun-Ha printed and fired nine SketchPath objects. Some pieces involved high degrees of manual intervention or finishing, which is common for 3D-printed clay works. These interventions

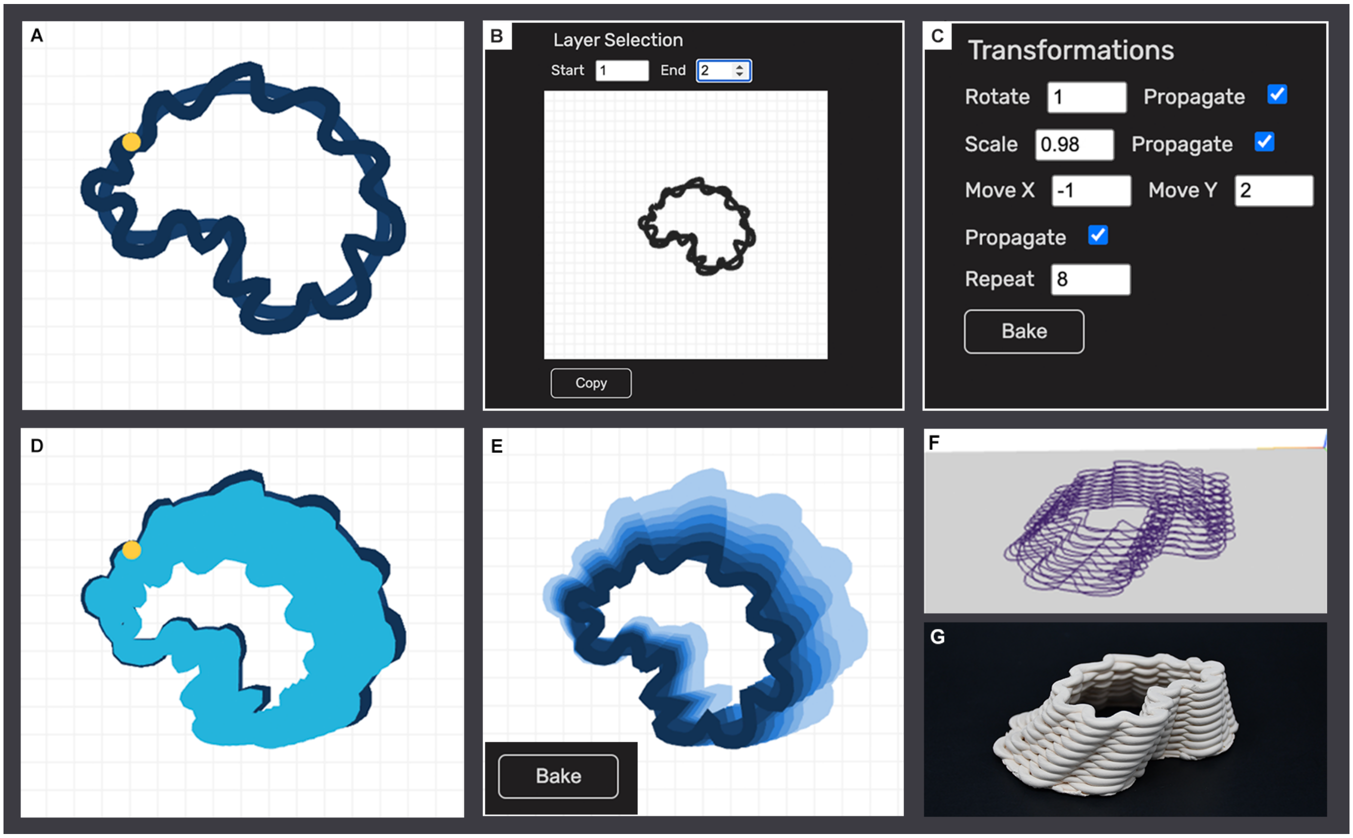

Figure 5: Workflow for Transformation Operations. A) The artist begins drawing a form on the canvas, 2 layers shown here. B) They then select a range of layers using the layer selection tool (layers 1 and 2 are selected here) and press 'copy,' which renders a light blue preview of the selected layers on the active drawing canvas (seen in D). C) In the Transformations tool panel, the artist applies eight repetitions with each transformation propagated. Each repetition incrementally has 1 degree of rotation, 0.98 scaling, and -1 in the X and +2 in the Y axes applied. D) These changes are previewed live on the drawing canvas displayed in light blue on top of the existing drawn form. E) When satisfied with the transformations, the artist presses the 'Bake' button in the Transformations tool panel, resulting in the rendering of the new layers as part of the final form. F) 3D toolpath preview. G) Transformations toolpath 3D printed in clay.

include joining other printed or hand-built clay forms to 3D-printed artifacts and adding support to the artifact during the printing process (e.g. additional pieces of clay, sponges, cloth, human hand). For example, Raina added slab bases onto various forms, rather than hand drawing the base for each object. Printed bases can separate or crack if not properly compressed, so slab bases are seen as a safe alternative for 3D-printed clay artifacts. Eun-Ha attached multiple prints to create large objects or forms that would be unprintable due to overhanging geometry. The residents said they spent 10-45 minutes on average drawing a single form with SketchPath. This process sometimes included restarting the drawing to refine the form's design. We report on the residents' (Raina and Eun-Ha) experience using SketchPath and producing forms as part of their established practice during the residency and Devon's experience using the system to create artifacts as part of the testing and development of SketchPath.

5.1 Ways of Work

The ways of working with SketchPath varied among the three authors who used the system. Raina used an 11-inch iPad and a stylus as her primary drawing device. This enabled her to comfortably draw for longer periods. Devon worked on a 32in. Wacom tablet, drawing with a stylus. Eun-Ha frequently chose to use a mouse and monitor instead of a tablet and stylus. She felt this provided more convenience since she was accustomed to mouse-keyboard CAD setups. Eun-Ha noted that she felt reluctant to invest many hours into drawing an individual piece due to the inability to save in-progress drawings and return to them later. All three authors used a combination of hand drawing and precision tools to generate textures and forms.

We employed two design approaches with SketchPath. We categorize the first approach as "planned design" where the artist pre-plans the form they want to make, and then draws or duplicates successive layers in SketchPath to create the pre-conceived

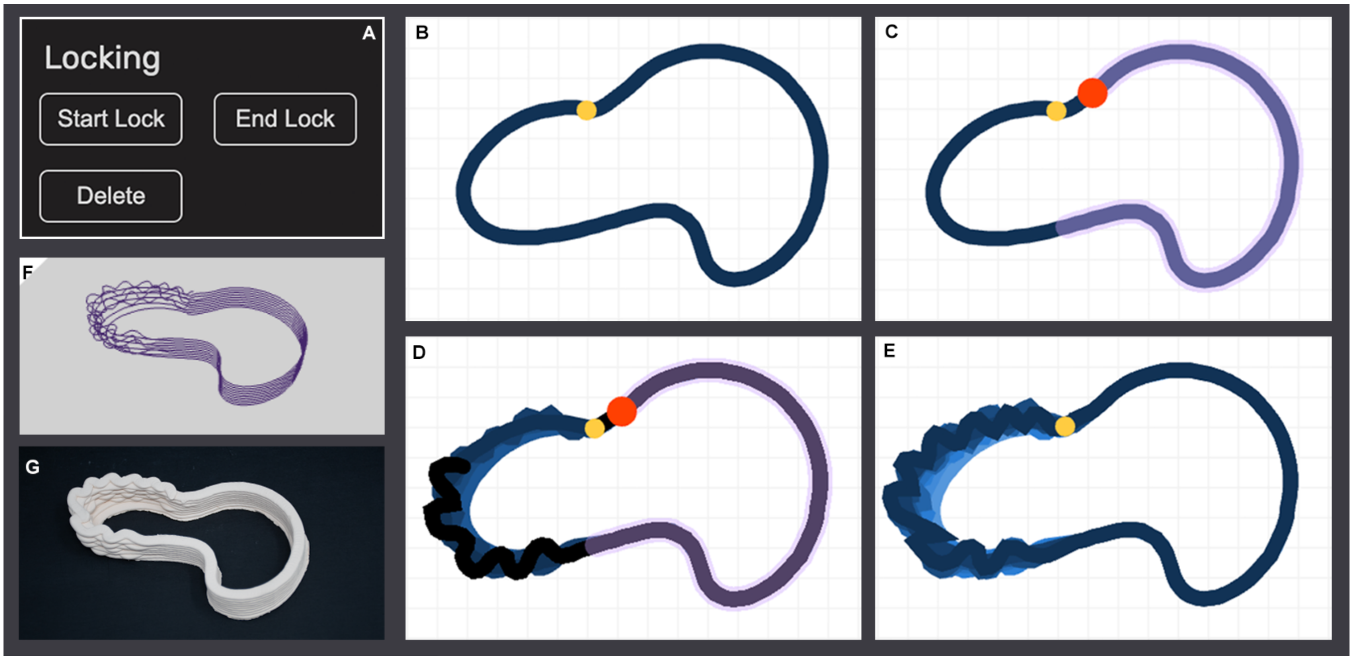

Figure 6: Workflow for Locking Operations. A) Locking tool panel. B) The artist draws a layer on the canvas. C) They press 'Start Lock' (seen in A) and select locked zones by tracing areas of the prior layer in light purple. Then, they click 'End Lock' (seen in A) to return to regular drawing mode. D) In drawing mode, once the artist draws over the bright orange dot, they are constrained to tracing inside the locked zone. Once they have traced the full locked zone, they can draw freely, as seen by the black squiggly line. E) When the artist is done tracing Locked layers they select the 'Delete' button (seen in A) to remove the locked zones and return to free drawing. F) 3D toolpath preview. G) Locking toolpath 3D printed in clay, the right side of the form shows the precise vertical stacking achievable while hand-drawing with locking, and the left side shows free-drawn squiggly textures.

shape. For example, Eun-Ha decided in advance to draw a pitcher and then built up the lines until the 3D toolpath render in the SketchPath interface (Fig. 4D) depicted a form she was satisfied with (Fig. 10D). When executing pre-planned designs, both residents expressed frustration with not being able to visualize the full forms profile until completed, saying it limited overall investment in drawing forms with planned profiles in SketchPath. With the drawing of each layer on top of the form, the artist contributes incrementally to the overall profile, hoping their alignment of stacked layers results in the desired proportions in the final form.

We categorize the second approach as "emergent design" where the artist starts with an abstract design principle or process which they iterate on until they have produced a form they are satisfied with. Eun-Ha described emergent design as akin to "digging a tunnel", where you have to keep going until you discover a satisfying form. As an example of emergent design, Raina drew various mountains that evolved from the base shape she sketched, each new layer being developed based on the curves of the prior line (Fig. 9D). She didn't have an idea of the specific mountain form she wanted to create as she worked but instead explored variations that reflected the aesthetic qualities of East Asian mountain features.

Devon implemented the delete layers functionality partway through the residency at the request of the artists. This shifted how the residents used the tool. Raina commented that deletion capabilities made the transformation tools more usable as different combinations of transforms could be tested and removed rapidly. Layer deletion also improved general usability, by increasing Raina and Eun-Ha's confidence in the printability of the toolpaths, and allowing them to remove minor mistakes easily. Both residents found that SketchPath was a less intensive way to work compared to Rhino/Grasshopper. Working on a tablet with a stylus allows for work in various environments and body positions, enabling a range of mental intensities to be engaged. The simplicity of drawing further contributes to the ability to create forms in as relaxed a mentality as one would use when doodling or in more a more concentrated state. In fact, Raina found SketchPath to be portable and flexible to the degree that she drew toolpaths with it during meetings and both residents commented that they would use it at the end of their intensive days while watching TV on the couch at home.

5.2 Design Outcomes

Between the three authors, we generated many forms with different qualities. We found that works produced through primarily hand-drawn operations created organic wavering coils that are uncharacteristic of 3D clay prints produced through numerical CAM tools or slicers (Fig. 8C). Both residents noted that they enjoyed the opportunity to create work that didn't look like it was 3D printed

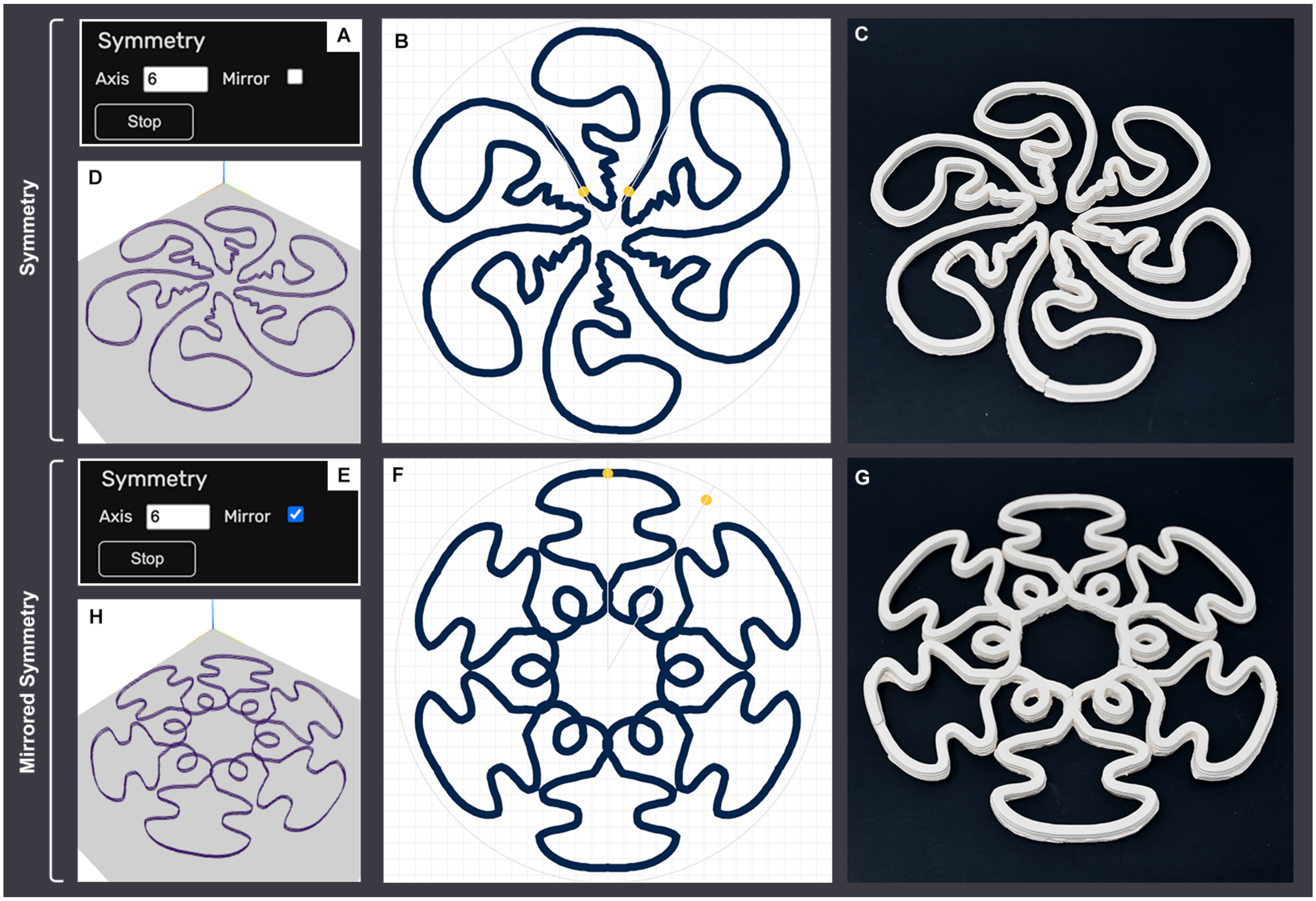

Figure 7: Workflow for Symmetry Operations. A) Symmetry tool panel where the artist inputs the number of rotational axes desired, 6-axis rotation shown here. B) The artist draws in the light grey slice of the circle UI element, and their drawing is symmetrically propagated. C) Six-axis symmetry toolpath 3D printed in clay. D) 3D toolpath preview. E) Symmetry tool panel, same as A, with mirror box checked. F) The artist draws in the slice of the circle shown, and their drawing is symmetrically propagated and mirrored. G) Six-axis mirrored symmetry toolpath 3D printed in clay. H) 3D toolpath preview.

because their artistic aesthetics aligned with the imperfections that emerged from hand-drawing forms. When designing works through a CAM process, the control of individual layers allows textural details to be incorporated at the layer level. Within the design space of clay 3D printed works, we found that SketchPath-produced forms tend to be more irregular and organic with some instances of numerically precise outcomes. Within the CAM-based design space, the manual imprecision stands apart from numerically generated organic forms, showcasing unique inconsistencies of toolpath and form.

We found the integration of hand-drawn lines and transformation tool operations produced vessels with numerically reproduced manual details. Raina employed a method of drawing approximately 15 layers which she would copy and repeat to build up a complete form. These pieces have strong hand-drawn qualities including imprecise stacking of lines, wavering edges, and manually drawn loops that are precisely repeated three times, demonstrating the merging of manual variation and digital repetition (Fig. 8D, F). Raina created a series of cups with unsupported loops where the primary coils that form the body were drawn to stack on top of each other, but when printed with the drawing repeated three times, we found a slight inward tendency during the drawing of the layers resulted in unsupported drooping in the main body repeated three times up the cup, visible in Fig. 8D on the right side of the vessel body. These "happy accidents" inspired all authors to engage in additional form exploration. We observed that when we used emergent design methods, we produced qualities and forms seemingly unique to SketchPath based on our survey of other 3D printed work. For example, Devon created organic vessels based on the technique of loosely repeating the form of prior layers to introduce slow-evolving variations (Fig. 8G). Devon also created rotationally symmetric forms with each layer traced by hand rather than using symmetry or locking. This resulted in rotationally symmetrical vessels with hand-drawn inconsistencies repeated around the form and found in the stacking of the layers (Fig. 8I). SketchPath enabled

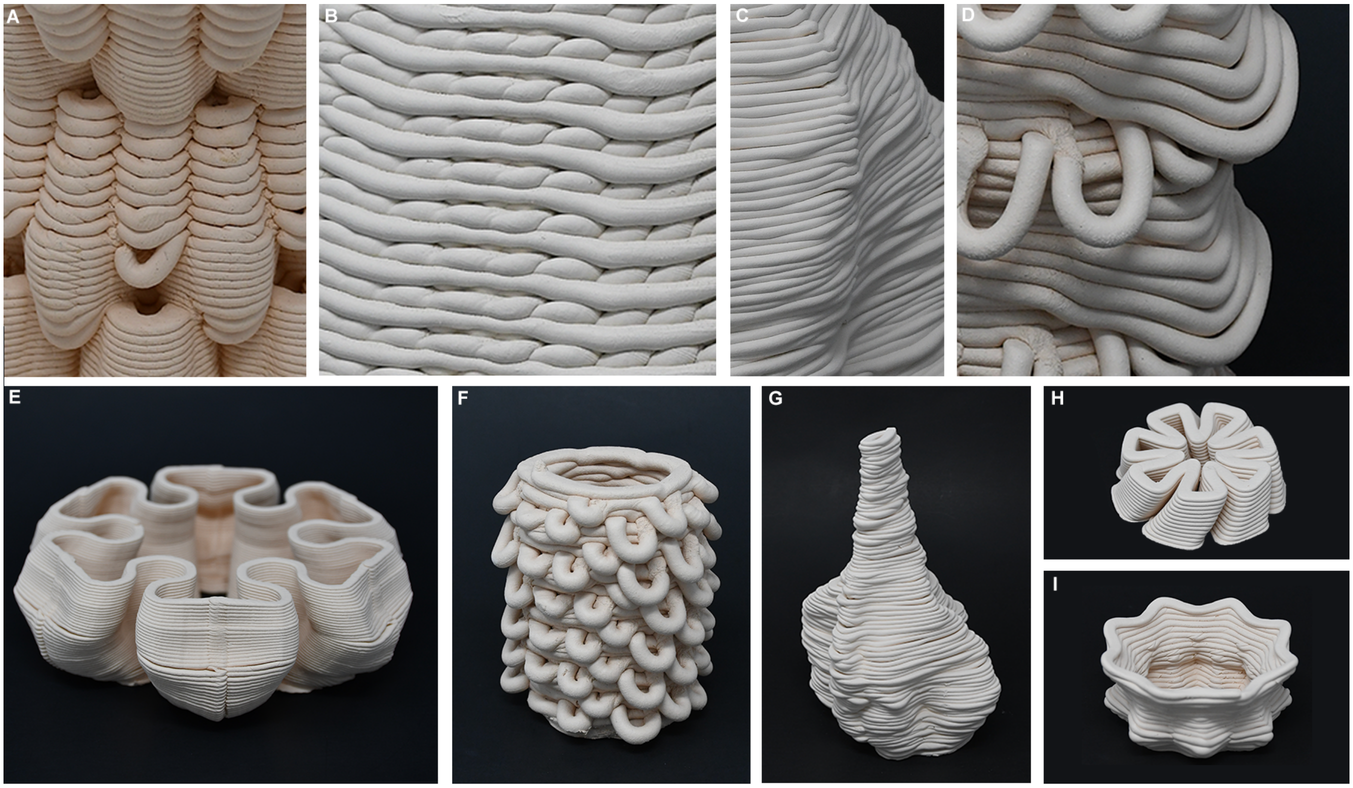

Figure 8: Featured design details and forms. A) Fine textural detail and droopy protrusions produced with symmetry and transformations, similar to numerically generated precision textures. B) Surface texture generated with transformations to create fine surface bumps, similar to numerical texturing. C) Organic stacking of hand-drawn layers creates a unique texture that would be hard to replicate numerically. D) Hand-drawn layers repeated in large groups droop identically, merging hand-drawn and machine-precision aesthetics. E) Six-axis mirrored symmetry layer transformed to form a curved profile, creating an organic precision profile. F) Four layers of hand-drawn loops repeated and rotated to mimic dense loopy textures of numerically generated forms. G) Organic hand-drawn vessel. H) A precise object made by one layer of symmetry repeated with a slight rotation, similar to numerically extruded forms. I) Form entirely hand-drawn in symmetry mode showing hand-drawn surface textures that are preserved in rotational symmetry.

artists to create irregularities in procedurally duplicated toolpath structures.

We did not seek to directly reproduce the precise textures that are possible through numerical methods with SketchPath; however, Eun-Ha and Raina used the tool to produce forms with similar qualities to works created with exclusively numerical approaches. Eun-Ha used one flat-shaped line with one rapidly drawn squiggly line layered on top to create surface textures that, when repeated with transformation, reproduce repetitive bumpy surfaces of numerically defined forms (Fig. 8B). Raina created many cups with loops that would protrude and droop (Fig. 8F) similar to numerically produced works in Fig. 2A. Symmetric and transformed designs often resemble numerical CAM-based forms because the repetitive nature of the transformation introduces precise copying of toolpath qualities in the final form (Fig. 8H). This can also be seen in Devon's exploration of 20-axis stacked symmetrical loops to create droopy textures (Fig. 8A) similar to numerically generated forms (Fig.2A).

6 DISCUSSION

Our work with SketchPath revealed how drawing can productively alter CAM-based design and digital fabrication as a whole. By shifting the design modality to drawing, SketchPath provided a means of direct manipulation for manual ceramicists without obscuring digital fabrication machine control. Working with drawing also enabled a new design space for clay-3D printing. The combination of manual and digital path specification allows artists to create work with repetitive but uniquely varied structures. This distinguishes the outcomes of SketchPath from numerical CAM-based design and hand-built work. The process of drawing also acts as a bridge between machine movement and human movement.

6.1 Drawing as a Method to Lower Barriers and Broaden CAM Expression

We developed SketchPath to bring CAM-based design closer to non-symbolic ways of working and designing. Much of fabrication research and systems development is aimed at helping novices

Figure 9: Works produced in SketchPath by Raina. A) Flat (4cm deep) pictorial drawing exploring the mapping between traditional pictorial drawing and SketchPath drawing. B) Cup made of 3 repeated hand-drawn sections. C) Freehand mountain spire. D) Five separate freehand mountains.

by simplifying the fabrication process, constraining design spaces, or abstracting fabrication design away from specific material processes. Hirsch et al. have shown that artists learn to work in digital fabrication by learning about machine and material behaviors, not through abstracted and automated tools [19]. SketchPath provides the low-level machine control desired by artists through direct toolpath manipulation.

Raina began the residency as a newcomer to all forms of digital fabrication. As a result, she was confronted with multiple learning requirements simultaneously: 3D form design, toolpath creation, and clay 3D printer operation. We found that SketchPath lowered the number of learning tasks compared to other clay 3D printing design workflows and simultaneously afforded opportunities to build an understanding of material and machine behavior. Raina learned Rhino and Grasshopper in parallel to using SketchPath. She noted that SketchPath presented opportunities for her to create highly irregular works in line with her artistic style (Fig. 9) at a time when she could only model basic forms in Rhino.

In the process, Raina stated she developed an understanding that "has a lot to do with how stable the pieces layer height and nozzle width are." SketchPath's design process includes nozzle width and line size as intrinsic parts of generating a form, as the artist has to draw successive layers intentionally overlapping lines of a set size to ensure the form will be printable. Further, the artist must consciously think about the stability and support provided by the lines drawn, resulting in Raina drawing various kinds of in-fill by hand to promote structural stability. Although Raina could produce very stylized forms quickly and easily, she did feel that she took on some of the burdens of correctly stacking layers to create successful prints. Slicers generally remove this burden by automatically generating layers with a pre-defined maximum offset. Eun-Ha did not feel she was burdened by correctly stacking lines in her process with SketchPath. The contrast between Eun-Ha as an experienced clay-3D printing practitioner and Raina as a newcomer to the field, highlights how CAM-based design, in general, relies on experienced practitioner knowledge to design viable forms. While SketchPath lowers the floor for CAM-based design and can act as a tool for hands-on learning about toolpath viability, one must still go through the learning process and handle the associated mental burden of considering design viability. By retaining direct toolpath control, SketchPath provides an alternate on-ramp to understand the facets of clay 3D printing for newcomers to the 3D printing space.

Eun-Ha was not new to 3D printing clay but still found it valuable to have the toolpathing generation process in her direct control rather than relying on automation from a slicer or numerical control. Despite having substantial clay 3D printing experience, the complexity of working with symbolic CAM-based tools without programming knowledge limited her capacity to generate certain kinds of forms. She noted that she could produce more granular toolpaths for symmetric forms through SketchPath than she would be able to make through symbolic CAM tools or by hand (Fig. 10B, C). Having experience trying out many of the available parametric or novice-focused software options for clay 3D printing, Eun-Ha commented that SketchPath granted a unique freedom in digital design for newcomers and experts.

Drawing in SketchPath is intended to describe X-Y CNC machine movements. As a result, the drawing process in SketchPath is somewhat coarse, and using the tool effectively is not dependent on a high degree of manual drawing dexterity or draftsmanship. Eun-Ha noted that "it didn't really matter whether I could draw or not because it's not super precise anyway." While the drawing control may be coarse, the movements and forms executed by an individual's hand, as well as drawing speed and control while tracing prior layers, all affect the way an individual draws a form.

6.2 Preserving Immediacy and Rarity through Non-Parametric CAM Design

We designed SketchPath as a direct modeling system rather than a parametric system. Various factors contributed to this design decision. The substantial time required to develop a direct-manipulation parametric system from scratch was at odds with our objective of deploying SketchPath in our residency. We also had a conviction that the concept of manually drawing planar layers would be diluted by parametric toolpath tuning. We discuss the implications of a non-parametric approach for aligning digital fabrication design with manual craft design practices.

6.2.1 Emergent Design. SketchPath's focus on non-parametric single-pass production of pieces (with the opportunity to erase layers off the top) led to exploratory workflows and emergent designs. Devon became interested in having a loose sense of the final form but following a line drawing constraint, tracing the inside or outside curves to generate emergent organic forms (Fig. 8G). Eun-Ha's exploratory approach also led her to develop unique forms by considering how each layer sits on the prior one (Fig. 10 B). Raina took an interesting initial approach to working with SketchPath by treating it primarily as a life-drawing tool. She explored trying to replicate forms from life, like a 3D layer-by-layer figure drawing practice, and using SketchPath to create flat pictorial scenes (Fig. 9A).

Parametric design is often desirable in digital fabrication because it allows the rapid variation of digital designs; however, we observed that avoiding parametric functionality in SketchPath had positive effects. SketchPath prioritized emergent design, creating one-off prints every time as an inversion of standard CAM-based practices. This practice aligns with manual creation, where artists invest time into manual form development and design to produce one-off art pieces. If residents wanted to modify a form's design, they would explore drawing a new form with a similar design or following similar principles, as one does in manual practices. Creating a non-parametric system to explore drawing forms layer by layer as a design modality persistently preserves the irregular geometry of each unique manual sketch and operation. Eun-Ha expressed that she enjoyed many of the exploratory outcomes of working with SketchPath. Raina desired more structural certainty as she got a handle on what was possible with 3D printing but appreciated the ability to rapidly generate a wide variety of forms early on.

While SketchPath files are pre-set for specific nozzle sizes, all authors tinkered with machine parameters, such as extrusion rates and print speeds, in the PotterBot live control interface while printing to increase the likelihood of a successful form. The variability of clay generally requires artists to rely on live control during clay-3D printing. Because of this, software design tools for clay 3D printing do not require the same level of precision as those for other domains of digital fabrication, like CNC milling. We capitalized on the variable nature of clay 3D printing to create a non-parametric system that prioritizes direct manipulation of the toolpath over the ability to parametrically refine printing variables to achieve a 'perfect' design. Also, the residents stated that, ideally, they would only print forms once, as they are looking to produce one-off art pieces. However, when working with tunable parametric models they often find themselves sinking time into making multiple iterations to get a print just right. By providing a modality of work that enables rapid form generation and variation without weighing down the workflow in editability and tuning, the residents could focus on testing ideas and generating unique forms.

6.2.2 Similarities to Hand Building. We intended the drawing structure of SketchPath to align with manual ceramics production methods. Here, we examine the opportunities SketchPath presents for skilled manual ceramicists. Residents commented that they saw SketchPath as an alternative to hand-building for daily practice as they could maintain manual qualities while capitalizing on machine precision. Eun-Ha said SketchPath would be good for forms "where it would be very difficult to hand build because it's using the symmetry, and to do the symmetrical parts by hand would be kind of impossible unless you're very, very good, have a very good eye, or are using template" (Fig. 10 B, C). Raina said, "I don't think I would ever try to make the loops hang off of a small vessel like this because they wouldn't survive and it would be laborious" (Fig. 8 F). They also felt SketchPath could be better than hand building when creating objects with detailed surface texturing (Fig. 8 B, C). Drawing digital layers also offers a different view of the design process. Residents noted that SketchPath was similar to coil building, but when thinking about designing for 3D printing with SketchPath,

Figure 10: Works produce in SketchPath by Eun-Ha. A) Caricature head. B) Symmetrical bowl. C) Symmetrical stand. D) Freehand pitcher.

there was a mentality switch necessary to go from seeing a whole form rendered at once in modeling software to building it up layer by layer. Raina commented that she spent a lot of time looking at the 3D toolpath to ensure the form developed as desired.

6.2.3 What if we kissed at the Intersection of Manual and Machine Qualities? [1] Forms produced with SketchPath have strong qualities that emerge from the artist's style, selectively blending both manual qualities and machine operations. The residents stated their appreciation for SketchPath as a digital design tool that enabled the creation of computationally controlled imperfections in line with their respective artistic styles. Eun-Ha's tendency to transform a couple of hand-drawn layers created tighter forms with computational precision and repeated minor manual imperfections that produce small textures on the forms' surfaces (Fig. 8B, Fig. 10). Her work demonstrates an approach that emphasizes computational precision when designing with SketchPath. This focus on small details, concise forms, and repetitive textures is seen in her works before the residency (Fig. 3A, B, C). In contrast, Raina worked with many hand-drawn layers or fully drawn forms and tended to draw looser lines, creating forms with larger areas of imperfectly stacked layers (Fig. 8D), larger surface textures (Fig. 9D), and more drooping or collapsing (Fig. 8D, F, Fig. 9). Raina's work falls at the more manual end of the SketchPath design space, approximating the looser approach to design seen in her prior works (Fig. 3 D, E, F). In particular, the increased unevenness of the coil stacking in her works mirrors the uneven, melty textures produced from her glazes on prior work (Fig. 3D, F) and large repeated manual marks of pressing coils together (Fig. 3E, F). The varied blending of the manual and machine qualities in their respective works demonstrate the particular stylistic nuances that individual artists can express through SketchPath.

[1]Section 6.2.3 title is a reference to a meme format of asking "What if we kissed at the intersection of [abstract concept 1] and [abstract concept 2]?" as if the abstract concepts were two streets that have a physical intersection [23]

6.3 SketchPath as a Bridge between Human and Machine Movement

Designing in SketchPath relies on the embodied experience of sketching, shifting the CAM-based design process away from a keyboard and drawing on spatial movements from both manual and machine coiling practices. When ceramic artists are hand coiling they build from manual dexterity in their hands, arms, and wrists, executing specific motions to build up a form. Similarly, when clay 3D printers are printing they execute specific engineered motions. In our case, we are working with Potterbots that can perform movement on the x, y, and z axes, and piston movements to cause extrusion, laying down compressed coils to build up forms. Most clay 3D printing design software steps away from this link between humans laying down coils through specific actions and machines laying down coils through specific actions, focusing instead on digitally designing a full form and then specifying how the machine should execute the print. We recognize that drawing on a digital tablet and manual ceramics fabrication practices like hand coiling constitute different interactions. However, we argue that both constitute some form of embodied expression in a manner that is fundamentally different from the act of using a mouse to select discrete points in geometry or typing symbolic characters. Therefore, we see SketchPath as an important step in the direction of creating embodied digital fabrication design technologies that preserve aspects of physical skill and engage in manual craft, while also remaining powerful for current CNC paradigms.

Building on the theory of action-oriented fabrication [4], SketchPath bridges human movement and machine movement by placing the artist in a space where they can design by tracing the outlines of a form through planar movements similar to the machine's movement capabilities or manual coiling practices. The distinction between SketchPath and prior action-oriented CAM tools is that the artist physically moves their body through drawing to describe machine action. During her first session using the system Raina remarked that she felt like the PotterBot as she was drawing the exact path that the PotterBot would later trace again while extruding coils. The parallel movement allows for a conceptual merging of the design and fabrication processes.

7 CONCLUSION

We developed a system that uses hand-drawn toolpaths to create forms for clay 3D printing. Our CAM-based system, SketchPath, allows artists who don't have prior CAD/CAM experience to enter the clay 3D printing space without investing time in learning complex symbolic or numeric software. Through collaboration with ceramicists, we refined the system. We observed the artifacts produced, noting that hand-drawn toolpaths from SketchPath enable a unique aesthetic merging of manual qualities and machine precision. SketchPath also allows artists to use some aspects of their existing manual skills in gestural design, focusing on visual form development without getting stuck in symbolic software issues.

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