CoilCAM: Enabling Parametric Design for Clay 3D Printing Through an Action-Oriented Toolpath Programming System

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Figure 1: CoilCAM enables the design of 3D printed clay artifacts through concise, mathematically defined toolpath operations. Here we show a functional tea set created with the system. A) Schematic of the toolpath operations required to create the teapot with CoilCAM. We use a Boolean union operator to combine the body and the spout and two Boolean difference operators to generate the handle. B) Tea set with 3D printed planter demonstrating CoilCAM's ability to create surface texture.

ABSTRACT

Clay 3D printing provides the benefits of digital fabrication automation and reconfigurability through a method that evokes manual clay coiling. Existing design technologies for clay 3D printing reflect the general 3D printing workflow in which solid forms are designed in CAD and then converted into a toolpath. In contrast, in hand-coiling, form is determined by the *actions* taken by the artist's hands through space in response to the material. We theorized that an *action-oriented* approach for clay 3D printing could allow creators to design digital fabrication toolpaths that reflect clay material properties. We present CoilCAM, a domain-specific CAM programming system that supports the integrated generation of parametric forms and surface textures through mathematically defined toolpath operations. We developed CoilCAM in collaboration with ceramics professionals and evaluated CoilCAM's relevance to manual ceramics by reinterpreting hand-made ceramic vessels. This process revealed the importance of iterative variation and embodied experience in action-oriented workflows.

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CCS CONCEPTS

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

KEYWORDS

Digital Fabrication; Computer-Aided Machining; Clay 3D Printing; Artist Residency

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1 INTRODUCTION

The 4,000-year-old practice of clay coiling, wherein craftspeople build vessels layer by layer with hand-rolled coils [11], exemplifies many key qualities of manual craft. Hand-coiling involves a non-hylomorphic workflow [27] where form is the result of a dialogue between the craftsperson's hands and the material. In this process, design and fabrication tasks happen simultaneously. Each manual operation impacts the final outcome and the artifact qualities are in flux and at risk throughout production [40]. The integration of design and fabrication in coiling is powerful because this process allows the craftsperson to experience material forces and modify their design in response.

Despite its ancient origins, hand-coiling is also aligned with emerging digital methods of clay fabrication. Similar to coiling, clay 3D printers fabricate 3D structures by extruding coils of clay, which are vertically layered and compacted in succession [50]. Clay 3D printing can extend clay production through the precision, repeatability, and programmable nature of computer-numerical-control (CNC) fabrication. Using clay 3D printers, craftspeople can manufacture physical forms that are, in part, defined by a digital model [34]. While clay 3D printers use similar materials and concepts as hand-coiling, they require fundamentally different tools. Clay 3D printing often involves a workflow that is similar to other forms of digital fabrication wherein craftspeople develop a geometry in computer-aided design (CAD) software and convert the geometry into machine instructions using computer-aided manufacturing (CAM) software [47].

Circumventing CAD and designing exclusively in CAM offers unique opportunities for clay 3D printing. In a CAM-based design workflow, the designer defines the artifact geometry by specifying toolpath operations to be executed by the CNC machine rather than by automatically slicing a solid digital model. CAM-based design requires extensive knowledge of the relationship between the machine and the material but affords a greater range of material expressiveness [37] by allowing the craftsperson to specify fabrication behaviors that take advantage of material properties [39]. These opportunities are particularly salient for the intersection of manual clay craft and digital fabrication. Ceramic craftspeople have extensive material knowledge and clay supports many different surface qualities and forms depending on how it is worked. To take advantage of the versatility of clay, some clay 3D printing practitioners use general-purpose programming tools to develop custom CAM-based design workflows [5, 17, 46].

We observed parallels between CAM-based design and hand-coiling techniques. In both cases, form emerges from the interaction between each action enacted by the craftsperson or machine and the material response. We introduce the term **action-oriented** to characterize manual and machine fabrication workflows in which form is conceived of through iterative manual or machine actions. We contrast action-oriented workflows with **artifact-oriented** workflows, in which generalizable fabrication operations are applied to a material-agnostic design–for example using a general-purpose slicing algorithm to create toolpaths from a solid CAD model. Our definition of action-oriented workflows builds on existing models of human-machine collaboration–namely Devendorf and Rosner's model of "coproductions" [14] and Andersen *et al.*'s concept of "digital craft-machine-ship" [1]; however, our focus is to categorize incremental actions that occur between material, manual or machine agents in the fabrication process, which, in turn, can directly inform new fabrication system abstractions.

We theorized that an action-oriented clay 3D printing system could enable craftspeople to design and fabricate both forms and surface textures while harnessing the material-specific properties of clay. To explore this theory, we developed **CoilCAM**, *a domain-specific visual programming system that supports CAM-based design for clay 3D printing*. CoilCAM includes a set of CAM abstractions–toolpath generator, mathematical shaping functions, and Boolean operators–that support the design of 3D-printed ceramics by authoring 3D printing machine toolpaths. We developed CoilCAM as a collaboration between two HCI researchers and two professional ceramic craftspeople. We structured our collaboration within a 10-week residency that followed a Research through Design (RtD) approach. We evaluated CoilCAM by reinterpreting three pieces originally created by hand by our craft collaborators. Our research builds on a growing body of work exploring the benefits of CAM-based design for additive thermoplastic fabrication [21, 39, 43, 45]. Unlike prior work, we contribute a *clay-specific* CAM-based design system and evaluate our approach with respect to techniques and outcomes in manual ceramics craft.

We make the following contributions:

(1) A clay 3D printing *design space* conceptualized by creating and analyzing a series of design samples (Section 4.1). Our design space highlights the form and textural opportunities of action-oriented workflows for clay 3D printing through four aesthetic qualities: generative, biomimetic, architectural, and organic.
(2) A clay 3D printing *design system* (CoilCAM) developed through an integrated examination of two action-oriented domains: hand-coiling and CAM-based design. Through CoilCAM, we demonstrate one implementation for action-oriented abstractions that are compatible with existing clay 3D printers (Section 4.3) and provide examples of action-oriented design patterns for clay 3D printing (Section 4.4).
(3) A set of *design implications* for future action-oriented fabrication technologies. We examine the implications of action-oriented CAM-based technologies by using CoilCAM to a) fabricate novel functional ceramic vessels and b) reinterpret ceramic pieces made through manual coiling and slab-building. This process demonstrates the importance of systematic and emergent variations in the design and fabrication of ceramic pieces, the necessity and pleasure of embodied experiences, and the potential of human-machine collaboration in clay 3D printing (Section 6). We also discuss how specific CoilCAM programming features can support aspects of manual and digital action-oriented workflows.

2 BACKGROUND

Our work builds on prior research in craft theory and CAM-based design workflows.

2.1 Craft-Inspired Research

We informed our clay 3D printing design space by drawing from craft material theory. Pye characterized craft as a technique where the resulting qualities depend "on the judgment, dexterity, and care" of the craftsperson [40] and the risk inherent to the process. Ingold argued that craft emerges from the dialogue between the hands of the maker and the material [27]. Bennett described how materials are alive, vibrant, and capable of agency within human-designed systems and institutions [4]. HCI researchers have examined the intersection of technology and craft from the perspective of hybrid [14, 53] and post-digital practices [7] and discussed tensions and similarities between these domains. We conceptualized the model of action-oriented workflows at the intersection of multiple contemporary discussions on collaborative making between human, machine, material, and environmental agents. Devendorf and

Rosner proposed "craft coproductions" as a model of collaboration that challenges dualism between digital and manual workflows [14]. Andersen *et al.* used the term "digital craft-machine-ship" to describe how humans, machines, and materials are entangled during fabrication, resulting in artifacts that can only be defined through the act of making [1]. In contrast to these illuminating and overarching theoretical models of collaborative fabrication, we use the term "action-oriented" to describe incremental actions and feedback between human, material, and machine agents in a fabrication process, which, in turn, can directly inform new fabrication system abstractions. By developing a functional action-oriented programming language, we investigate the decisions a craftsperson makes in response to specific machine behaviors.

Other researchers have used manual craft as an inspiration to develop systems for integrating digital and manual materials and methods. Magrisso *et al.* designed 3D printable joinery that extends traditional carpentry [32], Jacobs *et al.* expanded manual drawing through a domain-specific programming language [28] and Devendorf *et al.* developed a portable 3D-printing system that broadened the materials used in digital fabrication and the craftsperson's role in the process [15]. Researchers have investigated ways to lower barriers to programming through craft-oriented computational fabrication [29] or sought to reduce the need for manual craft skills by developing smart assistive tools [19, 42, 56]. Devendorf *et al.* demonstrated the benefits of informing engineering projects with technical craft knowledge through a collaborative residency [13]. With this work, we take inspiration from Devendorf's approach and use a residency model for our system development.

Our work intersects with interactive fabrication: the process of allowing makers to define an artifact's design as it is being fabricated. Researchers in this field have investigated the opportunities of real-time control in digital fabrication systems [38, 51]. Prior interactive fabrication works have primarily focused on the development of novel machines or the modification of CNC machine operation. By contrast, we focus on defining non-interactive machine behaviors through a novel set of CAM primitives.

2.2 CAM Approaches to Design Processes

Historically, digital fabrication workflows began with the design of 3D models in CAD, which were translated into machine instructions using CAM software. These instructions were then executed by a CNC machine [22]. The CAD design workflow is still in use today and is well-suited to the accurate and repeatable production of objects; however, it also restricts creators to a linear fabrication workflow and limits material engagement [34].

An alternative is to use CAM software to specify the design of a fabricated object by describing machine toolpaths. CAM-based design for 3D printing has been applied to food [52], self-shaping devices [44], and textile structures [6, 21]. CAM-based design workflows support outputs that would be extremely difficult or tedious to design in CAD–for example forms that require non-planar toolpaths, unsupported overhangs, and low-level extrusion features. Moving away from traditional layer-by-layer 3D printing, researchers have developed methods to generate 3D toolpaths [24] and control thermoplastic 3D printing parameters [43]. We contribute a system that supports CAM-based design to enable integrated control over an object's form and texture by using the material qualities of clay.

CoilCAM was prototyped using the Grasshopper programming language [10]. Unlike Grasshopper, which offers components for creating and modifying solid and mesh geometry, we contribute a set of primitives for toolpath specification and output URScript or GCode. Other researchers have built on Grasshopper to support the generation of CNC toolpaths. Most relevant to our work is Hoover's Xylinius library–a grasshopper plugin that translates CAD-designed geometries into GCode [25]. We bypass CAD and present a concise set of abstractions for clay fabrication.

2.3 3D Printing Clay and Ceramics Research

CAM-based design for additive fabrication has primarily focused on thermoplastic printing. We seek to extend these approaches to clay. Clay 3D printing was first introduced in 2009 by the Unfold Design Studio [48]. The process enables practitioners to create distinctive and unique vessels [12]. Clay 3D printing is used by many contemporary artists and designers. Keep combines CAD-based design and the Cura slicer software to create intricate generative forms [31], Herpt designs delicate vessels with complex textures [49], Brady makes speculative sculptures examining tensions between Indigenous craft and space colonialism [5], and Tihanyi uses material-specific techniques to fabricate textile-like ceramic objects [46]. Foran and Suon create intricate 3D-printed pottery homegoods [20], Czibesz creates self-intersecting looping vessels [9], and Doyle and the Computation+Construction Lab develop 3D-printed ceramic tiles for architectural structures [17]. Out of these nine prolific practitioners, we found that at least six (Brady, Tihanyi, Foran, Suon, Czibesz, and Doyle) rely extensively on creating works by programming toolpaths in CAM using general-purpose programming languages, and one (Keep) designs and builds 3D printing hardware. These practitioners show how computer programming, and CAM-based programming in particular, are already common in clay 3D printing craft. Their work demonstrates how clay 3D printing has the potential to blur the boundaries between craft and engineering. With CoilCAM, we seek to explore CAM-based design for clay 3D printing by building from manual ceramics.

Digital fabrication technologies for ceramics have only recently been explored by HCI researchers. Researchers have investigated clay 3D printing for data visualization [12], laser-induced surface decoration [16], software for slab-building pottery [26], and digital fabrication for ceramic object restoration [55]. We took inspiration from HCI digital fabrication clay research to develop a cohesive clay 3D printing system that supports a diversity of styles and vessel geometries. Architecture research in clay 3D printing has focused primarily on developing construction materials and methods including bricks [8], tiles [41], and houses [2]. We focus on functional craft objects. Companies that manufacture commercial clay 3D printers have developed custom software to use in combination with their tools [18, 33]. These software tools use a CAD-based approach to modeling and focus on generating cylindrical forms whereas our system supports the design of non-cylindrical geometries and does not limit craftspeople to predefined forms and textures.

3 METHODOLOGY

We developed the CoilCAM system as part of a craft research residency aimed at informing the design of new computational fabrication technologies through collaboration with craft experts. We invited two professional ceramic artists, Pilar Wiley and Avi Farber, to collaborate in our research lab at the University of California Santa Barbara for three months. In this paper, we focus on the activities during the residency that led to the development of CoilCAM. We used a collaborative process where we combined systems design and prototyping with the production of finished ceramic artifacts by professional craftspeople. Our design, engineering, and evaluation methods build on practices from participatory design [35], research through design [54], and coproduction [14], in that we used a collaborative design practice as the primary mode of inquiry to illuminate and challenge boundaries between the multifaceted domains of manual craft and digital fabrication.

3.1 Collaborators

Each author brought different skills and values to the process and contributed equally through different modalities to the design of the system. Sam is a Ph.D. student, new media artist, and HCI researcher who works on designing systems for art and fabrication applications. Pilar is a Los Angeles-based ceramic artist and an expert in manual coiling. She creates functional and sculptural clay objects including vases, planters, and lighting pieces. Avi is a New Mexico-based ceramic artist who combines throwing, slab-building, and 3D printing techniques to create functional and sculptural objects including cups, bowls, and flasks. He specializes in wood firing. Both Pilar and Avi derive the entirety of their income from ceramics and were excited about the creative and commercial opportunities of ceramic computational design and digital fabrication. Jennifer is a professor whose lab focuses on HCI research for digital fabrication and creativity support. Unlike user studies with external participants, we used a collaborative process for both design and evaluation and we reinterpreted manual artifacts created by Pilar and Avi in our evaluation.

3.2 Research Phases

Our research process was structured across six phases. In Phase 1, Sam and Jennifer conducted an exploration of the clay 3D printing design space to familiarize themselves with the process and prepare for collaboration with Avi and Pilar. This exploration included making the six design samples detailed in Section 4.1. In Phase 2 (Week 1), the entire team met and Sam and Jennifer conducted interviews with Pilar and Avi on their creative processes and attitudes towards technology. These interviews helped orient the subsequent phases and enabled the team to envision possible applications and projects that intersected with Pilar and Avi's interests. In Phase 3 (Week 1-2), the team began hands-on collaborative explorations and knowledge sharing. This phase was organized around a series of workshops on manual ceramics and computational design and fabrication, led by each member of the team. Pilar's hand-coiling demonstration and workshop were most salient to CoilCAM because they highlighted the similarities between CAM-based design for clay 3D printing and coiling and led us to formalize our concept of an action-oriented workflow. In Phase 4 (Week 3), we outlined the initial system components for CoilCAM primarily by synthesizing the opportunities revealed by our design space analysis (Phase 1) and coiling workshop (Phase 2). In Phase 5 (Week 4-9), we engineered the first version of the CoilCAM system and fabricated sample artifacts as we iterated on the system functionality. These artifacts served as a preliminary evaluation of the system. During this period, we met weekly to discuss opportunities and challenges of the approach, analyze sample artifacts, and refine our goals. In Phase 6 (Week 9-10), we conducted a collaborative evaluation of CoilCAM by attempting to reproduce key design features of three artworks made by Pilar and Avi using our system. We describe our evaluation methods in detail in Section 5. Following the recreation process, we conducted a two-hour discussion between all four authors about the resulting artifacts. We discussed Pilar and Avi's manual workflows for specific pieces and the differences and similarities between these processes and the CoilCAM workflow. We recorded and transcribed our discussion and analyzed the transcription to conceptualize themes on alignments and tensions between action-oriented digital and manual workflows.

3.3 Limitations

The primary limitations of our work relate to our collaborative methodology, the general limitations of clay 3D printing in comparison to manual craft, and the challenges of visual programming.

3.3.1 *Collaborative Design and Evaluation.*

We used a collaborative process between craftspeople and HCI researchers for our design and evaluation, all of whom are co-authors of this paper. We chose co-authorship because it accurately reflects the design and engineering contributions of our ceramic collaborators. Evaluating CoilCAM with external participants would likely yield insights about the versatility and usability of CoilCAM for a broader range of practitioners. Our collaborative approach provided critical opportunities not possible in a short-term study. Our methodology builds on prior work [13]. The 10-week residency enabled Sam and Jennifer to learn elements of ceramics production from Pilar and Avi, which were critical to engineering features in CoilCAM. Our regular group fabrication sessions provided insights into what manual ceramic craftspeople find exciting when using clay 3D printers and allowed us to collaborate on finished pieces. Finally, ceramics production involves many time-consuming steps from construction, drying, finishing, bisque-firing, glazing, and glaze-firing and it can take up to three weeks to complete a single piece depending on scale. The residency provided the necessary time and expertise to produce multiple iterations of finished pieces with our system.

3.3.2 *Reproducing Manual Ceramics Through 3D Printing.*

CoilCAM cannot recreate many forms of production found in manual ceramics. This is a limitation not only of our system but also of clay 3D printing technology in general, which cannot perform the same range of operations that are possible through manual fabrication. Because we used CoilCAM with existing 3D printing hardware, we knew we would be unable to exactly reproduce the manually fabricated pieces of our co-authors. We therefore deliberately chose to reinterpret their works by recreating key design features. It is possible for a skilled manual ceramicist to further modify a 3D-printed form to almost perfectly match a manual vessel–Pilar achieved this during the residency. Our research provides further insights into the overall limitations of clay 3D printing technology in comparison to the expressiveness of skilled manual production.

3.3.3 Visual Programming Language. In CoilCAM, we use a visual programming language to specify toolpaths. Visual programming languages can overcome some of the challenges of textual programming but they still require creators to conceptualize designs through mathematical abstractions [36]. We selected a visual programming representation for CoilCAM because it aligned with existing programming practices in clay 3D printing. CoilCAM improves on general-purpose visual languages by contributing a smaller set of domain-specific abstractions while supporting a greater variety of outcomes than existing parametric clay design systems.

4 SYSTEM

CoilCAM is a visual programming system that enables the creation of mathematically defined toolpaths to create 3D-printed ceramics. In this section, we first describe the clay 3D printing design space we identified through our RtD process and the specific design goals for CoilCAM within this space. We follow with a description of the CoilCAM system primitives and example applications.

4.1 Design Space

During Phase 1 of this work, we explored the range of clay material opportunities for 3D printing. We focused on CAM-based design rather than CAD-based design and slicing to examine the design opportunities of different clay toolpaths. We looked at ways to use gravity and viscosity as shaping mechanisms. We produced six design samples showcasing a range of forms and textures. We used these samples to conceptualize a CAM-based clay 3D printing design space, which we used to develop design goals for our system. To structure the design space, we analyzed our samples across two dimensions: 1) the form of design engagement required to produce each printed artifact ranging from "prior to fabrication" to "during fabrication" and 2) the alignment of the outcome with the machine toolpath spanning from "unaligned" to "aligned". By unaligned we mean a form that was not explicitly represented by the digital toolpath but dictated by the clay material behaviors in response to the fabrication environment. Figure 2 illustrates this design space and our six design samples. The two dimensions of our design space revealed the range of ceramic aesthetics that can emerge through varying forms of machine, manual, and material interactions. In the remainder of this section, we describe the design space in detail through four distinct aesthetic qualities within this space: generative, biomimetic, architectural, and organic. We sought to create a system that could support this aesthetic range.

Generative: We described the aesthetic of our design samples 2A and B as generative because they displayed emerging patterns similar to the outcomes of digital generative algorithms. In both cases, the primary design features were produced during the fabrication process and the physical geometry deviated substantially from the machine toolpath as illustrated on the right-hand side of Figure 2. The final geometry was the result of a combination of initial toolpaths, material viscosity, and material response to gravity. Design sample 2A was printed with a symmetrical toolpath on an uneven surface resulting in an asymmetric print. This required manual intervention to support the machine's actions. We manually adjusted the drooping filaments in real time as the printer extruded them to enable the printer to recover from perturbations and maintain a cohesive form. Design sample 2B was created by increasing the print's layer height progressively to prompt the viscous behavior of clay. Rather than model the geometric structure of the print, we used the toolpath to describe a *machine behavior* aimed at exploring different material properties as the layer height grew. As a result, the final print deviates significantly from the toolpath geometry.

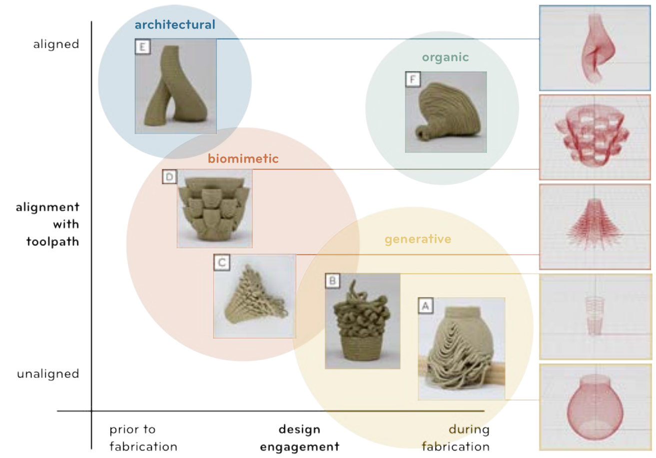

Figure 2: Design space for CAM-based clay 3D printing with four aesthetic qualities: generative, biomimetic, architectural, and organic. We organized six design samples across two dimensions: 1) engagement required by the craftsperson prior to and during fabrication and 2) alignment with the machine toolpath. A) Vase printed on an uneven surface. B) Cup printed with increasing layer height. C) Flower printed on a spherical surface. D) Pot with pocket features. E) Two rotating towers merging into one. F) Hand-coiled artifact using 3D-printed coils. The design for F was improvised and therefore doesn't have a toolpath representation.

Biomimetic: Design samples 2C and D contained repetitive structures and material variations that resemble organized yet diverse patterns found in nature. We, therefore, categorized these samples as biomimetic. The design for these samples took place both prior to and during the fabrication process. The resulting pieces partially align with the toolpath but also reflect some qualities of material behavior. We printed design sample 2C on a spherical jig and programmed the printer head to go back and forth from the center of the jig to the peripheral. This produced structures that were shaped by the spherical support and twisted due to the effects of gravity and clay viscosity. Similarly, we relied on gravity to deform unsupported portions of alternating gear-shaped layers to create the three-dimensional pods on design sample 2D. These examples show how designing a toolpath with the environmental context in mind enables the creation of forms with repeating yet irregular structures that create variations from a precise toolpath.

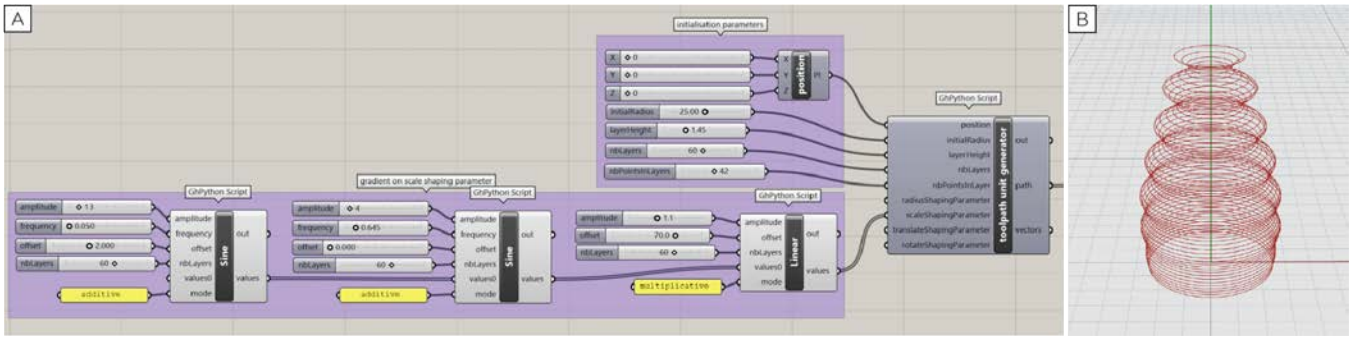

Figure 3: CoilCAM workflow in Grasshopper to make Figure 6B. A) The toolpath unit generator with a linked set of function operators acting on the scale shaping parameter and creating a gradient on the sinusoidal amplitude. B) The toolpath representation of that workflow.

Architectural: In design sample 2E, the layers of the toolpath are fully supported throughout the print resulting in a solid structure. We characterized this result as architectural for its structural features. We created this sample by combining two rotating towers at the top using Boolean operations on their toolpaths and by controlling the stops and restarts of the motor in order to achieve non-continuous prints. All design actions occurred in the software prior to the print. The result is aligned with the specified toolpath.

Organic: For design sample 2F, we sought to explore manual control of the toolpath. We shaped the form by hand as the printer extruded a coil. The irregularities in the layer height gave rise to an irregular organic aesthetic. The design of the piece was improvised during the fabrication process and the layers, though irregular, were aligned to the path taken by the hand. The piece's irregularity reflects Sam and Jennifer's level of manual dexterity and skill.

We further explored manual skills in clay production during Phase 3 of our residency when Pilar guided a workshop on hand-coiling. Manual coiling involves hand-rolling coils of clay, winding them into an initial base, and then successively layering coils to create a 3D volume. Pilar observed that clay 3D-printed vessels are effectively coil pots. Both clay 3D printers and coil potters build forms by positioning a cylinder of clay along a path. Each step with the hand-made or extruded coil iteratively shapes the final geometry. Expert coil potters use the material feedback to guide their coiling–determining if the piece can support additional weight or where to add or remove clay to maintain consistent thickness and integrity. Coil potters are able to manipulate the coil through twisting and packing in a manner not possible with 3D printing end effectors. Furthermore, while the design and fabrication process happens simultaneously in hand-coiling, 3D printers use predefined forms and therefore separate the design and fabrication tasks. We did not seek to reproduce the hand-coiling workflow with CoilCAM. Instead, we sought to build a CAM-based toolpath representation with parameters that aligned with properties we manually controlled in hand-coiling.

4.2 System Goals

We analyzed our design space of clay 3D printing (Phase 1) and Pilar's hand-coiling workshop (Phase 3) to define two design goals.

1) *Enabling the design and fabrication of forms and textures through toolpath specification:* Craftspeople should be able to create a wide range of clay 3D-printed objects with different forms and surface textures by specifying machine toolpaths.
2) *Supporting the expressive material properties of clay:* Craftspeople should be able to design artifacts that leverage their material knowledge and create geometries that exhibit material behaviors.

Our goals target design actions that occur prior to machine fabrication. Elements of our design space encompass human-machine interaction similar to interactive fabrication (Section 2); however, we sought to support expressive methods for defining toolpaths rather than real-time digital fabrication control. As a result, our system targets CAM-based design methods to support outcomes that are dictated by a combination of human intent, machine action, and clay material behaviors.

4.3 System Description

We developed CoilCAM as a visual programming system using Python Script components in the visual language Grasshopper.[1] Programming in CoilCAM is centered around the use of toolpath primitives that can be modified with mathematical operators. By combining different operators in different ways, the craftsperson can generate a wide variety of complex toolpaths. These toolpaths are then sent to a clay 3D printer to be executed. We selected Python and Grasshopper as our development platforms because this combination enabled us to iterate quickly on the system functionality in response to ideas that emerged during the residency. Our system primitives are language-agnostic and could be implemented using other programming frameworks. Figure 3 shows an implemented CoilCAM program we used to produce the vessel in Figure 6B. In the remainder of the paper, for clarity, we represent CoilCAM programs as a series of diagrams with color-coded nodes that correspond to our custom grasshopper components. The toolpaths generated by CoilCAM are compatible with any clay 3D printer. The majority of the artifacts in this paper were printed with a Lutum extruder[2] attached to a UR10e Robot arm. We translated our

[1]To download a functioning version of CoilCAM, visit http://coilcam.com
[2]https://vormvrij.nl/blog/the-lutum-eco-extruder-fro-clay-printing/

toolpath commands in UR Code using the Machina framework[3]. We also used our system with the 3D Potterbot 10 PRO[4] to make larger artifacts. Some of the ceramic pieces shown in the following figures have been decorated with glazes, underglazes, wood-firing, and pit-firing. These decorations are not a feature of CoilCAM but show how artwork made with our system can be decorated using similar techniques to hand-made artwork. In the remainder of this section, we describe the different components of the system and the design patterns we used to generate forms and surface textures.

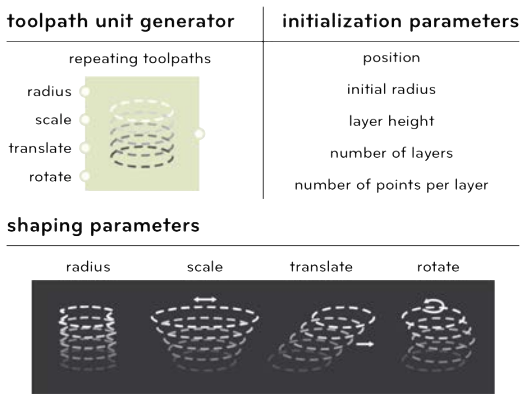

Figure 4: The toolpath unit generator and its initialization and shaping parameters. The default generator consists of a series of two-dimensional layers comprised of a set of points in a circular path. The generator is initialized with a position, a radius, a layer height, a number of layers, and a number of points in a layer. The generator contains four shaping parameters: radius, scale, translate and rotate. By connecting functions into the shaping parameters, the craftsperson can respectively create non-circular layers, scale up layers to create flared openings, translate layers to generate shifted forms, and rotate layers to make twisting forms.

4.3.1 Toolpath Unit Generator. Programming in CoilCAM is structured around procedural transformations of a cylindrical toolpath represented by the *toolpath unit generator* component. The default toolpath unit generator, represented as a green module in Figure 4, generates a 2D circular toolpath on the xy-plane comprised of a series of points along a circle. This circular toolpath is repeated to produce a three-dimensional toolpath as a series of layers with increasing height along the z-axis. The toolpath unit generator contains five initialization parameters–position, initial radius, layer height, layer count, and number of points along the layer (not represented on the toolpath unit generator module but listed in Figure 4)–and four shaping parameters–radius, scale, translate, and rotate (represented as input on the toolpath unit generator on Figure 4). The radius shaping parameter controls the shape of each layer by specifying the polar coordinate of each point along the toolpath of that layer. The scale, translate and rotate shaping parameters shape the toolpath by respectively scaling, translating, or rotating individual layers in succession. As illustrated in Figure 4, the craftsperson can use shaping parameters to modify the radial geometry of a layer, scale up successive layers to create a flared opening, shift layers through translation to create a tilting form, or iteratively rotate each layer to create a twisted form.

[3]https://github.com/RobotExMachina

[4]https://3dpotter.com/printers/potterbot-10-pro

4.3.2 Function Operators. When the craftsperson creates a new toolpath generator, the toolpath generator initialization parameters are assigned a default constant value and the shaping parameters are assigned a default array of values. The craftsperson can modify the initialization parameters' values with a slider to set a different constant. The shaping parameters can be modified in an iterative fashion by setting their input to a *function operator*: a component that returns a series of values corresponding to a predefined mathematical function. As shown in Figure 5, the system contains five function operators: linear, sinusoidal, square wave, staircase, and exponential. Function operators can be mapped as input to any toolpath unit generator shaping parameter. Alternatively, they can be chained in sequence to modify the output of a prior function operator. Each function operator can be used in two different modes that determine its behavior when connected to another component: an additive mode which increments the previous input values and a multiplicative mode which multiplies the previous input values. We represent schematically the operation mode using + and × over the connections between function operators.

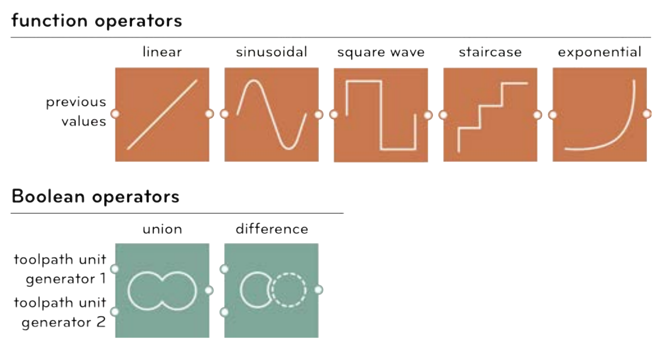

Figure 5: The system has two types of operators: function and Boolean operators. Function operators are used to define the toolpath unit generator's shaping parameters. Boolean operators are used to merge or subtract toolpath unit generators.

The modularity of function operators enables the craftsperson to develop a variety of forms and textures by chaining function operators together in different sequences. For instance, Figure 6A shows how we can create a linear gradient on the sinusoidal radius shaping parameter by linking a sinusoidal function operator with a linear function operator in multiplicative mode. Any combination of operators can be applied to any shaping parameter. This structure supports the reuse of chained operations and the rapid iteration through toolpath variations. Figure 6B illustrates how the same function operators produce different results when applied to the scale shaping parameter instead of the radius shaping parameter presented in Figure 6A.

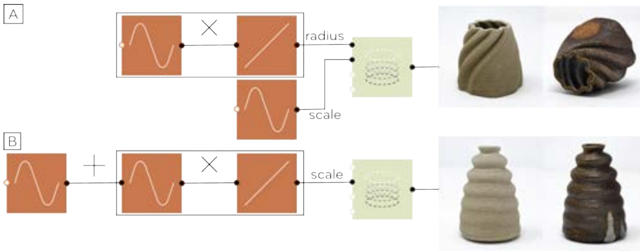

Figure 6: Gradient effect applied by chaining function operators. A first sinusoidal function operator defines the inward shape on the scale shaping parameter of both pieces. A second sinusoidal function operator is multiplied with a linear function operator to generate a linear gradient over the sinusoidal amplitude, which modulates A) the radius and B) the scale of the object.

4.3.3 Boolean Operators. Existing CAD tools for clay 3D printing are largely limited to the design and fabrication of cylindrical geometries. To support non-cylindrical forms, CoilCAM includes *union and difference Boolean operators*. As illustrated in Figure 5, Boolean operators accept two toolpath unit generators as input and perform either a union or difference operation between each toolpath of the first input and each corresponding toolpath of the second input. Each Boolean operator outputs a toolpath with properties that correspond to the Boolean operation. Figure 7 and Figure 8 show the process of using Boolean union and Boolean difference operators in CoilCAM and the resulting artifacts. The Boolean union operator enables the creation of forms that combine with each other at different layers of the print while the difference operator allows the generation of nesting forms.

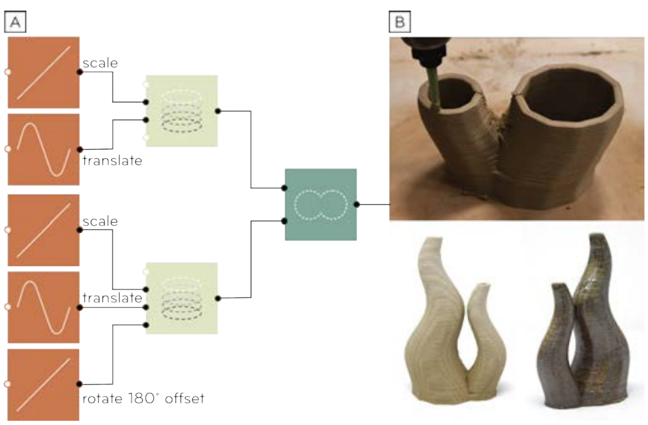

Figure 7: Boolean union operator in CoilCAM. A) Two toolpath unit generators are created by applying a linear function operator to their radius and a sinusoidal function operator to their translate shaping parameter. A linear function operator of 0 amplitude and 180° offset is applied to the rotation of the second generator to align the seam inward of the vessel. B) The two generators are then combined using a Boolean union operator to produce a two-headed wavy structure.

To enable different degrees of union between toolpath unit generators, we added an input to the Boolean union operator that specifies the fillet radius at the toolpath intersections. When specifying a non-zero fillet radius, the positions of the points on each resulting layer are adjusted to account for the fillet, and additional points are added to define the fillet's shape. Figure 9 demonstrates four versions of the same design using varying fillet radii ranging from 0 mm to 100 mm. These prints show the variation we can obtain by modifying one value on the Boolean union operator.

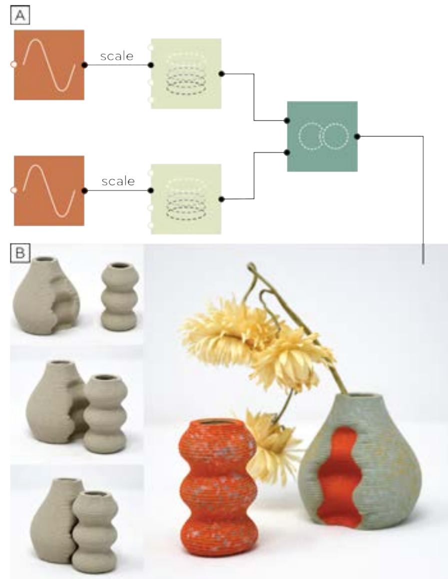

Figure 8: Boolean difference operator in CoilCAM. A) Two toolpath unit generators are shaped using a sinusoidal operator on the scale shaping parameter and combined using a Boolean difference operator. B) This approach creates complementary vessels that can fit in one another.

Boolean operators in CoilCAM build on the use of CAD-based Boolean functions in solid modeling; however, rather than calculate the Boolean of two solid 3D models, we calculate a series of 2D Boolean intersections between different toolpath layers. This approach ensures that we retain a viable toolpath from each Boolean operation without relying on a slicing workflow. Furthermore, our approach circumvents the technical modeling requirements associated with 3D solid Booleans in CAD software.[5]

4.3.4 Control of the Extruder's Motor. To achieve effects analogous to the retract functionality in FDM 3D printing, we developed a strategy to control the LUTUM stepper motor by stopping and restarting it at specific points along a toolpath. We use a short Python script in Grasshopper to send on/off information to the motor driver via serial communication. This functionality offers two benefits for clay 3D printing. First, it provides another mechanism for creating surface texture as illustrated in Figure 10. In this case, the Python script generates a series of on/off information

[5]For examples, see "Known Rhino limitations of Booleans" at https://wiki.mcneel.com/rhino/booleanfaq.

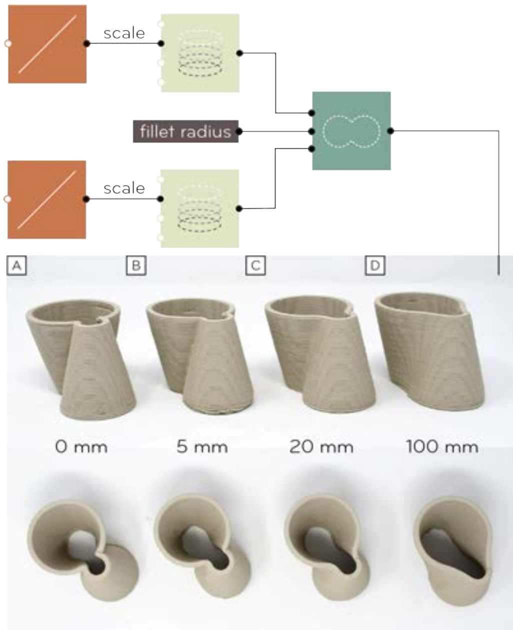

Figure 9: Boolean union operator used with a variable fillet radius. Two toolpath unit generators are shaped using the linear function operator on the scale shaping parameter and then joined together using a Boolean union operator with a variable fillet radius of A) 0 mm, B) 5 mm, C) 20 mm, and D) 100 mm. A higher radius, like in D, generates a more gradual union between the toolpath unit generators.

independently from the CoilCAM pipeline. Second, motor control allows the printing of non-continuous toolpaths on the same layer to produce forms that branch and merge as presented in Figures 7 and 12. In this second case, the Python script receives on/off information generated by the Boolean union operator. The Boolean union operator provides a list of points at which the motor needs to stop to produce a non-continuous extrusion within one layer.

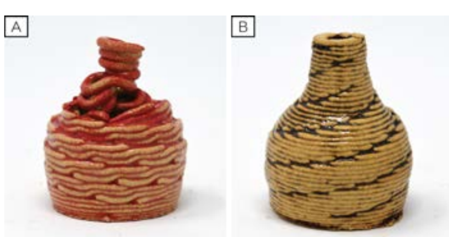

Figure 10: Surface textures generated by starting and stopping the LUTUM motor at specific points along the toolpaths. This functionality enables us to create varying patterns such as A) a wave motif and B) a staircase motif.

4.4 Design Patterns For Surface Texture and Form-Shaping

The set of 3D-printed examples presented in this section shows how the mathematical abstractions available in CoilCAM support 1) surface texture and 2) form-making in line with our second design goal. By developing these examples we found that specific combinations of linked function operators could support one or the other of these two aesthetic aspects. We defined these combinations as design patterns [23]. We observed that using discrete function operators like square wave and staircase are better aligned with ceramic surface texture generation while continuous function operators like linear and sinusoidal are better aligned with ceramic form creation. We describe these patterns in detail in this section.

4.4.1 Surface Texture Through Radius, Scale, and Rotation. In CoilCAM, the radius shaping parameter acts on the points contained in each layer of the toolpath unit generator. Modifying this shaping parameter enables the creation of surface texture by producing artifacts along the vessel surface. Surface artifacts can emerge in polymer-based 3D printing techniques; however, designers often seek to avoid or reduce them. In clay 3D printing these artifacts are a primary design affordance. Figure 11 shows a series of cups with varying surface textures created through iterating protrusions across each layer of the print. The protrusions are the result of the extruder rapidly moving out and then back across a circular layer. We use this sequence of cups to demonstrate the iterative process used to define increasingly complex surface textures. We start with a simple cup with no surface texture (Figure 11A). The craftsperson can quickly create a toolpath that produces surface protrusions by using the square wave function operator as input to the radius shaping parameter on a toolpath unit generator (Figure 11B). The craftsperson can alter the phase of the surface texture across a set of layers by using a staircase function as input to the rotate shaping parameter. This increases the offset of the rotation for each set of layers, resulting in a rotated texture (Figure 11C). Finally, the craftsperson can modulate the amplitude of the surface protrusions by connecting the square wave function operator to a sinusoidal function operator in multiplicative mode on the radius shaping parameter. This produces a texture gradient across each individual layer (Figure 11D). Because we use a staircase function operator as input to the rotate shaping parameter, the texture gradient rotates around the object.

4.4.2 Variation of Form Through Iterative Scaling and Translation. Layer-by-layer clay 3D printing necessitates that neighboring layers overlap each other at least partially to ensure the integrity of the structure. To create change in form while preserving overlap between subsequent layers, we modify the scale, translate, and rotate shaping parameters of the toolpath unit generator with continuous functions that evolve gradually such as polynomial, sinusoidal, and exponential. Figure 12 shows how combining continuous function operators with Boolean operators enables the creation of two twisting columns that merge at the top. We used a linear function operator to make each column's radius decrease gradually with height and a sinusoidal function operator to define a gradual translation of each column around a circle. We used a linear function operator

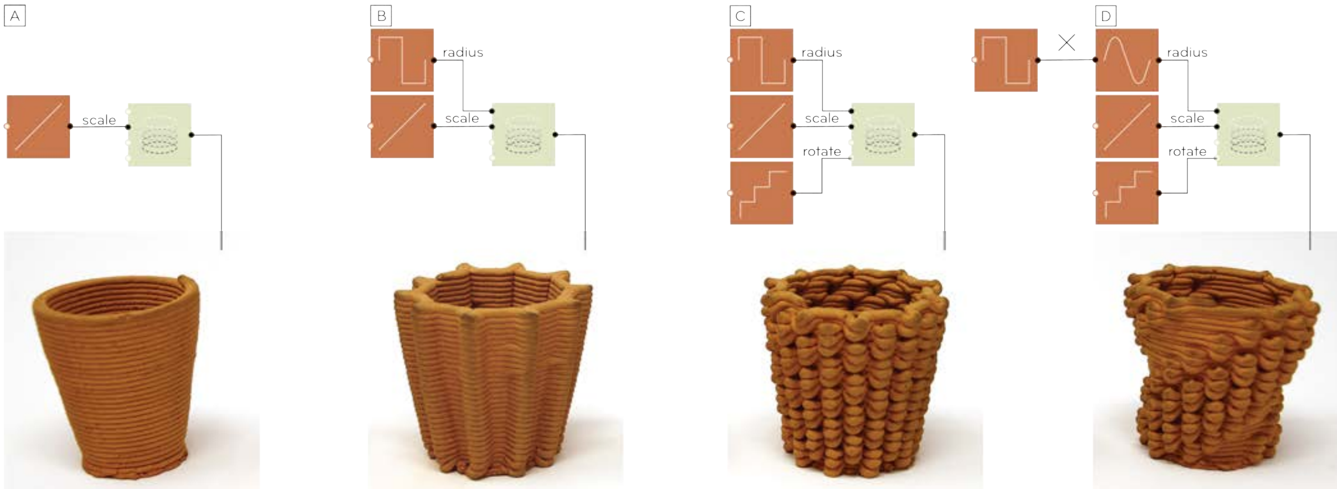

Figure 11: Design pattern for creating surface texture. A) We create a basic cup shape with a linear function operator connected to the scale shaping parameter of the toolpath unit generator. B) To create surface protrusions, we use a square wave function operator with a duty cycle of 25% on the radius shaping parameter. C) We add a staircase function operator on the rotate shaping parameter to create a rotational pattern across layers. D) We connect the square wave function operator to a sinusoidal function operator in multiplicative mode on the radius shaping parameter to generate a radial texture gradient on each individual layer.

as input to the rotate parameter of both generators to ensure that the seams are always facing the interior of the structure.

4.5 Crafting Functional Objects: Teapot and Set

As a preliminary evaluation of the expressiveness of CoilCAM, we applied the system to the creation of a teapot and a tea set. We selected the tea set as a test case because of the range of challenges it presents from both computational and craft perspectives. The teapot has a history as a test case model in computer graphics research due to its relatively complex and varied geometry. We sought to understand the degree to which CoilCAM could support the creation of toolpaths that produce these complex features (lid, handle, spout) in a format feasible for clay 3D printing. In ceramics craft, the tea set is recognized as a piece that requires craftsmanship (functional use, comfort, and stylistic consistency), while also offering the potential for individual creative expression. We sought to explore CoilCAM's ability to produce a set of well-made functional ceramic artifacts. We also like tea.

4.5.1 Teapot: Collaging Toolpaths Using Boolean Union Operators. With our first example, we explored the possibility of collaging toolpaths using Boolean union operators. Figure 13 was created using three toolpath unit generators for the body, spout, and handle. The body consisted of a 70-layer cylindrical structure with a narrowing opening created by a linear function operator mapped to the scale shaping parameter. The spout used a similar approach, however, we also used a linear function operator mapped to the translate shaping parameter to create an angle. The output of the spout and body toolpath unit generators were merged with a Boolean union operator. We created a rectangular form for the handle through a toolpath unit generator with a default layer structure consisting of 4 points and 8 layers and an uneven radius on the x and y axis (figure 13B). We deliberately designed the handle toolpath to be

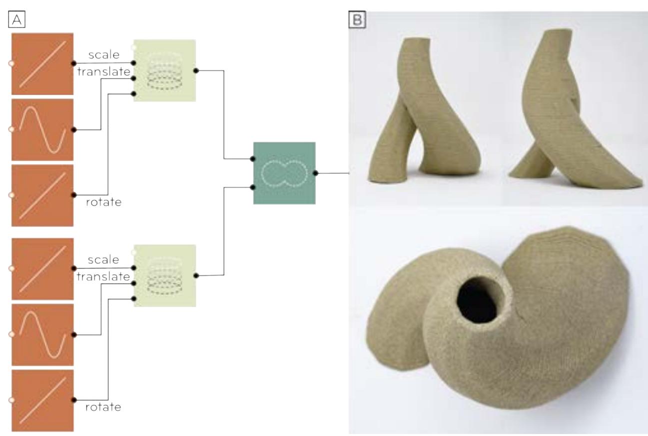

Figure 12: Design pattern used for form generation. A) Using a linear function operator on the scale and the rotate shaping parameter and a sinusoidal function operator on the translate shaping parameter enable us to join with a Boolean union operator B) two twisting columns into a single one.

unsupported to take advantage of the drooping quality of clay with gravity. In the resulting print, the layers of the handle sag as they stack on top of each other, resulting in a curved, layered structure (figure 13C). For the lid, we printed a 3-layer base structure with the same radius as the final layer on the teapot's body and added four inset layers that would fit into the teapot opening taking into account the thickness of the walls. We printed the lid's handle separately and assembled both parts together manually.

4.5.2 Tea Set: Using Boolean Difference Operations to Create Matching and Functional Artifacts. With this second example, we sought

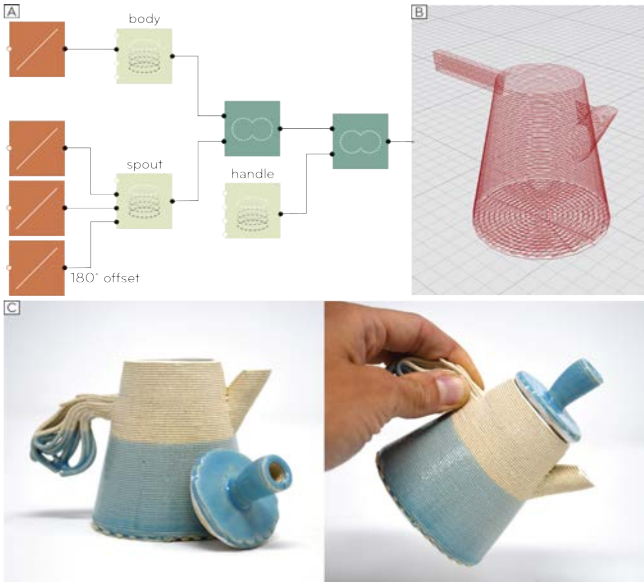

Figure 13: First teapot demonstration. A) The diagram to create the teapot using CoilCAM. We are using a Boolean union operation to combine the body and the spout and a second union to join the handle to the rest. B) The toolpath representation of the teapot in Grasshopper/Rhino. C) The final printed outcome exhibiting the drooping handle.

to design a tea set comprising a teapot and four different matching cups (Figure 1). For the body of the teapot, we set the number of points in each layer to three to obtain a triangle shape, the layer height to 1.2 mm, and the number of layers to 94 for a total height before bisque of 11.28 cm. We used two linear function operators as input to the scale and the translate shaping parameters to shape the teapot opening inward and to set the side with the spout perpendicular to the bottom of the pot. For the spout, we used a linear function operator on the scale shaping parameter to make it smaller at the top and a combination of linear and sinusoidal function operators on the translate shaping parameter to make its curve moves away from the body. We used a linear function operator to rotate the seam of the spout inward. We used the same operators for the spout to create the indented handles but applied a Boolean difference operator between the body of the teapot and these handles to create cavities for grabbing the side of the pot. To generate the cups, we used the same function operators as those used for the spout but varied the parameters to produce a larger diameter. We added handles to the cups using the same strategy as the handles on the teapot's body. Figure 1 shows the final artifacts in use and the full sequence of operations used to generate the teapot in CoilCAM. The resulting set is functional–the vessels are watertight and the pot is capable of pouring. Moreover, the set presents parametric variations–each cup has a unique geometry. Our design workflow shows how similar aesthetic features can transfer easily to the cups and pot through the reuse of function operator design patterns. CoilCAM provides an advantage to existing CAD-based tools for clay 3D printing by enabling the specification of cylindrical and non-cylindrical forms, as well as textures, through the same set of reconfigurable abstractions.

5 EVALUATION

To evaluate our system, we recreated signature artworks made by Avi and Pilar and used these artifacts as a foundation for a discussion between the authors of this paper on the design opportunities of clay 3D printing. CoilCAM is not intended to replace manual ceramic practices. Instead, the objective of our evaluation was to understand the alignments and limitations of our system in comparison to manual craft by using it to reinterpret key features of hand-made clay objects. We selected three pieces to reinterpret: 1) Avi's slab-built flask (Figure 14C), 2) Pilar's two-headed hand-coiled vessel (Figure 15C), and 3) Pilar's hand-coiled pot with hand-painted underglaze patterns (Figure 16C). We informed our recreation strategies in CoilCAM by engaging in hands-on tutorials on slab building and coiling led by Avi and Pilar respectively during Phase 3 of our collaborative process.

5.1 Remaking Avi's Hand-Built Flask Through the Assemblage of 3D-Printed Parts

To make his flasks by hand (Figure 14C), Avi draws a template on paper to define the body and cuts that shape twice in a slab of clay. He allows the slabs to firm up before assembling the two sides of the flask together. He uses the body of the flask as a template to cut out the bottom of the flask in another slab which he adds to the body. He then throws several spouts on the wheel and compares each to the shape of the flask, selecting for the best aesthetic fit. He then takes a ball of clay the size of a grape and rolls it between his palms to make an elongated shape. Using his thumb and index finger, he pulls the piece of clay into a tapered handle that he adds to the flask.

We approached recreating Avi's hand-built flask by 3D printing it in three parts. While it was possible to design and print the piece in one go, our approach provided the opportunity to test the manual assembly of 3D-printed CoilCAM parts. To make the three-part flask in CoilCAM, we designed each component separately using a sinusoidal function operator on the scale shaping parameter of each toolpath unit generator. As shown in Figure 14, each component is defined by a sub-portion of a sine wave and the body uses a different operator on the x and y axis to generate a form that is wider than deep. Once we had the three components we hand-scored them with a needle probe and assembled them. Our resulting flask resembles the structure of Avi's hand-built piece, with different proportions and less geometric irregularity. The addition of manual assembly allowed us to preserve key design features like the seam between the spout and the body.

The assembly strategy to recreate Avi's flask demonstrates how CoilCAM can be used for modular design in scenarios where parts of a larger piece need to be printed separately due to geometric complexity or size limitations of the printer build envelope.

5.2 Remaking Pilar's Two-Headed Vessel

To make her two-headed vessels (Figure 15C), Pilar uses a hand-coiling technique. She rolls a series of thumb-thick coils of clay and, starting at the base, winds them in a spiral into a round vessel. After

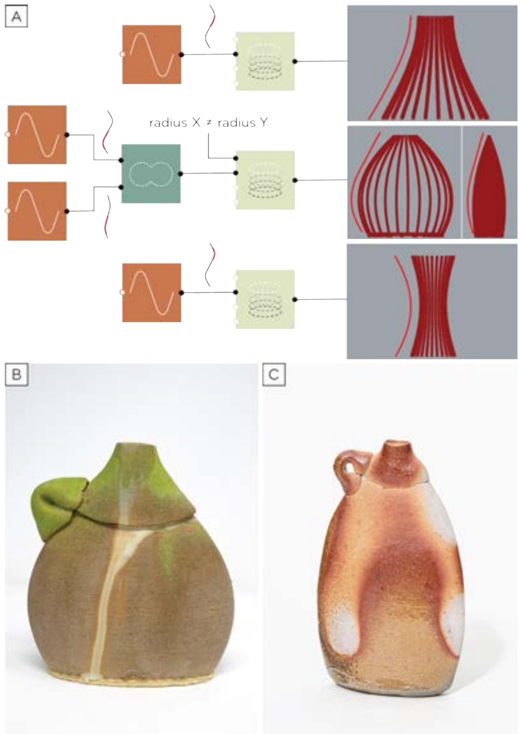

Figure 14: Avi's flask reinterpretation workflow. We designed three constitutive parts of the flask–the spout, the body, and the handle–separately and assembled them by hand. A) CoilCAM workflow to recreate Avi's flask. We highlight in red the sections of the sinusoidal function operators that we used to recreate each component of the flask. B) The 3D-printed flask after assembly. C) Avi's original hand-built flask.

the base takes form, she continues coiling the shape on a banding wheel which enables her to rotate the form as she layers the coils. To create a robust piece, Pilar twists the coil as she layers it. When she completes the body of the vessel, she creates a saddle-like structure to divide the opening into two. She then begins coiling each head. She uses a tensioned fabric loop to support the curvature at the bottom of the vessel and a sponge or balloon to support the saddle point while the vessel is drying.

With CoilCAM, we designed the vessel using three toolpaths–the base and two heads–which were printed in one go (Figure 15A). We created the base with two toolpath unit generators united by a Boolean union operator with a smooth fillet. These two shapes are defined by a sinusoidal function operator mapped to the toolpath's scale shaping parameter and the translation parameter so that the openings are offset away from the center. The two heads are shaped with a linear function operator on the scale and the translation and are adjusted to produce a continuous profile curve with the base. During fabrication, the base was printed first and then each head was printed consecutively on top of the base. We hand-smoothed the resulting form in a manner similar to the technique Pilar uses to smooth her coiled vessels. The final print is shown in Figure 15B.

Our reinterpretation of Pilar's two-headed vessel presents a similar shape to the original. However, making the saddle point between the two heads necessitated adding a little bit of extra material by hand and the resulting print lacks the smooth saddle of Pilar's hand-made form.

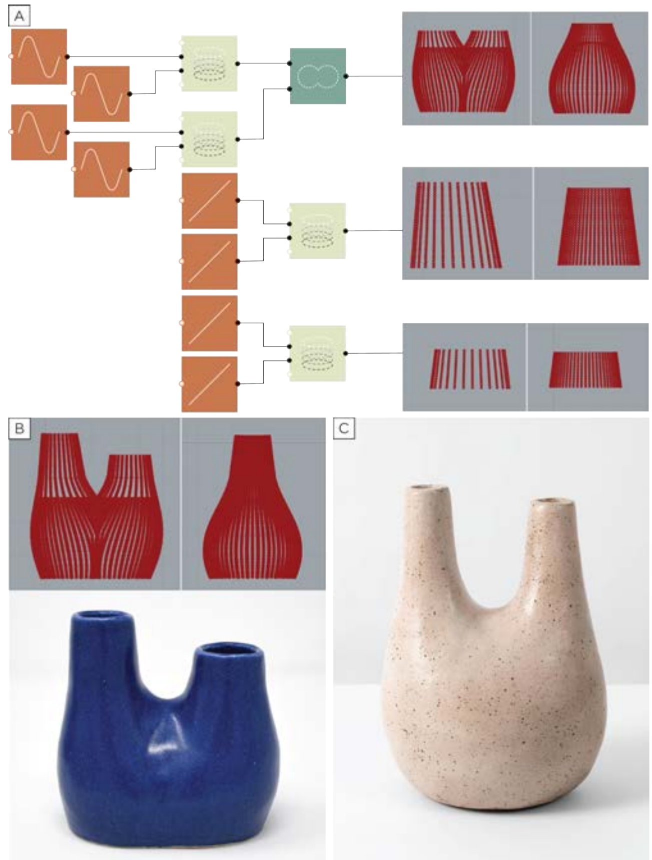

Figure 15: Pilar's two-headed vessel reinterpretation workflow. A) CoilCAM workflow to recreate the vessel. The body and the two heads were made using three different toolpath unit generators. B) The 3D-printed vessel. C) The original vessel by Pilar.

5.3 Using 3D Printing to Extend 2D Hand-Drawn Motifs Into 3D Reliefs

In this third example, we examined how CoilCAM could reinterpret manual surface ornamentation as physical texture. Pilar decorates her work with intricate patterns that she paints on with engobe and underglaze (Figure 16C). When she makes these patterns, she uses a decorating disk and a quilting ruler to define a radial grid. Using the grid, she adjusts the banana pattern according to the curve of her pot so that the forms increase in size as the pot diameter increases.

To explore a variation of Pilar's patterns, we used CoilCAM to create a round pot with a three-dimensional surface texture. As illustrated in Figure 16A, Sam wrote a simple program with our system and implemented a new direct manipulation feature for defining the profile curve of the pots. Pilar used this feature to define the final form. Our program used a square wave function operator on the radius and the scale shaping parameter of the toolpath unit generator to create radial extrusions and spacing between the extruded layers. During one of our collaborative sessions using this program, Sam and Pilar observed similarities between a test texture and Pilar's banana motif. As seen in Figure 15B, the two overlapping threads of clay extruding away from the surface create the characteristic curve of the bananas. We built on this to create a series of textured banana pots, that Pilar decorated with underglaze.

The use of CoilCAM to reinterpret 2D ornamentation into 3D textures suggests a broader opportunity to employ toolpath-based design to create figurative patterns.

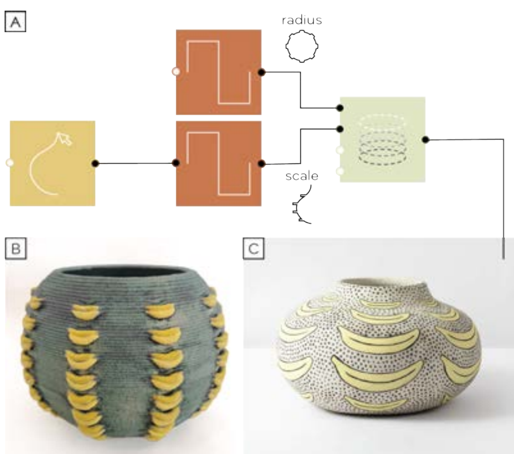

Figure 16: The three-dimensional reinterpretation of Pilar's banana underglaze pattern. A) CoilCAM workflow used to reinterpret the banana motif. We implemented an additional direct manipulation component to define the profile curve of the pot. We used a square wave function operator to create the bump on the radius shaping parameter. B) The 3D-printed artifact. C) Pilar's original pot with the banana decoration.

6 DISCUSSION

To analyze our evaluation (Section 5) and identify opportunities for future development, we conducted a two-hour conversation between the authors of this paper (Phase 6). We drew from the specific affordances of CoilCAM to probe more general alignments and tensions between action-oriented digital workflows for clay 3D printing and manual clay workflows. We extracted two themes from this discussion: 1) the importance of rapid variations for defining forms and textures and 2) the necessity and pleasure of embodied experience in making clay objects. Expanding on these themes, we present an example in which human-machine collaboration enabled the manual modification of 3D-printed coils of clay during the fabrication of the handle of our first teapot. We conclude this section by highlighting how CoilCAM's design features can support aspects of action-oriented workflows and point to new opportunities for future CAM-based design systems.

6.1 Using Action-Oriented Systems to Integrate Systematic and Emergent Variations

CoilCAM targets our first design goal by providing craftspeople with a new way to describe form and texture using machine toolpaths while also enabling them to reuse and iterate on parametric functional abstractions. CoilCAM supports an action-oriented design workflow because it enables craftspeople to incrementally adjust each step of a toolpath to produce different outcomes. We found that this level of control over rapid iterations was particularly powerful to establish and refine a form. For Avi, having the possibility to use "simple operations" and "get so many different shapes" was appealing as it could "drastically change the feel of the pot." He was particularly excited about how mathematically defined variations could simplify the hand-building workflow when making a spout. "Not knowing the proportion until [he] make[s] [these spouts]" made the manual process difficult whereas CoilCAM enabled the proportions to be "dialed in."

Our evaluation with CoilCAM also demonstrated a key distinction between action-oriented methods that rely on machine execution versus manual execution. When Avi adjusts the curve of a spout on the wheel, he described how the process is "way faster" in comparison to adjusting a curve in the software and waiting for it to print because he can modify the curve continuously "150 times a minute" by adjusting his hand on the material. CoilCAM does not support rapid manual adjustments, however, the system did support some forms of direct physical interaction as discussed in Section 6.3. We believe that CoilCAM may offer a fruitful starting point for developing future systems that integrate toolpath exploration prior to fabrication with interactive adjustments of a subset of toolpath parameters during fabrication. Such an approach could combine the benefits of pre-fabrication CAM and CNC adjustment during fabrication and enable the making of parametric variations without returning to the computer.

Both Pilar and Avi also enjoyed how CoilCAM supported material agency. Pilar appreciates the emergent quality of hand-making when sometimes a pot "turn[s] into another pot" during fabrication. She described how the generativity of hand-coiling was aligned with the generative process she used in CoilCAM to create the 3D banana pattern (Figure 16B). Rather than explicitly plan for the pattern, her experimentation with the 3D printer and prior experience with manual surface ornamentation led her to develop the pattern.

In both skilled hand-building and CAM-based design workflows, the distinguishing characteristics of a piece arise from integrating systematic and emergent variations. In CoilCAM, a craftsperson can engage in emergent practice through iterative adjustments of the toolpath parameters as for Avi's flask. They can also use toolpath specifications as a space to explore the emergent material qualities of the clay. Our experiences suggest that CoilCAM provides a space for novel material aesthetics while maintaining a conceptual link to the emergent qualities of skilled manual ceramics. We argue that regardless of where or when design action occurs, future action-oriented systems should preserve the opportunity for both systematic and emergent design actions.

6.2 Embodied Experience: a Pleasure and a Necessity

In many manual action-oriented workflows, the direct connection between a craftsperson's body and the material is both a critical source of design information and an enjoyable process. Pilar and Avi described the importance of physically interacting with 3D-printed or hand-made objects to evaluate the aesthetic of the form. Avi stated that "because it's hard for [him] to nail the exact proportions when [he is] looking at the little spout on the wheel," he makes multiple spouts and tries them directly on the body of his flask to see "if they fit the feel that [he is] going for [in] the piece." For both 3D printing in general and CoilCAM in particular, the visualization on the screen was not sufficient to evaluate the aesthetic of an object. Avi and Pilar needed to see and interact with the material version. Physical interaction also helped them determine the next fabrication step. Pilar, for instance, touches the clay to evaluate its "state of dryness" and might "give it a minute to firm up before [she] continue[s]" building her vessels. Because CAM-based design allows craftspeople to describe artifacts as a series of operations, rather than a finished artifact, we see the opportunity to extend systems like CoilCAM to support these forms of material assessment and adjustment in future systems. Existing clay 3D printing control interfaces support GCode-level adjustments during fabrication, like modifying global travel speed or the extrusion rate. Because CoilCAM contains toolpath parameters, artists could iteratively adjust higher-level toolpath properties like the degree of material overhang or the toolpath step-over in response to manual material feedback.

Both Pilar and Avi engage in multi-step embodied workflows meaning that they use a wide range of manual techniques when making a pot. Pilar uses a complex set of steps to position her hand-drawn banana pattern (Figure 16C) and Avi uses three different hand-building techniques to fabricate a flask. When evaluating the 3D-printed flask made with CoilCAM, they were both excited about the opportunities to assemble 3D-printed parts together by hand. Pilar remarked that by manually forming the printed handle, "you can engage with the [3D-printed] lines in this really cool way and really us[e] the best of this material in the process." We did not design CoilCAM specifically to support manual assembly, however, the evaluation revealed how rapid iteration through machine-printed parts could support this strategy.

At the start of the paper, we defined action-oriented workflows as encompassing both manual craft operations and CAM-based design practices. Both practices require material knowledge, however, for the latter, it is possible to engage in action-oriented design without working the material manually. Given the critical information expert craftspeople receive when touching clay, and the visceral pleasure of clay manipulation for non-experts and experts alike, we argue that action-oriented system developers *who are designing tools specifically for clay 3D printing* should look for opportunities to preserve manual material engagement. We believe collaboration with manual practitioners is a valuable method in this pursuit. While manual manipulation of 3D-printed clay forms feels somewhat obvious in hindsight, Sam and Jennifer's awareness of the vast potential of manually smoothing, assembling, repairing, and decorating 3D-printed greenware only emerged during the residency when Pilar and Avi repeatedly demonstrated the opportunities of doing so.

In the following section, we describe how CoilCAM can provide a level of direct physical interaction for craftspeople by supporting human-machine collaboration and can present additional opportunities for action-oriented interactive fabrication systems.

6.3 Human-Machine Collaboration for Material Expressiveness

As previously stated, we did not design CoilCAM as an interactive fabrication system. In practice, however, we found that the combination of CoilCAM toolpathing and clay 3D printing created opportunities for direct physical manipulation *during* the fabrication process. For example, when printing our first teapot, we explored manual intervention on a pre-programmed toolpath (Section 4.5.1). We planned for a gravity-shaped handle where the craftsperson could manually intervene in shaping the final curvature of the handle (Figure 17C) using tools (Figure 17A) or hands (Figure 17B) to provide different forms of support as the machine printed each layer. The handle integrates the precision and automation of the machine and the flexibility of the craftsperson's hand in enabling material expressiveness. Depending on the skill of the craftsperson, they can manually alter the toolpath at each layer in a precise manner. This process demonstrates how combining human and machine action-oriented workflows during digital fabrication can enable craftspeople to create unique forms that diverge from the toolpath. Furthermore, it demonstrates how this integration preserves the opportunity for skilled manual adjustment as the piece is constructed.

Figure 17: Human-machine collaboration. The teapot is designed with a gravity-shaped handle. The craftsperson uses A) a tool and B) a finger to support the handle and create an opening as shown in C.

We believe that future digital fabrication systems could better integrate skilled human actions and precise machine actions to express the aesthetic qualities of a material like clay. As a starting point to consider pathways for human-machine collaboration in clay 3D printing, we identified different tasks taken by each agent during our fabrication process and listed them in Table 1. Extrapolating from these tasks, future clay 3D printing workflows might enable a skilled craftsperson to make modifications to a print during fabrication by interweaving external elements (decorations, handles, hooks, etc.) into the extruded clay. Alternatively, the craftsperson could work to support the machine action by manually adding supportive jigs for particularly ambitious prints.

While action-oriented systems don't necessarily require human intervention during machine fabrication, we found that embracing

Table 1: Human and Printer Tasks Involved in Clay 3D Printing Using CoilCAM.

Human	Printer
Support or make clay support in real-time.	Provide coils of clay.
Smooth seams.	Press coils of clay so they fuse to one another.
Define and send toolpath to the printer.	Execute toolpath commands.
Help coils of clay stick to the bed.	Ensure precision in positioning and repeatability.
Clean the printed piece by removing unwanted parts in real-time or after fabrication.	
Add parts to the print (e.g. base or handle) or assemble parts together.	

a collaborative approach can enable novel material opportunities by taking advantage of both machine precision and manual skill.

6.4 Future Development of Systems for Action-Oriented Workflows

To connect our discussion to the CoilCAM programming language, we highlight the key takeaways from the prior discussion and describe their relation to the design features available in CoilCAM. We follow with a discussion on the implications of action-oriented technologies for existing models of digital fabrication research.

CoilCAM's existing feature set supported action-oriented production in the following ways:

(1) CoilCAM's **parametrizable visual programming nodes** enabled craftspeople to work through **systematic and emergent variations** which support the exploration of design and material qualities in similar ways to manual fabrication.
(2) CoilCAM's **continuous and discrete function operators** enabled the design of both form and surface texture that support **material expressiveness**.
(3) CoilCAM's **representation of machine actions** enabled craftspeople to plan for **manual modifications** such as part assembly of 3D-printed clay artifacts.
(4) **The low-level control CoilCAM provided over toolpath operations** enabled skilled craftspeople to plan for **collaborative opportunities** with the 3D printer and clay during fabrication.

These design features demonstrate how CAM-based design strategies can support aspects of both manual and digital action-oriented workflows. More broadly, the results of our work provide support for viewing digital fabrication workflows as a form of craftsmanship [30] and show how skilled manual production and digital fabrication are complementary rather than opposing factors [14].

CoilCAM directly contradicts the personal digital fabrication model that situates digital fabrication users as consumers and circumvents skill development [3]. Instead, CoilCAM advocates for software systems to encompass expert domain knowledge. While we are also motivated by the goal of supporting new entrants, our research demonstrates the fundamental limits of reproducing tacit knowledge and design action exclusively through fabrication software. Rather than solely focusing on a consumer-oriented model to grow fabrication applications, we argue that the field of *skilled manual-digital fabrication* is a critical focal point for future HCI fabrication systems research, especially as we seek to expand the professional manufacturing applications of this technology. To pursue this direction, our model of action-oriented workflows can serve as a useful example in emphasizing system representations that reveal the design actions of humans and machines and create opportunities for fruitful interactions between the two.

7 CONCLUSION

Through a collaborative approach between HCI researchers and professional craftspeople, we combined craft and computational knowledge to create CoilCAM, a domain-specific system for clay 3D printing supporting toolpath specification using visual programming. CoilCAM supports elements of manual and digital action-oriented workflows by leveraging machine precision and automation while maintaining space for skilled and flexible manual fabrication. We used CoilCAM to design novel functional craft objects and recreate manual craft artifacts created by our craft collaborators. Through the analysis of these pieces and an evaluative discussion, we highlighted the affordances of action-oriented workflows for generating forms and textures, the necessity of rapid variations and embodied experience in ceramic making, and the opportunities of working at the toolpath level for human-machine interaction.

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