An Adaptable Workflow for Manual-Computational Ceramic Surface Ornamentation

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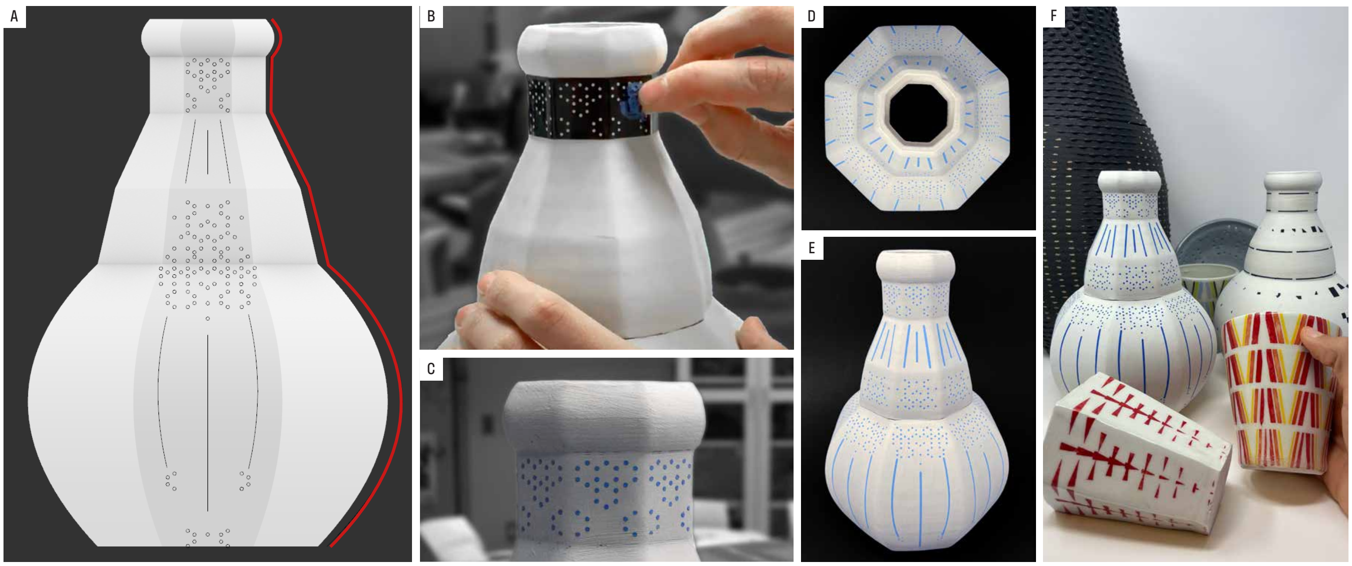

Figure 1: CeramWrap example workflow. A) The digital model of a 3D-printed vase with generated decoration patterns. B) The craftsperson installs the vinyl-cut stencil on the neck after unrolling its surface and applies blue underglaze. C) The resulting pattern after the stencil is removed. D) A top and E) a side view of the final vessel. F) Artifacts decorated with CeramWrap.

ABSTRACT

Surface ornamentation is a rich component of ceramic manufacture wherein craftspeople use multiple methods to create intricate patterns on vessels. Computational fabrication can extend manual ceramic ornamentation through procedural pattern generation and automated fabrication; however, to be effective in traditional ceramics, computational fabrication systems must remain compatible with existing processes and materials. We contribute an interactive design workflow, CeramWrap, in which craftspeople can procedurally design and fabricate decorative patterned stencils tailored to radially symmetrical vessels. Our approach extends manual techniques through a workflow where craftspeople design and edit repetitive motifs directly on a 3D digital model of a vessel and then interactively adjust the unrolling of the 3D design to a 2D format suitable for digitally fabricating stencils and templates. Through a series of example artifacts, we demonstrate how our workflow generalizes across multiple vessel geometries, supports manual and digital clay fabrication, and is adaptable to different surface ornamentation methods.

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CCS CONCEPTS

• **Human-centered computing** → **User interface design**; **Interaction paradigms**.

KEYWORDS

Manual-Computational Workflows, Computational Fabrication, Craft, Ceramics, Surface Ornamentation

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1 INTRODUCTION

Throughout the history of ceramics, creators from different traditions have employed a wide variety of decorative techniques [5, 20, 30, 66]. While varying in aesthetic and cultural meaning, many different forms of pottery involve crafting intricate patterns made of repetitive geometric components on the surface of 3D forms and vessels. Craftspeople produce such patterns by manually executing procedural workflows during which they repeat a series of steps across the surface of a vessel. In the process, craftspeople employ a broad range of additive and subtractive decorating techniques. Computational design techniques for pattern-making share similarities with manual craft approaches [28]. Both involve the creation of precise, repeating and often mathematically describable patterns for ornamentation. Computational design has distinct advantages in pattern generation because it enables designers to parameterize and edit complex motifs and automate the generation and fabrication of visual instances [35].

Human-computer interaction (HCI) and computer graphics researchers have explored computational methods to augment manual craft through computational design and digital fabrication techniques. Many of these methods have the objective of reducing or eliminating the need for manual skills in craft production. In the process, they introduce fundamentally different workflows and materials into the craft [16, 45, 56, 70] or enact sharp boundaries between digital and manual fabrication tasks [17, 37, 54]. While there are benefits to developing novel manufacturing processes, it is equally critical to understand how we might develop computational fabrication techniques that complement, rather than supplant, established forms of manual production [24].

Creating computational technology that accommodates complex and non-linear workflows can bridge the gap between HCI research and existing craft practices. As theorized by Tim Ingold [26], Jane Bennett [3], and Donna Haraway [22], materials are evolving and craftspeople must continuously adapt to this state of flux. While HCI workflows typically prioritize streamlined and unambiguous processes, manual fabrication with physical materials requires adaptable techniques. In this regard, ceramics ornamentation is a compelling domain to study.

Skilled manual ceramics craftspeople create remarkably precise procedural ornamentation on 3D surfaces. This ornamentation is typically produced in two ways: (1) by applying each decorative element manually–e.g., drawing, which is flexible but hard to do consistently, or (2) by using pre-made templates–e.g., patterned transfer sheets, which are easily repeatable but do not conform to vessel geometry. In addition, manual ceramic craftspeople continually adjust their surface ornamentation approach in response to the dynamic material qualities of clay. The development of a compatible computational workflow requires methods that are equally flexible and support rapid modifications. We see opportunities to address these challenges through an *adaptable workflow* that supports the computational design and fabrication of patterned stencils that conform to unique radially symmetrical ceramic vessels. We present CeramWrap, a versatile manual-computational workflow for procedurally generating custom visual elements on a 3D digital model and fabricating corresponding 2D patterned surfaces as stencils that can be used as guides during the ornamentation of physical ceramic vessels. Through CeramWrap, we seek to support craft-compatible computational fabrication workflows for ceramics craftspeople who may [18, 36, 48, 58] or may not [7, 8, 21, 39, 42, 50–52, 60–62] use digital methods in their practice.

The CeramWrapworkflow consists of four stages: (1) The measurement of a physical vessel created by a craftsperson and the creation (or update) of a corresponding virtual model, (2) an interactive process for procedurally designing patterns directly on a 3D digital model, (3) an interactive technique to unroll 3D patterned surfaces into 2D surfaces, and (4) the fabrication of the patterned stencils from the unrolled surfaces and their application on the ceramic vessel for ornamentation. We intentionally avoid enforcing a one-shot workflow through these stages. A craftsperson engaging with the CeramWrap workflow is encouraged to iterate through these stages until they achieve a stencil fit on their vessel that aligns with their desired decoration method and tolerance.

In developing CeramWrap, we draw inspiration from prior HCI research that integrates computational design and fabrication with specific domains of craft, such as woodworking [40], ceramics form making [6, 10, 13, 25, 69], and textile production [2, 19, 32, 68]. This research provides valuable insights into the potential of HCI and craft integration; however, each craft practice presents unique workflows, material opportunities, and constraints. With this work, we focus on the novel domain of computational-manual ceramic surface ornamentation.

We make the following contributions:

- A design space for ceramic decoration that explores multiple ornamentation methods used by ceramic craftspeople. This design space enabled us to map out existing workflows and determine potential areas where computational assistance could be beneficial.
- CeramWrap, an interactive and adaptable workflow that combines manual and digital processes for creating decorative patterns on ceramic vessels.
- A demonstration of our workflow's versatility through six example vessels made using three building approaches–slab building, 3D printing, and wheel throwing– and decorated using three different decoration methods–underglaze brushing, hole drilling, and sgraffito.

2 RELATED WORK

Our work focuses on the creation of patterns on 3D ceramic artifacts. We draw from three domains of study: HCI research in clay and ceramics, procedural design for digital surface ornamentation and physical craft, and computer graphics techniques that generate geometric mappings between 3D and 2D surfaces.

2.1 Clay Research in HCI

The study of clay in HCI is relatively new. Researchers have designed computational tools to generate slab-building templates [25], developed parametric programming systems for clay 3D printing [6], and explored data visualization in 3D-printed clay artifacts

[10, 11]. The existing approaches primarily center on the formation of ceramic vessels, with limited investigations into their surface decoration. Only a few instances of HCI research examined the post-processing of digitally fabricated artifacts such as decoration, sanding, and support removal. Dick *et al.* looked at laser-cutter-induced crackles in glazes to generate imagery on surfaces [13] and Zheng *et al.* explored the integration of interactive electronic circuits on glazed ceramic ware [69]. With this work, we investigate the design of vessel-conforming patterns to be used with traditional methods of surface decoration.

2.2 Procedural Design in Craft and HCI

HCI researchers have explored procedural approaches for material and craft exploration. Jacobs and Buechley applied computational design to the production of personal objects such as lamps and garments [28]. Subbaraman *et al.* developed a programming library that enables low-level machine control for FDM 3D printing [59]. Magrisso *et al.* introduced an interactive workflow for 3D-printing joinery in wooden furniture [40] and Zheng *et al.* created a parametric system for laser cutting joinery[68]. We draw inspiration from these expressive integrations of procedural design and physical fabrication for the novel domain of procedural ceramics surface decoration.

Computer graphics researchers have also explored procedural pattern generation on 3D surfaces. Mancinelli *et al.* developed an interactive method for drawing Bézier curves on the surface of 3D meshes [41]; Nazzaro *et al.* introduced a direct-manipulation system for recursively applying surface decorations [43]; and Fanni *et al.* created stacking volumetric textures on surfaces for digital ornamentation and fabrication [16]. Unlike prior work, pattern generation is only one stage of our workflow. Our work is further differentiated because rather than filling specified regions with point sampling or recursion, we draw our surface patterns on a tangential plane and project them on the 3D surface, and we use mathematical functions to instantiate procedural motifs.

2.3 Unrolling Surfaces into Planar Geometry

Computer graphics researchers have explored techniques for mapping 2D images onto 3D surfaces and unrolling 3D geometries into 2D surfaces. These methods are typically used for texture mapping on digital models [63]. Liu *et al.* expanded these techniques to unrolling of pottery ornamentation to support archaeology research and archiving [38]. These methods target digital applications, whereas we address challenges related to physical making.

In the context of fabrication, Konaković *et al.* developed a method for unrolling double-curvature surfaces with auxetic materials [31], Ion *et al.* made paper reconstructions of 3D models using developable patches [27], and Pietroni *et al.* introduced a method for interactive creation of garment sewing patterns [49]. We extend the scope of this body of work by incorporating the constraints of ceramic decoration into computational unrolling and fabrication. Namely, we optimize the positioning of patterns on ceramic vessels by producing 2D stencils that can be fabricated using standard digital fabrication tools and applied to the surface of ceramic vessels in an efficient manner.

Ceramic artists also map 2D designs onto 3D surfaces as part of their craft. For example, Camila generates 3D models using mathematical functions, digitally unrolls them, and uses the resulting 2D shapes as templates for slab-building sculptures [18]. Pharis uses marine design software intended for boat manufacturing to unroll the surfaces of his digital designs for slab building [48]. Sing creates detailed stencils using 2D vector illustration tools, which he uses to decorate wheel-thrown pieces [58]. Link fabricates a complex assembly of small modular molds for slip-casting ceramics and creates intricate forms and surface textures [36]. These diverse practices illustrate various approaches that translate between 2D and 3D used in the fabrication and ornamentation of ceramic vessels. With our work, we contribute a computational workflow that integrates and extends these existing practices. As HCI researchers Mert, Samuelle, and Jennifer benefit immensely from the technical fabrication knowledge of Camila and other ceramics practitioners in our work. We argue that future UIST fabrication research can be similarly enriched by technical partnerships with artists and craftspeople [12].

3 TRADITIONAL CERAMIC CRAFT AND METHODS OF SURFACE DECORATIONS

Traditional ceramic craft encompasses diverse skills, techniques, and materials that align with the dynamic material properties of clay. We summarize the ceramic manufacturing pipeline and discuss methods for ceramic surface decoration. Our knowledge of this pipeline was, in large part, acquired through our lab's Experimental Clay Residency Program [15], We then present a design space of contemporary surface decoration techniques that we use to inform CeramWrap's interactive workflow.

3.1 Ceramic-Making Pipeline

Ceramics manufacture is structured around multiple time-dependent steps which correspond with and are constrained by the material properties of the clay. For instance, the techniques used for decorating greenware (unfired clay) differ from those used on bisque-fired ceramics. Consequently, it is critical to have a good understanding of the ceramic-making pipeline to determine when and how to apply ornamentation. It is important to stress that the pipeline presented below is ubiquitous for ceramic making and glazing; however, variations exist. For example, many native potters skip the bisque-firing step altogether. This diversity of practice further demonstrates the need for an adaptable approach for manual-computational workflows for practices that span a large portion of the pipeline.

First, the craftsperson creates a form with wet clay, which typically involves following a ceramic-making technique such as wheel throwing, hand coiling, slab building, casting, 3D printing, or a combination of these techniques. The craftsperson waits for a variable amount of time for the piece to firm up, ranging from hours to weeks depending on the scale and thickness of the object. During drying, water evaporates from the clay, and the object goes through distinct phases called *plastic*, *leather hard*, and *bone dry* [34, 53]. Decorative underglazes can be applied at any of these steps of the process [9].

Once the piece is sufficiently dry, the craftsperson *bisque fires* the piece in a kiln at lower temperatures (1820-1945 F/ 998-1063 C)

	Wet	Leather hard	Bone dry	Bisque fired	Glaze fired
Rim Diameter	103.5	98.5	97.9	96	91.54
Base Diameter	67.7	63.3	61.8	60.8	58.88
Profile Height	114	109	106.5	103.4	97.49
Wall Thickness	6	5.64	5.35	5.27	5.1

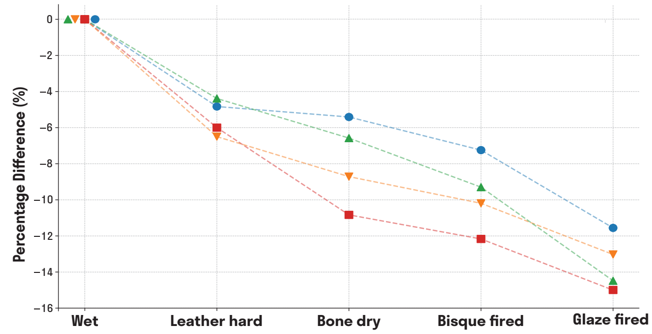

Figure 2: Ceramics shrink non-uniformly based on the vessel geometry. (Left) Four measurements at five phases of clay were recorded from a tapered cylinder printed with Nara 5. (Right) A plot of the same data points visualizing the percentage change.

to remove all moisture from the clay and make it water-insoluble through partial vitrification. After this first firing, the ceramic piece is porous and ready to absorb glazes [33]. When all decorations are complete, the craftsperson *glaze fire*s the piece at a higher temperature (1888-2345 F/ 1031-1285 C) to bring the clay to its final vitrified state. At this state, underglazes are chemically fused with the clay body, and glazes become glass-like. The ceramic piece is then ready for use [4].

Throughout the ceramic-making pipeline, clay shrinks and deforms, affecting the surface decoration application.

Shrinkage: Clay objects shrink due to evaporating water content or chemical transformation. Shrinkage is dependent on the material composition. Clay manufacturers provide estimated shrinkage rates between wet clay and glaze firing–e.g., Aardvark's Nara 5 has a predicted final shrinkage rate of 12%. However, shrinkage is also affected by vessel geometry and it is common to observe non-uniform shrinkage across different parts of the same vessel. Figure 2 reports four measurements of a tapered cylinder at five phases of clay and plots the percentage differences. Craftspeople accommodate shrinkage in their design process by drying pieces in a controlled manner to avoid cracking and by fabricating vessels with consistent wall thickness.

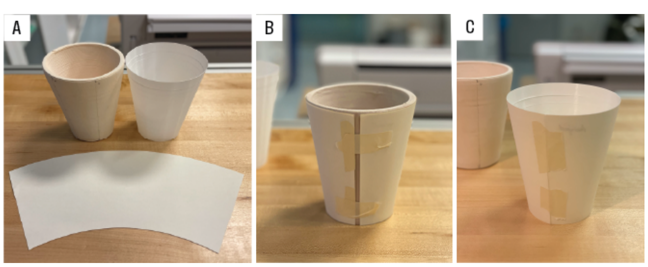

Figure 3: A test setup for deformations affecting the clay object. A) Clay and PLA cups, and the unrolled surface fabricated in paper. B) Cut-out shows a loose fit due to deformations. C) Same cut-out aligns well with the PLA object.

Deformation: When sufficiently moistened, clay is an extremely plastic material. Right after the fabrication, wet clay vessels are easily deformed, either intentionally by the craftsperson or through steps in the fabrication process. For example, wheel-thrown vessels are deformed when removed from the bat, and 3D-printed vessels are frequently deformed around the under-supported regions of the vessel. Clay in the leather-hard phase is less subject to severe deformation, yet any action taken on the vessel is reflected in the final vitrified ceramic. Craftspeople often further modify or refine vessels in the leather-hard phase through operations like trimming, carving, and drilling. The vessel stops being deformable when it reaches the bone-dry phase. Craftspeople may make minor alterations through sanding or polishing, however, larger operations are infeasible because the vessel becomes extremely fragile.

It is generally infeasible to predict deformations since they originate from complex interactions between the material, object geometry, craftsperson, and environment. This is true for both manual ceramics and clay 3D printing [6]. Figure 3 shows an initial test of our workflow that revealed the degree of deformation on a simple clay 3D-printed tapered cylinder; we 3D printed a clay cylinder, removed it from the bat, and bisque fired it (Left in Figure 3A). We measured and recreated the digital vessel as explained in Figure 6. We fabricated the unrolled surface of the recreated vessel with paper (Front in Figure 3A) but the paper did not conform to the ceramics piece neatly (Figure 3B). In order to confirm the accuracy of our unroll function, we then 3D printed the recreated digital model in PLA using an Ender 3 Pro (Right in Figure 3A). The fabricated template fit perfectly with PLA object (Figure 3C). We then iterated on the digital model one additional time by incorporating the gaps around the lip and base in the digital model to achieve a perfect fit on the deformed ceramics cup. This simple test shows the severe impact of deformation on a simple ceramic vessel and reinforces the importance of engaging in cyclical workflows when working across digital and manual domains.

3.2 Surface Ornamentation

In developing a computational-manual ornamentation workflow, one of our primary motivations was to understand how parametric design could extend existing forms of ceramic surface decoration. Ceramic craftspeople across different cultures decorate pottery in rich and distinctive ways. Pueblo pottery is known for its striking geometric patterns [30], Chinese blue-and-white porcelain often showcases intricate flower motifs [66], and Turkish *çini* pottery blends calligraphic, geometric, and vegetal decorations in hierarchical grid structures [20]. Decoration techniques are myriad and include, but are not limited to hand-drawing, painting, transfer, masking, dipping, engraving, stamping, and slab rolling. Decorators also use many different materials including glazes, underglazes, and slips [21, 52]. Craftspeople also use manual tools to lay down patterns precisely on the surface of a pot such as decorating disks to identify the radial symmetry and quilting rulers to annotate on curved surfaces [61]. They may also use digital fabrication techniques to create surface textures on 3D-printed or slip-cast vessels. We classify a subset of surface ornamentation methods into three categories: additive, subtractive, and surface texture. We then describe a design space for ceramic ornamentation by drawing from examples from contemporary potters who work across manual and digital methods. Our objective in creating this design space was to inform the design of a computational workflow that can support multiple forms of existing ceramics surface decoration.

Additive: Ceramicists use techniques for externally adding colors to the surface of their artifacts. The primary methods of uniformly coloring the surface of artifacts are *dipping*, *spraying*, or *brushing* solid color as a base coat. To create decorative patterns, craftspeople draw or paint directly on the surface of the vessel using brushes or other tools to apply colored slips, underglazes, or glazes [62]. For more intricate and challenging motifs, ceramicists can acquire transfer papers with pre-designed patterns and apply them on the surface of the object [39]. It is also common to use materials like masking tape, newspaper, or vinyl as cut-out stencils to hide portions of the surface from colored material [58]. Once colorants are applied to a broader area, removing the stencils creates sharp edges between the previous and currently applied layers.

Subtractive: Ceramicists can also use subtractive methods for surface decoration. Impression-based techniques like press rollers, stamps, or found objects can displace the malleable surface of the clay and leave the texture of the impression object on the surface [7]. Carving-based techniques remove clay from the surface, leaving a channel depending on the tool used. Sgraffito, a technique related to carving, enables craftspeople to create designs on a pre-colored vessel by scratching away the upper layer of color and exposing the clay body underneath [21].

Surface Texture: Ceramic craftspeople can create volumetric surface textures by using mold-making and slip-casting techniques. Intricate designs can be carved on the inner surface of molds and then transferred to the final design through slip-casting [44]. Another approach to producing surface textures is clay 3D printing, where a mechanical extruder deposits clay layer by layer to build a form. Craftspeople can create complex surface details by programming the nozzle head to deposit extra material along the surface of the vessel [29, 64].

3.3 Design Space

We compiled eight representative ceramic works to develop our design space. We analyzed the ornamentation present in these examples and characterized them according to four aesthetic dimensions: the type of decorative elements, the element positioning on the vessel surface, the element alignment to a grid structure, and the alignment of the ornamentation to the vessel geometry. We illustrate this analysis in Figure 4 and describe each dimension below.

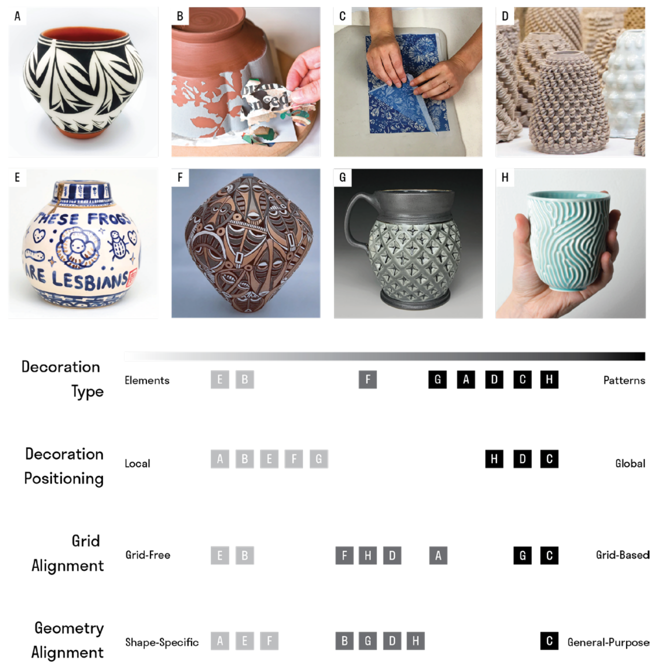

Figure 4: Design space for ceramic surface decoration. A) Pot by Cochiti Pueblo ceramicist Jeff Suina. B) Paper resist technique on a ceramic bowl by Anna and Kevin Ramsay, 2017. C) A demonstration of applying underglaze transfer on a slab of clay by Anne Bailey. D) *the bottery* by Emerging Objects, 2019. E) *THESE FROGS ARE LESBIANS* by Catalina Cheng, 2021. F) *The Voice of Ancestors* by Djakou Kassi Nathalie, 2019. G) Stamped mug by Royce Hilderbrand, 2022. H) *Coral Cup* by Nervous System, 2018.

Type of Decorative Element: We observed that ornamentation on pottery often showcases individual elements, patterns, or a combination of both. For instance, in Figure 4E, Catalina Cheng uses text and figurative imagery in the central part of their pot as distinct elements and repetitive motifs around its neck and bottom [8]. Conversely, in Figures 4D and H, Emerging Objects [14] and Nervous System [44] demonstrate how textures are created as a pattern to cover the surface of a 3D-printed vessel and a slip-cast cup, respectively.

Type of Decorative Element Positioning: We observed that the positioning of surface decoration on ceramics can be applied locally or globally. Craftspeople using direct decorative manual techniques, such as drawing, painting, sgraffito, and carving, have the ability to precisely adjust the position, rotation, and scale of each element independently (as seen on Figure 4A, B, E, F, and G). While craftspeople using complete patterns do not have this level of control over individual element transformations, they can apply multiple elements simultaneously on larger surfaces (Figure 4C, D, H).

Grid Alignment: We observed that the decorative elements on ceramic surfaces can be arranged according to grid structures. In Figure 4A and G, Jeff Suina [60] and Royce Hilderbrand [23] respectively, follow well-defined grids in which decorative elements repeat systematically around a pot or across a clay slab. In Figure 4F, Djakou Kassie Nathalie follows a loosely defined grid structure to design her carved figures [42]. In Figure 4B, Anna and Kevin Ramsay showcase how to use newsprint as paper resist on ceramic vessels; their flower example is free from grid-like structures [51].

Alignment with Vessel Geometry: We observed that certain techniques and types of ornamentation can be tailored to conform to the specific shape of a vessel, while others are intended for general-purpose decoration and impose certain constraints on vessel geometry. Stencil and underglaze transfer sheets are generally optimized for planar surfaces. In Figure 4C, Anne Bailey shows how to apply a pre-designed underglaze transfer pattern from the market onto a slab of greenware clay [39]. This decorated slab can then be used for tiles or vessel construction. Conversely, hand-painted decoration provides the flexibility to adapt a design to the specific curvature of a vessel. Surface textures as seen in Figures 4D and H can also achieve shape specificity when using a shape-dependent generative system.

Our analysis highlighted the vast array of aesthetic possibilities inherent in contemporary pottery ornamentation practices. We also observed how ornamentation methods that can adapt to 3D geometries tend to be challenging to execute consistently, while methods that prioritize repeatability are less able to accommodate specific vessels or necessitate a complete revision of the fabrication process. We see an opportunity to use computational methods to adapt elements to fit specific 3D vessels while also providing support for the systematic repetition of patterns. We drew from this opportunity to develop a computational-manual workflow that can support both single elements and patterns and use local and global positioning techniques that may be grid-based or grid-free while providing vessel-specific capabilities.

3.4 Collaboration

In addition to the design space described above, our workflow was informed by a collaboration between HCI researchers and a professional ceramicist. Mert and Samuelle are Ph.D. students and HCI researchers making software for digital fabrication applications. Camila is a professional ceramic artist and researcher who creates sculptures inspired by 3D mathematical functions. She works extensively with manual and CAD-based methods and her work often involves the creation of complex slab-building templates through the unrolling of 3D virtual models. Jennifer is an assistant professor and director of a research lab that designs computational tools informed by art and craft practice.

4 WORKFLOW

CeramWrap is an interactive adaptable workflow to create surface decorations on ceramic vessels using computational fabrication and manual methods. Our workflow consists of four stages:

(1) Measuring and averaging physical vessel dimensions and creating or updating a digital vessel model.
(2) Decorating the digital model through procedural pattern generation.
(3) Unrolling the 3D patterned surfaces of the vessel into 2D surfaces suitable for fabrication.
(4) Fabricating and applying the stencil to the physical vessel for manual ornamentation.

These stages are demarcated in blue in Figure 5. CeramWrap integrates computational techniques with existing ceramic practices of surface decoration. As highlighted in red in Figure 5, our workflow can be used with different methods for form building–e.g., slab building, clay 3D printing, and wheel throwing– and surface decorations–e.g., underglaze brushing, subtractive drilling and carving, and sgraffito. Due to the complexity of ceramic manufacture, our workflow is also non-linear: later steps often require updating earlier ones. Finally, CeramWrap is developed using the Rhino and Grasshopper software which supports the 3D modeling of digital vessels and the parametric design of decorative patterns.

4.1 Measuring the Physical Vessel and Updating the Virtual Model

The first stage in our workflow begins after a craftsperson has fabricated their vessel either through manual methods (wheel throwing or slab building) or digital fabrication (clay 3D printing). They then measure the dimensions of this physical vessel at a phase suitable for the chosen decoration technique and create or update the virtual model based on these measurements. We presently assume the digital model is generated using simple 3D modeling functions available in Rhino such as the loft function that creates a 3D surface by connecting two or more closed curves or the revolve function by moving a profile curve around a closed curve. As a result, CeramWrap is limited to radially symmetrical surfaces.

As described in Section 3.1, clay undergoes various transformations before becoming ceramics that impact the dimensions and form of a vessel. Its dimensions at the time of surface decoration application will be different from the original dimensions. Therefore, measuring is a critical part of the workflow because each of CeramWrap's following stages will be executed with respect to the physical vessel's dimensions at the time of surface decorations.

To make precise and consistent measurements, the craftsperson can use established ceramics measurement techniques. For the purposes of this paper, they divide the physical vessel's base circumference into six equal regions using the grooves on a banding wheel. They expand these points to the side of the vessel with a laser level. The craftsperson then marks the critical points for digital reconstruction along the laser level (for example, the intersection points of different segments of the red profile curve in Figure 1A). Using these markings as guides, the craftsperson takes three diameter measurements at different heights and six vertical measurements along the walls of the vessel. The craftsperson then uses the averaged dimensions to generate or update a radially symmetrical digital model. The measurements are taken on the outer surface of the vessel to account for the material thickness. This procedure is illustrated in Figure 6 with a tapered cylinder.

Depending on the precision required by the decorative patterns, the craftsperson may repeat the measurement stage multiple

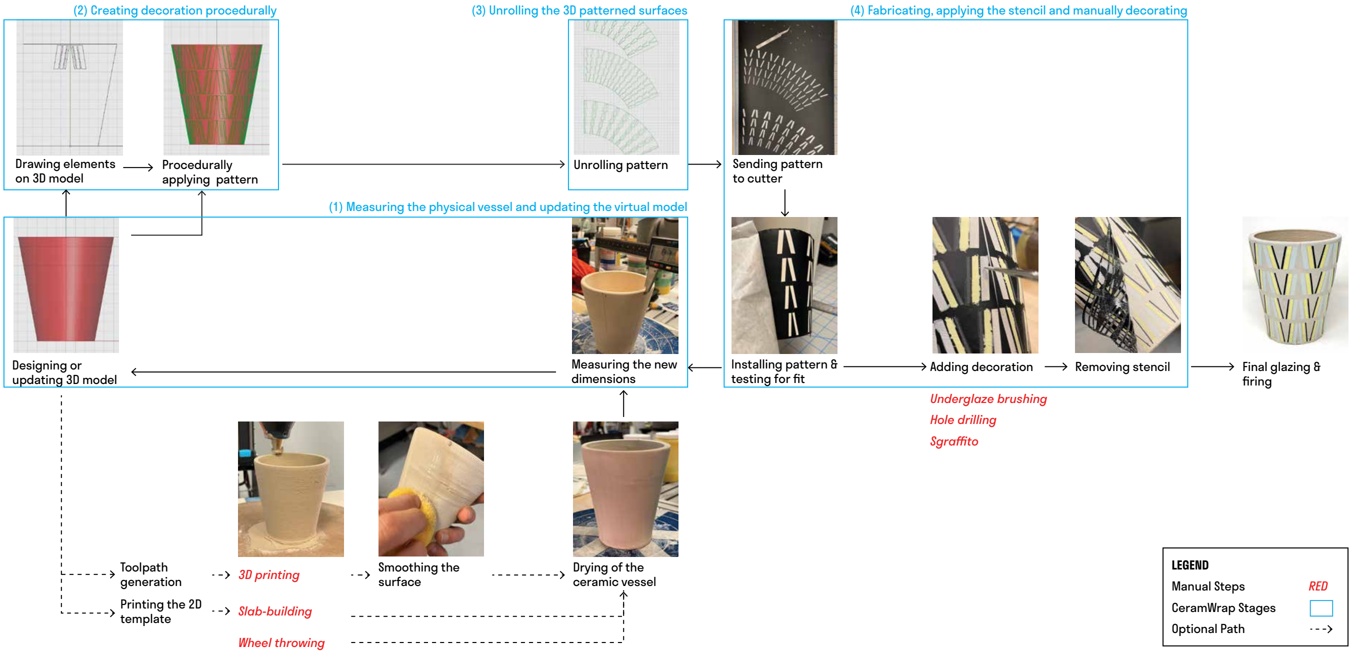

Figure 5: The interactive workflow of CeramWrap aligns with ceramic craft practices. The flowchart shows a simplified version of our workflow, and images represent the production steps of one of our examples (Figure 10). The steps framed by blue rectangles refer to the four stages of our workflow.

times until the digital is an adequate representation of the physical piece. CeramWrap automatically propagates any update to the digital model to the following stages of the workflow, enabling the craftsperson to generate, fabricate and test the fit of the template on the physical vessel quickly.

This stage of our workflow is beneficial for two reasons. First, it ensures that the surface deformations and variable shrinkage rate of a drying ceramic vessel are represented as accurately as the intended design necessitates. Second, it opens up our workflow's capabilities to not only clay 3D printing but also to traditional methods of form building in ceramics, such as wheel throwing and slab building.

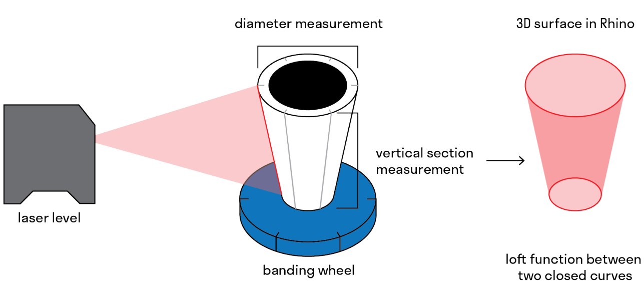

Figure 6: Marking the vessel for measurements. The banding wheel and the laser level are used to divide the vessel into six sections with vertical markings. Three diameter and six vertical measurements are taken with calipers and averaged to create a virtual model of the vessel's surface using simple modeling functions available in the Rhino software.

4.2 Procedurally Generating Patterns on 3D Model

Ceramicists use manual tools to create grid-based designs on ceramic vessels [62] or work with non-parametric direct-manipulation tools to generate fitting stencils [58]. These approaches to pattern creation can be difficult to reproduce consistently or challenging to evaluate aesthetically before the application. Mathematically defined procedural design strategies can support the rapid instantiation of visual elements within a grid structure and the visualization of these elements onto 3D digital models.

To support these procedural strategies, the pattern generation stage of our workflow includes a custom Python component that enables craftspeople to create and display patterns on virtual models of ceramic pieces. With Rhino's 2D drawing functions, the craftsperson draws one instance of a decorative element in front of the model's front face (e.g., top green circle in Figure 7B and C). They use this decorative element (`curve` parameter in Figure 7A) and the CAD 3D model created in the previous stage (`surface` parameter in Figure 7A) as input to CeramWrap's pattern script. They specify the horizontal and vertical repetition parameters for the element's new instances (`nbInRadius` and `nbInHeight` parameters, respectively) and how these instances should scale and translate (`scalingFunction` and `translatingFunction` parameters, respectively) across the surface. This will result in the decorative instances propagating across the surface of the virtual model as

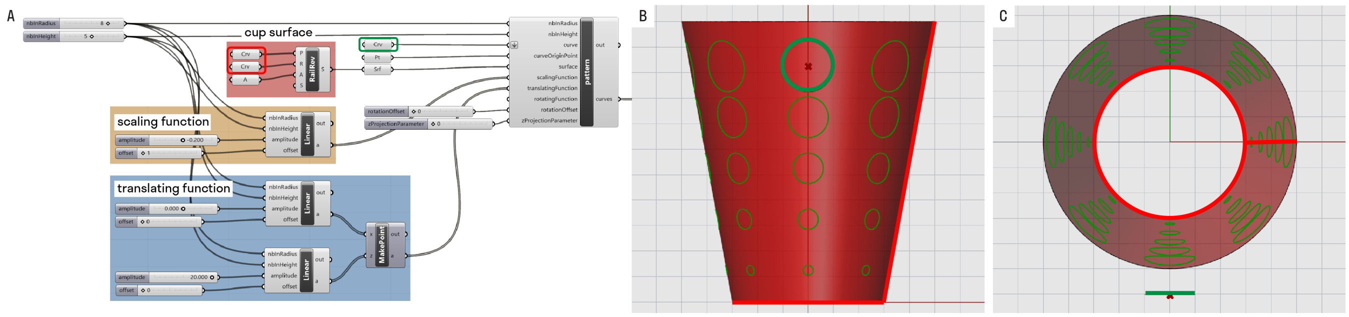

Figure 7: CeramWrap's custom Python component to generate patterns on the surfaces. A) The Grasshopper program generates eight columns by five rows of circles on the surface of a tapered cylinder. B) A side and C) top view of the generated pattern on the cup. The curves used to create the cup shape are highlighted in red, and the curve used for the initial circle element is green.

illustrated by the thin-stroke green circle in Figure 7B and C. In Figure 7, a linear function is used as the `scalingFunction` parameter to decrease the size of the circles towards the bottom of the cup, and a 2D linear function is used as the `translatingFunction` parameter to distribute the circles' center vertically at equal distances. The craftsperson can also use the global rotation offset (`rotationOffset` parameter) to move the entire pattern around the model to optimize its location relative to the stencil's creases created in the following stage. To accommodate multiple colors or multiple pattern decorations, the pattern generation script can be used multiple times on the same virtual model.

This approach enables both the rapid prototyping of grid-based patterns directly on 3D surfaces and the customization of each element's scale, position, and rotation. It also generates as output the necessary curves used by the unrolling stage presented in the following section.

4.3 Unrolling 3D Patterned Surfaces into 2D Surfaces

The third stage of our workflow consists of unrolling the 3D pattern generated in the previous stage into a 2D surface. Ideally, the unrolling results in a one-to-one mapping between the 3D points on the virtual model's surface and the generated 2D surface, but, in general, perfect mapping is impossible. However, a particular class of mathematical surfaces–i.e., *developable surfaces*– allows for a perfect match between smooth digital surfaces with zero Gaussian curvature and unrolled geometry suitable for fabrication [46, 67]. Any geometry with planar surfaces–e.g., a polygon extruded along a line– and single curvature–e.g., a circle extruded along a line– are examples of developable surfaces. When a model contains double-curvature surfaces–e.g., a circle extruded along a curve– there is no exact mapping between a 3D and a 2D surface suitable for fabrication. Unrolling this type of surface requires discretizing one of the curvatures and creating an approximation of the 3D geometry. In Rhino, this simplification equates to discretizing one of the rail curves used to create the 3D model into a polyline with a small number of edges. The approximated single-curvature surface can then be unrolled into a planar surface suitable for fabrication. Since the mapping between the original 3D model and the approximated 2D surfaces is not preserved, in practice, we avoid placing decorative elements at the edges of the approximated 3D vessel.

For unrolling the 3D patterned surfaces created in the previous stage into 2D surfaces, CeramWrap implements a Python component based on the Rhino API unroll function as shown in Figure 8. The craftsperson uses the decorative elements' curves on the 3D surface from the previous stage (`pattern` parameter) and the 3D model surface of the vessel (`brep` parameter) as input to this script. In general, the script outputs a flat representation of the patterned surfaces composing the 3D model, where the 2D surfaces are connected in the exact order of their arrangement within the model (Figure 8B). The unrolling script may yield intersecting 2D surfaces unsuitable for fabrication, especially in vessels with numerous surfaces of varying curvatures. To address this issue, the craftsperson can use the `explode` and `spacing` parameters to separate the generated 2D surfaces with a specified spacing offset. By doing so, the connections between the sides of the surfaces are lost, but the resulting geometries can be fabricated. Exploding the generated 2D surfaces is also necessary when working with a double-curvature vessel model that has been simplified along one of its dimensions since the 2D surfaces will not match perfectly the original model.

The craftsperson can also unroll regions of interest on the vessel geometry selectively using the Selectable Preview plugin [1] framed by a red rectangle in Figure 8A. In Figure 8B, we show the interactive selection of three quadrants of a tapered cylinder vessel and its corresponding unrolled surface. This selective unrolling facilitates the design of horizontal and vertical patterned strips across a vessel. Figure 1 shows the application of selective unrolling on the neck and the middle section of the vessel. We unrolled the neck section in one piece because of the simplicity of the 2D generated surface (Figure 1B) and we unrolled the bottom bulbous section in separate pieces to facilitate the installation of the stencil on the surface.

CeramWrap's unroll script also enables labeling the edges of the unrolled geometry and the 3D form in digital space using `p_3D` and `p_2D` output parameters. By turning the preview of the `Points` components on and adjusting the `Label Size` parameter in Figure 8A, the craftsperson can visualize digital labels for corresponding edges. Once the 2D patterned surfaces are generated, the craftsperson exports the results in a machine-readable vector format using Rhino's export functionalities. The craftsperson may or may not choose

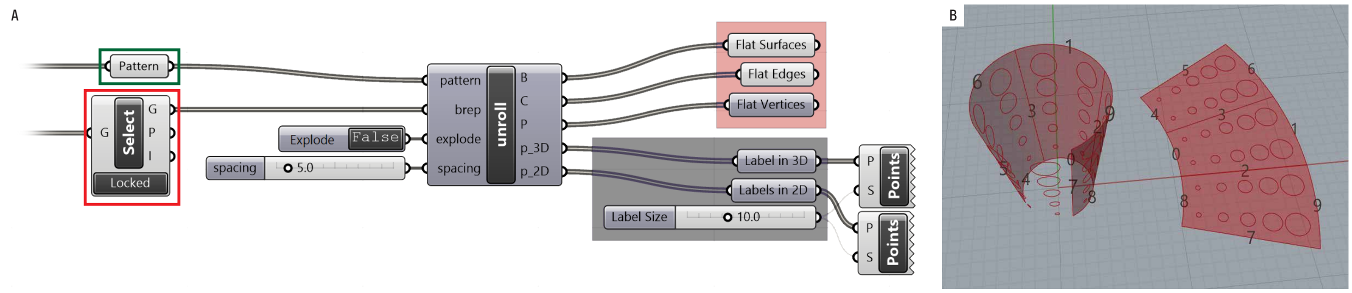

Figure 8: Interactively unrolling the 3D patterned surface. A) The Grasshopper program unrolls the selected faces of a tapered cylinder (in red) with the pattern from Figure 7 (in green). B) A perspective view of the selected 3D surfaces and corresponding 2D unrolled surfaces, along with patterns and labels for reference.

to keep the digital labels on the screen before exporting–in which case these labels would be fabricated along with the stencil.

CeramWrap's interactive surface unrolling and procedural pattern generation methods provide multiple benefits for creating custom surface decorations for ceramic vessels. The workflow supports selective unrolling of a region of interest on the vessel geometry, which aligns with existing ceramic decoration practice that focuses on the design of vertical and horizontal patterns as illustrated in our design space. In cases where the 3D model contains double-curvature regions, interactively designing patterns on the 3D surface helps reduce issues arising from the approximated unrolled geometry and the physical object.

4.4 Fabricating and Applying the Transfer Geometry

The fourth stage of our workflow consists of fabricating a stencil from the 2D patterned surfaces created in the previous stage, applying the stencil on the surface of the physical vessel, and manually decorating the vessel with a method of choice. This stage also involves the possibility of going back to the measuring stage if the stencil does not fit the physical vessel adequately. The entire workflow is built to support these discrepancies and facilitates a rapid update of the stencil. This fourth stage, which involves the stencil alignment on the physical vessel and manual decoration, requires a high level of craftsmanship and necessitates a profound understanding of the materials and decoration techniques in use.

During this stage, the craftsperson cuts their patterned stencils in the material of their choice, such as newsprint, paper, or vinyl, on a digital fabrication machine, such as a laser cutter or a vinyl cutter. We found that newsprint paper works well with vessels in the leather-hard phase, standard linen or copier paper in the leather-hard and bone-dry phases, and adhesive vinyl in the bone-dry or bisque-fired phases. The craftsperson should therefore choose the stencil material that best fits the decorative technique they want to use based on the required clay phase for that technique.

Once fabricated, the craftsperson applies the stencil to the clay surface. To apply a newsprint stencil on greenware, they can use water to create adhesion between the clay and the paper while avoiding excessive moisture to maintain the structural integrity of the vessel. After aligning the newsprint stencil with the vessel, additional water is applied to adhere the stencil to the surface. The craftsperson can then apply their desired surface decoration medium through the stencil's openings. This time-sensitive approach requires relatively fast decoration application since evaporation will deadhere the newsprint and extra water will weaken the greenware. This process is demonstrated in Figure 12D and E, where the newsprint stencil is applied on the bowl and holes are marked for drilling.

To apply a vinyl stencil on a bone-dry or bisque-fired surface, the craftsperson must first remove the decorative element parts of the stencil using tweezers. Then, using a transfer tape, they release the stencil from the liner material. They align the transferred vinyl with the ceramic surface and apply force to ensure good adhesion while avoiding buckling in the stencil. After carefully removing the transfer tape, the craftsperson applies the decoration medium like glaze or underglaze, lets it dry, and removes the vinyl carefully. Stage four of Figure 5 demonstrates the fabricated 2D vinyl stencil, its installation on the vessel, the decoration through underglaze brushing, and the removal processes.

Lastly, a paper stencil can be used for applications where the bleeding of the decoration medium is not an issue, such as for the sgraffito technique. In this case, the craftsperson aligns and tapes the paper on the leather-hard or bone-dry vessel. Then they use sharp clay tools to carve the outer surface of the vessel. Figure 13D shows an example of this procedure.

The choice of the stencil material impacts the surface decoration process. Laser-cut newsprint presents challenges for fabricating patterns inside hollow regions, and fine spacing between decorative elements complicates alignment and installation on ceramic vessels. Vinyl-cut stencils with transfer tape address these challenges but take longer to install on the clay vessel. Figure 10B shows thin regions between different-colored areas on the vinyl.

CeramWrap's generation of 2D patterned surfaces in vector format supports multiple stencil fabrication materials and techniques. The stencils generated through our workflow can therefore be customized to fulfill the requirements of the craftsperson's desired surface decoration method. The iterative process which takes place through the four stages of the workflow also supports rapid updates of the stencil to achieve a desired fit with the ceramic vessel.

4.5 Limitations

CeramWrap's workflow does not include explicit support for 3D modeling of vessel geometry. While 3D modeling can pose challenges for many people, HCI researchers have previously explored methods to reduce the tedium associated with 3D modeling for digital fabrication [47, 55, 57, 65]; our focus is on the 2D ornamentation of 3D forms and we see opportunities to incorporate existing entry-level 3D modeling strategies in future work. To simplify some of the 3D modeling challenges, we limited CeramWrap to radially symmetrical vessels which we produce with Rhino's loft and revolve functions. This limits the modeling process to just a few steps. Radial symmetry is extremely prevalent in ceramics, especially in pots created through wheel throwing. Limiting our application space to radially symmetrical forms allowed us to examine specific challenges related to surface ornamentation by reducing the focus on form-making and digital modeling while remaining inclusive of a broad swath of existing ceramics production.

As discussed in Section 3, physical distortions and non-uniform shrinkage during the ceramic-making pipeline are unavoidable and involve a discrepancy between the evolving physical material and the perfectly symmetrical digital model. We argue that addressing this discrepancy through a non-linear computational workflow complements the dynamic nature of ceramics craft more meaningfully than attempting to exhaustively reproduce a dynamic physical object in a digital model. We leverage the continuous editability of parametric systems for modeling, pattern generation, and selective unrolling, as well as the speed of digital fabrication for rapid iteration in response to material change.

Our workflow is tailored to decorative elements that can be organized in a rectangular grid or arranged in a grid-free manner. This produces various effects aligned with manual ceramics patterning as evident in our design space. At the moment, CeramWrap does not support raster designs or non-rectangular tessellations but we see potential for future work in this direction.

5 EVALUATION THROUGH MAKING EXAMPLE ARTIFACTS

We apply CeramWrap's interactive workflow to six example vessels with varying geometries and curvature types. These examples demonstrate how CeramWrap enables the computational design and fabrication of ornamentation on vessels with planar, single, and double-curvature surfaces, fabricated with manual methods or clay 3D printing. We use the workflow with underglaze brushing, drill piercing, and sgraffito surface decoration techniques.

5.1 Underglaze on Planar Surfaces of Slab-Built Hexagonal Cup

In our first example, we apply a repeating pattern to a symmetrical slab-built vessel. We prepared a hexagonal cup comprising six planar walls and one hexagonal base in Rhino with a repeating pattern around the walls of the vessel. We unrolled the 3D surfaces, and laser cut the result to create a paper template. We cut slabs of clay using this template and assembled the pieces manually. Following the bisque firing, we measured the sides of the cup and updated the digital model. We then used CeramWrap to generate and unroll an ornamentation pattern for the slab-built form. As shown in Figures 9A, B, and C, we used three triangle elements repeated ten times vertically and six times horizontally. The side triangles use a sinusoidal translating function while the middle one follows a linear function. All three use the same linear function to sequentially scale down the triangle motif. We fabricated the resulting stencil on a vinyl cutter, applied it to the vessel, and brushed red underglaze through the stencil (Figures 9D and E). We show the final artifact in Figure 9G.

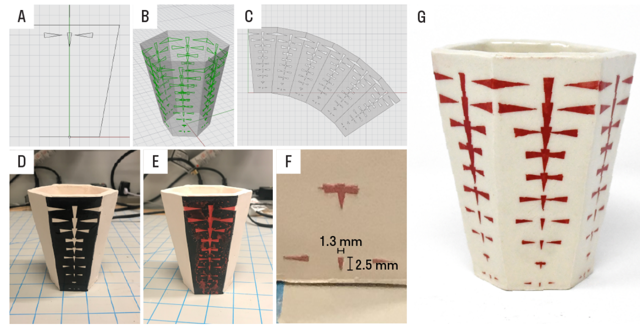

Figure 9: Workflow for a hexagonal cup with planar surfaces. A) Three triangle elements are used to generate the pattern. B) The generated pattern on the virtual model. C) The unrolled 2D stencil with generated patterns. D) The vinyl-cut stencil is applied on one side of the cup. E) Red underglaze is brushed through the stencil. F) Once the vinyl is removed, the precision of successfully transferred detail falls in the range of millimeters. G) The final glazed cup.

This example demonstrates the initial benefits of CeramWrap's workflow for manual ceramics fabrication. First, we show how the generation of a vinyl stencil with CeramWrap and its application onto a bisque surface aligns with a manual clay ornamentation workflow–in this case, the ornamentation of a slab-built planar vessel. This example also shows how CeramWrap incorporates the precision of computational design and digital fabrication with manual ceramics craft. As shown in Figure 9F, this process provided a high level of detail fidelity within the millimeter range; the smallest triangle dimensions on the surface are 2.5 mm tall and 1.3 mm wide. The precision of our workflow is further evident in the continuity of the final ornamentation across different surfaces. The aligned triangle stencils on each face produce diamond shapes at the top corners of the cup.

5.2 Underglaze on Single-Curvature Surface of 3D-Printed Cylindrical Cups

In our second example, we apply three-color ornamentation to a 3D-printed tapered cylinder cup (the workflow stages are shown in Figure 5). This example showcases the successful application of CeramWrap to a digitally fabricated and manually adjusted vessel with a single curvature. We clay 3D printed the cup, smoothed the surface with a sponge at the leather-hard phase, and bisque fired it. To account for the shrinkage and deformations, we measured the diameters and height of the vessel and updated the Rhino model that was used to create the 3D printing file with these new measurements (see Figure 6).

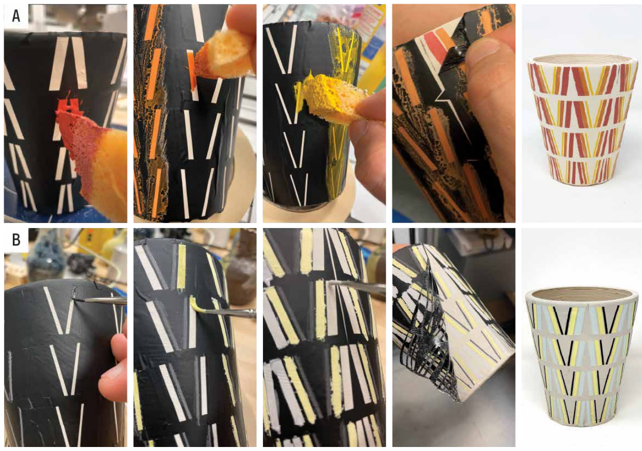

Figure 10: Two approaches to use CeramWrap with multi-color designs. A) Using separate stencils for each color. B) Using one stencil and weeding the vinyl one color at a time.

We used CeramWrap to create a repeating pattern with nested chevrons of varying thicknesses in vertical columns. We used this pattern to create a three-color vinyl stencil for the vessel. We demonstrate two approaches to applying this multi-color pattern. First, we demonstrate the successive application of three different stencils corresponding to each color as seen in Figure 10A. This approach has the advantage of ensuring complete masking of each color channel during underglaze application and builds on existing multiple-masking techniques for cylindrical vessels [58]. The trade-off is that aligning multiple stencils requires a high degree of manual skill. Furthermore, applying stencils over previously applied underglaze introduces an additional risk of damaging that ornamentation upon removal. An alternative approach, as depicted in Figure 10B, is to use a single stencil for all three colors and successively remove vinyl portions that correspond to the different color channels. This method requires increased manual precision during the underglaze application but can be facilitated by using a finer brush.

Collectively, both completed cups demonstrate how CeramWrap can be adapted to support varying forms and degrees of manual skill. CeramWrap's parametric representation of the surface ornamentation and its automated unrolling technique reduces the labor in generating multiple variations of a stencil. This enables the craftsperson to produce different stencils at varying scales and deliberately negotiate the intersecting constraints between vessel structure, pattern complexity, and ornamentation method.

5.3 Underglaze on Planar and Single-Curvature Surfaces of 3D-Printed Octagonal Vase

In our third example, we apply ornamentation to a faceted octagonal vase with both planar and single-curvature surfaces (Figure 1). To test our workflow's adaptability on different types of surfaces on the same vessel, we revolved a profile curve on an octagonal rail curve. We deliberately chose two types of curvatures along the profile curve (as shown in red in Figure 1A), containing segments of two curves and three lines. This operation resulted in three planar and two single-curvature surfaces on each face. We used a clay 3D printer to fabricate the vessel and smoothed the outer walls with a sponge.

We bisque fired the vase to prepare it for masking with vinyl. In order to account for the shrinkage during the firing process, we measured intersecting edges of each surface and updated the digital model based on the average measurements. We designed a surface pattern consisting of 135 dots and 6 lines on the digital model (Figure 1A) and repeated this pattern on all sides of the vessel. We vinyl-cut the stencil, manually removed the dots and line geometries, and installed them on the object surface in sections. We added blue underglaze with a sponge through the holes of the stencil (Figure 1B) and removed the vinyl once the underglaze was dry (Figure 1C).

This example demonstrates how CeramWrap can produce continuous and visually cohesive elements across multiple surfaces. We also show the benefits of generating stencils that can be unrolled both horizontally (Figure 1B) and vertically to support different decorative layouts and surface types for the same vessel.

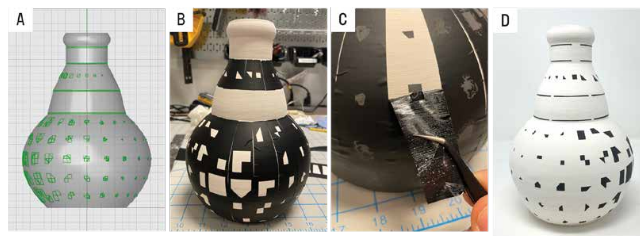

Figure 11: Generative geometrical pattern on double-curvature vase. A) The pattern is made of squares and triangles that are randomly turned on and off, creating a range of distinct shapes. B) We approximated the large double-curvature region with 20 vertical slices. The stencils cover the surface adequately for our purpose. C) We peeled off the stencils individually after the black underglaze was dry, leaving well-defined geometrical shapes. D) The final artifact.

5.4 Underglaze on Single and Double-Curvature Surfaces of 3D-Printed Circular Vase

In our fourth example, we apply a generative, non-repeating pattern to a vase composed of single and double-curvature walls. We generate a digital model by revolving the same profile curve from the previous example on a circular rail to produce a symmetrical vase with two double-curvature and three single-curvature surfaces (Figure 11). We 3D printed the vase, smoothed the outer wall at leather-hard phase, and bisque fired the piece. We then updated the digital model using the averaged dimensions around the defining points on the profile curve.

To create the non-repeating pattern on the bulbous base and the middle section of the neck, we extended CeramWrap's pattern-making component to enable randomization on the likelihood of the elements being projected onto the surface. We created a grid of 20 horizontal by 5 vertical decorative motifs consisting of different groupings of squares and triangles. To account for the curvature of the base in our motif distribution, we used a logarithmic function as the vertical component of the `translatingFunction` parameter of the pattern script and an absolute value function on the horizontal component of the `scalingFunction` parameter to create larger elements on one side of the vase and smaller on the other (Figure 11A). In order to simplify the double-curvature region and to better reflect the pattern construction, we approximated the rail curve of our vessel with an icosagon (20-gon). We fabricated the unrolled stencils (20 vertical slices for non-repeating patterns and 2 continuous horizontal slices for patterns with lines) with the vinyl cutter and installed them on the vessel (Figure 11B).

This example illustrates how our workflow supports the computational ornamentation of vessels with complex non-planar geometry through a systematic method for simplifying double-curvature surfaces into single-curvature fabricatable stencils. The vertical unrolling approach generates a sufficiently precise approximation of the bulbous surface for our application method; the stencils cover the entire surface and enable the transfer of neatly defined geometrical elements (Figure 11C).

5.5 Drill Piercing on Double-Curvature Surface on Wheel-Thrown Colander

As our fifth example, we demonstrate CeramWrap's adaptability to produce evenly spaced subtractive surface decoration on a wheel-thrown vessel. We created a double-curvature vessel by throwing and trimming a bowl on a potter's wheel (Figure 12A). We generated a digital version of the thrown bowl by averaging top and bottom diameters, photographing and digitally tracing the profile of the vessel. To create a drilling template, we approximated the double-curvature surface of the digital model with ten vertical sections and generated a pattern for drilling 3/32" and 3/16"-diameter holes (Figures 12B and C). We laser cut the template on newsprint and adhered them to the greenware with a wet sponge (Figure 12D). We marked each hole position with a probe and removed the template. Following a drying period, we drilled the holes to produce a colander (Figure 12E). The final product is shown in Figures 12F and G.

In addition to showcasing the versatility of CeramWrap for wheel-thrown and subtractive fabrication methods, this example demonstrates how our workflow can be adapted to different degrees of *tolerance* in the ornamentation process. Drilling exhibits a higher tolerance than the underglaze application through stencils because it does not require the edges of the template to closely adhere to the walls of the vessel. We took advantage of this by designing a template that conformed to the global geometry of the bowl and manually adjusting the template to align the template with the contours of the bowl. This also reduced the fabrication time in comparison to the stenciled examples.

5.6 Sgraffito on Double-Curvature Surfaces of 3D-Printed Textured Vessel

For our sixth example, we demonstrate how CeramWrap's workflow enables the augmentation of clay 3D-printed surface textures with sgraffito ornamentation. This example uses a large double-curvature vase that has three untextured regions without bumps on the surface (Figures 13A and B). As a design choice, we modulated the strength of the surface textures radiating out from these flat 3D surfaces. We repeated the textured layers every eight layers and 3D printed the

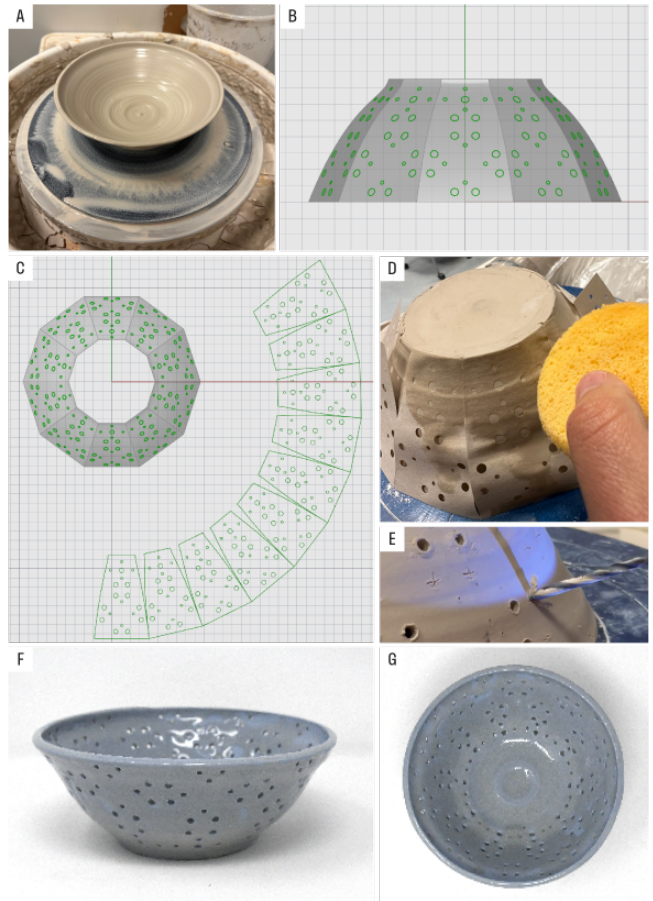

Figure 12: Double-curvature colander with two-size drilled pattern. A) We threw a bowl on the wheel. B) We created a digital model of the bowl. C) We unrolled the surfaces to obtain the 2D template. D) We laser cut the template in newsprint and applied them using a wet sponge. E) The template enabled us to mark the patterns and drill the surface. F) A side and G) a top view of the final glazed artifact.

vessel using a 1 mm layer height. We sprayed the entire surface with black underglaze (Figure 13C) in between the leather-hard and bone-dry phases to use the sgraffito technique to further ornament the surface.

To unroll an approximated single-curvature surface, we discretized the profile curve of the vessel with an angle tolerance of 11 degrees. This operation converted the smooth profile curve into a polyline with ten vertices. We took diameter measurements at physical locations that correspond to these vertices and recreated the current state of the vessel digitally. As for the pattern, we repeated an ellipse-shaped decorative element using linear functions (green elements in Figure 13A) on the flat surfaces to reflect the position and distribution of the 3D-printed bumps. We unrolled the surfaces and laser cut non-adhesive paper templates since newsprint application with a wet sponge would have removed the black underglaze. We sequentially taped each template section to the vessel and used

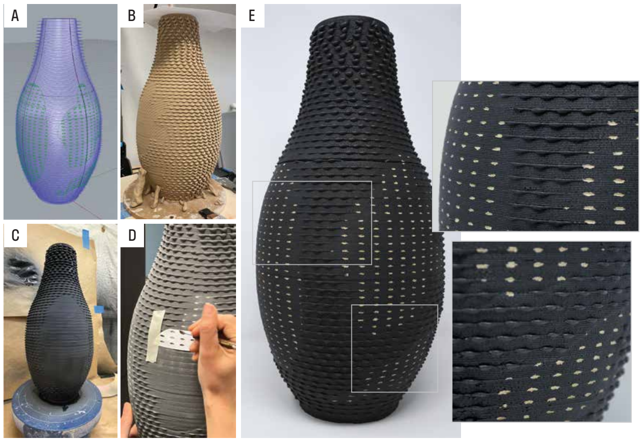

Figure 13: 3D-printed large vase with surface textures and a sgraffito pattern that aligns with surface bumps. A) The toolpath (blue) with surface bumps and 3 flat regions; pattern on flat regions (green). B) 3D-printed vase on the printer bed with manual supports. C) Spraying the vase with black underglaze. D) Applying the laser-cut paper of the unrolled surface with tape and carving the surface with a sharp clay tool. E) The final artifact with close-up images of the surface.

them as guides to scratch off the underglaze with a small pottery carving tool (Figure 13D). Following the surface ornamentation, we fired the vessel (Figure 13E).

This example demonstrates how CeramWrap can integrate the unique surface ornamentation opportunities of manual and 3D-printed ceramics. We generate a precise template that corresponds with the layers of the 3D-printed vessel while retaining opportunities for manual skill in the sgraffito application.

5.7 Summary of a Non-Linear Workflow for Ceramic Ornamentation

The use of CeramWrap in making the previous examples demonstrated key aspects of manual-computational approaches for ceramic surface ornamentation:

(1) Precise digital design and fabrication procedures can be integrated into existing manual ceramics craft practices: Surface decorations were applied using a range of techniques (underglaze brushing, drilling, sgraffito) through digitally generated stencils, on vessels fabricated with various methods (slab building, wheel throwing, clay 3D printing).
(2) Manual-computational workflows can adapt to the evolving nature of materials: By rapidly propagating changes in the pattern design and generation of CeramWrap stencils, we were able to adapt to the shrinkage and distortion of a ceramic vessel.
(3) Manual-computational workflows can support different levels of technical requirements: CeramWrap can be used by craftspeople showing various degrees of skill at different steps of the fabrication process and can accommodate varying alignment tolerance between the stencils and the vessel, depending on the ornamentation techniques employed.

Our evaluation through the making of six artifacts demonstrates the opportunities of digital fabrication systems in supporting non-linear workflows. While we investigated the integration of computational tools with manual ceramic ornamentation, we see the potential for broader HCI system research in the realm of craft. We believe that by considering the complementary nature of manual and digital processes, we can design tools that accommodate flexible interactions between the computer and the physical world.

6 CONCLUSION

CeramWrap is an interactive workflow for applying surface decorations on clay vessels that can adapt to different manual ornamentation methods of manual ceramics craft. Rather than presenting a rigid technique, CeramWrap embraces the iterative and often cyclical nature of craft in an effort to augment established skilled ceramic ornamentation.

Our workflow enables craftspeople to utilize computational tools for designing and transferring intricate patterns onto their ceramic creations. First, it introduces a procedural design method that uses mathematical functions to repeat decorative elements along the surfaces of a digital 3D vessel. Second, it supports the unrolling of these patterned 3D surfaces into 2D surfaces suitable for fabrication, which once digitally fabricated serve as stencils for guiding surface decoration on ceramic vessels.

We demonstrate the application of CeramWrap in multiple forms of digital and manual ceramics craft by using our workflow to ornament vessels made using various fabrication techniques, such as slab building, 3D printing, and wheel throwing, at different pottery phases, ranging from leather-hard to bisque-fired. Additionally, CeramWrap can create stencils for decoration, using different materials such as newsprint, vinyl, and printer paper, and support various ornamentation techniques like underglaze brushing, hole drilling, and sgraffito. The examples themselves exhibit a mix of precision and manual variation that reflects both our use of computational methods and the fabricator's manual skill. As we consider future pathways for supporting digital design, customization, and personal fabrication, CeramWrap provides insight into the expressive potential of computational fabrication workflows that align with the versatility of skilled manual production.

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REFERENCES

[1] alantai. 2019. Food4Rhino Selectable Preview 0.2. https://www.food4rhino.com/en/app/selectable-preview

[2] Lea Albaugh, Scott E Hudson, and Lining Yao. 2023. Physically Situated Tools for Exploring a Grain Space in Computational Machine Knitting. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3544548.3581434

[3] Jane Bennett. 2010. *Vibrant Matter: A Political Ecology of Things.* Duke University Press, Durham & London.

[4] Linda Bloomfield. 2017. Firing Clay: The Lowdown on the Ceramic Firing Process. https://ceramicartsnetwork.org/daily/article/Firing-Clay-The-Lowdown-on-the-Ceramic-Firing-Process

[5] Dietrich Von Bothmer. 1987. *Greek Vase Painting*. Metropolitan Museum of Art, New York.

[6] Samuelle Bourgault, Pilar Wiley, Avi Farber, and Jennifer Jacobs. 2023. CoilCAM: Supporting variations of forms and surfaces in clay 3D printing through action-oriented parametric workflows. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3544548.3580745

[7] Amy Brummond. 2021. In the Studio: Transfer + Stamp + Color. https://ceramicartsnetwork.org/pottery-making-illustrated/pottery-making-illustrated-article/In-the-Studio-Transfer-Stamp-Color

[8] Catalina Cheng. 2020. THESE FROGS ARE LESSBIANS. https://catalinacheng.square.site/gallery

[9] Val Cushing. 1994. *Cushing's Handbook.* Self-published, Alfred, NY.

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

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

[12] Laura Devendorf, Katya Arquilla, Sandra Wirtanen, Allison Anderson, and Steven Frost. 2020. Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376820

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

[14] Emerging Objects. 2019. The bottery. http://emergingobjects.com/project/the-bottery

[15] University of California Santa Barbara Expressive Computation Lab. 2023. Experimental Clay Residency Open Call. https://ecl.mat.ucsb.edu/residency23

[16] Filippo Andrea Fanni, Fabio Pellacini, Riccardo Scateni, and Andrea Giachetti. 2022. PAVEL: Decorative Patterns with Packed Volumetric Elements. *ACM Transactions on Graphics* 41, 2 (Jan. 2022), 19:1–19:15. https://doi.org/10.1145/3502802

[17] Jack Forman, Mustafa Doga Dogan, Hamilton Forsythe, and Hiroshi Ishii. 2020. DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-Extrusion. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA, 1222–1233. https://doi.org/10.1145/3379337.3415876

[18] Camila Friedman-Gerlicz. 2023. Online works of Camila Friedman-Gerlicz. https://camilafg.com/category/work/

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

[20] Henry Glassie. 1993. *Turkish Traditional Art Today.* Indiana University Press, Bloomington, IN.

[21] Patricia Griffin. 2020. Sgraffito Decoration. https://ceramicartsnetwork.org/pottery-making-illustrated/pottery-making-illustrated-article/Sgraffito-Decoration-251022

[22] Donna J. Haraway. 2016. *Staying with the Trouble: Making Kin in the Chthulucene.* Duke University Press, Durham & London. https://doi.org/10.1215/9780822373780

[23] Royce Hilderbrand. n.a.. @royce_hilderbrand_pottery. https://www.instagram.com/royce_hilderbrand_pottery/

[24] Mare Hirsch, Gabrielle Benabdallah, Jennifer Jacobs, and Nadya Peek. 2023. Nothing Like Compilation: How Professional Digital Fabrication Workflows Go Beyond Extruding, Milling, and Machines. *ACM Trans. Comput.-Hum. Interact.* Just, Accepted (Jul 2023). https://doi.org/10.1145/3609328

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

[26] Tim Ingold. 2009. The textility of making. *Cambridge Journal of Economics* 34, 1 (07 2009), 91–102. https://doi.org/10.1093/cje/bep042 arXiv:https://academic.oup.com/cje/article-pdf/34/1/91/4746308/bep042.pdf

[27] Alexandra Ion, Michael Rabinovich, Philipp Herholz, and Olga Sorkine-Hornung. 2020. Shape Approximation by Developable Wrapping. *ACM Trans. Graph.* 39, 6, Article 200 (nov 2020), 12 pages. https://doi.org/10.1145/3414685.3417835

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

[29] Jonathan Keep. 2022. Jonathan Keep. Home Page. http://www.keep-art.co.uk/

[30] Rick Kinsel and Pueblo Pottery Collective. 2022. *Grounded in Clay: The Spirit of Pueblo Pottery.* Merrell, London.

[31] Mina Konaković, Keenan Crane, Bailin Deng, Sofien Bouaziz, Daniel Piker, and Mark Pauly. 2016. Beyond Developable: Computational Design and Fabrication with Auxetic Materials. *ACM Trans. Graph.* 35, 4, Article 89 (Jul 2016), 11 pages. https://doi.org/10.1145/2897824.2925944

[32] Mackenzie Leake, Frances Lai, Tovi Grossman, Daniel Wigdor, and Ben Lafreniere. 2021. PatchProv: Supporting Improvisational Design Practices for Modern Quilting. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–17. https://doi.org/10.1145/3411764.3445601

[33] Lesley. 2021. What Happens to Clay When it is Fired in a Kiln? https://thepotterywheel.com/what-happens-to-clay-when-it-is-fired/

[34] Lesley. 2022. The 8 Stages of Clay - An Amazing Journey from Dirt to Art. https://thepotterywheel.com/stages-of-clay/

[35] Jingyi Li, Sonia Hashim, and Jennifer Jacobs. 2021. What We Can Learn From Visual Artists About Software Development. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 314, 14 pages. https://doi.org/10.1145/3411764.3445682

[36] Joris Link. 2023. Joris Link. http://www.jorislink.nl/

[37] Wallace Lira, Chi-Wing Fu, and Hao Zhang. 2018. Fabricable eulerian wires for 3D shape abstraction. *ACM Transactions on Graphics* 37, 6 (Dec. 2018), 1–13. https://doi.org/10.1145/3272127.3275049

[38] Ye Liu, Bo Zhang, and Liang Wan. 2017. Automatically unrolling decorations painted on 3D pottery. In *Proceedings of the Computer Graphics International Conference*. ACM, Yokohama Japan, 1–6. https://doi.org/10.1145/3095140.3095177

[39] Lyla at Baileys. 2018. New! Underglaze Transfers, Part 1: How to Apply Underglaze Transfers to the Clay Surface. https://www.baileypottery.com/blog/post/new-underglaze-transfers-part-1-how-to-apply-underglaze-transfers-to-the-clay-surface.html

[40] Shiran Magrisso, Moran Mizrahi, and Amit Zoran. 2018. Digital Joinery For Hybrid Carpentry. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–11. https://doi.org/10.1145/3173574.3173741

[41] Claudio Mancinelli, Giacomo Nazzaro, Fabio Pellacini, and Enrico Puppo. 2023. b/Surf: Interactive Bézier Splines on Surface Meshes. *IEEE Transactions on Visualization and Computer Graphics* 29, 7 (2023), 3419–3435. https://doi.org/10.1109/TVCG.2022.3171179

[42] Djakou Kassi Nathalie. 2019. The Voice of The Ancestors. https://www.signatureafricanart.com/artists/33-djakou-kassi-nathalie/works/75-djakou-kassi-nathalie-the-voice-of-ancestors-2019/

[43] Giacomo Nazzaro, Enrico Puppo, and Fabio Pellacini. 2021. GeoTangle: Interactive Design of Geodesic Tangle Patterns on Surfaces. *ACM Trans. Graph.* 41, 2, Article 12 (nov 2021), 17 pages. https://doi.org/10.1145/3487909

[44] Nervous System. 2018. Coral Cup. https://n-e-r-v-o-u-s.com/blog/?p=8222

[45] Keunwoo Park, Conrad Lempert, Muhammad Abdullah, Shohei Katakura, Jotaro Shigeyama, Thijs Roumen, and Patrick Baudisch. 2022. FoolProofJoint: Reducing Assembly Errors of Laser Cut 3D Models by Means of Custom Joint Patterns. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 271, 12 pages. https://doi.org/10.1145/3491102.3501919

[46] Nicholas M. Patrikalakis, Takashi Maekawa, and Wonjoon Cho. 2009. Differential geometry of developable surfaces. https://web.mit.edu/hyperbook/Patrikalakis-Maekawa-Cho/node190.html

[47] Huaishu Peng, Amit Zoran, and François V. Guimbretière. 2015. D-Coil: A Hands-on Approach to Digital 3D Models Design. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 1807–1815. https://doi.org/10.1145/2702123.2702381

[48] Mark Pharis. 2023. Mark Pharis Pottery. https://www.markpharis.com/roberts-studio

[49] Nico Pietroni, Corentin Dumery, Raphael Falque, Mark Liu, Teresa Vidal-Calleja, and Olga Sorkine-Hornung. 2022. Computational Pattern Making from 3D

Garment Models. *ACM Trans. Graph.* 41, 4, Article 157 (jul 2022), 14 pages. https://doi.org/10.1145/3528223.3530145

[50] Sarah Pike. 2022. Squish squish stamp stamp. https://www.instagram.com/p/CbxVbd6rSwl/

[51] Anne Ramsay and Kevin Ramsay. 2017. Combining the Sgraffito Technique with Stencils for a Striking Look. https://ceramicartsnetwork.org/daily/article/Combining-the-sgraffito-technique-with-stencils-for-a-striking-look

[52] Emily Reason. 2010. Slip Trailing and Carving for Raised and Recessed Surface Decoration. https://ceramicartsnetwork.org/daily/article/Addition-and-Subtraction-Slip-Trailing-and-Carving-for-Raised-and-Recessed-Surface-Decoration

[53] A. Reijnders. 2005. *The Ceramic Process: A Manual and Source of Inspiration for Ceramic Art and Design.* University of Pennsylvania Press, Incorporated, Philadelphia, PA. https://books.google.com/books?id=qWy9DAAAQBAJ

[54] Thijs Roumen, Conrad Lempert, Ingo Apel, Erik Brendel, Markus Brand, Laurenz Seidel, Lukas Rambold, and Patrick Baudisch. 2021. autoAssembler: Automatic Reconstruction of Laser-Cut 3D Models. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21).* Association for Computing Machinery, New York, NY, USA, 652–662. https://doi.org/10.1145/3472749.3474776

[55] Yuliy Schwartzburg and Mark Pauly. 2013. Fabrication-aware Design with Intersecting Planar Pieces. *Computer Graphics Forum* 32, 2pt3 (2013), 317–326. https://doi.org/10.1111/cgf.12051 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.12051

[56] Roy Shilkrot, Pattie Maes, Joseph A. Paradiso, and Amit Zoran. 2015. Augmented Airbrush for Computer Aided Painting (CAP). *ACM Transactions on Graphics* 34, 2 (March 2015), 19:1–19:11. https://doi.org/10.1145/2699649

[57] Maria Shugrina, Ariel Shamir, and Wojciech Matusik. 2015. Fab Forms: Customizable Objects for Fabrication with Validity and Geometry Caching. *ACM Trans. Graph.* 34, 4, Article 100 (jul 2015), 12 pages. https://doi.org/10.1145/2766994

[58] Kenny Sing. 2023. TURN studio. https://www.turn.studio/

[59] Blair Subbaraman and Nadya Peek. 2022. p5.fab: Direct Control of Digital Fabrication Machines from a Creative Coding Environment. In *Designing Interactive Systems Conference (DIS '22).* Association for Computing Machinery, New York, NY, USA, 1148–1161. https://doi.org/10.1145/3532106.3533496

[60] Jeff Suina. 2022. Art Gallery. https://www.jeffsuina.art/art

[61] Kaname Takada. 2017. Earthenware with Intricate Surface Patterning. https://ceramicartsnetwork.org/ceramics-monthly/ceramics-monthly-article/Earthenware-with-Intricate-Surface-Patterning

[62] Sumiko Takada and Kaname Takada. 2017. Smooth and Exacting Surface Decoration. https://ceramicartsnetwork.org/ceramics-monthly/ceramics-monthly-article/Smooth-and-Exacting-Surface-Decoration

[63] Marco Tarini, Cem Yuksel, and Sylvain Lefebvre. 2017. Rethinking texture mapping. In *ACM SIGGRAPH 2017 Courses (SIGGRAPH '17).* Association for Computing Machinery, New York, NY, USA, 1–139. https://doi.org/10.1145/3084873.3084911

[64] Timea Tihanyi. 2020. Textile Traditions. https://www.timeatihanyi.com/textile-traditions

[65] Cesar Torres and Eric Paulos. 2015. MetaMorphe: Designing Expressive 3D Models for Digital Fabrication. In *Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition* (Glasgow, United Kingdom). Association for Computing Machinery, New York, NY, USA, 73–82. https://doi.org/10.1145/2757226.2757235

[66] Victoria and Albert Museum. n.a. Chinese blue-and-white ceramics. https://www.vam.ac.uk/articles/chinese-blue-and-white-ceramics

[67] Eric W. Weisstein. 2023. "Developable Surface." From MathWorld–A Wolfram Web Resource. https://mathworld.wolfram.com/DevelopableSurface.html

[68] Clement Zheng, Ellen Yi-Luen Do, and Jim Budd. 2017. Joinery: Parametric Joint Generation for Laser Cut Assemblies. In *Proceedings of the 2017 ACM SIGCHI Conference on Creativity and Cognition (C&C '17).* Association for Computing Machinery, New York, NY, USA, 63–74. https://doi.org/10.1145/3059454.3059459

[69] Clement Zheng, Bo Han, Xin Liu, Laura Devendorf, Hans Tan, and Ching Chiuan Yen. 2023. Crafting Interactive Circuits on Glazed Ceramic Ware. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23).* Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3544548.3580836

[70] Amit Zoran, Roy Shilkrot, and Joseph Paradiso. 2013. Human-computer interaction for hybrid carving. In *Proceedings of the 26th annual ACM symposium on User interface software and technology.* ACM, St. Andrews Scotland, United Kingdom, 433–440. https://doi.org/10.1145/2501988.2502023