Clay ARTools: Precise Machine Toolpath Editing for Clay 3D Printing With Craft-Inspired Direct Manipulation Tools in AR

Joyce E Passananti
Computer Science
University of California, Santa Barbara
Goleta, California, USA
joycepassananti@ucsb.edu

Emilie Yu
Media Arts and Technology
UCSB
Santa Barbara, California, USA
emyu@ucsb.edu

Timea Tihanyi
School of Art + Art History + Design
University of Washington
Seattle, Washington, USA
timea@uw.edu

Tobias Höllerer
Media Arts and Technology
University of California Santa Barbara
Santa Barbara, California, USA
holl@cs.ucsb.edu

Jennifer Jacobs
Media Arts and Technology
University of California Santa Barbara
Santa Barbara, California, USA
jmjacobs@ucsb.edu

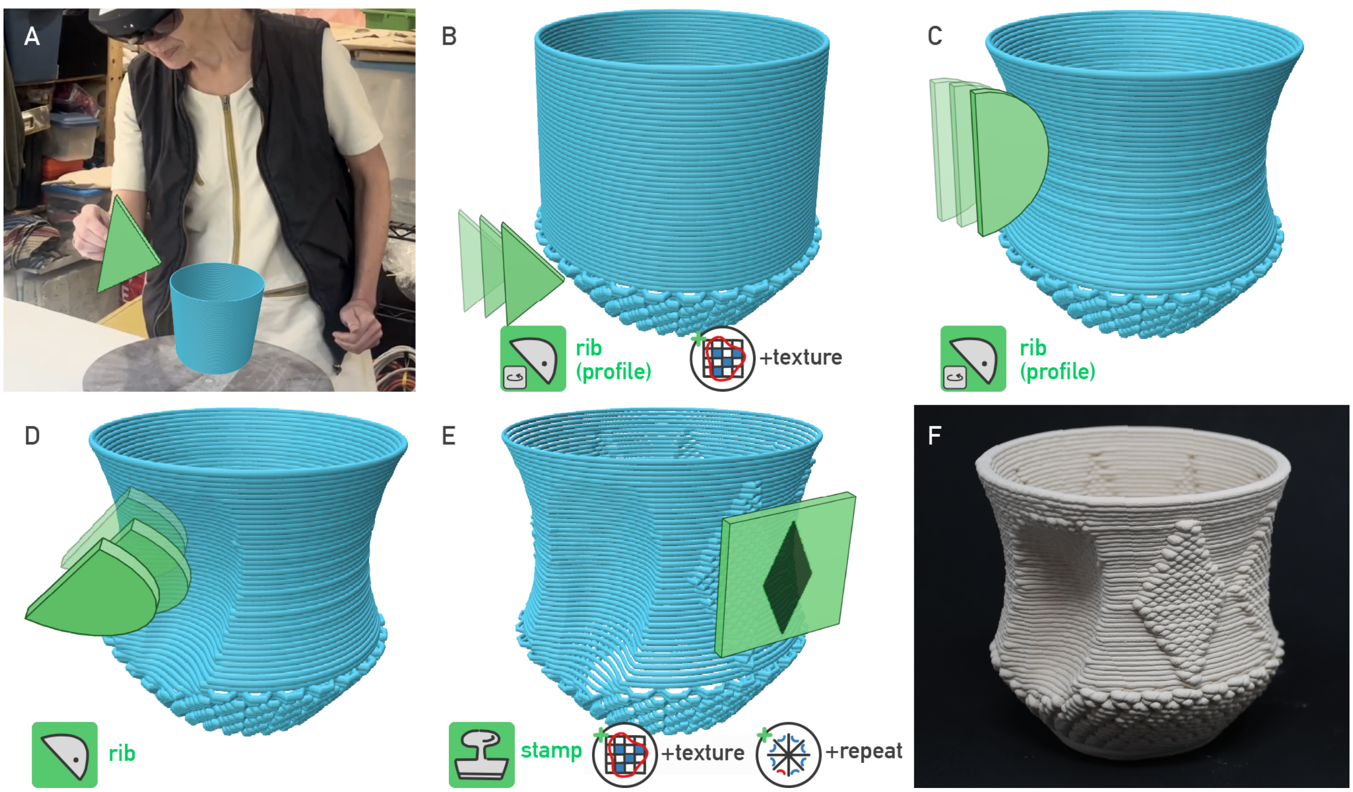

Figure 1: Clay ARtools is a system to design machine toolpath for clay 3D printing. A) Wearing an AR headset, the ceramicist uses a digital ceramic tool to modify the toolpath. B, C) The rib tool in profile mode affects the overall shape of the toolpath. With a texture modifier, she adds a wavy texture to the foot (B). D) The rib tool can also create local deformations. E) She applies a repeated motif across the cup, by using a stamp tool with texture and repeat modifiers. F) 3D printed ceramic cup.

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Abstract

Ceramics practice is an embodied activity where creators use manual tools in unique ways to shape physical material. Clay 3D printing uses the same material as manual ceramics craft, enabling new opportunities for form and texture by precisely controlling the 3D printing toolpath. However, current clay 3D printing design workflows require developing forms through digital software rather than tool-based making. We present Clay ARtools, an augmented reality (AR) system for designing clay 3D printed vessels. We developed Clay ARtools in collaboration with a professional ceramicist to create AR toolpath editing operations that reference manual use of ceramic tools. Through the design and fabrication of 3D-printed clay artifacts, we demonstrate how AR ceramic tools enable precise and controllable modifications of the toolpath, from the overall form down to individual toolpath points. We demonstrate how extending physical tool metaphors with digital representations and numerical precision enables craft-like interaction with CAM-based design techniques.

CCS Concepts

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

Keywords

Creativity Support, Fabrication, Virtual/Augmented Reality, Interaction Design

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1 Introduction

Additive fabrication technology — also commonly called 3D printing — offers the potential to make physical objects in a precise and reproducible manner, from the shape and scale of the overall form down to textural and substructural details. Directly specifying low-level machine motion enables exploring a range of unique material possibilities beyond what can be achieved through higher-level digital representations, such as mesh-based or solid geometry CAD representations [5, 35]. Researchers, designers, and artists have leveraged direct machine toolpath control to program material appearance [17], incorporate shape-changing behaviors [94], develop novel surface textures [44, 81], and improve structural stability [28]. Researchers refer to the process of directly designing machine toolpaths as "CAM-based design", to highlight the additional design possibilities in comparison with CAD [15]. One area of additive fabrication where CAM-based design is particularly relevant is clay 3D printing. Clay 3D printing is an additive fabrication technique in which a 3D printer extrudes ceramic paste to create ceramic artifacts. CAM-based design allows designers to produce robust ceramic forms and novel aesthetics which are difficult to achieve through CAD-based design and automatic toolpath generation. Directly programming the clay deposition toolpath opens a rich space for material exploration and supports a wide range of aesthetic outcomes (see Fig. 3).

Human-computer interaction (HCI) researchers have developed desktop systems for CAM-based designs that lower the barrier-to-entry for machine toolpath programming, through learner-oriented code libraries [61], visual programming [15], 2D sketching [30, 41], and paper craft [91]. However, in existing CAM-based design systems, precise toolpath control comes at the cost of forgoing embodied spatial design. Established and embodied 3D operations from physical ceramics – like pressing a rib against a vessel to define its profile (see Fig. 2A) – are abstracted as general-purpose operations in desktop design tools (e.g., using a revolve operation on a 2D curve). Because of this reliance on 2D mouse interaction, desktop CAM disregards the ceramicist's "skilled body" [42], which is trained in shaping clay.

Augmented Reality (AR) systems can support embodied and in-situ 3D design workflows in digital art and animation [7, 46, 69, 80]. Gestural immersive interfaces are not equivalent to skilled direct manipulation in the physical world, but they provide a pathway to explore embodied interaction with digital content. Hand or controller tracking technology and pass-through rendering techniques can support the design of interactions that bring some of the gestural qualities of manual creation to the digital space, and anchor the digital design activity within a relevant physical context. In the context of digital fabrication, AR systems can help situate digital design operations within the physical space of machine execution [32, 60, 66, 89] and facilitate designing new fabricated objects that fit in the designer's physical environment or with physical objects [8, 26, 37, 75, 77, 97].

Researchers have demonstrated how AR can support people in editing CAD representations [8, 75] or defining an approximate toolpath shape through embodied interaction [26, 32, 52]. These prior approaches do not provide the level of control necessary for skilled CAM-based design for clay 3D printing, which involves computationally precise manipulation of the toolpath at the resolution of individual points (e.g. Fig. 3A, E). The challenge of supporting precise toolpath manipulation is exacerbated by AR 3D mid-air interaction, which is prone to noise from both tracking and human motor abilities [6], making the selection and manipulation of 3D toolpath points non-trivial.

Our objective is to address the gap between embodied 3D interactions in AR and precise toolpath manipulation in CAM-based design, to support ceramic practitioners in designing clay 3D-printed artifacts (see Fig. 1). We pose the following research questions (RQ):

- **RQ1** How can 3D mid-air direct manipulation in AR support precise editing of machine toolpaths for clay 3D printing?
- **RQ2** How can elements of physical ceramic tools and practices be translated into AR design workflows for clay 3D printing?

To investigate these questions, we developed Clay ARtools, a system for CAM-based design in AR that takes advantage of parallels between *digital operations* of toolpath editing, and *physical operations* performed in traditional ceramics workflows. Our primary insight in developing Clay ARtools is that we can design digital operations inspired by physical ceramic tools, and maintain computational precision by extending the digital proxies to support CAM-based toolpath editing.

Ceramics practice is highly mediated by *physical tools* that allow the craftsperson to form the shape and texture of a vessel. For example, a rib tool – a flat wooden or plastic tool with a shaped edge – helps achieve symmetrical profile shaping when applied

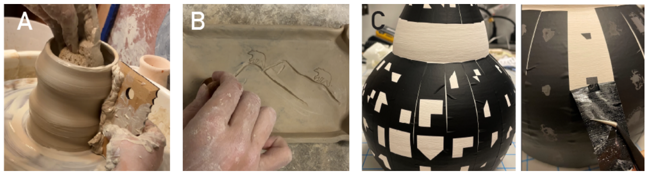


Figure 2: Ceramic tools. A) A rib can form the overall shape of the vessel while throwing. B) Bear-shapes. C) Stencil mask to selectively apply a decorative effect with underglaze [86].

to spinning forms thrown on a pottery wheel, and a stamp tool – a carved shape that can be pressed against the clay – facilitates applying a motif on the surface of a pot (Fig. 2A and B). Tools can be manipulated, combined, or sequenced, and applied freely by the ceramicist, yet through their physical shape, they encode a specific set of material effects. We theorized that *digital ceramic tools* in an AR system could similarly encapsulate precise, customizable toolpath editing capabilities while rendering them familiar through embodied 3D manipulation.

To explore this theory and associated RQs, we collaborated with a professional ceramicist with experience in both clay 3D printing and traditional ceramics to develop our prototype system. Being in dialog with a ceramicist directly informed our software development process [87], in particular the design of digital ceramic tools.

To investigate RQ1, we applied Clay ARtools to the design and fabrication of multiple forms and textures. We present a set of 3D-printed clay artifacts to represent design possibilities of ARTools from a combination of digital tools and modifiers. To address RQ2, we demonstrate system use through our collaboration with a professional ceramicist and compare digital workflow metaphors to physical ceramic practices.

We contribute the following:

- A system that enables precise editing of machine toopaths for clay 3D printing through 3D embodied interactions in AR.
- A collection of 23 artifacts demonstrating applications of our system to expand fabrication possibilities in clay 3D printing through reference of craft-inspired editing methods.
- An account and reflection on our collaborative system development method, and a discussion of key considerations for digital design system creation that directly reference existing physical workflows.

2 Related work

Our research builds on prior work on digital systems to support ceramics workflows (Section 2.1), in particular those that relate to the design of 3D-printed clay vessels. We seek to support embodied design in the context of a digital fabrication workflow, hence we relate to the existing literature on using extended reality technology to support design for fabrication, and contrast our CAM-based approach to prior work (Section 2.2). Finally, using physical tools as metaphors to design digital operations is a broader theme within HCI that we draw from to develop Clay ARtools (Section 2.3).

2.1 Design tools for ceramics

Clay 3D-printing is based on direct-ink-write printing machines that extrude a clay paste to build up 3D forms. Clay 3D-printers are now relatively affordable equipment for a ceramic studio [1]. Artists leverage both 3D form and texture qualities to create unique objects shown in Fig. 3. Timea meticulously designs the patterned surfaces of her work by layering minute-scale 3D solids on a cylindrical surface, which then will be translated into surface texture as small bumps (Fig. 3E). Bryan Czibesz [21] leveraged the precision of 3D-printing to create complex symmetric forms with sharp geometric features (Fig. 3C). Clay 3D printing is often adopted by artists with an existing ceramics practice, integrating it into broader studio workflows [87]. To support greater involvement from ceramic artists, several barriers of entry need to be addressed – particularly the steep learning curve to achieve fluency with complex digital environments, and disconnect between 2D design interfaces and 3D outcomes. We see an opportunity to translate the affordances of familiar clay tools into a digital design system, making clay 3D-printing workflows more intuitive and closer to actual physical practice.

Currently, clay 3D printed objects can be designed using general purpose 3D modeling or computer-aided-design (CAD) software and a slicer to compute a machine toolpath. Clay-specific slicers can facilitate obtaining a viable toolpath with thicker walls [28] and fewer travel moves [31, 34], or add textural effects [85]. Alternatively, some software tools let users directly edit the toolpath, to allow for fine-grain control of clay material behavior. *Potterware* and *Clayon* support the creation of toolpaths through a simple WIMP user interface, exposing a few design parameters that define a rich but ultimately finite design space [20, 62].

To gain more control over toolpath editing, artists and designers use symbolic programming or node-based programming in software like Rhino Grasshopper. This type of *CAM-based design* has been explored in and beyond the domain of clay 3D printing, as a way to offer finer control to the user over machine behavior, and in turn, over material-specific outcomes [78, 81]. Bourgault et al. [15] proposed a node-based programming environment to support exploration of a variety of forms and textures generated by combining basic mathematical operators. Direct manipulation interfaces [36] have been developed for CAM-based design, such as defining the toolpath through sketching [30], or editing form and texture based on cut paper pieces [91]. Following this line of work, we show how 6-degrees-of-freedom hand input in AR can support the user in performing 3D form and surface texture edits globally, over the entire vessel.

Finally, some work has focused on adding surface texture to 3D-printed artifacts by manipulating the toolpath [50, 88, 100]. Kaplan et al. [41] introduce a painting metaphor to apply texture effects onto the surface of a 3D shape, and they demonstrate that people could quickly learn to use the tool to selectively apply textures. Extending the productive "paint-brush" metaphor proposed in *ConTextural* [41], we design additional tools inspired by physical ceramic tools – ribs and stamps – to support both form and texture editing.

[1] 3D PotterBot 10 Micro, a commonly used 3D printer, is currently priced at 3.5K USD

Figure 3: 3D printed clay artifacts showcasing a variety of form and textural qualities. A) Design studio Emerging Objects creates texture effects that form a global pattern [63]. B) Designer Virginia San Fratello plays with the material properties of clay to form drooping loops on organic looking forms [67]. C) Bryan Czibesz stacks layers of intersecting paths defined parametrically to create sharp geometric forms [21]. D) Monica Silva Lovato uses a clay-specific slicer to create more stable structures and surface texture [28]. E) Timea Tihanyi prints porcelain with a fine nozzle to create intricate textures akin to woven patterns [83]. F) Bold Design Studio defines precise geometrical zones where surface texture is applied on the vessel [14]. G) Raina Lee creates organic forms by stacking hand-drawn lines [30].

2.2 Extended reality (XR) for digital fabrication

Researchers have studied opportunities for XR technologies to facilitate fabrication tasks. Immersive visualization can support complex fabrication or assembly tasks by providing real-time guidance to a person executing some manual steps of the process [40, 52, 54, 66, 95, 101]. Researchers have also used augmented reality overlays or near-workspace display during machine operation to provide access to machine or system state information [4, 70, 82, 89, 90].

Beyond giving guidance and information during fabrication, XR technologies have the potential to support the design workflow [56]. In particular, augmented reality enables designing digital content in a person's real world context and environment. Building on this capability, Stemasov et al. [76] envision a workflow for personal fabrication in which novice users can pick and re-mix 3D models from a library and adapt these pre-existing designs to their environment. Embodied interactions in AR such as sketching mid-air can further facilitate searching for models in a library [77]. To support novices in creating customized designs for fabrication beyond simple adaptations, researchers have proposed systems that expose parametric representations of 3D shapes [58, 75], a simple modelling workflow [8, 97], or a way to combine functional design elements [26]. These systems let the user design and visualize the results in relation to their real environment. In-situ design can also facilitate negotiating material constraints when planning a design in a given spatial context [37].

Leveraging the opportunity to use tracked 3D input, Willis et al. [99] proposed to let people design freeform shapes for laser-cut planar fabrication via moving a 3D tracked pen in space. The idea of directly translating 3D sketch motion to a fabricated artifact was also demonstrated in *Sketch Furniture* [29], a performance showcasing mid-air 3D strokes being fabricated directly as solid tubular forms to create chairs, a table and lamps. Finally, mixed-reality techniques can support design and fabrication workflows that interleave digital design, with physical making [96], or robotic fabrication [60].

These approaches focus on the design of the overall 3D form to be fabricated, in line with the *CAD-based* design paradigm of modeling a geometric form first, to be later translated into machine instructions. Instead, we propose to use 3D inputs enabled by hand-tracking in AR to let the user directly edit the machine toolpath, in order to support fine-grained control over emergent textures and material properties specific to clay 3D printing. Closest to our work, Mitterberger et al. [53] applied the idea of direct toolpath creation through hand motions to robotic plastering, and Passananti et al. [59] showed the potential of a grab and pull interaction applied to a clay 3D printing toolpath. We extend the interaction design space beyond direct creation of the path and grab and pull, and demonstrate that introducing *tools* to the editing workflow extend the space of achievable designs in AR CAM-based editing.

2.3 Interaction design based on tools and body motion

HCI researchers and interface designers have used physical tools and embodied actions as inspiration to design interactive systems at large. Drawing a parallel to real-world interactions that are often mediated by tools [57, 64], researchers have theorized that exposing commands as virtual tools in the workspace could help users learn and execute complex operations [12]. In the "instrumental interaction" model, Beaudouin-Lafon [12] applies "reification" to commands, reifying them as tools that affect objects of interest, and can themselves be manipulated and modified. Exposing abstract commands as manipulable objects can for instance enable users to perform alignment and distribution of 2D graphical objects faster than with command menus [19]. In this work, we propose to reify toolpath manipulation commands as tools that are actual objects in the 3D scene that the user can create, edit, and use to affect the toolpath geometry.

Jacob et al. [38] argue for interface design that is based on real-world knowledge and skills of the users, as a way to reduce the mental effort necessary to operate a computer system. In most standard AR/VR development toolkits (e.g [1]), interaction design is based on naïve physics: buttons can be pushed in, windows can be grabbed and dropped in 3D space, and spatial navigation is in part mapped to the user's body motion in the physical space. AR/VR systems that use the user's hand motion to design in 3D space – through sketching [69, 73], or sculpting by push-pulling the surface [2] – rely on the person's body awareness and skills in finely controlling their body motion.

While artists have developed highly intricate practices in such systems (e.g., 3D paintings [43, 73]), fine control in 3D mid-air interactions can be challenging for people who have not yet gained skill in this technique [6, 9, 98]. In order to bridge the gap between mid-air embodied interaction and the requirement for precise editing capabilities in CAM-based design, we propose introducing mediators to the user's action on the toolpath in the form of digital ceramic tools.

Creativity support tools commonly employ metaphors based on physical tools that artists use in an equivalent real-life art or craft workflow. 2D graphic editing software expose pixel editing features through tools such as paint brushes, paint buckets, erasers, and stacked layers. Shugrina et al. [72] design novel color mixing and color editing tools inspired by the way painters use paint palettes. Digital 3D surface modeling software exposes surface manipulation effects as tools inspired by physical sculpting techniques [2, 51], sometimes putting emphasis on realistically simulating elastic material [22]. We design digital modeling tools for the purpose of physical craft artifact production, and explore a different tradeoff point between realism and expressive power [38], favoring precise toolpath-level operations compared to physics-based realism.

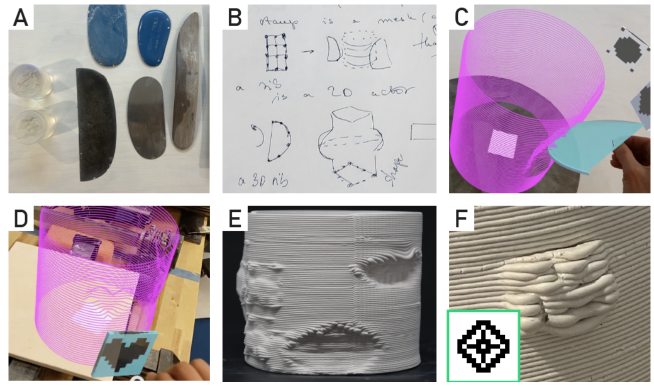


Figure 4: Collaboration with a ceramicist. A) We use traditional ceramic tools found in Timea's studio as prompts to sketch new features (B). C, D) We demonstrate a prototype version of the tool with the first implementation of the rib and stamp tool. E) The rib tool deforms the surface. F) Textural, pixel-level patterning translates poorly to the clay surface, motivating further development of the texture modifier.

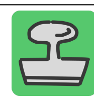
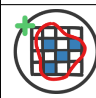
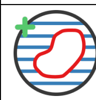
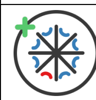
3 Methodology

We developed Clay ARtools by iteratively building and testing novel AR interaction techniques (RQ1) in collaboration with Timea, a professional clay 3D printing artist. We chose this approach in order to translate aspects of physical ceramic tools to AR workflows in ways that are relevant to ceramicists (RQ2). Our method aligns with the design and validation methods in prior craft-oriented HCI systems and fabrication research. By building craft software tools in collaboration and dialog with craft professionals, researchers can gain insight into complex craft practices that inform new design and engineering methods [33, 86, 102] and assess the viability of artifacts created with a system in relation to professional standards for quality and aesthetics [49]. In these works, as well as other fabrication systems papers, artifacts produced with the system [3, 16, 65, 68, 86] provide the primary means of validation by demonstrating the expressive range, floor, and ceiling of the system [45]. Timea is a co-author, not a participant, to reflect her technical contribution [24].

3.1 Collaboration structure

Joyce is an HCI PhD student with a background in computer science and AR development. She also has experience in manual ceramics, focusing primarily on combining functional vessels and additional surface decorations. Timea is a ceramic artist based in the US, who regularly uses clay 3D printing. She uses clay 3D printing to integrate ceramics with computational elements, such as physicalized data, interactive installations, and generative algorithms. She directs a studio where she teaches and researches new methods for clay 3D printing. Emilie, Jennifer and Tobias are HCI researchers. Joyce and Timea have both independently explored XR technology as an interaction modality to design forms for clay 3D printing. The collaboration with Timea emerged from these early explorations with the intent of developing a system that uses XR interactions for CAM-based design.

Table 1: We designed toolpath editing operations as digital tools and modifiers inspired by traditional ceramics tools. This table summarizes the tools and modifiers we implement in Clay ARtools (right side), and the corresponding traditional ceramics tools that served as inspiration (left side).

Existing physical ceramics tools		**Available toolpath operations in Clay ARtools**		
Name	*Function*	*Name (type)*	*Icon*	*Function*
Rib	Shape vessel on the wheel (Fig. 2A).	Rib (tool)		Shape toolpath by deforming it locally (e.g. Fig. 6A). *In profile mode:* shape toolpath by defining its profile (e.g. Fig. 6B).
Brush	Paint on vessel surface.	Brush (tool)		Select area on toolpath (e.g. Fig. 6C).
Stamp	Imprint pattern on vessel (Fig. 2B&D).	Stamp (tool)		Displace toolpath points that fall within a 2D stencil region (e.g. Fig. 8).
		Texturing (modifier)		Displace toolpath points within a region according to a 2D per-point pixel map (e.g. Fig. 9B, C).
Masking tape	Locally prevent application of technique (Fig. 2C).	Masking (modifier)		Mark toolpath points as unaffected by further edits (e.g. Fig. 9A).
Grid (e.g. stencil)	Plan a regular repetitive motif on a vessel.	Repetition (modifier)		Apply the same toolpath edits at multiple regularly-spaced locations (e.g. Fig. 11).

During system ideation and development, Joyce traveled six times over a period of eight months to visit Timea's studio, spending a combined total of 14 days working on-site with Timea. Once the system was completed, we conducted three additional in-person sessions over the span of two weeks where Timea practiced using Clay ARtools to design and fabricate several pieces. This allowed authors to engage in multiple loops of ideation, development, and testing over an extended period and provided HCI researchers with access to Timea's extensive knowledge of clay 3D printing and her assessment of the tools created and artifacts produced using Clay ARtools.

3.2 Research activities

3.2.1 Ideation. We conducted an ideation session over five days. We used two methods to guide discussion: an analysis ofTimea's prior ceramics pieces, and hands-on experimentation with prior XR systems for clay 3D printing [59, 84]. The ceramics pieces served as a basis for defining usage scenarios of our AR CAM-based design workflow. Applying a critical lens on the existing software systems allowed us to discuss specific affordances and limitations of XR to design clay 3D prints. Using these systems enabled us to compare trade-offs between mesh and toolpath editing, various direct manipulation techniques, and design outcomes.

3.2.2 Early prototype evaluation. After developing an initial prototype, we evaluated it with Timea over a three-day session (Fig. 4C and D). Our goal was to assess the expressiveness of the first features we developed – early versions of the rib and stamp tool – to validate the applicability of the tool metaphor, and calibrate our design to achieve a balance between physical tool simulation and expressivity. During this period, Joyce showed a live demo of how the new features work, then let Timea use the system in open-ended testing sessions, while watching a live preview of the AR session and answering any questions about how to use the system. We also created test prints (Fig. 4E and F) and discussed the aesthetic quality of the results, and whether these outcomes met expectations. This session informed the design of the final version of our digital ceramic tools (see full description in Section 4). For instance, the need to support fine-grained texture definition commonly seen in Timea's work, but poorly supported by the stamp tool (see Fig. 4F), motivated us to develop texturing modifiers (Section 4.3.2) and reserve stamping for applying larger shapes with few high-frequency details.

3.2.3 Artifact creation and discussion. We conducted a series of four collaborative use sessions with Timea, focused on producing artifacts (3 hours, 3 hours, 3.5 hours, and 2 hours). The goal of these sessions was to validate the system's functionality and workflow in professional clay 3D printing artistic practice. We provide greater detail in Section 6. During these sessions, we also worked on enabling Timea's independent use of the system, including configuring G-code generation to work with her studio printers, and documenting technical steps outside of the main system (e.g. transferring toolpath files from the Hololens to a computer).

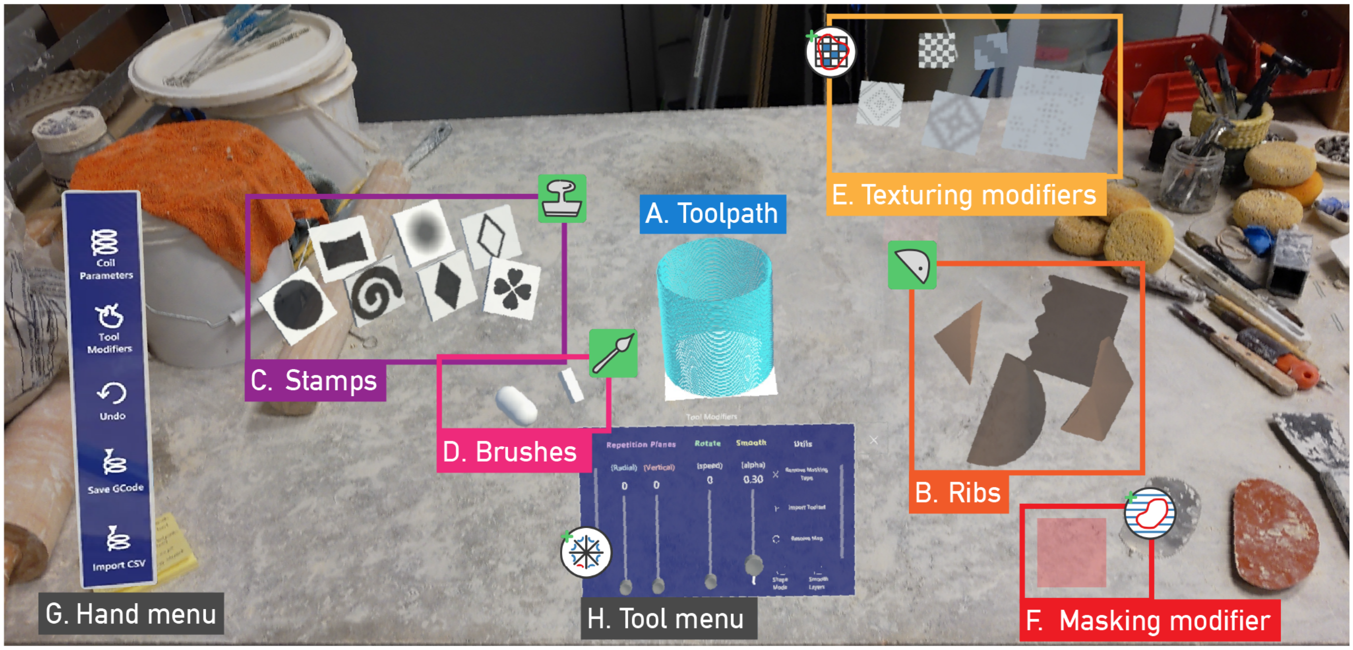


Figure 5: Digital toolset overlaid on ceramics workspace with the HoloLens 2. We overlay the visual icons used throughout the paper to reference the tools and modifiers next to the corresponding AR objects. A) Toolpath, visualized as a thin tube mesh. B) Rib tools. C) Stamp tools. D) Brush tools: round (capsule) and square (cuboid). E) Texturing modifiers. F) Masking modifier. G) Hand menu for toolpath and tool menus, undoing edits, and importing/exporting toolpaths. H) Tool menu for adding and adjusting the repetition modifier, and adjusting other tool properties such as smoothing.

4 Clay ARtools: an AR system for CAM-based design

We developed Clay ARtools to investigate how 3D mid-air interaction in AR can effectively support CAM-based design for clay 3D printing (RQ1). Based on our ideation and prototyping sessions, as well as on our review of existing research in CAM-based design, we set the following design goals (DG) for this system:

- **DG1**: Support definition of 3D form and surface texture of a vessel for clay 3D printing.
- **DG2**: Support complex toolpath manipulation via embodied 3D input.
- **DG3**: Enable application of effects at the precision level of individual toolpath points.
- **DG4**: Integrate the digital design environment with the clay studio space and custom tools.

Our key insight in developing the system was to expose toolpath editing operations as digital tools inspired by traditional ceramics tools. Performing this mapping of physical operations to digital edits serves as an inquiry into how to meaningfully translate physical practice into an AR design workflow (RQ2).

In the following section, we first provide an overview of the complete AR system (Section 4.1), then explain how we implemented toolpath operations as combinations of tools (Section 4.2) and modifiers (Section 4.3). We describe the authoring workflow for tools and tool modifiers (Section 4.4). Finally, we detail additional features of the system (Section 4.5).

4.1 System overview

We developed Clay ARtools as a Unity application [93] running on the HoloLens 2 for gesture-based interaction. The system allows a user to modify a toolpath for clay 3D-printing through mid-air manipulation of *digital ceramic tools*, and the application of *tool modifiers*. The digital tools let the user perform operations on the toolpath (Fig. 5A) Tool modifiers can be added to the digital ceramic tools and allow users to specify additional effects, such as toolpath-level surface detailing or repetition of edits around the vessel (DG3). Tools and tool modifiers are inspired by corresponding physical ceramic tools as detailed in Table 1. Similarly to traditional practice, our system uses tools to extend manual capabilities: the tool defines the effect, while manual input applies it to the toolpath (DG2). This balance of computational precision with freeform manual action allows ceramicists to edit shape and create intricate effects through simple gestures (DG1, DG2).

A toolpath is represented as a sequence of 3D points that define both the underlying geometry for fabrication and the interaction space for editing. The system's tools interact directly with these points, enabling form and texture details at the precision level of the toolpath (DG3). For visualization, the path is rendered as a spiralized tube mesh between points, shown in Fig. 5A.

Artists rely on their tools to organize their workflow and express a distinct artistic style. To integrate the digital design environment with the clay studio and its custom tools (DG4), Clay ARtools includes a tool-authoring pipeline (see Section 4.4) for importing

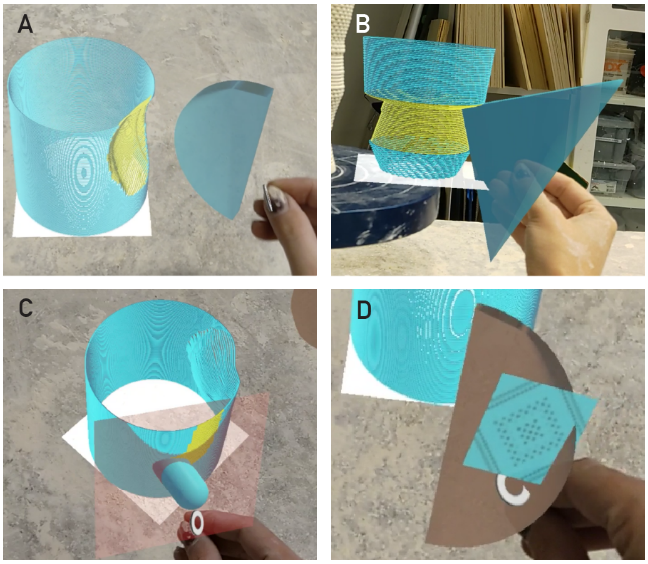


Figure 6: Tool Use Demonstration. A) Curved rib used for local toolpath deformation. The system colors the newly updated area in yellow. B) Triangular rib in *profile mode* for radially-symmetric shaping. C) Round brush with *mask* modifier to protect areas from later edits. D) A *texture* modifier is drag-and-dropped onto a curved rib tool to apply the modifier to the rib.

physical tools as digital representations or creating new digital tools.

4.2 Digital ceramic tools

Digital ceramic tools allow users to modify the clay deposition path through 3D hand motion. We design three types of tools as virtual proxies to physical ceramic tools: stamps, ribs, and brushes. The tools are present in the 3D workspace (see Fig. 5B, C, and D). The user can grab tools mid-air, move and orient them freely, and apply uniform scaling through two-handed object manipulations. Tools affect the toolpath upon coming in contact with any point on it. The tools support applying operations on the toolpath through gestural 3D interaction (DG2).

4.2.1 Rib. The rib tool supports dynamically editing surface and shape through continuous 3D motion of the hand in space. A rib tool is defined by its profile curve, represented as a uniformly sampled 2D polyline. From the profile curve, the system creates a 3D mesh via extrusion, to support visualization of the rib in the 3D scene and collision detection (Fig. 5B). For all toolpath points that come in contact with the rib, we snap these points to the closest location on the rib's profile curve, projected onto the point's original layer height. To avoid excessive jaggedness caused by rib displacement with noisy hand-tracking, we apply Laplacian smoothing – based on the neighboring points on the same layer and across layers – after rib displacement. We enable the user to adjust the amount of smoothing applied to points, and toggle smoothing between layers, via a menu (Fig. 5H). To simulate the effect of using a physical rib

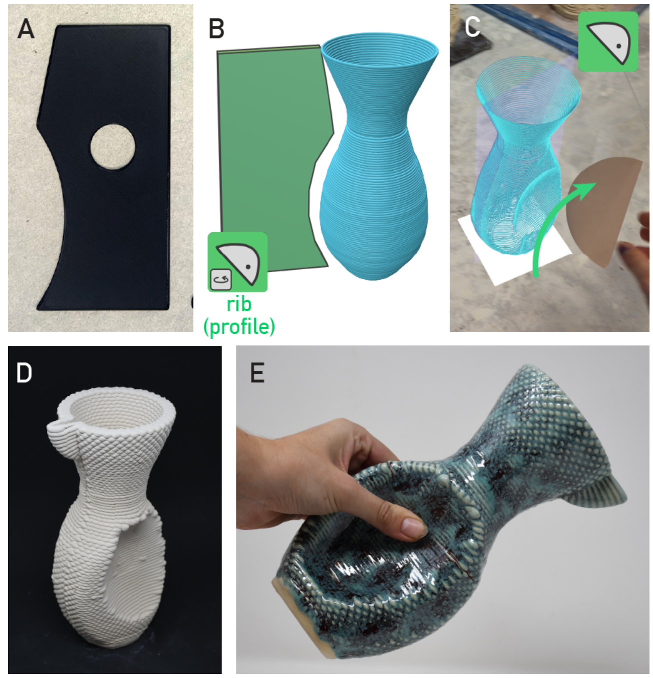


Figure 7: Demonstration of rib tool use. A) Physical rib tool. B) The rib tool (green) created by tracing the profile curve of the physical rib. It is used in profile mode to define the overall shape of the vessel. C) Using a half-circle rib tool to create a handle and spout. D, E) Final vessel.

tool on the pottery wheel to shape the profile of a vessel (as seen in Fig. 2A), we implement "profile mode", to let the effect of the rib apply deformation to the entire vessel via its effect on a single column of points in the toolpath. Touching any toolpath point will automatically affect all points along that layer (see Fig. 6B). Profile mode supports the creation of radially symmetric shapes (e.g. Fig. 1A and B). While using the rib tool, profile mode can be toggled on and off via the menu (Fig. 5H).

Figure 8: Stamped vessel with textures. A) A black-and-white flower stamp with a light checker-board texture modifier, and a repetition modifier with 6 repetitions around the vessel. B) A gradient circle stamp with a texture modifier composed of long black lines that generate droops along the surface. The droop size is affected by the stamp gradient (larger at the bottom of the circle).

4.2.2 Stamp. The stamp applies an image stencil onto the 3D surface when pressed against it. A stamp's effect is defined by a 2D grayscale image (see Fig. 8), where pixel grayscale values will define deformation values (white corresponds to no deformation, black corresponds to maximum deformation). Toolpath points are displaced along the surface normal direction at that point. Stamps are represented as cube meshes, scaled to resemble tiles with their respective image displayed to scale on the surface (Fig. 5C). We detect collisions of the stamp mesh with the toolpath tube mesh, and dynamically compute a local parameterization map for each toolpath point, defining the contact point as the center of the map, and the orientation of the map based on the stamp up vector [71]. This gives us (u, v) parameters for each point, that we use to sample the stamp image pixels. We designed stamps to be used with images that define a simple stencil shape (e.g., flower, circle). For high-frequency texture maps that aim to precisely affect individual toolpath points, we implemented the texturing modifier (Section 4.3.2)

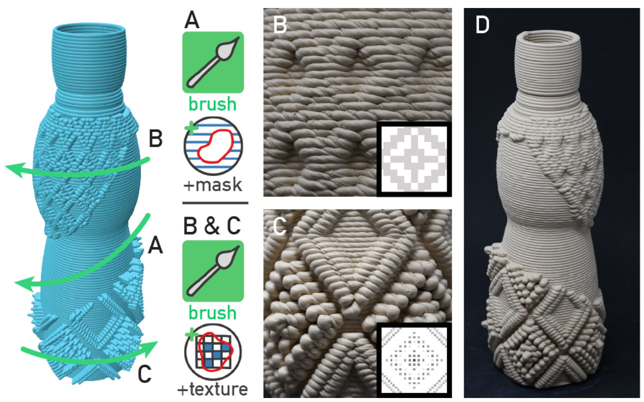


Figure 9: Contrasting textures on a bottle. A) A mask is applied in a diagonal gesture across the form, defining a zone that will remain unaffected by subsequent edits. B, C) Two distinct textures are then brushed on: one above (B) and one below (C) the masked region. D) The final fabricated bottle.

4.2.3 Brush. The brush tool is a non-shaping tool that can be used to define freeform regions by selecting toolpath points, without affecting their position otherwise. Our system provides two brushes: round (capsule shape) and square (elongated cube) (Fig. 5D). We detect toolpath points selected by the brush via collision detection. The brush tool is useful to select regions onto which modifiers (Section 4.3) are applied (see Fig. 9).

4.3 Tool modifiers

Tool modifiers augment tool use through computational behaviors that affect toolpath points in a procedural and precise manner. We implement three tool modifiers: repetition, texturing, and masking. Modifiers can be applied to any of the three tools, and can be used in combination (for instance, we add a texture modifier and a repetition modifier to the flower stamp, see Fig. 8A). Texturing and masking modifiers, which directly transform the local effect of the tool, can be applied via grabbing and dropping a modifier (Fig. 5E, F) on a tool, and removed by moving it off the tool (see

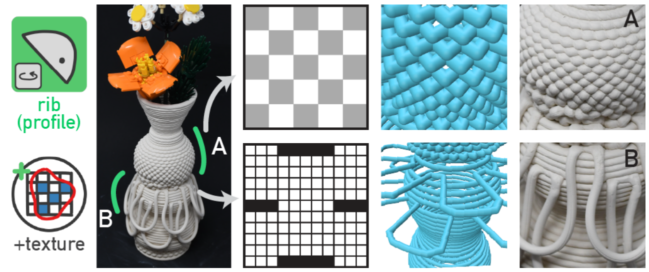


Figure 10: Tall vase with textures. A) Adding a texturing modifier on the rib tool with a light gray checkerboard, we sculpt the shape while applying a slight displacement to every other point along a layer, to create a wavy texture. B) Another texture modifier with offset black lines creates large droops. From left to right: tool and modifier, final artifact, texture images, toolpath visualization, close-up of texture on final artifact.

Fig. 6D). Repetition can be turned on and off and adjusted through a 2D menu interface (Fig. 5H). Modifiers allow users to retain the physical logic of hand tools while greatly expanding expressive possibilities for digital edits and toolpath manipulations.

4.3.1 Repetition. The repetition modifier supports the creation of patterns that repeat radially around the vessel or vertically along its height. We apply radial repetition by copying edits and re-applying them at regular intervals around each layer of the point cloud. We use toolpath point indices to map deformation of a point to its corresponding position around the layer. Vertical repetition extends the same logic across sections of stacked layers. A tool operation can be repeated around the circumference and/or repeated across sets of layers to form tiled motifs (see Fig. 11).

4.3.2 Texturing. The texturing modifier enables applications of surface textures defined using grayscale images. In these images, each pixel maps to a point on the toolpath, and the pixel intensity value defines the displacement amount along the surface normal (see texture image and resulting toolpath in Fig. 10). We adjust the range of displacement linearly based on the toolpath's layer height parameter, as a proxy for printer nozzle diameter (e.g., the droops on the pitcher Fig. 8 are smaller than on the vase Fig. 10 for black pixels indicating maximum displacement). This ensures that displacement values are reasonable compared to the size of the extruded clay coil – thicker coils are more sturdy and can handle larger unsupported displacements. We sample texture images by wrapping them around the toolpath horizontally (along circumference) and vertically (along layers), and tiling them. This ability to apply continuous, repeating textures mirrors the use of pattern rollers (Fig. 2D) in physical ceramic workflows. Texture images can be created in any 2D raster-editing software and imported in the system at runtime, where they appear as planes depicting the corresponding grayscale image (Fig. 5E).

4.3.3 Masking. Masking defines toolpath points that cannot be affected by further edits, similar to using masking tape to preserve some areas in traditional ceramics (e.g. Fig. 2C). The system tracks points that have been marked as masked, and any tool effect checks

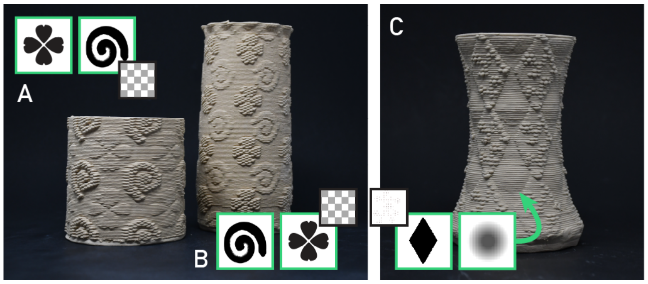


Figure 11: Stamped textures repeated radially and vertically. A) A cup showing a repeated flower stamp and spiral stamp (with a light checkerboard texture) B) A vase showing the flower stamp (with a texture) and spiral stamp repeated in a similar grid fashion. C) A diamond stamp (with a light bump texture) is applied to a curved vessel and repeated in a grid. The repetition of diamonds creates diamond-shaped negative space. A smooth round bump stamp is applied in this negative space with the same repetition.

against this set before applying changes. Marking points as masked can be done through any tool, such as by brushing it on (see Fig. 9A), or applying it with the rib to the set of points deformed by the rib's action. These points will then be unaffected by further edits. The user can clear all points of masking through the tool menu (Fig. 5H).

4.4 Tool authoring workflow

To support DG4, we sought to support a simple tool authoring workflow. Just like physical tools in a ceramics studio can be collected and modified to cater to the ceramicist's needs, digital ceramics tools in Clay ARtools can be created and modified. The rib tool shape, stamp tool stencil shape, and texturing modifier are authored via 2D grayscale images. These can be authored in any image editing software and imported into the system at runtime with an "import tools" button on the tool menu. The user can connect to the HoloLens Device Portal via the device's IP address and upload image files to the designated rib, stamp, and texture folders within the system's local storage. The system automatically reads these files and generates corresponding tool objects based on the images.

To create a rib tool, the user imports a black-and-white image on which the system performs edge-detection to define the rib's profile curve. This allows importing a drawing or an edited photograph of a physical rib (see Fig. 7). For a stamp tool, the user designs a grayscale image at a relatively high resolution (e.g. 100x100). To author texturing modifiers, the user designs small tileable grayscale images (e.g. 2x2 to 30x30).

4.5 Implementation details

We rely on the MRTK `ObjectManipulator` to recognize hand gestures and let the user manipulate digital objects in the scene. Tools and tool modifiers can be grabbed with hand gestures, supporting near and far object manipulation. To detect when the user brings a tool in contact with the toolpath, we use Unity Physics collision detection based on approximation of the tool shapes as a convex mesh.

We implement additional utility features in Clay ARtools, such as parametric specification of the initial cylindrical toolpath shape: the user can define the cylinder radius, height, layer height, toolpath resolution through a menu (Fig. 5G). We also support exporting the toolpath designed in the system to a GCODE file adapted to different clay 3D printers[2]. We implement basic export/import of design files to be able to iterate on a design by re-importing its file into the system. Finally, the system also supports an "undo" feature (see Fig. 5G), to let the user remove edits step-by-step. In particular, we separate modifier application from tool applications (so that texturing added to a stamp can be undone while preserving the stamp effect).

5 Applications

We present artifacts created with Clay ARtools that demonstrate how the system expands fabrication opportunities in clay 3D printing. Each example shows a way in which Clay ARtools combines direct manipulation in AR with computational design features. Across these applications, we highlight aesthetic qualities of shaping and surface texturing (DG1) that rely on directly editing the machine toolpath. We fabricated these artifacts using the Eazao Zero and 3D Potterbot 10 XL, with nozzle sizes varying from 1.5mm to 6mm. For all vessels, we provide additional pictures of the fabricated artifacts (e.g., glazed), and toolpath visualizations, in Supplemental Material.

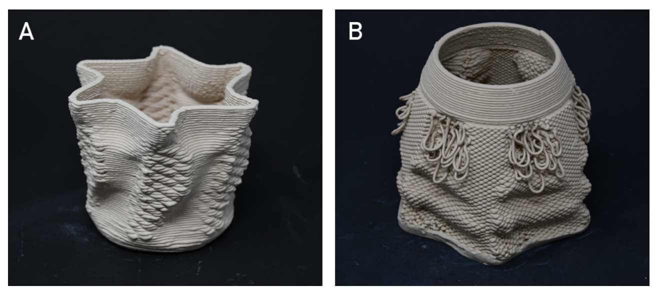


Figure 12: We used the repetition modifier in combination with freeform shaping edits made with the rib tool to create organic and symmetric shape variations. A) A star shaped cup. B) A 6-fold symmetric pot with horizontal grooves.

5.1 Procedural repetition of embodied input

We demonstrated how Clay ARtools supports complex toolpath manipulation via embodied 3D input (DG2) by applying the repetition modifier to freeform shaping edits with the rib tool.

We designed three variations on a bowl form (Fig. 13), by editing a base form through manual rib edits that are procedurally repeated six times around the vessel with the repetition modifier. By using different rib shapes, we obtained different shaping effects: in B we used the flat side of a triangular rib to obtain a faceted shape, while in C and D we used a curved rib to create rounded indents and bumps. Applying slightly different inward and outward motions on the form with the same rib also led to varied effects (on the bottom bumps of D we pressed the rib from the inside of the vessel outwards

[2]We currently support the 3D Potterbot 10 Micro, the 3D Potterbot 10 Super, and the Eazao Zero. Adding a new printer configuration is straightforward.

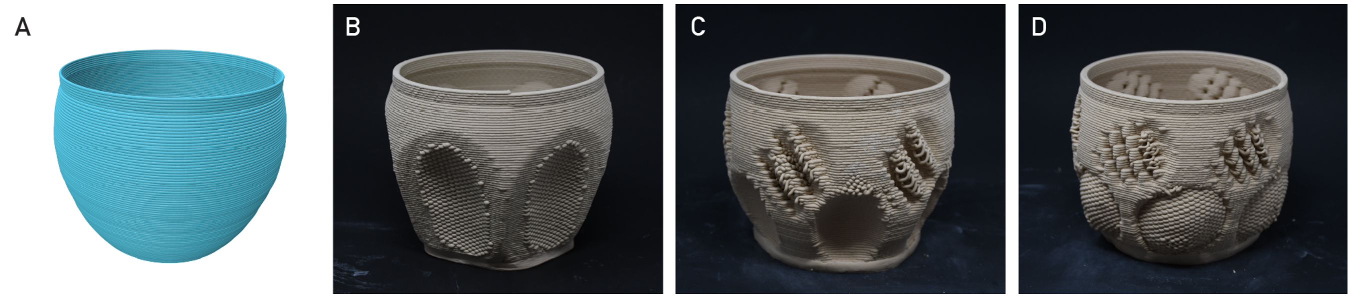


Figure 13: Variation in bowl design from the same base form, through repetition of rib interactions. A) Toolpath rendering of the base bowl form (for reference). B) Bowl 1: six-sided faceted form with textured walls. C) Bowl 2: deformed through inwards rib impressions. D) Bowl 3: deformed through inwards and outwards rib deformations.

through the first deformed bump). Lastly, different texture modifiers applied to the ribs served to create varied texture patterns in the shaped areas: slight checkerboard bumps in B, longer diagonal loops in C and D. For all three designs, we applied at most three edits to the toolpath, choosing from a simple set of two digital ceramic rib tools and three additional surface textures. The variation in the resulting designs demonstrates expressive variation and potential of gestural editing in combination with procedural repetition enabled by Clay ARtools.

In several other examples, a single gestural edit is expanded into a complex, form-spanning surface texture through the use of the repetition modifier. For instance, we made a single stamp impression and used radial repetition to create tiled motifs around vessels (Fig. 8 and Fig. 11). Similarly, we applied freehand rib edits that are repeated six-times around forms to apply organic shape variation consistently around the shape (Fig. 12).

5.2 Applying CAM-based surface textures

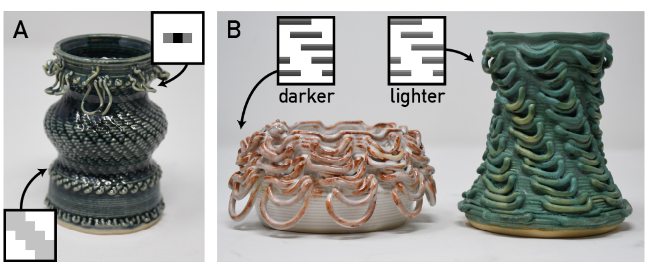


Figure 14: We applied a texturing modifier (inset pixel maps) to the rib tool, shaping these vessels while applying textural effects. A) The middle section of the vessel showcases a woven-like texture, while the top edge has regularly-spaced large unsupported loops. B) We explored variation of lightness on the same pattern, to achieve wide drooping loops repeating diagonally around the vessel. Darker pixel values created oversized loops that made the entire walls sag (left).

The texturing modifier allowed applying effects on the toolpath at the precision level of individual points (DG3). This enabled us to create vessels that showcase texture effects typical of CAM-based design, such as large unsupported loops that droop under their own weight and form intricate features (Fig. 14A), or larger repeated motifs at the scale of the overall vessel (Fig. 14B). We created these effects by applying texturing modifiers to the rib tool, which we then used to shape the toolpath in profile mode.

We authored custom tools (DG4) to experiment with material behavior through designing and fabricating samples. We experimented with varying lightness values within motifs (Fig. 14B) by editing the 2D pixel images of texturing modifiers. By printing the outcome of the first vessel (left), we realized that the large loops were drooping too much, thus causing the walls to sag and the overall vessel to loose stability as the print went on. After creating a variation of that texturing modifier, we created the second vessel (right) which yielded a more stable structure.

We also took advantage of existing CAM-based design strategies in clay 3D printing, such as applying a weave-like texture to thicken the toolpath in areas with steeper angles (e.g. Fig. 1B, Fig. 14A). While this approach aligns with prior work on structurally-aware slicing strategies when shaping steeper angles [28], here we applied it at will on a user-defined area.

5.3 Gesturally-defined form

The digital ceramics tools allowed us to apply toolpath operations through 3D hand motions. This supported definition of surface texture and 3D form via embodied 3D input (DG2). We used the brush tool to "paint" a bumpy texture onto a cylindrical vase (Fig. 15A), and a round rib tool to sculpt the surface of a large plant potter vessel (Fig. 15B, C). These edits preserved the variation of direct manipulation – capturing traces of the maker's hand for drawing and shaping. Simultaneously, it was possible to apply texturing modifiers to the tool, to benefit from the algorithmic precision of point-level toolpath displacement for surface texturing. This combination produced artifacts that combine organic shaping and computationally defined textures, and it enabled the creation of forms and surfaces that can't be modeled through desktop CAM-based design or direct manipulation sculpting.

5.4 Referencing existing objects during design

In this example we looked at how Clay ARtools supports in-situ design for the purpose of referencing existing objects or surrounding environment (DG4). We designed a set of nested cups (shown

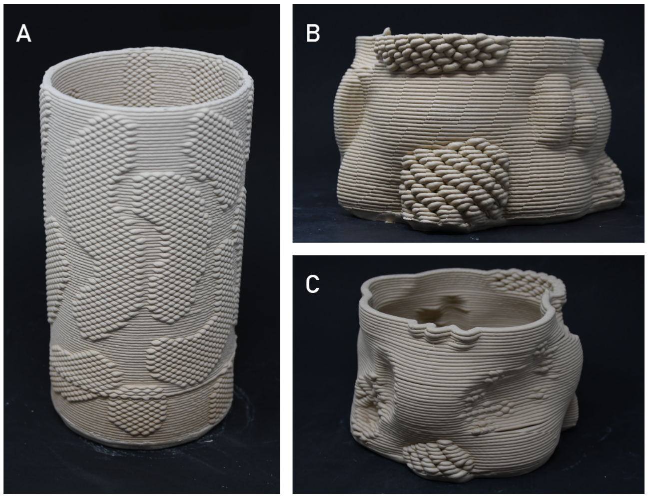


Figure 15: We applied effects on the toolpath through gestural interaction. A) We painted textural zones with the brush tool on this tall cylindrical vase. B) We used a round rib tool to sculpt this short plant pot.

in Fig. 16) through iterative use of the system – first designing and fabricating a cup, then placing the now physical cup back in our design environment as a reference. We were able to use the first cup to define complementary form and texture when designing our second cup. The resulting designs complement each other in aesthetic qualities and functionally "nest" when placed next to each other. This workflow illustrates the potential for Clay ARtools to allow for design in the context of existing physical artifacts to create complementary forms.

In other vessels created with Clay ARtools, we took advantage of in-situ design to design functional parts of the vessels, such as handles, in reference to the hand for practical use (e.g., pitcher handle Fig. 7 E, bottle handle Fig. 9A).

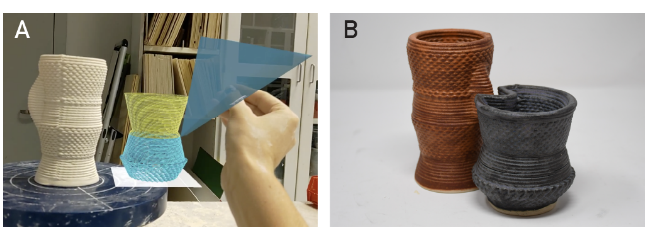


Figure 16: A set of nesting cups designed in reference to each other. A) We edited the second design in relation to the first vessel, which had been fabricated and placed in the design environment. B) Resulting set of fabricated artifacts with complementary forms and surface texture application.

6 Artist workflow

To gain insight into how Clay ARtools could be used in professional clay 3D printing, Joyce and Timea organized four sessions, with the goal for Timea to develop hands-on operational fluency with the system, and for the team to use the system to design and fabricate clay 3D printed vessels. We conducted these sessions as part of our overall collaborative system development methodology (see Section 3). In the following section, we first relate how Timea used the system to develop two clay 3D-printed vessels (Section 6.1). We also asked her to comment on her experience using the system, through thinking-aloud during system use and open-ended discussion. In particular, we were interested in her experience with creating custom digital tools and in using those tools as part of the complete workflow of producing clay 3D-printed artifacts. We report these insights in Section 6.2.

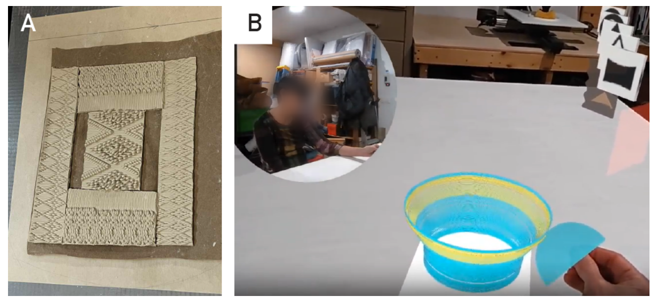


Figure 17: Timea's process of designing tools and working with Clay ARtools to make a vessel. A) She visually inspects printed surface textures for comparison with texture bitmap. B) She refines a bowl shape through small gestures with the rib tool (in profile mode).

6.1 Workflow description

Because of Timea's interest in intricate surface texturing in her professional clay 3D printing practice, Joyce and Timea decided to center the sessions around the goal of using the system to design surface textures and integrating those within larger vessels. This provided an opportunity for Timea to experiment with all features of Clay ARtools, from tool design to final artifact fabrication.

6.1.1 Designing texturing modifiers as 2D bitmaps (sessions 1-2). Timea and Joyce worked together in a pixel editing interface, Piskel [23], to draw grayscale bitmap images that could serve as texturing modifiers (Fig. 18, insets). Timea began by identifying key elements from her previous ceramic works such as the definition of individual "bump" extrusions for fine-level specification of points that make up highly complex patterns, reminiscent of textile textures. She then designed four pixel maps (Fig. 18), experimenting with different variations: isolated grey pixels (corresponding to slight outward displacements, creating bumps) among a white background (corresponding to no displacement) (A, C), dense variations of grayscale levels (B), and sparse dark pixels with the intention to create drooping loops (D). Each pixel map took between 1-5 minutes to draw, depending on its complexity. In session 2 she then fabricated a test cylinder that demonstrated the effect of each texture on the final clay form. Timea examined the fabricated texture samples alongside their corresponding texture images to compare how grayscale values mapped to extrusion depths, and used this mapping to revise the motifs and generate new ones.

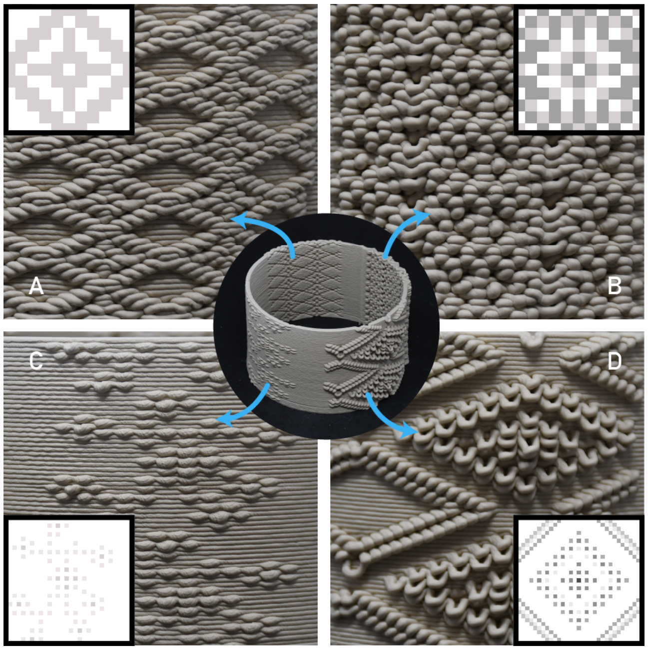


Figure 18: Vessel with surface textures created with Timea, referencing geometric themes and motifs inspired by textile patterns in her existing clay 3D printing practice. We use the brush tool four times with a texturing modifier corresponding to each grayscale bitmap images in inset.

6.1.2 *Gaining fluency with the system (session 3).*

In session 1, Timea observed a demonstration and experimented with the system's features briefly. During session 3 Timea became more comfortable with the HoloLens 2 interaction gestures (e.g. pinch to grab) and was able to more productively experiment with the tools and modifiers. She experimented with combining tools and modifiers to simultaneously shape forms and apply textures. As she practiced, Joyce guided her in using additional features, including modifying the geometry of the initial toolpath, editing in "profile" mode, undoing edits, saving designs, and importing previous designs. After roughly two hours of guided experimentation with Joyce available to answer questions, Timea felt confident in her ability to use the system independently.

6.1.3 *Vessel 1: textured vase (session 3).*

In this design, Timea sought to explore the repetition modifier by repeating a pattern both radially and vertically. She used the system for approximately 10 minutes to create this design. After defining the base toolpath shape parameters – a tall cylinder – she activated the repetition modifier on both the radial and vertical axes. She chose 10 radial repetitions and 3 vertical repetitions, outlining a relatively small section that was repeated a total of 30 times across the entire vessel. She then used the small section as the focus of her edits, with the repetition grid enabling these edits to apply across the vessel (Fig. 19A). Specifically, she chose a circular stamp tool with a texturing modifier applied, using the texture bitmap images she created (see Fig. 18A). She shaped the surface by slightly pushing it outwards at the center of the unit section, creating a small textured bump. She then moved the curved, half-circle rib gently through the side of the vessel, in between the repeating stamp motifs, to add a slight indentation.

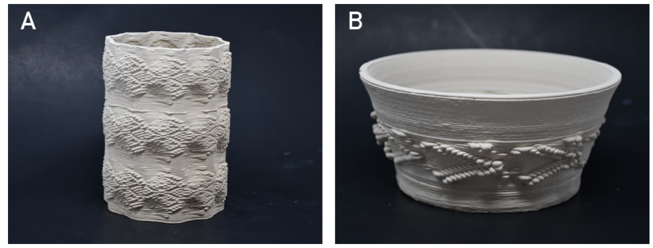


Figure 19: Printed artifacts designed by Timea. A) A cylindrical vase with repeating stamped textures and gestural impressions. B) A bowl with a horizontal stripe of repeated, stamped texture.

6.1.4 *Vessel 2: bowl (session 4).*

In session 4, Timea used the system during a short 10-min session to create a functional 3D printed vessel (Fig. 19B). Her goal was to experiment with form and see how the texture images she created could be applied with different tools on non-cylindrical surfaces. She first experimented with the base shape, adjusting initial radius and height parameters of the toolpath. She then used the half-circle rib in profile mode to define the side curvature of the vessel, resizing the rib frequently while exploring different curvatures and ultimately forming a bowl shape with a slight straight overhang; a minor adjustment of the curve is shown in Fig. 17B. After creating a shape she was satisfied with, she saved this design as a base form for future iteration, then started to add surface detail through a combination of tools and textures. She specified 8 radial sections for repetition, then added a surface texture to a rectangular stamp and applied it to the side of the vessel. She applied a different texture to the brush tool, which she used to draw on some additional "dots" of texture. She decided she preferred the bowl without the brushed edits and undid them before saving and printing her design.

6.2 Experience

Timea's experience using the system provided additional insight into usability, how working with digital ceramics tools compare to manual craft workflows, and how it compares to alternative workflows common in professional clay 3D printing practice.

Usability of the system. By the final session, Timea was able to configure tools, shape forms, apply textures, and prepare prints independently. She described the learning experience as similar to adopting any new craft tool, emphasizing that she needs to "give [herself] the time and experience to do it". She explained that familiarity with the Hololens, and the gestural interactions it can detect, was one of the biggest hurdles she faced towards learning to use the system effectively. She also noted that learning how to use the system could be facilitated by starting with a minimal tool set and adding capabilities gradually.

Similarities between digital ceramics tools and craft tools. Our discussion on Timea's experience working with Clay ARtools explored how the system aligned with familiar craft logic. She noted that in traditional making, craftspeople rely on tools that support consistency so that precision comes from the tool rather than from "eyeballing" and that "predictability is what makes a tool trustworthy." She described the system similarly: not as a device that adds surgical accuracy, but as one that supports predictable outcomes. Here, this predictability came from seeing and editing the toolpath directly, without an external slicer determining the final geometry. She emphasized that "what you see is what you get," especially when watching the machine follow the same motions she applied in mid-air. This removed the "unknown" she associated with other CAD-based workflows. She explained that "the opportunity happens when you have the form in front of you," allowing her to better judge proportions, plan textures, and experiment with motifs in context.

Contrasting with other workflows. She also compared the system with the desktop CAD software (Rhino and Grasshopper) she typically uses, in which she meticulously models form and texture with 3D primitives, such as small layer-scale cubes to create textural bumps. She reflected that in her usual workflow she tended to think of form and motif design in a highly structured fashion, working on simple cylindrical shapes and building larger patterns layer-by-layer: "with my [textured] forms, they're all the cylindrical form, because that's what Rhino allows". In contrast, the gestural interaction-based tools in Clay ARtools allowed her to apply textures across broader surfaces and shapes, in ways that felt more free-form and were applicable to irregularly-shaped forms.

6.3 Limitations

While our co-development process provided valuable insight into both system design and evaluation, we acknowledge the absence of a formal user study or structured usability assessment, in particular among users with varied levels of expertise with clay 3D printing. The HCI researchers relied on a collaboration with Timea as an expert ceramicist with interest and some experience in XR technology, in order to gain insights in how to design features that are relevant to clay 3D printing practice first, and broadly usable second. Timea's experience with the system generated insights about our proposed design, precisely because of her pre-existing knowledge of both traditional ceramics, and clay printing technology. In the future, we are interested in exploring further to what extent digital ceramic tools can be used by ceramicists with no experience in clay 3D printing for CAM-based design. how with backgrounds in traditional ceramics or clay 3D printing would use and adapt the system in their personal craft practice.

7 Discussion

Our main objective in this work was to investigate how AR interactions can effectively support the practice of 3D printing with clay (RQ1), and our secondary objective was to explore methods for translating physical ceramic tools and practices into a digital design workflow (RQ2). In the following section, we discuss how our process of designing, developing, and using Clay ARtools addresses these research questions. We draw from our experience developing Clay ARtools and assessing its creative applications through making demonstrative artifacts as well as themes that emerged in discussion and deliberation between Joyce and Timea.

7.1 Designing digital proxies for physical tools

In Clay ARtools, we defined digital ceramic tools through which the user can edit the toolpath. We report on key design decisions and considerations from the process of designing and using the system to make artifacts. We believe that these insights can be applicable beyond the specific use case of AR for CAM-based design, given the omnipresence of physical tool metaphors in creativity support tools (Section 2.3).

7.1.1 Supporting meaningful AR proxies to physical tools without attempting to simulate material craft. Implementing digital proxies for physical ceramic tools prompted us to question to what extent we should reproduce realistic physical behaviors of the tools, for instance, through physics-based simulation. Simulating elastic behaviors of a surface to allow the user to "sculpt it" is a common technique for 3D modeling applications [2, 22, 39]. However, we sought to enable precise and controllable edits of the toolpath (DG3), which is difficult to achieve with physics-inspired solvers that often affect large spatial regions following a localized user edit. Our final implementation of the rib and stamp tool favored a "naïve" interpretation of physics [38], accounting for some physical effects while ignoring others. Contact between a digital tool and the toolpath triggers changes, yet these changes are applied in a procedural manner that disregards Newton's second law–motion of the toolpath is de-correlated from forces applied by the tool onto it. In the case of digital ceramic tools, leaning into unrealistic physics *increases expressivity* of the tools by allowing both the reproduction of visual aesthetic reminiscent of using physical tools – such as radially symmetric vessels – as well as the creation of vessels that fall outside traditional ceramic techniques – e.g. with fine surface textures (Fig. 18) and highly irregular forms (Fig. 15B, C). Timea reflected that the tools worked in ways that were predictable and consistent.

We did not intend our system and digital fabrication workflow to replace traditional ceramic practice – we sought to extend the range of what can be achieved in the craft of clay 3D printing (which we demonstrated in Section 5). This motivated us to design digital proxies that don't tend towards a simulation of the tools they are inspired by, but instead enable new capabilities inherent in digital design and fabrication. Our recommendation for designing digital proxies for physical tools echoes the call of Jacob et al. [38] to "go beyond a precise imitation of the real world", and consider different levels of realism as valid design alternatives.

7.1.2 Customizing and hacking digital tools. Our system exposes three tool types – rib, stamp, brush – and three tool modifiers – texture, reflection, masking. Despite this purposefully small and manageable set of options, the artifacts we made with the systems showcase a variety of aesthetics and styles, from finely-controlled texture (Fig. 11), to forms that emerge out of clay material properties (Fig. 10). This variability in the outcomes is in part achieved through the possibility to author tools – for instance, we created custom textures inspired by Timea's ceramic printing work (Fig. 18).

Just like a ceramicist would curate their tools along years of practice, or a digital artist would build a set of Photoshop brushes that best suit their needs, we created artifacts with Clay ARtools while continuously brainstorming and adding new tool and texture shapes. For instance, we iterated on the large loop texture across multiple artifacts: first trying uniformly spaced large loops in Fig. 10B, then creating offset trios of loops in Fig. 14B.

We found that the possibility of rapidly customizing the system through a simple tool authoring workflow – 2D bitmap image editing – greatly expanded the potential for experimentation, in particular in the context of CAM-based fabrication with clay, where the final outcome sometimes largely differs from the toolpath (see Fig. 10B), and building an intuition about material behavior is essential to create viable designs.

In addition to this planned customization of digital ceramic tools, we found while using the system to create artifacts that the usage scenarios of the tools themselves could be reconsidered and that the tools could be repurposed or “hacked” to achieve specific outcomes. For instance, while we originally conceptualized texture modifiers as applying small-scale tiling effects on the toolpath (e.g., a 2x2 or 11x11 grid as in Fig. 8), Timea gravitated towards using the textures as large-scale effects painted with a brush all over the surface of the vessel (e.g., using a 33x33 grid in Fig. 18 bottom right).

We are excited to see early evidence that designing customizable digital proxies of craft tools enables practitioner-specific interactions, and potentially could open the door to creative tool misuse [47]. Future research could investigate further the potential for digital tool metaphors inspired by a physical workflow to encourage tool re-purposing behaviors [64]. Creativity support researchers have advocated for building systems that enable end-user programming of tools [48]. In our scenario of clay 3D printing, we observed that effective end-user tool programming needed to go hand-in-hand with the option to have a quick feedback loop with fabrication, in order to test custom tools. For instance, Timea inspected the printed version of the textures, to figure out which grayscale values to use in designing pixel motifs (Fig. 17A). Generally, in our tool creation process, we often applied adjustments to the tools as we observed their effects on the stability and aesthetic of the fabricated clay vessel (Fig. 14B). Incorporating end-user tool creation within other digital fabrication workflows will similarly necessitate building-in quick pathways going from tool creation, down to the physical, material outcome.

7.2 Where does AR fall short in embodied authoring for clay-3D printing?

Through our work session with Timea, we identified some limitations with respect to our goal of supporting embodied authoring (DG2). These insights point to exciting opportunities for future work in developing AR systems to bridge embodied input and computational design for fabrication.

7.2.1 Further support for precise toolpath editing. One of our design goals (DG3) was to support application of CAM-based effects with point-level precision. Our artifacts demonstrated a high degree of precision in texture application to individual toolpath points. We also enabled periodic repetitions across a toolpath, which creates precise symmetry effects. The general challenges of precise mid-air AR interaction still makes precise manipulation and application of tools through direct manipulation difficult. For instance, it would be difficult to finely control stamp placement on the vessel surface. We see opportunities to address this in future development of AR toolpath editing systems. In particular, we see the potential to explore computational alignment techniques, such as aligning a straight edge of a stamp or rib with a straight edge on the surface of the vessel. It would be feasible to extend well-known interaction techniques for alignment in 2D and 3D design systems, such as magnetic guidelines [13, 19]. Such approaches would preserve the gestural interaction of the system, while enabling precise positioning of ornamentation relative to overall vessel geometry.

7.2.2 Lack of tactile and material feedback. Digital proxies of physical tools in AR are purely virtual, and so is the toolpath. Hence, the interaction provides no haptic feedback. This limitation is true for many AR and VR design technologies; however, while the lack of tactile feedback may be less noticeable when transitioning from desktop CAD to immersive design, its absence is much more evident when the practitioner is coming from a manual craft. In using Clay ARtools, Timea noted that tactile feedback “ is so critical to any crafts person because that interaction is between the tool, the material and the hand.” Without the tactile feedback from material resistance, the tool use becomes substantially different from physical workflows despite reference to physical tool functionality.

The detrimental influence of lack of haptic feedback in AR on task performance is well-known (e.g. [6, 11]), and past and current efforts in HCI research seek to address it through the development of novel techniques or hardware [11, 18, 74, 79]. An interesting future direction to mitigate the lack of tactile qualities for our system could be to integrate physical tools as tracked proxies [25] that control the position and orientation of the digital tools. While this is not comparable to the tactile feedback of pushing on a malleable material, we are interested in investigating whether holding a tangible tool can further facilitate a sense of dexterity and precision in the use of craft tools [10].

Additionally, similar to most CAM-based design tools [15, 30, 41], our system visualized the machine toolpath of the clay 3D printer rather than attempting to simulate the material behavior of the actual extruded clay coil. This visualization was helpful to users with experience in clay 3D printing, but it can take time to build an intuition for how a final vessel will look like based on seeing the machine toolpath. As explained by Timea when discussing the toolpath visualization: “from that to the object, there’s still quite a lot that happens”, in particular she emphasized changes occurring due to clay slumping and collapsing (see the difference between the toolpath and final artifact in Fig. 10). While augmented reality visualization supports an in-situ and real-scale preview of the machine toolpath, it cannot act as a stand-in for material experimentation. In the future, integrating physical or procedural simulation models for clay behavior in the system could support the visualization of more accurate digital proxies for the final printed artifacts, opening new possibilities for design iteration based on material behavior [92].

7.3 Opportunities for embodied and in-situ digital interactions to support skilled manual craft practices

Our work sought to support CAM-based design for clay 3D printing, with a focus on enabling skilled practitioners to extend what they can do with this medium. We identify further opportunities for system development leveraging XR technology in this space.

7.3.1 Transitioning from skilled physical practice to a digital proxy. Traditional ceramics workflows require the practitioner to have some degree of manual skills in order to obtain a satisfactory result. Ceramicists build up physical skills over time, through continuous practice and interaction with the material, as well as through formal and informal learning – e.g., classes, apprenticeship, learning from peers. Ceramic skills – and manual craft skills in general – rely on motor memory and dexterous hand motion, which a user could potentially leverage within an AR system, since AR devices support 6-degrees-of-freedom hand tracking, and interaction through dedicated gestures [42]. In practice, we observed through the experience of Timea in using the system that effective mid-air 3D interaction in Clay ARtools was in-and-of-itself a new skilled physical practice that had to be learnt (Section 6.2). This observation is consistent with prior studies on learning to perform precise manual tasks in AR/VR [98]. In addition, systems with large and extensible feature sets like Clay ARtools could benefit from careful interface and documentation design, to progressively familiarize users with the tool. The experience of Timea familiarizing herself with the system indicated the importance of helping users build intuition for how and when to combine tools and modifiers, and how sequencing operations influence results.

We found that designing digital tools in AR after physical tools from a skilled craft practice offered benefits and drawbacks with respect to the learning process. On one hand, we relied on ceramicist's familiarity with how physical tools are manipulated in 3D space, and embodied understanding of how they like to shape vessels. On the other hand, the resemblance to physical tools could create an uncanny feeling of working with something familiar, yet alien. In particular, we note that physical tools in manual craft allow for extremely flexible and practitioner-specific uses that can not easily be translated to a generic digital effect. Practitioners often rely on using tools with personal gestures and processes to achieve unique outcomes compared to their peers. We strived to support open-ended tool use through free mid-air tool manipulation (DG2), and tool customization (DG4). In the future we would like to evaluate whether using the digital ceramic tools can enable ceramicists to transfer or develop highly specialized and personal tool application techniques over time.

7.3.2 Designing embodied and in-situ design workflows for expert craftspeople. In our literature review, we found that AR/VR systems for personal fabrication were often positioned as a way to facilitate the design process for novice users [8, 69, 75, 76, 97, 99]. XR systems are poised as more approachable alternatives for casual users than traditional CAD/CAM software, in particular alleviating the challenge of navigating 3D space and designing 3D forms through direct manipulation in 3D.

In this work, we demonstrated that embodied and in-situ design can be applied to augmenting skilled making practices by supporting novel outcomes that are hard to achieve through typical craft and computational workflows, making such tools relevant even for artists with established workflows and practices in other software, such as Timea.

A direction we find particularly interesting, in alignment with practices of expert craftspeople, is extending our system toward interactive fabrication workflows. When using Clay ARtools, Timea relied on cycles of designing, printing, and refining, which caused her to frequently express a desire to combine the embodied, in-situ interaction modality with direct control during fabrication.

Existing interactive fabrication workflows allow machine motion to be edited live during fabrication [27, 60], which can be especially beneficial for fabrication methods where material behavior is hard to predict and can heavily impact the design (such as clay 3D printing). The Digital Pottery Wheel [55] gives craftspeople continuous control over a clay 3D printing machine, by letting them adjust 1D parameters of the toolpath through levers, knobs and a pedal. This interaction is facilitated by the unique plastic properties of wet clay and by the rapid extrusion rate and relatively large coil size of direct-write clay 3D printers. While such local toolpath adjustments are well-suited for live machine motion control, they differ significantly from embodied craft manipulation. In particular, it is hard to define global edits at the scale of the overall form, such as the vessel-wide deformations that our rib or stamp tool supports. We see potential for in-situ AR design systems, such as Clay ARtools to be extended to support emerging forms of real-time clay 3D printing or other forms of direct-write printing control: in-situ rendering could provide a digital proxy of the whole machine toolpath to support planning global edits that affect future machine motion, and 3D gestural interaction methods could support toolpath manipulation operations that are embodied and aligned with manual clay manipulation techniques.

8 Conclusion

In this work, we propose a system for CAM-based design in AR, that combines embodied interactions with precise toolpath-level editing. We achieve this combination by introducing *digital ceramic tools* that we design as digital proxies for physical tools. We complement these digital tools with *modifiers* that introduce controllable, procedural operations. Modifiers augment tool use and support the creation of computationally-supported effects that go beyond what can be achieved by gestural interaction alone. We demonstrate the expressivity of our system through the production of 23 clay 3D-printed artifacts, showcasing regular and organic 3D forms, functional shaping elements, and a variety of intricate surface textures. Developing this system in collaboration between HCI researchers and a professional ceramicist, we report insights on design and implementation choices that we found crucial in order to leverage AR capabilities in a clay 3D printing workflow, and in defining a productive translation of ceramic tools and practices into an AR CAM-based editing workflow. In the future, we hope to investigate the applicability of digital proxies of physical tools as interaction primitives in other craft and fabrication domains that heavily rely on skilled use of specialized tools (e.g. chisels, lathes, saws, in wood-working).

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References

[1] 2023. Mixed Reality Toolkit. https://github.com/MixedRealityToolkit
[2] Adobe. 2023. Medium. https://www.adobe.com/products/medium.html
[3] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, Glasgow Scotland Uk, 1–13. doi:10.1145/3290605.3300414
[4] Lea Albaugh, Scott E Hudson, and Lining Yao. 2023. An Augmented Knitting Machine for Operational Assistance and Guided Improvisation. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–15. doi:10.1145/3544548.3581549
[5] 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*. ACM, Hamburg Germany, 1–14. doi:10.1145/3544548.3581434
[6] Rahul Arora, Rubaiat Habib Kazi, Fraser Anderson, Tovi Grossman, Karan Singh, and George Fitzmaurice. 2017. Experimental Evaluation of Sketching on Surfaces in VR. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 5643–5654. doi:10.1145/3025453.3025474
[7] Rahul Arora, Rubaiat Habib Kazi, Danny M. Kaufman, Wilmot Li, and Karan Singh. 2019. MagicalHands: Mid-Air Hand Gestures for Animating in VR. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New York, NY, USA, 463–477. doi:10.1145/3332165.3347942
[8] Oğuz Arslan, Artun Akdoğan, and Mustafa Doga Dogan. 2025. TinkerXR: In-Situ, Reality-Aware CAD and 3D Printing Interface for Novices. In *Proceedings of the ACM Symposium on Computational Fabrication (SCF '25)*. Association for Computing Machinery, New York, NY, USA, 1–19. doi:10.1145/3745778.3766651
[9] Mayra Donaji Barrera Machuca, Wolfgang Stuerzlinger, and Paul Asente. 2019. The Effect of Spatial Ability on Immersive 3D Drawing. In *Proceedings of the 2019 Conference on Creativity and Cognition (C&C '19)*. Association for Computing Machinery, New York, NY, USA, 173–186. doi:10.1145/3325480.3325489
[10] Anil Ufuk Batmaz, Aunnoy K Mutasim, and Wolfgang Stuerzlinger. 2020. Precision vs. Power Grip: A Comparison of Pen Grip Styles for Selection in Virtual Reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. 23–28. doi:10.1109/VRW50115.2020.00012
[11] Olivier Bau and Ivan Poupyrev. 2012. REVEL: tactile feedback technology for augmented reality. *ACM Transactions on Graphics (TOG)* 31, 4 (2012), 1–11.
[12] Michel Beaudouin-Lafon. 2000. Instrumental interaction: an interaction model for designing post-WIMP user interfaces. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems (CHI '00)*. Association for Computing Machinery, New York, NY, USA, 446–453. doi:10.1145/332040.332473
[13] Eric A. Bier. 1990. Snap-dragging in three dimensions. *ACM SIGGRAPH Computer Graphics* 24, 2 (March 1990), 193–204. doi:10.1145/91394.91446
[14] bold-design. 2022. Impression 3D céramique - Séries d'expérimentations. https://bold-design.fr/lab/impression-3d-experimentations/
[15] Samuelle Bourgault, Pilar Wiley, Avi Farber, and Jennifer Jacobs. 2023. CoilCAM: Enabling Parametric Design for Clay 3D Printing Through an Action-Oriented Toolpath Programming System. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–16. doi:10.1145/3544548.3580745
[16] Leah Buechley and Ruby Ta. 2023. 3D Printable Play-Dough: New Biodegradable Materials and Creative Possibilities for Digital Fabrication. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3544548.3580813
[17] Xavier Chermain, Cédric Zanni, Jonàs Martínez, Pierre-Alexandre Hugron, and Sylvain Lefebvre. 2023. Orientable Dense Cyclic Infill for Anisotropic Appearance Fabrication. *ACM Trans. Graph.* 42, 4 (July 2023), 68:1–68:13. doi:10.1145/3592412
[18] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. Claw: A multifunctional handheld haptic controller for grasping, touching, and triggering in virtual reality. In *Proceedings of the 2018 CHI conference on human factors in computing systems*. 1–13.
[19] Marianela Ciolfi Felice, Nolwenn Maudet, Wendy E. Mackay, and Michel Beaudouin-Lafon. 2016. Beyond Snapping: Persistent, Tweakable Alignment and Distribution with StickyLines. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. Association for Computing Machinery, New York, NY, USA, 133–144. doi:10.1145/2984511.2984577
[20] Clayon. 2021. Clayon Documentation. https://www.clayontec.com/docs/
[21] Bryan Czibesz. 2018. Curves : Stacks : White. https://bryanczibesz.com
[22] Fernando De Goes and Doug L. James. 2017. Regularized kelvinlets: sculpting brushes based on fundamental solutions of elasticity. *ACM Trans. Graph.* 36, 4 (July 2017), 40:1–40:11. doi:10.1145/3072959.3073595
[23] Julian Descottes. 2017. Piskel - Free online sprite editor. https://www.piskelapp.com/
[24] Laura Devendorf, Katya Arquilla, Sandra Wirtanen, Allison Anderson, and Steven Frost. 2020. Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–13. doi:10.1145/3313831.3376820
[25] Mustafa Doga Dogan, Eric J Gonzalez, Karan Ahuja, Ruofei Du, Andrea Colaço, Johnny Lee, Mar Gonzalez-Franco, and David Kim. 2024. Augmented Object Intelligence with XR-Objects. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. ACM, Pittsburgh PA USA, 1–15. doi:10.1145/3654777.3676379
[26] Shuo Feng, Bo Liu, Yifan Shan, Roy Zunder, Wei-Che Lin, Tri Dinh, Harald Haraldsson, Ofer Berman, and Thijs Roumen. 2025. Y-AR: A Mixed Reality CAD Tool for 3D Wire Bending. In *Proceedings of the ACM Symposium on Computational Fabrication (SCF '25)*. Association for Computing Machinery, New York, NY, USA, 1–17. doi:10.1145/3745778.3766654
[27] Frikk Fossdal, Rogardt Heldal, and Nadya Peek. 2021. Interactive Digital Fabrication Machine Control Directly Within a CAD Environment. In *Symposium on Computational Fabrication*. ACM, Virtual Event USA, 1–15. doi:10.1145/3485114.3485120
[28] Camila Friedman-Gerlicz, Deanna Gelosi, Fiona Bell, and Leah Buechley. 2024. WeaveSlicer: Expanding the Range of Printable Geometries in Clay. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–16. doi:10.1145/3613904.3642622
[29] Front. 2007. Sketch Furniture. http://www.frontdesign.se/sketch-furniture-performance-design-project
[30] Devon Frost, Raina Lee, Eun-Ha Paek, and Jennifer Jacobs. 2024. SketchPath: Using Digital Drawing to Integrate the Gestural Qualities of Craft in CAM-Based Clay 3D Printing. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–16. doi:10.1145/3613904.3642684
[31] Jaime Gould, Camila Friedman-Gerlicz, and Leah Buechley. 2024. TRAvel Slicer: Continuous Extrusion Toolpaths for 3D Printing. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24)*. Association for Computing Machinery, New York, NY, USA, 1–17. doi:10.1145/3654777.3676349
[32] Xinyue Gui, Ding Xia, Wang Gao, Mustafa Doga Dogan, Maria Larsson, and Takeo Igarashi. 2025. Draw2Cut: Direct On-Material Annotations for CNC Milling. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, 1–17. doi:10.1145/3706598.3714281
[33] Bo Han, Jared Lim, Kianne Lim, Adam Choo, Ching Chiuan Yen, Genevieve Ang, and Clement Zheng. 2025. Slip Casting as a Machine for Making Textured Ceramic Interfaces. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, 1–18. doi:10.1145/3706598.3714396
[34] Jean Hergel, Kevin Hinz, Sylvain Lefebvre, and Bernhard Thomaszewski. 2019. Extrusion-based ceramics printing with strictly-continuous deposition. *ACM Transactions on Graphics* 38, 6 (Dec. 2019), 1–11. doi:10.1145/3355089.3356509
[35] 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.* 31, 1 (Nov. 2023), 13:1–13:45. doi:10.1145/3609328
[36] Edwin L. Hutchins, JAmes D. Hollan, and Donals A. Norman. 1986. Direct Manipulation Interfaces. In *User Centered System Design*. CRC Press. Num Pages: 38.
[37] Ramya Iyer, Mustafa Doga Dogan, Maria Larsson, and Takeo Igarashi. 2025. XR-penter: Material-Aware and In Situ Design of Scrap Wood Assemblies. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*.

ACM, Yokohama Japan, 1–16. doi:10.1145/3706598.3713331

[38] Robert J.K. Jacob, Audrey Girouard, Leanne M. Hirshfield, Michael S. Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. 2008. Reality-based interaction: a framework for post-WIMP interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. Association for Computing Machinery, New York, NY, USA, 201–210. doi:10.1145/1357054.1357089

[39] Alec Jacobson, Ilya Baran, Jovan Popović, and Olga Sorkine. 2011. Bounded biharmonic weights for real-time deformation. In *ACM SIGGRAPH 2011 papers (SIGGRAPH '11)*. Association for Computing Machinery, New York, NY, USA, 1–8. doi:10.1145/1964921.1964973

[40] Gwyllim; Newnham Jahn. 2018. Making in Mixed Reality. Holographic design, fabrication, assembly and analysis of woven steel structures. In *ACADIA // 2018: Recalibration. On imprecisionand infidelity. [Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-0-692-17729-7] Mexico City, Mexico 18-20 October, 2018, pp. 88-97.* CUMINCAD. https://papers.cumincad.org/cgi-bin/works/paper/acadia18_88

[41] Daphna Kaplan, Mirela Ben Chen, and Yoav Sterman. 2025. ConTextural: A Toolpath-Based Texture Editing Tool for Extrusion 3D Printers. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, 1–16. doi:10.1145/3706598.3713753

[42] Scott R. Klemmer, Björn Hartmann, and Leila Takayama. 2006. How bodies matter: five themes for interaction design. In *Proceedings of the 6th conference on Designing Interactive systems*. ACM, University Park PA USA, 140–149. doi:10.1145/1142405.1142429

[43] Nick Ladd. [n. d.]. VR PAINTINGS. https://www.nickladd.tv/vrart

[44] Gierad Laput, Xiang 'Anthony' Chen, and Chris Harrison. 2015. 3D Printed Hair: Fused Deposition Modeling of Soft Strands, Fibers, and Bristles. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. Association for Computing Machinery, New York, NY, USA, 593–597. doi:10.1145/2807442.2807484

[45] David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. 2018. Evaluation Strategies for HCI Toolkit Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–17. doi:10.1145/3173574.3173610

[46] Boyu Li, Linping Yuan, Zhe Yan, Qianxi Liu, Yulin Shen, and Zeyu Wang. 2024. AniCraft: Crafting Everyday Objects as Physical Proxies for Prototyping 3D Character Animation in Mixed Reality. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. ACM, Pittsburgh PA USA, 1–14. doi:10.1145/3654777.3676325

[47] Isabel Li, Ace S. Chen, Eric Rawn, Shm Garanganao Almeda, Bjoern Hartmann, and Jingyi Li. 2025. Reimagining Misuse as Creative Practice: Impressions and Implications of Usage Norms on Digital Artists. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–14. doi:10.1145/3706598.3714068

[48] 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 (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3411764.3445682

[49] 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* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–11. doi:10.1145/3173574.3173741

[50] Zofia Marciniak, Kongpyung Moon, and Andrea Bianchi. 2024. Decoupling Geometry from Surface Finish by Parameterizing Texture Directly in G-code for Fused Deposition Modeling (FDM) Printing. *Archives of Design Research* 37, 2 (May 2024), 7–23. doi:10.15187/adr.2024.05.37.2.7

[51] Maxon. [n. d.]. Maxon - ZBrush - Brush System. https://www.maxon.net/en/zbrush/features/brush-system

[52] Daniela Mitterberger, Kathrin Dörfler, Timothy Sandy, Foteini Salveridou, Marco Hutter, Fabio Gramazio, and Matthias Kohler. 2020. Augmented bricklaying. *Construction Robotics* 4, 3 (Dec. 2020), 151–161. doi:10.1007/s41693-020-00035-8

[53] Daniela Mitterberger, Selen Ercan Jenny, Lauren Vasey, Ena Lloret-Fritschi, Petrus Aejmelaeus-Lindström, Fabio Gramazio, and Matthias Kohler. 2022. Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-site Robotic Plastering. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA, 1–18. doi:10.1145/3491102.3501842

[54] Alexandra Moisi, Joseph Clair Kenny, Oliver Bucklin, Petrus Aejmelaeus-Lindström, Ananya Kango, Gonzalo Casas, Daniela Mitterberger, Fabio Gramazio, and Matthias Kohler. 2025. Interactive Digital Twins: Integrating XR and Motion Capture for Timber Assembly. In *Proceedings of the ACM Symposium on Computational Fabrication (SCF '25)*. Association for Computing Machinery, New York, NY, USA, 1–18. doi:10.1145/3745778.3766661

[55] Ilan E Moyer, Samuelle Bourgault, Devon Frost, and Jennifer Jacobs. 2024. Throwing Out Conventions: Reimagining Craft-Centered CNC Tool Design through the Digital Pottery Wheel. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–22. doi:10.1145/3613904.3642361

[56] A.Y.C. Nee, S.K. Ong, G. Chryssolouris, and D. Mourtzis. 2012. Augmented reality applications in design and manufacturing. *CIRP Annals* 61, 2 (2012), 657–679. doi:10.1016/j.cirp.2012.05.010

[57] François Osiurak, Christophe Jarry, and Didier Le Gall. 2010. Grasping the affordances, understanding the reasoning: toward a dialectical theory of human tool use. *Psychological Review* 117, 2 (April 2010), 517–540. doi:10.1037/a0019004

[58] Joyce Passananti, Ana Cardenas Gasca, Jennifer Jacobs, and Tobias Höllerer. 2024. Augmented Reality for Digital Fabrication: Evaluating impact of AR visualization of machine toolpaths for Clay 3D printing. In *2024 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. 465–468. doi:10.1109/ISMAR-Adjunct64951.2024.00135 ISSN: 2771-1110.

[59] Joyce E Passananti, Ana CardenasGasca, Jennifer Jacobs, and Tobias HÖLlerer. 2023. SculptAR: Direct Manipulations of Machine Toolpaths in Augmented Reality for 3D Clay Printing. In *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. ACM, San Francisco CA USA, 1–3. doi:10.1145/3586182.3615822

[60] Huaishu Peng, Jimmy Briggs, Cheng-Yao Wang, Kevin Guo, Joseph Kider, Stefanie Mueller, Patrick Baudisch, and François Guimbretière. 2018. RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3173574.3174153

[61] Franklin Pezutti-Dyer and Leah Buechley. 2022. Extruder-Turtle: A Library for 3D Printing Delicate, Textured, and Flexible Objects. In *Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22)*. Association for Computing Machinery, New York, NY, USA, 1–9. doi:10.1145/3490149.3501312

[62] Ronald Rael, Virginia San Fratello, Barrak Darweesh, Constantina Tsiara, and Alexander Curth. 2020. POTTERWARE. https://www.potterware.com/

[63] Ronald Rael, Virginia San Fratello, and Phirak Suon. 2017. Bad Ombres v.1. https://emergingobjects.com/project/bad-ombres-v-1/

[64] Miguel A. Renom, Baptiste Caramiaux, and Michel Beaudouin-Lafon. 2022. Exploring Technical Reasoning in Digital Tool Use. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–17. doi:10.1145/3491102.3501877

[65] Michael L. Rivera and Scott E. Hudson. 2019. Desktop Electrospinning: A Single Extruder 3D Printer for Producing Rigid Plastic and Electrospun Textiles. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, Glasgow Scotland Uk, 1–12. doi:10.1145/3290605.3300434

[66] Alec Rivers, Andrew Adams, and Frédo Durand. 2012. Sculpting by numbers. *ACM Transactions on Graphics* 31, 6 (Nov. 2012), 1–7. doi:10.1145/2366145.2366176

[67] Virginia San Fratello. 2024. Totems des Femmes. https://www.instagram.com/vasfsf/

[68] Valkyrie Savage, Sean Follmer, Jingyi Li, and Björn Hartmann. 2015. Makers' Marks: Physical Markup for Designing and Fabricating Functional Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, Charlotte NC USA, 103–108. doi:10.1145/2807442.2807508

[69] Steven Schkolne, Michael Pruett, and Peter Schröder. 2001. Surface drawing: creating organic 3D shapes with the hand and tangible tools. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 261–268.

[70] Eldon Schoop, Michelle Nguyen, Daniel Lim, Valkyrie Savage, Sean Follmer, and Björn Hartmann. 2016. Drill Sergeant: Supporting Physical Construction Projects through an Ecosystem of Augmented Tools. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 1607–1614. doi:10.1145/2851581.2892429

[71] Nicholas Sharp, Yousuf Soliman, and Keenan Crane. 2019. The Vector Heat Method. *ACM Trans. Graph.* 38, 3 (June 2019), 24:1–24:19. doi:10.1145/3243651

[72] Maria Shugrina, Jingwan Lu, and Stephen Diverdi. 2017. Playful palette: an interactive parametric color mixer for artists. *ACM Trans. Graph.* 36, 4 (July 2017), 61:1–61:10. doi:10.1145/3072959.3073690

[73] Smoothstep. 2021. Quill. https://quill.art/

[74] Carolin Stellmacher, Florian Mathis, Yannick Weiss, Meagan B Loerakker, Nadine Wagener, and Johannes Schöning. 2024. Exploring mobile devices as haptic interfaces for mixed reality. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. 1–17.

[75] Evgeny Stemasov, Simon Demharter, Max Rädler, Jan Gugenheimer, and Enrico Rukzio. 2024. pARam: Leveraging Parametric Design in Extended Reality to Support the Personalization of Artifacts for Personal Fabrication. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–22. doi:10.1145/3613904.3642083

[76] Evgeny Stemasov, Tobias Wagner, Jan Gugenheimer, and Enrico Rukzio. 2020. Mix&Match: Towards Omitting Modelling Through In-situ Remixing of Model Repository Artifacts in Mixed Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu HI USA, 2020-04-21). ACM,

1–12. doi:10.1145/3313831.3376839

[77] Evgeny Stemasov, Tobias Wagner, Jan Gugenheimer, and Enrico Rukzio. 2022. ShapeFindAR: Exploring In-Situ Spatial Search for Physical Artifact Retrieval using Mixed Reality. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA, 1–12. doi:10.1145/3491102.3517682

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

[79] Ryo Suzuki, Adnan Karim, Tian Xia, Hooman Hedayati, and Nicolai Marquardt. 2022. Augmented reality and robotics: A survey and taxonomy for ar-enhanced human-robot interaction and robotic interfaces. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 1–33.

[80] Ryo Suzuki, Rubaiat Habib Kazi, Li-yi Wei, Stephen DiVerdi, Wilmot Li, and Daniel Leithinger. 2020. RealitySketch: Embedding Responsive Graphics and Visualizations in AR through Dynamic Sketching. In *Proc. ACM Symposium on User Interface Software and Technology (UIST)*.

[81] Haruki Takahashi and Homei Miyashita. 2017. Expressive Fused Deposition Modeling by Controlling Extruder Height and Extrusion Amount. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Denver Colorado USA, 5065–5074. doi:10.1145/3025453.3025933

[82] Rundong Tian and Eric Paulos. 2021. Adroid: Augmenting Hands-on Making with a Collaborative Robot. In *The 34th Annual ACM Symposium on User Interface Software and Technology*. ACM, Virtual Event USA, 270–281. doi:10.1145/3472749.3474749

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

[84] Timea Tihanyi and Zoe Kaputa. 2023. Touching Space. https://www.timeatihanyi.com/touching-space

[85] Mert Toka. 2025. merttoka/ClayToolkit. https://github.com/merttoka/ClayToolkit original-date: 2024-05-02T17:22:32Z.

[86] Mert Toka, Samuelle Bourgault, Camila Friedman-Gerlicz, and Jennifer Jacobs. 2023. An Adaptable Workflow for Manual-Computational Ceramic Surface Ornamentation. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3586183.3606726

[87] Mert Toka, Devon Frost, Samuelle Bourgault, Avi Farber, Camila Friedman-Gerlicz, Raina Lee, Eun-Ha Paek, Pilar Wiley, and Jennifer Jacobs. 2024. Practice-driven Software Development: A Collaborative Method for Digital Fabrication Systems Research in a Residency Program. In *Designing Interactive Systems Conference*. ACM, IT University of Copenhagen Denmark, 1192–1217. doi:10.1145/3643834.3661522

[88] Cesar Torres, Tim Campbell, Neil Kumar, and Eric Paulos. 2015. HapticPrint: Designing Feel Aesthetics for Digital Fabrication. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. Association for Computing Machinery, New York, NY, USA, 583–591. doi:10.1145/2807442.2807492

[89] Jasper Tran O'Leary, Eunice Jun, and Nadya Peek. 2022. Improving Programming for Exploratory Digital Fabrication with Inline Machine Control and Styled Toolpath Visualizations. In *Proceedings of the 7th Annual ACM Symposium on Computational Fabrication*. ACM, Seattle WA USA, 1–12. doi:10.1145/3559400.3561998

[90] Jasper Tran O'Leary, Thrisha Ramesh, Octi Zhang, and Nadya Peek. 2024. Tandem: Reproducible Digital Fabrication Workflows as Multimodal Programs. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–16. doi:10.1145/3613904.3642751

[91] Amy Traylor, Ruby Ta, Alyssa Johnson, and Leah Buechley. 2024. PaperCut: A Craft-Centered Approach to Digital Fabrication Using Cut Paper as a Design Medium. In *Proceedings of FabLearn / Constructionism 2023: Full and Short Research Papers (FLC '23)*. Association for Computing Machinery, New York, NY, USA, 1–4. doi:10.1145/3615430.3615439

[92] Hannah Twigg-Smith, Emily Whiting, and Nadya Peek. 2024. KnitScape: Computational Design and Yarn-Level Simulation of Slip and Tuck Colorwork Knitting Patterns. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–20. doi:10.1145/3613904.3642799

[93] Unity Technologies. 2022. Unity 2020.3.43f1. https://unity.com/releases/editor/whats-new/2020.3.43f1

[94] Guanyun Wang, Ye Tao, Ozguc Bertug Capunaman, Humphrey Yang, and Lining Yao. 2019. A-line: 4D Printing Morphing Linear Composite Structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3290605.3300656

[95] Ziqi Wang, Florian Kennel-Maushart, Yijiang Huang, Bernhard Thomaszewski, and Stelian Coros. 2023. A Temporal Coherent Topology Optimization Approach for Assembly Planning of Bespoke Frame Structures. *ACM Trans. Graph.* 42, 4 (July 2023), 144:1–144:13. doi:10.1145/3592102

[96] Christian Weichel, John Hardy, Jason Alexander, and Hans Gellersen. 2015. ReForm: Integrating Physical and Digital Design through Bidirectional Fabrication. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. Association for Computing Machinery, New York, NY, USA, 93–102. doi:10.1145/2807442.2807451

[97] Christian Weichel, Manfred Lau, David Kim, Nicolas Villar, and Hans W. Gellersen. 2014. MixFab: a mixed-reality environment for personal fabrication. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. Association for Computing Machinery, New York, NY, USA, 3855–3864. doi:10.1145/2556288.2557090

[98] E. Wiese, J. H. Israel, A. Meyer, and S. Bongartz. 2010. Investigating the learnability of immersive free-hand sketching. In *Proceedings of the Seventh Sketch-Based Interfaces and Modeling Symposium (SBIM '10)*. Eurographics Association, Goslar, DEU, 135–142.

[99] Karl D.D. Willis, Juncong Lin, Jun Mitani, and Takeo Igarashi. 2010. Spatial sketch: bridging between movement & fabrication. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10)*. Association for Computing Machinery, New York, NY, USA, 5–12. doi:10.1145/1709886.1709890

[100] Xin Yan, Lin Lu, Andrei Sharf, Xing Yu, and Yulu Sun. 2021. Man-made by Computer: On-the-Fly Fine Texture 3D Printing. In *Symposium on Computational Fabrication*. ACM, Virtual Event USA, 1–10. doi:10.1145/3485114.3485119

[101] Ya-Ting Yue, Xiaolong Zhang, Yongliang Yang, Gang Ren, Yi-King Choi, and Wenping Wang. 2017. WireDraw: 3D Wire Sculpturing Guided with Mixed Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3693–3704. doi:10.1145/3025453.3025792

[102] 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, Article 474, 18 pages. doi:10.1145/3544548.3580836