# Augmented Reality for Digital Fabrication: Evaluating impact of AR visualization of machine toolpaths for Clay 3D printing

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## ABSTRACT

In digital fabrication, machine toolpaths specify how a machine translates a digital design into a material outcome. Material-focused approaches design directly at the toolpath level to create unique patterns, such as weaving effects in clay 3D printing. Visualizing toolpaths in AR can help practitioners gauge, interpret, and plan machine behavior. To better understand the potential of AR to aid the understanding of machine toolpaths, we present a user study involving nine 3D printing practitioners with varying backgrounds. We investigate the effectiveness of two AR modalities—head-worn (Hololens) and hand-held (iPad)—in visualizing machine toolpaths to improve the design process for clay 3D printing, and compare with the baseline workflow of desktop-only visualization. Findings indicate that Hololens and iPad modalities enhance contextual visualization and aid in understanding machine toolpaths, contingent on factors such as comfort, display characteristics, and integration to existing workflows. This study highlights the potential of AR for optimizing clay 3D printing design workflows and informs the development of tailored AR tools for enhanced user experience.

**Index Terms:** Human-centered computing Empirical studies in HCI; Augmented Reality; Digital Fabrication

## 1 INTRODUCTION

The process of digital fabrication has machines translate digital designs into material outcomes through instructions that specify fabrication actions and parameters. The term *toolpaths* is used to describe the precise movements the fabrication machine actuators follow. In traditional 3D printing workflows, practitioners specify designs using CAD models, and a separate slicer software generates the toolpath to resemble the CAD model optimally [10]. New material-focused digital fabrication approaches have centered the expressive potential of designing at the machine toolpath level, unlocking new forms of creative control [2] and allowing practitioners to take advantage of material properties [1].

Visualizing the toolpath is critical to predicting material behavior that relies on machine specifications such as extrusion speed, nozzle size, or layer height, which can significantly impact the final printed object's appearance and structural integrity. AR visualizations have the potential to enhance understanding of machine toolpaths by allowing practitioners to preview toolpaths embedded in the real-world 3D context. However, current AR research in digital fabrication has been mostly focused on CAD design workflows and does not consider toolpath design. To contribute to the understanding of AR's potential in supporting digital fabrication design at the machine toolpath level we formulate the following research questions:

- **RQ-1** What is the impact of AR in dimensional estimation of designs specified by machine toolpaths?
- **RQ-2** What is the impact of AR in referencing existing objects in designs specified by machine toolpaths?

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To investigate these questions we focused on the particular application of clay 3D printing. Due to the unique material properties of clay, 3D printing practitioners must understand the machine movement as specified by the toolpath to assess design features and feasibility. We conducted a user study to evaluate the dimensional and contextual understanding of machine toolpaths using AR. We compared the visualization of machine toolpaths in Desktop versus two AR modalities: hand-held tablets and head-worn displays (HMDs). The user study comprised nine participants with varying levels of experience in ceramics and CAD software. Participants were first given an overview of clay 3D printing and the design system. They were then trained on the design system and introduced to the Hololens and iPad operation and interfaces. Afterwards, participants were tasked with completing two design tasks.

## 2 RELATED WORK

Researchers have employed augmented reality (AR) in design systems to bridge the gap between physical objects and the digital models used by fabrication machines; for instance, by allowing users to create, monitor and adjust 3D models in the fabrication environment [4, 7, 9, 11, 12]. User evaluations have shown that AR systems can support in-situ fabrication, and can lower barriers for 3D modeling and customization by providing useful design visualization context based on existing objects. Researchers have also explored barriers and measurement strategies in rapid prototyping [8] and challenges for augmenting real-world objects with fabricated objects [5].

Research systems that leverage AR for fabrication base the visualization and editing of 3D modeling in CAD operations. This follows a canonical fabrication workflows began with designing 3D models in CAD software, which were then translated into machine instructions using CAM software to be executed by CNC machines. While this CAD-to-CAM pipeline enables accurate and repeatable production, it also restricts creators to a linear workflow, limiting expressive opportunities [10]. Artists and researchers have sought to push the boundaries of what is enabled by traditional 3D modeling and computer-aided design CAD by leveraging CAM to specify designs for digital fabrication [1, 10]. However, these systems still rely on traditional desktop 3D modeling applications. Limited research has addressed CAM and AR in fabrication contexts including systems for guiding plastering using AR [6] and using AR to integrate physical human input with robotic manipulation of melting wax [3].

## 3 USER STUDY

Our study focuses on the effect of three AR visualization conditions on understanding machine toolpaths: Hololens, iPad, and Desktop. In the study, participants had to perform two tasks that involved creating and visualizing toolpaths for clay 3D printing. The first task involves dimensional estimation of standard objects, and the second consists of referencing physical objects. Both tasks rely on a desktop tool for designing machine toolpaths through the adjustment of parameters along with the modalities of AR visualization. We describe the demographics of the nine participants involved, followed by the procedure, tasks, and analysis for the data collected.

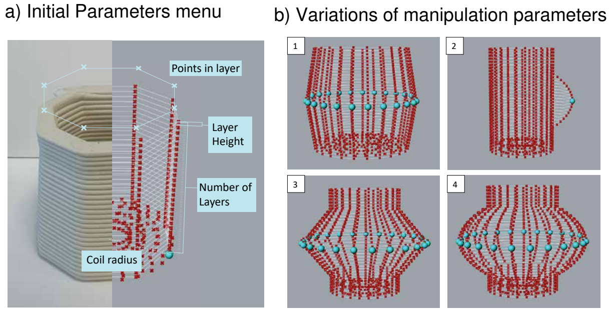

Figure 1: Parametric 3D toolpath editor. (a) The *Initial Parameters* menu specifies properties of a cylindrical coil which can be adjusted with sliders. (b) A manipulation can be applied to the entire “layer” (1) or a single “point” (2) or and can be applied with either a “linear” (3) or “curved” (4) style.

### 3.1 3D Machine Toolpath Design System

We designed and built a custom system that enables visualization and editing of a machine toolpath for clay 3D printing. The machine toolpath corresponds to the movement along the x, y and z axes that a clay extruder follows as it deposits clay layer by layer, to 3D print an object. The system is implemented using the 3D modeling software Rhino3D [1], Grashopper [2] and HumanUI [3]. In this section we present our software: a parametric 3D tolpath editor, and the AR visualization in Hololens and iPad.

#### 3.1.1 Parametric 3D toolpath editor

The user is first presented with a base cylindrical coil. Toolpath parameters for this base coil are set before any manipulation options and parameterize the initial radius, number of layers, layer height, and number of points in layers (Figure 1-a). The *manipulations* menu specifies an operation to modify the toolpath. Manipulations parameters are: selected point, which allows to select of a point or layer which is highlighted in blue. The distance parameter radially displaces the selected point or layer by the distance value. Brush height represents the number of layers above and below the selected point that are affected by the operation. Users can then further edit the coil through a simple workflow in three main stages. First, the user selects the operation they’d like to perform, a shape operation applied around the layer or a single control point (Figure 1-b1,b2). Next, they choose the modifier function which specifies how the operation will be applied to neighbouring layers: linear or curved (Figure 1-b3,b4). Lastly, they adjust parameters that control the shapes achieved with a modification.

#### 3.1.2 AR Visualization

The 3D modeling software integration with AR environments is performed with the aid of Fologram [4], a Rhino3D library that supports bi-directional synchronization of geometry. Fologram overlays digital 3D geometry created with Rhino3D, onto physical space using AR devices such as smartphones, tablets, or AR glasses. We used the Fologram plugin for Grasshopper to stream the coil geometry from Rhino to the AR devices. The devices pair quickly with the software on desktop through a QR code, and are placed in the surroundings manually or automatically with a printed QR code at a desired location. We explored two AR modalities: HMD and handheld AR. For HMD we used a Hololens 2, which allows a hands free experience and fully immersive visualization of the virtual coil in physical space. We evaluated an iPad for mobile AR, which still constrains the visualization to a screen but allows visualization of the dimensions with respect to other objects and dimensions in the environment.

### 3.2 Participants

We recruited nine participants with an interest in clay 3D printing and varying prior experience with ceramics and CAD software. We recruited participants from diverse backgrounds, including art educators (2), ceramic artists (3), graduate students (2), and architect and a designer (2). The range of backgrounds aids in understanding how AR is received by different communities and workplaces and comparing perceived opportunities and preferences in those settings during the discussion. Most participants had significant prior experience with ceramics, as we were specifically interested in recruiting participants that could discuss how AR visualization would help in translating clay artists’ material understanding of properties and expectations. We also invited participants with a range of CAD experience, to compare traditional CAD workflows with integration of AR for visualization.

### 3.3 Procedure

We ran the study with participants working on the tasks in parallel to facilitate discussion and exchange of ideas during the study, enhancing their understanding of the technology and potential applications.

We started the session by introducing participants to clay 3D printing and showing them how a clay 3D printing machine fabricates a toolpath created with our system. This overview consisted of a brief description of how slicers produce gCode based on 3D models and an explanation of the design affordances of toolpath-level design for clay 3D printing. It also included a demo of the clay 3D printer fabricating an example toolpath. They were encouraged to interact with the clay to identify material properties such as moisture, grit, etc., and we showcased previously fabricated clay objects to give an understanding of how compression of layers, layer height, and overhang of layers factor into the resulting piece.

We showed participants the design system and introduced them to the two AR devices, providing instructions on pairing the devices to their desktops and placing the AR design in their surroundings. Participants experimented with the software using the three visualization conditions until they felt comfortable with each. They completed a training task that required them to create a toolpath for a bowl using the desktop and modify its dimensions using both AR modalities. Following the training stage, participants completed the two tasks described below.

#### 3.3.1 Tasks

We split each task into three stages, with the objective remaining the same across stages but the objects used in the task changing. Participants cycled through visualization conditions, using desktop, iPad, and Hololens visualization each for one stage. All participants used each visualization condition once per task, counterbalanced to control for the order in which participants used each condition. For tasks requiring measuring objects, participants were allowed to use the reference grid in Rhino with dimensions (1mm x 1mm) and a standard ruler.

During Task 1, participants replicated the dimensions of a familiar “household object”. We prompted participants with a different object on each stage: for stage 1 an 8oz. mug, for stage 2 an espresso cup, and for stage 3 a cereal bowl. All participants confirmed they were familiar with all objects described, and we provided participants with approximate volumes to further standardize.

During Task 2, participants recreated the shape and dimensions of a given object using varied dimensions and curvature. We handed participants a different object on each stage: For stage 1 a curved

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[1] https://www.rhino3d.com/

[2] https://www.grasshopper3d.com/

[3] https://www.food4rhino.com/en/app/human-ui

[4] https://fologram.com/

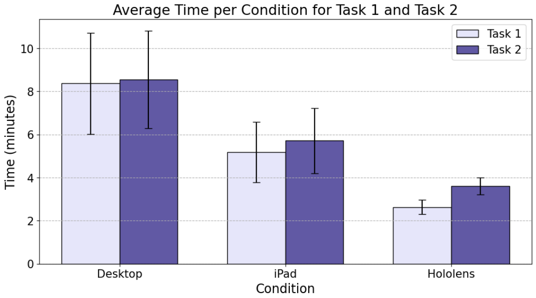

Figure 2: Task Timing: Average time taken with each condition for Task 1 and 2. Means are plotted with standard error bars

bowl, for stage 2 a tall vase, and for stage 3 a small shot glass. We notified participants that their performance would be timed but were not given any explicit time restrictions and were allowed to continue designing as long as desired.

### 3.4 Analysis

We analyzed the design sessions and task performance through multiple methods. We recorded the time taken to complete each task, and compared between visualization modalities. We further evaluated performance through accuracy of design dimensions with given or expected dimensions. To asses affects of each AR device, we conducted one-way repeated measures ANOVAs. ANOVAs where the assumption of normality was violated (based on the Shapiro-Wilk test of normality) were re-analyzed using Friedman's test, a non-parametric equivalent of repeated measures ANOVA. The results remained consistent, therefore initial ANOVAs are reported for clarity. Furthermore, ANOVA is known to be robust to violations of normality. All ANOVAs were conducted using the rstatix package in R. Pairwise comparisons with Bonferroni correction were used to follow-up significant main effects identified through the ANOVAs and provide further insight on direct comparisons between desktop - AR device, as well as between-device comparisons.

Only one variable violated homogeneity of variances (time). This was analyzed using Friedman's test (a non-parametric equivalent of the repeated measures ANOVA), and followed up by pairwise comparisons using the Wilcoxon signed rank test with Bonferroni correction. We use the Cohen (1988) criteria of .2 = small effect, .5 = medium effect, and .8 = large effect to interpret effect size of each pairwise comparison.

## 4 RESULTS

### 4.1 Quantitative Analysis of Task Performance

Performance on tasks was measured for two metrics: time and accuracy. We compare each AR modality to the baseline: desktop (no AR), as well as between modalities. In the baseline desktop condition, we hypothesized a trade-off between the two metrics- participants that took longer completing the tasks would produce more accurate dimensions and shapes, and participants that completed the tasks faster would have less accurate dimensions of their final design.

#### 4.1.1 Time

Participants were not given time constraints for the tasks, and time taken varied greatly between participants across tasks (as shown in Figure 2).

**Task 1.** A one-way ANOVA was performed to compare the effect of AR condition on time taken for Task 1 and revealed a statistically significant difference in time between at least two groups (F(2,16) = 3.72, $p = 0.047 < 0.05$). Pairwise comparisons using the Wilcoxon test revealed that the time taken using only the desktop - no AR condition was significantly greater than time taken with the aid of AR: hololens [W = 0, $p = 0.027 < 0.05$, eff size = 0.89, large]. There was no statistically significant difference between time taken using desktop - no AR and AR: iPad (p=0.44). Timing trended lower for AR: hololens than AR: iPad (p=0.08) however was not significant between AR modalities. These results suggest Hololens AR visualization reduces time required to understand the dimensions of a design. The iPad visualization did not significantly reduce time when compared to just the desktop visualization, suggesting the iPad visualization was perhaps not as informative as the Hololens visualization, or the integration of the iPad device into the workflow was not as seamless.

**Task 2.** A one-way ANOVA was performed to compare the effect of AR condition on time taken for Task 2 and revealed no statistically significant difference in time between any two groups (F(2,16) = 1.855, p = 0.19). An additional Friedman test was performed and similarly reported no significance of AR condition on task timing. These results indicate that having AR visualization did not significantly reduce the time required to replicate dimensions and shape of an existing object.

#### 4.1.2 Accuracy

Accuracy of specified design objectives was measured and compared both participant designs and reference objects across each task.

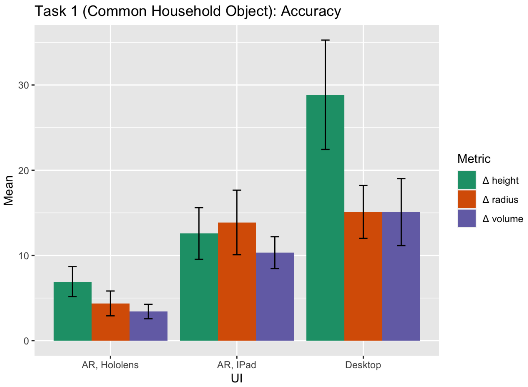

Figure 3: Task 1 Accuracy: Metrics for radius, height, and volume difference from the nearest edge of the specified range. *volume difference scaled by 1/1000 to show on the same scale.

**Task 1.** In Task 1 participants estimated dimensions of common household items without the aid of physical reference objects, given expected dimensions and volumes for each object. Researchers sourced ten household vessels fitting each object description to produce a range for height and radius that serves as a baseline. Accuracy for each dimension (height, radius, and volume) was evaluated based on proximity to the nearest edge of each established range.

One-way repeated measures ANOVAs were performed to compare the effect of AR condition on accuracy of dimensions, analyzed through three independent variables: height, radius, and volume. The ANOVAs revealed a main effect for AR condition on radius (F(2,16) = 4.152, $p = 0.035 < 0.05$), as well as height (F(2,16) = 9.554, $p = 0.002 < 0.05$). Pairwise comparisons using the Wilcoxon test revealed that the design radius with AR: hololens visualization was significantly more accurate than the radius produced through only desktop visualisation [W = 2.0, $p < 0.05$, eff size = 0.81, large]. Similarly, height was significantly more accurate in the Hololens condition than with desktop only condition [W = 2.0, $p < 0.05$, eff size = 0.80, large]. These values for pairwise comparisons within dependent variables are similar due to strong correlation between radius and height dimensions for the approximate shape of the familiar objects: mug, espresso cup, and cereal bowl. With the Hololens visualization, 8 of 9 participants produced designs with both dimensions within the range identified independently by researchers. This can be compared with the desktop only condition, in which 1 of 9 participants produced designs with both dimensions inside the range.

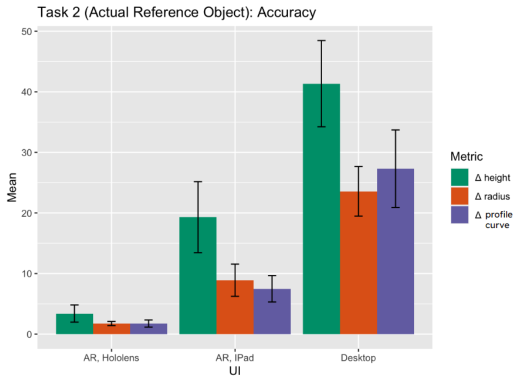

Figure 4: Task 2 Accuracy: Metrics for radius, height, and profile curve difference from the nearest edge of the specified range.

**Task 2.** In Task 2, accuracy was assessed by comparing the profile curve of the participant designs with that of the reference objects, sampled at the rate of the "layer height" parameter.

The ANOVAs revealed a statistically significant difference between at least two groups for radius ($F(2,16) = 14.87$, $p = 0.0002 < 0.05$), as well as height ($F(2,16) = 12.75$, $p = 0.0005 < 0.05$). Pairwise comparisons using the Wilcoxon test revealed that the design radius from the Hololens condition was significantly more accurate than the radius produced through only desktop visualisation [$W = 0$, $p = 0.012 < 0.05$, eff size = 0.88, large], and significantly more accurate between the Hololens and iPad conditions [$W = 0$, $p < 0.05$, eff size = 0.89, large]. Similarly, the height was significantly more accurate in the Hololens condition than with desktop only [$W = 0$, $p < 0.05$, eff size = 0.80, large], and significantly more accurate between the Hololens and iPad conditions [$W = 0$, $p < 0.05$, eff size = 0.89, large]. AR condition was identified as a main effect for profile curve ($F(1.19\ 9.56) = 13.12$, $p = 0.0004 < 0.05$), and followup pairwise t-tests identified a more accurate profile curve with the Hololens than with the iPad [$W = 1$, $p < 0.05$, eff size = 0.85, large], or Desktop [$W = 0$, $p < 0.05$, eff size = 0.89, large]. The Hololens condition showed significantly improved accuracy for shape and dimensions (height, radius) over both iPad and desktop conditions.

## 5 DISCUSSION AND FUTURE WORK

Overall, AR improved dimensional estimation abilities as demonstrated by decreased time to complete design tasks and improved accuracy of design dimensions. Specifically, the Hololens condition demonstrated statistically significant improvements over the desktop condition, with no significant difference between the two AR conditions or between the iPad and desktop conditions.

While we observed significant results for both time and accuracy between the Hololens and desktop conditions for dimensional estimation in task 1, this was not the case for replicating dimensions in task 2. Instead, accuracy was more significantly improved, and no significant effect on time was revealed. Previous work in this area has identified issues such as "eyeballing", or coarse measurements that reduces time and effort at the cost of accuracy [5]. Here, we see AR visualizations enabling a much improved estimation at a quick glance, while still minimizing time.

Hololens visualization helped users achieve design objectives significantly faster and with significantly improved accuracy of intended dimensions and shape. However, challenges remain in integrating AR seamlessly into fabrication workflows, suggesting opportunities for further refinement.

## ACKNOWLEDGMENTS

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