SculptAR: Direct Manipulations of Machine Toolpaths in Augmented Reality for 3D Clay Printing

Joyce Passananti*
joycepassananti@ucsb.edu
University of California, Santa Barbara
USA, Santa Barbara, CA

Ana María Cárdenas Gasca
acardenasgasca@ucsb.edu
University of California, Santa Barbara
USA, Santa Barbara, CA

Jennifer Jacobs
jmjacobs@ucsb.edu
University of California, Santa Barbara
USA, Santa Barbara, CA

Tobias Höllerer
holl@ucsb.edu
University of California, Santa Barbara
USA, Santa Barbara, CA

ABSTRACT

Specifying designs for additive manufacturing using machine toolpaths unlocks design attributes such as surface textures and shapes determined by material and machine constrains compared to higher level representations like 3D geometries. Current methodologies for authoring these designs necessitate a high level of programming or geometric understanding, posing a significant barrier to entry and limited control. Additionally, the confinement of these workflows within computer screens obscures the comprehension of material and dimensional constraints. To bridge this gap, we demonstrate the direct manipulation of machine toolpaths in Augmented Reality for clay 3D printing. Our application relies on hand interactions to edit path control points. We also provide a set of options that allow the user to control how their changes to one control points are broadcast to others to determine surface shapes and textures. By leveraging AR interactions in a physical context, our proposal aims to leverage existing physical workflows and enable practitioners to apply their understanding of material properties and visual understanding of physical 3D objects.

CCS CONCEPTS

• **Human-centered computing**; • **Interactive systems and tools**; • **Augmented Reality**;

KEYWORDS

Digital Fabrication, Direct Manipulation, Augmented Reality, Computer-Aided Machining, Clay 3D printing

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1 INTRODUCTION

Current research has sought to exploit direct manipulation interactions in 3D immersive environments to improve 3D modeling approaches, more commonly supported by desktop applications that visualize 3D models in screen displays. Researchers have explored multiple forms of 3D input modalities in immersive environments like 3D sketching [1, 2, 13] and hand gestures [5, 10] to leverage traditional manual dexterity skills such as 2D sketching to improve 3D modeling [13] and also to improve conventional approaches to 3D modeling in desktop environments by interacting with virtual 3D models similarly to real objects [8].

In parallel to these explorations in 3D modeling, virtual models have become an important component in creative production disciplines like industrial design, architecture, fashion, and sculpture, amongst many others. They are particularly important since digital fabrication has closed the gap between what can be imagined and modeled virtually in 3D and what can be precisely manufactured. This close relation necessitates equal progress in systems supporting the expressive and accessible design of form, aesthetics, and functionality. Artists and researchers have sought to push the boundaries of what is enabled by traditional 3D modeling and computer-aided design (CAD) by building custom fabrication workflows for 3D printers [3, 6] or computer-controlled drawing machines [9]. For example, Tim Ingold's model of morphogenesis [4] has inspired work that enables clay 3D printing workflows to better leverage the material properties by directly interacting with the machine toolpaths [3].

These approaches that seek to expand the creative possibilities of virtual representations of manufacturable objects remain contained on a 2D screen which creates a divide between the material, the fabrication space, and the designer or craftsperson. We see an opportunity in the intersection of expressive opportunities of custom manufacturing workflows that leverage toolpath control and the design in a 3D dimensional context where the physical hand dexterity of professionals and their awareness of 3D forms is relevant.

We draw from research which has showcased that Augmented Reality (AR) can be leveraged in contexts of digital fabrication to better integrate with existing objects [7, 11, 12] and in workflows of interactive fabrication [7]. We differentiate our work in that we seek to integrate these approaches to improve 3d manufacturing by leveraging immersive technologies such as AR with the expressive

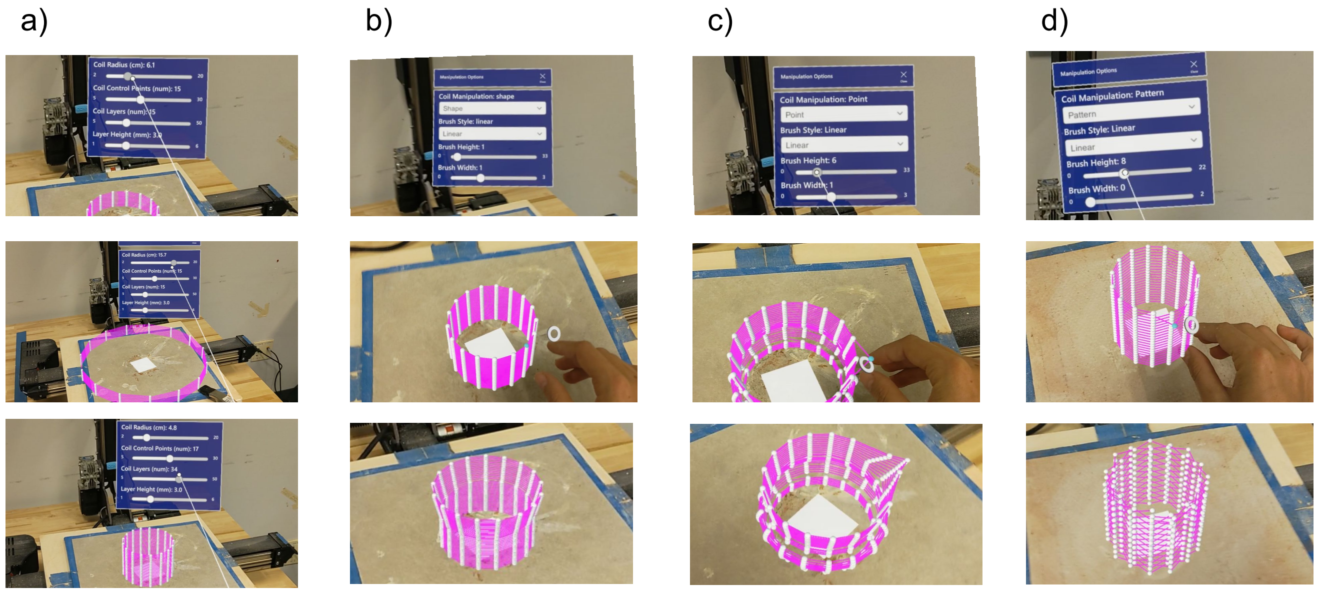

Figure 1: The Hololens interface for SculptAR, where the user can specify manipulation parameters and visualize their toolpath in AR. a) Toolpath controls parameterize the initial cylinder. b) Manipulations of type "shape" operation, linearly distributed across control points with varying brush heights. c) Manipulations of type "point" operation, linearly distributed to nearby control points with varying brush height and width. d) Manipulations of type "pattern" operation, this alternates the linear distribution

potential that the control of machine toolpaths offers. We also seek to create a balance between approaches like directly specifying the machine toolpath through hand gestures [7] and creating parametric designs that don't require any manual input [3]. We demonstrate the possibilities of this intersection by investigating a particular field of digital fabrication: Clay 3D printing.

We present SculptAR, an AR system for direct manipulation of toolpaths in 3D. The visualized path represents the machine path that will be followed by an extruder to print the clay piece. With SculptAR we seek to support fabrication workflows where clay artists can previsualize and dimension their vessel in the fabrication context and manipulate the shape textures and forms created by these toolpaths in an immersive 3D context. By visualizing the machine toolpath directly, we allow clay artists to leverage their unique knowledge and experience of the material to design structurally sound vessels by accurately visualizing overhang and layerheight. We envision this being a valuable affordance for designing to the limits of the machine capabilities and supporting a new level of collaboration between artist and machine. This work describes our system design and demonstrates its use to create a 3D-printed vessel.

2 AR DIRECT MANIPULATION SYSTEM

We developed ScupltAR, an application that enables direct manipulation of a machine toolpath in AR though a set of control points. We explored two AR modalities: head mounted display (HMD) and hand-held AR for different affordances. We developed two versions of our application: 1) a Unity version for the Hololens 2, and 2) a Rhino + Grasshopper version streamed to the iPad over Fologram.

Both the HMD and iPad versions of SculptAR support the editing of a machine toolpath illustrated with a coil and controlled through control points distributed along the coil. In the iPad version, the toolpath is generated by a Grasshopper Python Script through these control points to create Rhino Geometry objects that are streamed to an AR device. The 3D modeling software integration with AR environments is performed with the aid of Fologram, a library that supports bi-directional synchronization of geometry. On the HMD there is no integration with Rhino, and all the operations are executed through the HMD.

The tool supports the end-to-end fabrication of clay vessels with pre-visualization of real design dimensionality. The immersive AR setting allows users to design within the context of machine constraints such as printer bed size and orientation. Users can select an origin position to place their model, edit the coil, and export their model into Gcode, which can be executed by a clay 3D printing machine.

2.1 User interface

ScupltAR was designed for simple, intuitive hand interactions by clay artists, and thus relies on a minimal interface. The user is first presented with a base cylinder described by control points. Toolpath parameters for this base cylinder are set before any hand manipulations and parameterize the initial radius, number of layers, layer height, and number of points in layers. By editing these

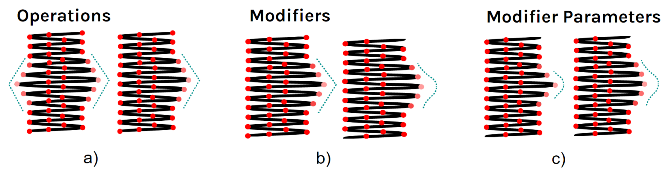

Figure 2: The set of manipulation options for control point editing. The vertices shown in each illustration represents a direct manipulation of a control points from it's original position in line with the cylinder shape to a new position. a) The two operation modes: shape and point. b) The distribution function for broadcasting the operation manipulation to surrounding control points. c) The parameters for controlling the size of the distribution as specified by the modifier function and operation manipulation

controls, users can specify the base geometry size and shape they wish to work with, as shown in Figure 1-a.

The HMD interface supports these options through a hand menu attached to the wrist, that can be accessed at any time. The user can select either "toolpath parameters" or "manipulation parameters" to open the appropriate panel. The iPad version supports these options in a side menu that is synchronized through Fologram with Grasshopper. Both interfaces use sliders to control parameter values, updating changes to the coil in real time as the user makes changes. The user is presented with a separate set of options for customizing each manipulation, as described in detail below.

2.2 Coil editing interactions

Our application supports coil editing through a simple workflow with three main stages. First, the user selects the operation they'd like to perform as Figure 2-a show: 1) a symmetrical shape operation or 2) a single control point manipulation. Next, they choose the modifier function as shown by Figure 2-b which specifies how the operation will be applied to surrounding key points: 1) linear or 2) polynomial, where they can further select the polynomial modifier as either squared or square root. Lastly Figure 2-c shows the parameters the user can control for operation distribution size to determine brush height for symmetrical shape operations and brush height and width for point operations. These enable the user a high level of precision over each manipulation, and through combination support a wide set of design decisions that mimic affordances in the physical space. Note these selections and parameters can be changed in any order, at any time throughout the editing process.

When a control points is grabbed, the initial position of that point is tracked and the displacement to the new release position is calculated. This displacement is then modified by the specified function as it's distributed to nearby control points, as shown in Figure 1 b), c), and d) for the shape, point, and pattern operations, respectively.

The interactions are supported differently through the HMD and iPad versions. The fully immersive environment of the HMD allows users to point or hover over their desired control point, see the selected point highlighted, and pinch to grab and move the point. The mobile AR trades the benefits of full immersion for precision, allowing users to tap on a control point viewed on their screen and move it in 3D space before releasing. We are interested in further evaluating the benefits of these two methods.

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