ClayArtisanX: Bridging Craftsmanship and Digital Fabrication in Ceramic 3D Printing

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Abstract. The advancement of extrusion-based clay 3D printing has sparked a wave of artistic exploration in ceramics. Emerging techniques and tools have empowered designers to evolve beyond creators, taking on roles as innovators in material science, manufacturing processes, and human-machine collaboration. However, mainstream slicing software primarily caters to engineering and manufacturing needs, restricting designers' creative freedom with its rigid layer-by-layer slicing approach. This study examines the role of designers in clay 3D printing and introduces a novel design tool that seamlessly integrates craftsmanship with digital fabrication. By conducting expert user interviews, the study identifies key challenges faced by practitioners and develops a comprehensive design-to-manufacturing workflow. This workflow is implemented via a digital plugin for modeling, slicing, and G-code generation, providing designers with a flexible and efficient solution to bridge the gap between traditional craftsmanship and digital fabrication.

Keywords: Digital Fabrication; 3D printing; clay; Design tools

1 Introduction

Computer-aided design and digital fabrication have profoundly transformed creative methods and expanded the design possibilities for artists and designers [1]. The concept of digital craftsmanship can be traced back to McCullough's seminal work, *Abstracting Craft* (1998), which proposed studying digital design practices as a form of craftsmanship. As computational and fabrication technologies have advanced, the definition of digital craftsmanship has continually evolved [2]. The term "Digital" introduces innovative computational and fabrication techniques, while "Crafting," as a practice rooted in handmade production, embodies materials, culture, and traditional design methodologies [3–5].

In the realm of clay 3D printing, which uniquely blends craftsmanship with digital fabrication, many practitioners aim to bridge the gap by integrating traditional craftsmanship techniques with digital manufacturing technologies [6]. The Belgian design studio pioneered clay 3D printing in 2009 by adapting a desktop FDM printer to develop the first-generation clay extruder [7]. In collaboration with UK artist Jonathan Keep, an open-source community for clay 3D printers was established and maintained. This initiative supported artists and designers in constructing their 3D printers while fostering the sharing of ideas and creations within the community. Examples of clay 3D printing works and printers are shown in Figure 1.

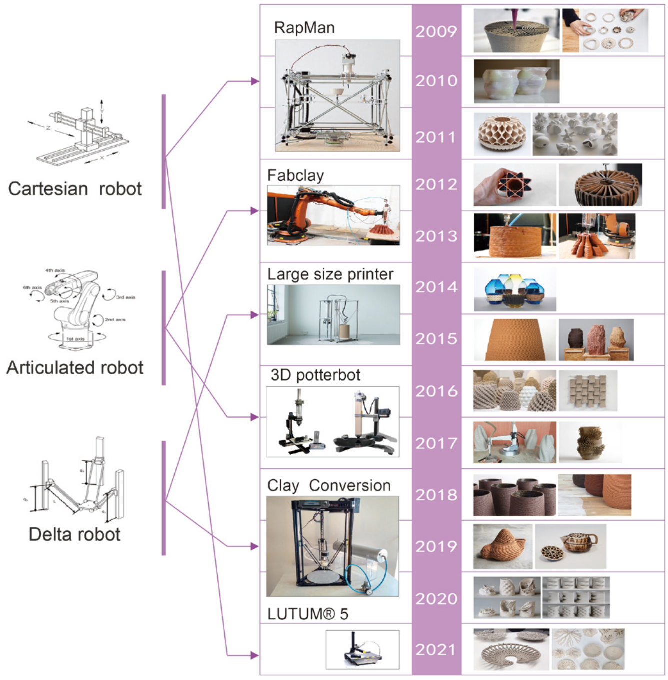

Fig. 1. Artistic works created by using clay 3D printing.

However, despite the availability of fully open-source equipment, clay 3D printing continues to face numerous challenges and uncertainties, which significantly dampens enthusiasm for creative exploration. Designers, in particular, grapple with dual challenges in both engineering and design (Figure 2).

(1) Material Challenges: Clay materials, characterized by their larger particle sizes, offer lower 3D printing precision compared to other materials such as plastics and metals, often resulting in visible layer marks [8]. Additionally, as a natural material, clay possesses high moisture content and significant rheological properties, which can lead to deformation and collapse during the printing process, resulting in frequent failures. Furthermore, clay undergoes substantial shrinkage due to its high moisture content. The solid-phase content of clay used in 3D printing typically ranges from 42% to 49% by volume, with shrinkage reaching up to 20% during drying and sintering [9]. The inherent anisotropy of the layer-by-layer 3D printing process further exacerbates issues such as cracking and warping. Addressing these challenges necessitates a comprehensive consideration of design, manufacturing, and material factors to minimize deformation, collapse, cracking, and warping in clay 3D printing.

(2) Design Challenges: Designers frequently spend significant time exploring the capabilities and limitations of materials and manufacturing platforms, which hinders efficient design iteration and optimization. Most existing modeling and slicing software is not specifically tailored for clay materials, making it challenging for designers to achieve successful prints on clay 3D printers using parameters typically optimized for traditional materials like plastics and metals [10]. This lack of specialized software severely impacts the creative design process, limiting the full potential of clay 3D printing.

To tackle these equipment and material challenges, researchers have increasingly focused on solutions from both design and software perspectives. A critical area of exploration is understanding the role of designers in clay 3D printing and developing design tools that enable a seamless integration of traditional craftsmanship with modern manufacturing techniques [11–12].

Through expert user experiments, this study identifies the key challenges faced by clay 3D printing practitioners and introduces an integrated design-to-manufacturing workflow implemented via a digital plugin for modeling, slicing, and G-code generation. This tool offers designers a more flexible and efficient solution, effectively bridging the gap between traditional craftsmanship and digital fabrication.

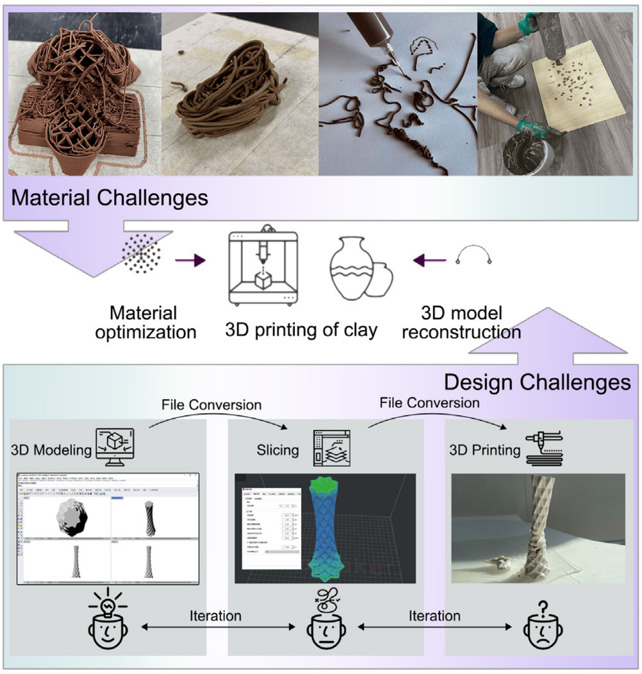

Fig. 2. Material and design challenges in 3D printing of clay.

2 Materials and Methods

2.1 Clay Preparation

This section investigates the printability of traditional clay materials for 3D printing. The consistency of clay was first evaluated by measuring the extrusion force required to extrude the same volume of five common clay types: China clay, Ball clay, Fine stoneware, Coarse stoneware, and Red clay. This was done at a uniform rate through a narrow nozzle under consistent conditions. Next, the effects of varying air compressor pressures on extrusion speed were analyzed for different nozzle diameters. These experiments established baseline parameters, including clay consistency, water content, extrusion force, air pressure, and nozzle diameter, to facilitate smooth and reliable extrusion. Based on the findings, the slicing data in the digital plugin was optimized to align printing parameters with the material properties of the clay, significantly improving print success rates. This process is illustrated in Figure 3.

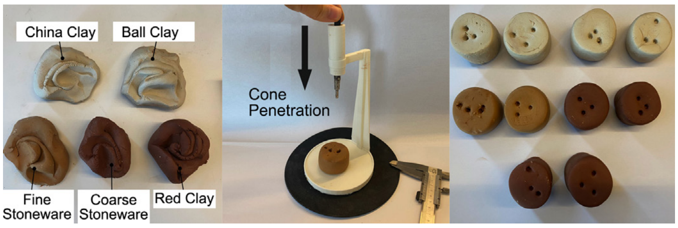

Fig. 3. Consistency measurement of five types of clay.

2.2 ClayArtisanX: Digital Plugin Development

For the most common XYZ-type 3D printers, the typical workflow begins with the designer creating a 3D model, which is then exported in STL file format to third-party slicing software. The software slices the model and generates a G-code that the 3D printer can interpret. Finally, the G-code is imported into the 3D printer to initiate the printing process. As illustrated in Figure 2, the file undergoes two key conversions: first, the model file is transformed into a slicing-compatible format, and second, it is converted into machine-readable G-code. Each stage, including modeling, slicing, and printing, often requires iterative adjustments due to discrepancies between the design and the printed result, which arise from indirect interactions and complex operations. This entire workflow reflects the transition from design to manufacturing, where each conversion and iteration step can introduce deviations from the intended outcome.

To address these issues, this paper proposes a workflow that enables direct control over G-code generation within the modeling software, as shown in Figure 4. By customizing the Grasshopper plugin within Rhino, the model file is converted directly into machine-readable printing paths, facilitating seamless integration between design and manufacturing. This visual programming-driven approach introduces a novel method of digital craftsmanship, integrating material properties, geometric shapes, and digital fabrication. The proposed workflow not only enhances design flexibility but also establishes a more intuitive and direct connection between the design and production processes.

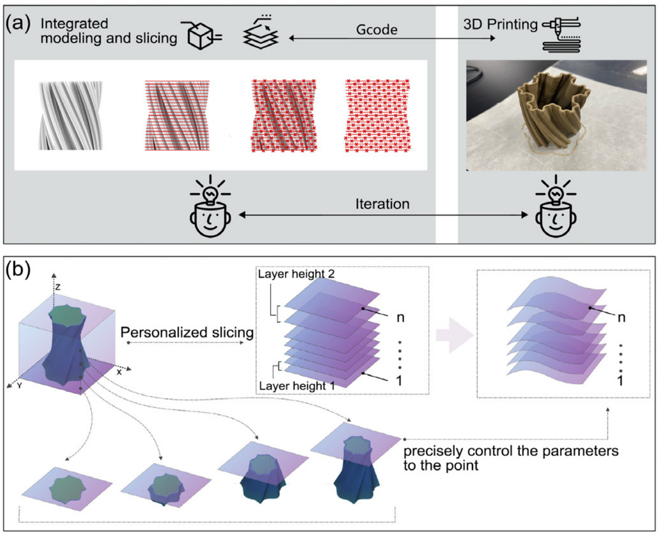

Fig. 4. (a) ClayArtisanX workflow; (b) Special slice illustration.

2.3 Printing Platform

Printing tests were carried out by using a clay 3D printer with a traditional XYZ structure, utilizing Liquid Deposition Modeling (LDM) technology. The material storage system applied continuous pressure to a suspended clay tank via an air pump. The extrusion system featured a wear-resistant screw rod that ensured stable and controllable extrusion, allowing for the continuous extrusion of up to 2 kg of clay in a single session. The printer supported a build volume of 300 × 300 × 400 mm. The equipment setup is illustrated in Figure 5.

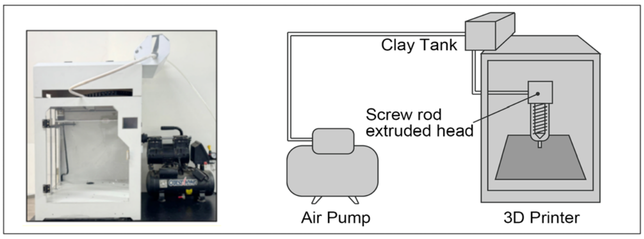

Fig. 5. Clay 3D printer setup.

3 Experiments & Results

3.1 User Experiments

Using a personas-based approach [13], this study categorizes users by integrating their professional backgrounds, needs, and preferences into distinct persona characteristics. This approach establishes a unified framework for understanding user roles, facilitating more focused and effective participant interviews.

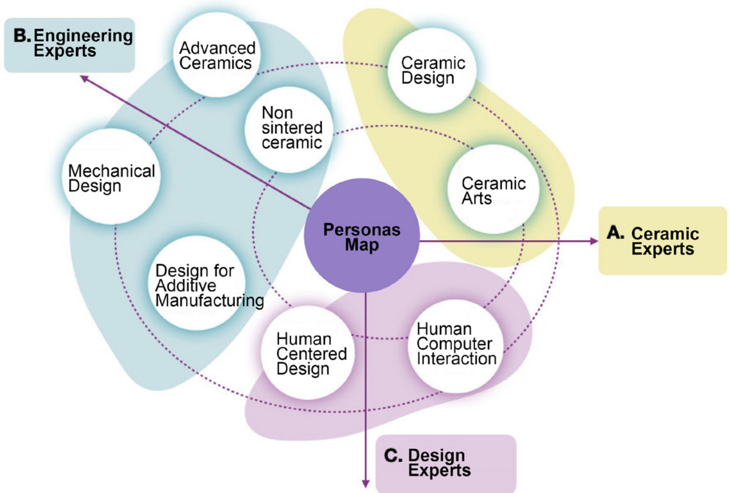

Fig. 6. Personas map.

Eight expert users participated in this experiment, with their professional fields represented by the text within the white circles in Figure 6. Based on their backgrounds, the users were classified into three main categories:

Persona A: Ceramic experts with an interest in new technologies, aiming to explore the artistic potential of ceramic materials.

Persona B: Engineering experts experienced in 3D printing, with a focus on researching 3D printer control systems and key forming technologies.

Persona C: Design experts with an interest in human-computer interaction, aiming to investigate the integration of humans, machines, and materials in digital craftsmanship.

Based on these three personas, clay 3D printing tests were conducted, and case analyses were performed on selected representative works. The user experiment setup included a computer with the ClayArtisanX plugin installed and a 3D printer. Multiple cameras were positioned at various angles to capture the experimental process. The setup is depicted in Figure 7.

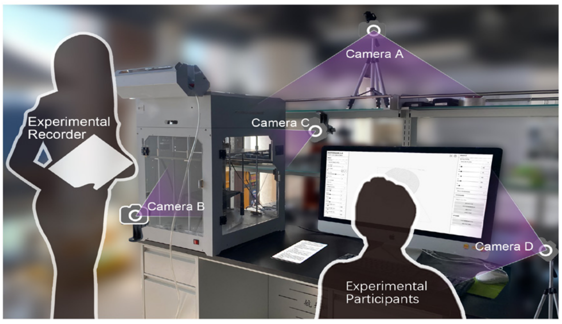

Fig. 7. User experiment setup.

3.2 3D printed works and design analysis

The collection of works is presented in Figure 8 (a). Following the three user personas, eight participants conducted clay 3D printing tests using the ClayArtisanX plugin. An overview of their printed works is displayed, with one representative work selected from each persona for detailed case analysis.

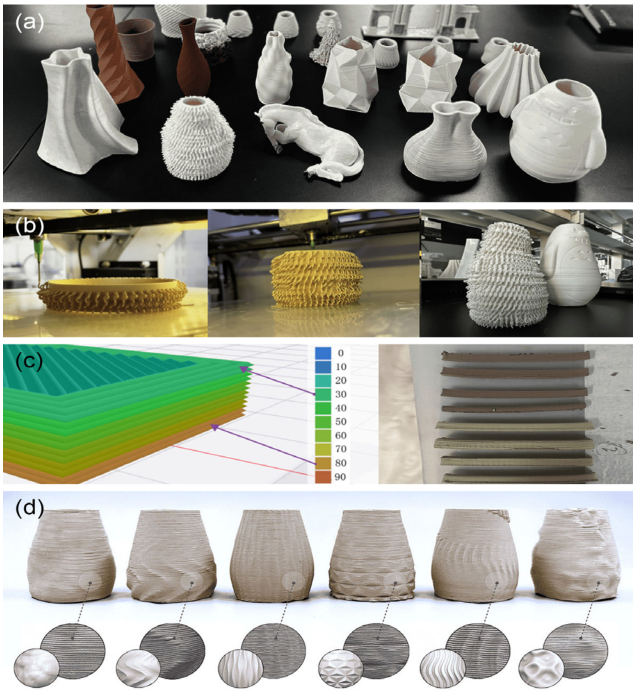

Fig. 8. (a) Overview of clay 3D printed works; (b) Special printing path planning; (c) Functional gradient design; (d) Parametric generation of various surface textures.

(1) Persona A: Ceramic Experts

The participant began by downloading an open-source 3D model from the internet, printing it with clay, and firing it to create a ceramic object. However, the smooth surface failed to effectively capture the essence of the original design. To address this issue, the author utilized the ClayArtisanX plugin to create a customized printing path that highlights the digital craftsmanship unique to clay 3D printing. By designing a distinctive slicing path, a layered, curled surface was achieved, as shown in Figure 8 (b). This specialized path allowed for a natural drooping effect during printing, resulting in intricate surface details and a "fuzzy" texture that enhanced the realism and dimensionality of the piece.

(2) Persona B: Engineering Experts

A significant challenge in clay 3D printing is edge curling and warping, primarily caused by anisotropic shrinkage during the ceramic sintering process, which makes the edges susceptible to deformation or even cracking [14]. To mitigate this issue, adjustments were made to the printing parameters of the flat base layer, including speed, layer height, and ventilation, to minimize deformation during sintering and reduce edge warping, as illustrated in Figure 8 (c). Through multiple rounds of testing, it was determined that a clay mixture containing 28% water, combined with optimized printing speeds, significantly reduced base layer warping. During the slicing process, the base layer was divided into 12 layers with a layer height of 0.6 mm. The ClayArtisanX plugin was utilized to fine-tune printing parameters within the G-code generation component, enabling advanced slicing settings.

(3) Persona C: Design Experts

Focusing on the surface texture characteristics of clay digital craftsmanship, the ClayArtisanX plugin was utilized to apply various surface textures to the same model, exploring new possibilities for digital expression in clay. A printing test was conducted with the clay 3D printer configured as follows: a nozzle diameter of 0.8 mm, a layer height of 0.6 mm, an extrusion width of 1.0 mm, and a printing speed of 40 mm/s. The clay material used was white kaolin clay with a water content of 28%, and the air compressor pressure was set to 6 bar. The resulting print is shown in Figure 8 (d).

4 Discussions and Limitations

Observations and case analyses of the practical works highlight certain limitations, as they primarily remain at the forming stage with minimal post-processing. This underscores the significant potential and opportunities for advancing digital craftsmanship in clay. For designers working with digital tools, the greatest challenge lies in leveraging technology to craft a unique visual language without being constrained by algorithmic limitations [15]. While isotropic clay materials were used in the tests and prints conducted in this study, clay 3D printing has the potential to produce structures with anisotropic characteristics or varying functional gradients by carefully controlling deposition parameters. Tools that enable structured parameter control across different regions to achieve multifunctional structures are particularly valuable for researchers. Although the ClayArtisanX plugin developed in this study addresses both manufacturing and design, future work should emphasize the customization of material properties to further enhance its applicability.

5 Conclusion

This open-ended exploration validates the usability and practicality of the proposed design tools while offering a fresh perspective on personalized customization in clay 3D printing. As additive manufacturing technology continues to advance, the variety of printable clay types is expected to increase, presenting both new opportunities and challenges for the evolution of digital clay craftsmanship. With the growing range of printable clay, compatible glazes and decorative techniques may emerge, expanding the possibilities for post-processing 3D printed works. Looking ahead, digital clay craftsmanship has the potential to evolve into digital ceramic craftsmanship, enabling the creation of even more remarkable and accessible 3D-printed pieces for the public. Future design practices should explore innovative post-processing methods and techniques to fully realize the creative potential of digital clay craftsmanship.

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