ARTISTA: Redefining Pottery Design with Virtual Reality and Physically Simulated Clay

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Abstract: Virtual Reality (VR) applications have gained significant popularity in various fields, including design and manufacturing. This paper introduces a novel VR application that simulates a 3D clay printer. The application utilizes the Oculus Quest 2 Head Mounted Display (HMD), enabling users to create virtual pots by manoeuvring a virtual extruder that extrudes and deposits strands of clay in layers. Two features define this application: incorporating a virtual coiling technique, offering guided assistance throughout the pottery prototyping process, and integrating physical simulation that provides users with real-time feedback on the final results achievable using a real 3D clay printer. Users can now design and iterate virtually without physically printing, reducing material waste and improving the overall creative process. Moreover, this application saves the information necessary to create the designed pottery piece with a 3D clay printer. We present a preliminary version that enables artisans in VR to craft unique, handmade virtual pottery pieces, fostering creativity and enabling the exploration of many design possibilities.

1 INTRODUCTION

Additive manufacturing, colloquially known as 3D printing, has revolutionized product design, prototyping, and manufacturing processes across diverse industries (Camacho et al., 2018; Rayna and Striukova, 2016). With its capacity for innovative approaches to intricate geometries, customized products, and eco-friendly manufacturing (Camacho et al., 2018), 3D printing technology has become a driving force in modern production. Among the array of materials employed in 3D printing, clay has emerged as a captivating medium, combining artistic expression with functional design due to its inherent malleability and ecological appeal (Ming et al., 2022; Perrot et al., 2018). However, while 3D printing has opened up new horizons in creativity, the tools traditionally used for modeling 3D objects, such as Computer-Aided Design (CAD) or 3D modeling software, often present a steep learning curve (Balan et al., 2019), making them less accessible to less experienced users, such as artisans accustomed to shaping pots by hand. The intricate interfaces and complex commands may inhibit the transition from traditional craftsmanship to digital design. Integrating Virtual Reality (VR) technology into the design process can effectively address the need for a more user-friendly approach. VR provides an immersive and intuitive interface that eliminates the complexities often associated with traditional CAD or 3D modeling software. VR empowers users to interact with virtual creations using natural gestures and movements made possible through intuitive controllers. Implementing this ancient clay processing method could be useful for providing artisans with a more accessible and compelling tool for crafting intricate 3D models and making this processing methodology known to a wider audience.

This paper introduces ARTISTA, a VR application that simulates a 3D clay printer. Utilizing the Oculus Quest 2 HMD and its controllers, ARTISTA enables artisans to seamlessly transition from shaping clay by hand to crafting virtual pots in an immersive environment. By providing a natural and intuitive interface, ARTISTA empowers artisans to explore new de-

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sign possibilities and express their creativity without the steep learning curve associated with traditional 3D modeling software. Moreover, the key feature of ARTISTA is incorporating physically simulated clay strands, delivering real-time feedback on the virtual clay's behavior as it would manifest in the tangible world. This unique attribute allows artisans to design and iterate virtually, predicting the final results that could be achieved using a real 3D clay printer. Through this iterative process, artisans can refine their designs, optimize production, and minimize material waste, offering a cost-effective and sustainable approach to the creative process. Furthermore, the final virtual pottery design created in ARTISTA can be seamlessly translated into a printable format, allowing artisans to bring their virtual creations into the physical world through a real 3D clay printer. This integration of the virtual and physical realms offers a holistic and efficient solution for artisans to easily explore, refine, and ultimately craft their unique pottery pieces.

2 RELATED WORK

The application of VR technology in manufacturing processes has seen significant advancements, with researchers exploring its potential in virtual design and prototyping. Additionally, integrating physical simulation within VR environments has opened new routes for enhancing realism and user interaction. Furthermore, VR has emerged as a powerful tool for additive manufacturing, empowering users with novel ways to optimize design workflows. Moreover, VR has been recognized as a user-friendly solution for non-experts in CAD, particularly for artisans seeking to transition from traditional craftsmanship to digital design. This section provides an overview of the related work in these diverse areas.

2.1 VR for Virtual Design and Prototyping in Manufacturing

The modern demand to speed up product development while reducing associated costs has driven manufacturing companies to explore innovative technologies. Among these technologies, VR has emerged as a transformative tool in the realm of manufacturing applications as it plays a significant role in designing new products, specifically in two key applications: design and prototyping. For design purposes, the Massachusetts Institute of Technology (MIT) developed a virtual workshop for mechanical design. The project aimed to create a simulated workshop that enables designers to engage in conceptual design work while considering manufacturing processes. This virtual workshop includes tools such as a band saw, drill press, milling machine, radial arm saw, and table saw (Mujber et al., 2004). In the context of prototyping, the University of Illinois, Chicago, and Purdue University collaborated to design and implement a VR-based CAD system. This work aimed to offer a simplified method for designing complex mechanical parts by utilising VR techniques (Mujber et al., 2004). These studies underscore the vast potential of VR as an intuitive and immersive platform for exploring and refining designs, offering a more or less realistic metaphor of the real task. By immersing users within a VE that mirrors the real environment, VR accelerates product development and contributes to cost reduction through more informed decision-making.

2.2 Physical Simulation in VR

In recent years, scientists have been leading in introducing physical simulation within VR environments, revolutionizing how users interact and engage with virtual worlds. The paper (Song et al., 2008) focused on merging physics-based simulation with mixed-reality gaming experiences. This study emphasizes the fusion of precise finger tracking and physics-based models to create lifelike hand interactions within mixed reality contexts. By integrating physics simulation, users can interact more intuitively with virtual objects, fostering an environment of engagement and immersion. Another example of VR with physical simulation is the NeuroTouch research project of the National Research Council of Canada, which extends the realm of physical simulation into medical education, specifically in neurosurgery. This project introduces physics-based simulations of tissue and blood properties and behaviors, offering trainees a platform to practice intricate surgical procedures (Bernardo, 2017). The emphasis here is on enhancing surgical proficiency through accurate simulation. Further expanding the spectrum, (Höll et al., 2018) introduces an innovative approach to enhance hand-object interactions within VR. Using the Coulomb friction model, the authors efficiently implement convincing interactions, from pushing to dexterous manipulations.

2.3 VR for Additive Manufacturing

VR has been harnessed as a transformative tool within Additive Manufacturing (AM), fostering innovative approaches to optimize design workflows, evaluate parts, and enhance education. In (Dashti et al., 2022), authors recently introduce a novel approach to Virtual Pottery modeling, integrating traditional techniques into a virtual experience. The process involves basic pottery creation on a VR wheel with haptic feedback, followed by free-form modeling using clay tools and mesh expansion. A unique sound texture is applied to identify and address errors in the model, preparing it for 3D printing in VP applications. In (Renner et al., 2015), the authors present a software application that immerses users in a VR environment to simulate the AM process. The application replicates machine movements and print attributes by parsing G-code files from CAM software. Visual relationships between print settings and physical movements are established through color-coded segments, aiding learning and error identification. Novice and expert users can modify settings in the VR environment before and after printing, reducing iteration time and costs for desired part quality. To prove the efficacy of VR in evaluating AM parts, (Ostrander et al., 2019) compared Immersive VR and Non-Immersive CAD. Designers assess parts of varying complexity, revealing that VR enhances evaluation speed but may exhibit limitations in identifying fine details compared to CAD. Despite these differences, VR stands out for its efficiency and usability in design evaluation. Another analysis (Ostrander et al., 2020) explores the pedagogical potential of interactive and passive VR for teaching AM concepts. The findings suggest that both modes of VR are effective in teaching introductory AM concepts, with interactive VR demonstrating a specific advantage in enhancing AM self-efficacy. Collectively, these contributions underscore VR's profound impact on AM. From process training to design evaluation and education, VR enriches the AM landscape by providing immersive and interactive platforms that accelerate learning, enhance decision-making, and transform how professionals engage with AM processes and concepts.

3 BACKGROUND

In this section, we will describe the technologies chosen for this project, with an introduction of the selected game engine, the VR device, and the toolkit employed to simulate the clay.

The application was developed with *Unity 3D*, a cross-platform game engine released by Unity Technologies that is widely used for developing 2D and 3D games, simulations, and interactive experiences. Unity is known for its intuitive and user-friendly interface and vast tools. It allows the use of C# scripting, enabling developers to create logic and behaviors in the game. Moreover, Unity provides a built-in physics engine that simulates realistic interactions between objects in the game world. To interact with the application in VR, we have chosen the Oculus Quest 2 which offers the Quest Link and Air Link functionalities, allowing users to utilize the device when connected to a PC via a USB cable or a stable WiFi Internet connection, thus leveraging the PC's GPU computing power. Furthermore, the Oculus Quest 2 features built-in tracking sensors with six Degrees of Freedom (6DoF) technology, translating the user's VR head and body movements without requiring external sensors (Capece et al., 2018). The Oculus Integration tool, available in the Unity Asset Store, is essential for developing content in Unity and provides significant support for using the advanced functionalities of this device. The clay consistency was simulated with *Clayxels* (Florian and Andrea,), a game toolkit available for download from the Unity Asset Store. Clayxels proved highly useful, as it facilitates the sculpting and animation of custom assets with volumetric primitives (*e.g.*, cubes, spheres, cylinders), both in the editor and during gameplay. Furthermore, Clayxels allows the user to "freeze" the created assets as standard Unity meshes and export them in FBX format for external use. Unfortunately, the Clayxels toolkit is not supported for mobile VR. It needs a powerful GPU to avoid rendering issues (*e.g.*, glitches) and manage the interactions between clays. We utilized the Quest Link functionality as a solution to address this challenge. Figure 1 depicts the scene view window of the Unity Editor with the 3D environment developed for ARTISTA, representing a pottery workshop. The development was done on a PC that mounts a 13th gen Intel i9 CPU, 32 GB DDR5 RAM and an NVIDIA GeForce RTX 4090 GPU.

Figure 1: A view of the scene created for ARTISTA. A table is visible at the bottom of the image, serving as the workspace for artisans to craft their pottery. In the center of the scene, virtual controllers and the user interface are positioned above the table.

4 METHODOLOGY

The proposed application ARTISTA is based on employing the features of VR technology to create an immersive environment where artisans can manufacture with a simple and natural interface(Erra et al., 2018), regardless of their experience in real-life manufacturing or 3D modeling. Indeed, ARTISTA allows artisans to create and simulate the 3D printing of the artifact: the process is completely driven by the artisan's hand, and the simulated clay physics provides visual feedback of the potential outcomes that could be replicated using a real 3D clay printer. In this section, we provide an overview of the key features of ARTISTA, including the selected technique for simulating the modeling process, the developments in clay physics, and the interface integration with the 3D clay printer.

4.1 The Coiling Technique as a Guide for Placing Clay

The initial challenge encountered was how to provide artisans, who approached virtual modeling for the first time, with a tool for designing the shape of the pot. Hence, to address this issue, we turned to an ancient technique that has been employed by various cultures throughout history to create pottery and ceramic objects: the *coiling technique* (Peterson and Peterson, 2003; Castro e Costa et al., 2017). Utilizing this method, artisans form these objects employing long ropes of clay as their fundamental building blocks. They meticulously mold ceramics by hand, layer upon layer, using these coiled clay ropes as the primary medium. In detail, to create a pot or ceramic object using the coiling technique, the artisan begins by rolling out long coils or ropes of clay by hand or by an extrusion machine (Peterson and Peterson, 2003). These coils are then stacked and joined together, one on top of the other, to build up the pot's walls, forming a cylindrical shape (Peterson and Peterson, 2003; Castro e Costa et al., 2017). Then, the coils are smoothed and blended to create a seamless surface, usually employing hands or proper utensils (Peterson and Peterson, 2003; Castro e Costa et al., 2017). After the object is constructed and dried to the desired state, it is typically fired in a kiln to harden the clay and transform it into a durable ceramic material. Therefore, this technique can be easily learned by novice artisans or those who may not have access to a potter's wheel. The images in Figure 2 are two visual examples that demonstrate this technique.

This technique was adapted for the application into a VR environment to serve as a guiding tool, assisting users in the pot's design. In particular, from a collection of geometric primitives (including torus, triangle, rectangle, pentagon, and hexagon), users can choose the shapes that define the layers of the pot. They have the flexibility to determine the quantity of primitives utilized and the ability to manipulate them. Indeed, users can rotate these primitives along the y axis and independently resize them along the x and z axes, enhancing the customization of their creations. Once users define the "skeleton" formed by layers, like in Figure 3, the application allows them to manipulate a virtual nozzle with the Oculus Quest HMD controllers after selecting their preferred hand. The virtual nozzle is used to extrude and deposit the strands of clay within the virtual scene, beginning from the first layer and progressing to the last, providing users with real-time feedback on the evolving form of the pot they are modeling. The strands of clay consist of Clayxels' *ClayObject* components, which are fundamental elements of this game toolkit and can

(a)

(b)

Figure 2: Two examples of handcrafted pots created using the coiling.

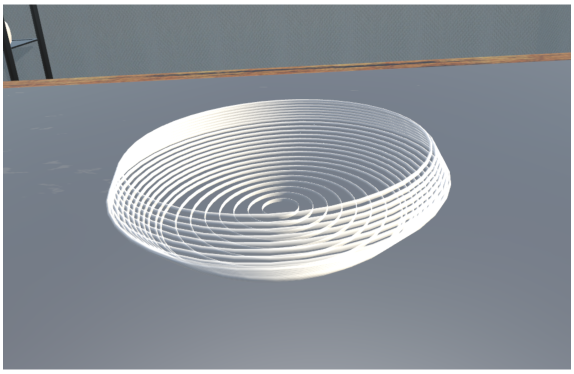
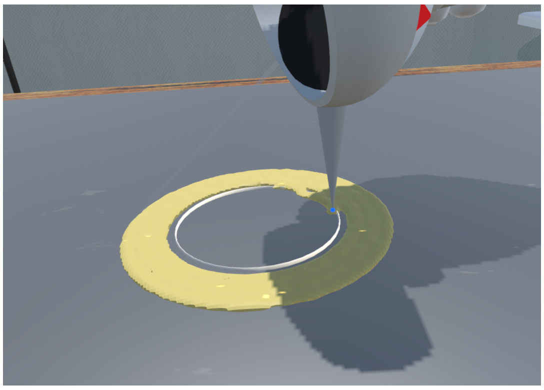


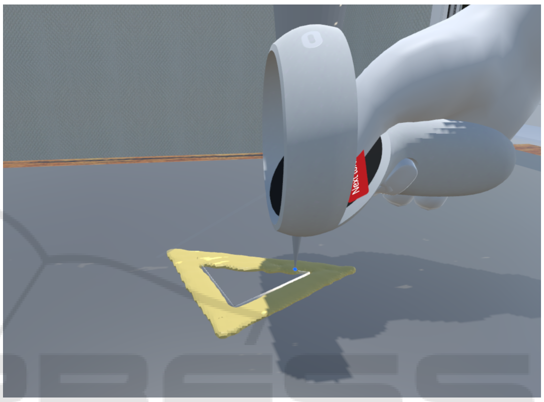
Figure 3: The image depicts a set of layers that will be employed as a "skeleton" to create a virtual pot. In such a case, concentric torus primitives were utilized to delineate the pot.

be blended. Users can deposit the clay following the shape of the primitive and can choose to switch to the next one if the expected result is achieved. Otherwise, if the achieved outcome does not meet their expectations, users can undo the depositions, switch to the previous primitives, and repeat the process. Indeed, throughout the deposition process, only the current layer is visible to the users until they decide to switch to the previous or the subsequent, which then will appear within the scene. The images presented in Figure 4 are two distinct instances of the deposition process utilizing two different primitives, torus and triangle, respectively.

After the strands of clay are deposited near the current primitive, the application can adjust their positioning, aligning them more closely with the shape of the primitive. Initially, the developed algorithm iterates through the ClayObjects in the current layer and adjusts their position's vertical (y) coordinate to match the current primitive. This means that the primitive and the ClayObjects are at the same height, and only the other coordinates require alignment. Subsequently, a collision evaluation is conducted using ray casting to determine interactions with the primitive. Generally, a ray is defined by an origin point O in space and a directional vector d. In this specific case, O represents the center of the primitive, and d is the distance between the origin and the position of the i^{th} ClayObject. When the rays hit the primitive, the ClayObjects are aligned to be exactly in contact with the surface of the primitive. This alignment involves overwriting the x and z coordinates of their positions with the relative coordinates of the hit point. In addition, it checks if the ClayObject's collider overlaps with other colliders. If an overlap occurs, it reduces the collider's size iteratively until there is no overlap. The usage of this capability depends on the users' choice to prioritize precision. After the current layer



(a)



(b)

Figure 4: Two instances of using the primitives as layers to form the pot. In Figure 4a, the clay is deposited following the perimeter of the torus primitive. In Figure 4b, the user creates a triangular-based pot employing triangle primitives.

is completed, they can opt to employ this feature, triggered by pressing a button on the controller.

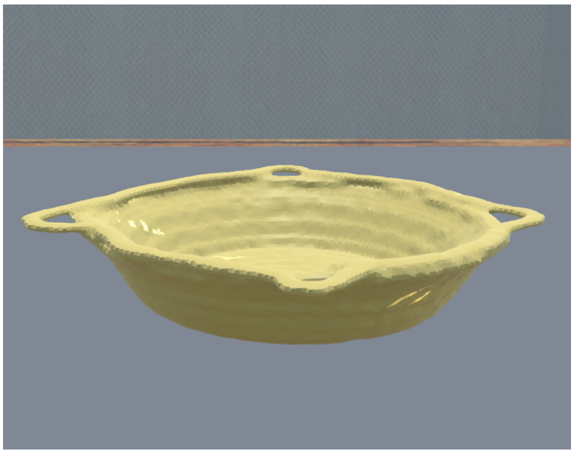
4.2 Clay Physics Simulation

The clay physics simulation was initially directed towards realising a custom physics engine. This decision resulted from the initial challenge when integrating Unity's default physics engine with the ClayObject components. Indeed, despite the inclusion of the fundamental components of the Unity physics engine, ClayObjects showed no response to run-time simulated forces, including gravity. The Clayxel documentation advises integrating these components in the *ClayContainer* object, which will affect the physical behavior of the ClayObjects as a single block. This approach was not adopted due to the expense of employing a separate ClayContainer for each ClayObject comprising the pot. This would result in a substantial increase in memory usage and a corresponding diminution in application performance. The custom physics engine was developed with C# scripts, implementing the component *PotClay*. This component envelops the individual ClayObject and manages its fall and collisions with other ClayObjects and assets in the scene. The PotClay imparts an initial velocity to the ClayObject, enabling its fall frame by frame until a collision occurs. In such instances, the initial velocity is reset to zero, which ceases the ClayObject's movement. By employing this approach, it was observed that the fall of the clay quite closely mirrored real-world behavior when deposited directly onto the table or previously laid clay layers. However, when users aimed to replicate specific pouring effects, such as depositing clay strands beyond the pot's edge and letting them cascade along the sides of the pot, it became evident that the behavior of the custom physics engine did not align with real-world physics. Indeed, to achieve a faithful simulation of clay physics, it was essential to establish interconnections between the ClayObject components, forming a linked chain of these elements. It became necessary to enhance the physical behavior of the ClayObject and impose constraints on the current ClayObject's position with the preceding one, particularly when the distance between them was minimal.

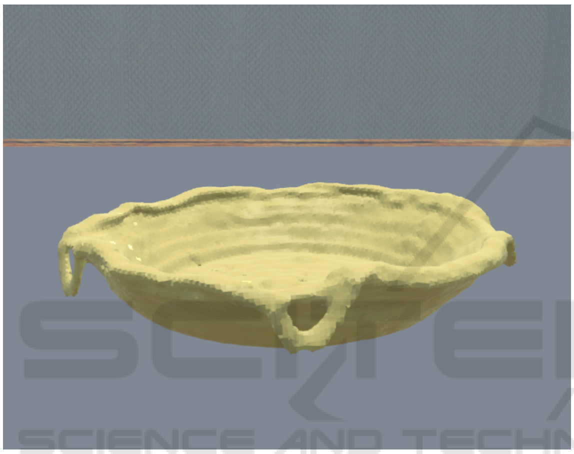
To accomplish this objective, we transformed the ClayObjects into rigid bodies and incorporated collider and joint components at run-time during their creation in the game. In physical terms, a rigid body (Featherstone, 2014) is an object that reacts to external forces without undergoing deformations. Utilizing this concept, we applied physical behaviors to ClayObjects, including gravity, movement, and collision, by assigning appropriate velocity, damping, and mass values to simulate clay material closely. A collider is responsible for determining collision interactions between objects by defining an invisible area around a specific object where collisions can occur. It is possible to define the behavior of colliders by setting properties such as static and dynamic friction and bounciness. In our case, a cuboid-shape collider was utilized to manage collisions between the ClayObjects. It was customized to regulate the balance between static and dynamic friction among the clay elements, mitigating undesired bounciness. The joint component (Featherstone, 2014) constrains the movement of a set of ClayObjects and was utilized to replicate the desired behavior for the strands of clay, as described above.

Consequently, adopting these components necessitated abandoning the physics engine explained above. Incorporating these components into the ClayObjects themselves during run-time revealed that the default physics engine, indeed interacts seamlessly with these components. In this context, two distinct types of joints were utilized. A fixed joint type was initially employed to establish connections between the ClayObjects. This component creates a fixed linkage with zero degrees of freedom between the interconnected objects. Indeed, they are prevented from experiencing relative rotations, although they can shift in sync when one is subjected to move. Throughout the development process, it became evident that utilizing this type of joint was inadequate for accurately reproducing the physics of the strands of clay. When these strands were deposited over the edges of the pot, they did not behave as anticipated; instead of falling naturally, they remained suspended in midair and oscillated as a pendulum. The fixed joint was substituted with a hinge joint type to ensure accurate replication of strand physics. In contrast to the first, the hinge joint allows a connection between two components capable of rotation along a shared axis. The inclusion of this joint to establish connections and create the chain of ClayObjects led to a notable enhancement in the physics simulation. This degree of freedom given by the relative rotation allows the clay strands to fall realistically when deposited over the edges of the pot. To enhance the application's usability, physics simulation is disabled by default when users deposit the clay strands. Users can activate the physics simulation by clicking on a button in the user interface. This feature simplifies the process of shaping the pot layer by layer, and users can evaluate the final result at their convenience. Additionally, users can deactivate the physics simulation and return to the previous shape of the pot if they wish to make alterations to it or continue the deposition of the clay strands. In this way, users have complete control over the creative phase of pot modeling and visualize a preview of the potential result. Figure 5 illustrates an example of this feature, showing the same pot with and without the physics simulation enabled.

Furthermore, this decision also enabled the identification and resolution of issues related to the bounciness of the ClayObject. In fact, despite its introduction to the collider, the ClayObjects initially displayed an undesired degree of elasticity when collisions enabled the physics. They rebounded in multiple directions, creating the impression of an exploding pot, which was not the intended behavior for clay strands. Even with the bounciness set to zero, a slight rebound effect remained between ClayObjects, giving back the perception of the pot expanding. This effect was caused by the default velocity of the colliding rigid bodies, which tended to induce bouncing if it was not null. To address this unexpected behavior, the C# script *ClayNoBounce* was introduced to



(a)



(b)

Figure 5: Two depictions of a virtual pot are shown. Figure 5a displays the pot without physics simulation, while Figure 5b, with active physics simulation, reveals clay deformations influenced by gravity and collisions, evident in the excess clay along the border due to gravity.

manipulate and eliminate it. This script controls the collisions between ClayObjects by setting their velocity to a zero vector, thereby preventing bouncing and the associated pot expansion effect.

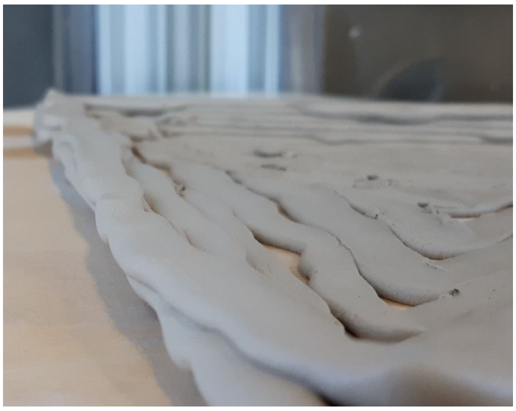
4.3 Virtual Pot 3D Printing

After users approve the pot and assess the physics-based clay preview, they can save the model for 3D printing. It's crucial to note that the generated pot model is not a basic 3D mesh with polygons. Furthermore, ARTISTA necessitates a direct interface with the 3D clay printer in the game environment without using external third-party software. Addressing these two challenges initially involved employing a C# script as a component of the ClayObjects upon their creation in the game. This script is responsible for storing crucial information related to the ClayObject, including its position coordinates, relative rotation, and deposition time, which is useful for computing the deposition velocity. This information is indispensable to the 3D printer as it generates the G-code, which outlines the steps required to reproduce the virtual pot in the real world physically. In this manner, the 3D clay printer replicates the deposition path followed by the user at identical velocity, faithfully tracing the virtual pot and reproducing it in the physical world. For instance, Figure 6 displays the initial 3D printed version of the pot modeled in Figure 4b. Figure 6a shows the pot overview, illustrating the extruder's alignment with user movements. Figure 6b provides a close-up of the pot's layered clay strands.

5 CONCLUSIONS

In this paper, we have introduced ARTISTA, a VR application that can enhance the creative process of pottery design. ARTISTA empowers artisans and designers by providing an immersive platform where they can craft unique virtual pottery pieces. The key innovation of ARTISTA lies in the integration of physically simulated clay strands, which offer real-time feedback on the virtual clay's behavior as it would manifest in the tangible world. This unique feature enables artisans to design, iterate, and refine their pottery virtually, predicting the final results that could be achieved using a real 3D clay printer. By doing so, ARTISTA can significantly reduce material waste and enhance the overall creative process, offering a cost-effective and sustainable approach to pottery design. Moreover, the seamless transition from virtual design to real-world 3D clay printing ensures that the artistry born in the virtual realm can be brought to life. Looking ahead, the future of ARTISTA holds exciting possibilities. One promising avenue involves conducting an in-depth empirical evaluation to assess how ARTISTA impacts artisans' and designers' creativity, skill development, and efficiency. Gathering user insights will enable us to refine and enhance the application's features and user experience. To further expand its utility, ARTISTA could incorporate dedicated educational modules. These modules would teach pottery techniques and the rich history and cultural significance of pottery. By doing so, ARTISTA can become a VR tool for beginners and experienced artisans, promoting learning and creativity. Furthermore, implementing collaborative features within ARTISTA would enable multiple users to share the same virtual pottery studio, encouraging teamwork, creative

(a)



(b)

Figure 6: Preliminary example of a clay pot produced using a 3D printer.

exchange, and the potential for artisans to collaborate on collaborative projects.

REFERENCES

Balan, L., Yuen, T., and Mehrtash, M. (2019). Problem-based learning strategy for cad software using free-choice and open-ended group projects. *Procedia Manufacturing*, 32:339–347.

Bernardo, A. (2017). Virtual reality and simulation in neurosurgical training. *World neurosurgery*, 106:1015–1029.

Camacho, D. D., Clayton, P., O'Brien, W. J., Seepersad, C., Juenger, M., Ferron, R., and Salamone, S. (2018). Applications of additive manufacturing in the construction industry–a forward-looking review. *Automation in construction*, 89:110–119.

Capece, N., Erra, U., and Romaniello, G. (2018). A low-cost full body tracking system in virtual reality based on microsoft kinect. In De Paolis, L. T. and Bourdot, P., editors, *Augmented Reality, Virtual Reality, and Computer Graphics*, pages 623–635, Cham. Springer International Publishing.

Castro e Costa, E., Duarte, J. P., and Bártolo, P. (2017). A review of additive manufacturing for ceramic production. *Rapid Prototyping Journal*, 23(5):954–963.

Dashti, S., Prakash, E., Navarro-Newball, A. A., Hussain, F., and Carroll, F. (2022). Potteryvr: Virtual reality pottery. *Vis. Comput.*, 38(12):4035–4055.

Erra, U., Malandrino, D., and Pepe, L. (2018). A methodological evaluation of natural user interfaces for immersive 3d graph explorations. *Journal of Visual Languages & Computing*, 44:13–27.

Featherstone, R. (2014). *Rigid Body Dynamics Algorithms*. Springer US.

Florian, H. and Andrea, I. Clayxels. Online available at: https://www.clayxels.com/.

Höll, M., Oberweger, M., Arth, C., and Lepetit, V. (2018). Efficient physics-based implementation for realistic hand-object interaction in virtual reality. In *2018 IEEE conference on virtual reality and 3D user interfaces (VR)*, pages 175–182. IEEE.

Ming, C., Mirjan, A., Medina Ibáñez, J., Gramazio, F., and Kohler, M. (2022). Impact printing. *3D Printing and Additive Manufacturing*, 9(3):203–211.

Mujber, T. S., Szecsi, T., and Hashmi, M. S. (2004). Virtual reality applications in manufacturing process simulation. *Journal of materials processing technology*, 155:1834–1838.

Ostrander, J. K., Ryan, L., Dhengre, S., McComb, C., Simpson, T. W., and Meisel, N. A. (2019). A comparative study of virtual reality and computer-aided design to evaluate parts for additive manufacturing. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 59186, page V02AT03A029. American Society of Mechanical Engineers.

Ostrander, J. K., Tucker, C. S., Simpson, T. W., and Meisel, N. A. (2020). Evaluating the use of virtual reality to teach introductory concepts of additive manufacturing. *Journal of Mechanical Design*, 142(5):051702.

Perrot, A., Rangeard, D., and Courteille, E. (2018). 3d printing of earth-based materials: Processing aspects. *Construction and Building Materials*, 172:670–676.

Peterson, S. and Peterson, J. (2003). *The Craft and Art of Clay: A Complete Potter's Handbook*. Laurence King.

Rayna, T. and Striukova, L. (2016). From rapid prototyping to home fabrication: How 3d printing is changing business model innovation. *Technological Forecasting and Social Change*, 102:214–224.

Renner, A., Holub, J., Sridhar, S., Evans, G., and Winer, E. (2015). A virtual reality application for additive manufacturing process training. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 57045, page V01AT02A033. American Society of Mechanical Engineers.

Song, P., Yu, H., and Winkler, S. (2008). Vision-based 3d finger interactions for mixed reality games with physics simulation. In *Proceedings of the 7th ACM SIGGRAPH international conference on virtual-reality continuum and its applications in industry*, pages 1–6.