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Bridging the Gap: Exploring a Design-via-Making Approach in Architecture through Digital Guidance Systems

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Abstract

This research explores the concept of the *Albertian split* (Carpo, 2011) (Cardoso Llach, 2015) in architecture, emphasizing the divide between design and construction and its impact on creativity. The study proposes a design-via-making approach, using digital technology to bridge the gap without traditional drawings. Two case study projects are presented, investigating the development of a guiding system prototype. The methods section details the prototype's development, highlighting the use of immersive display systems for a richer guiding system providing real-time comparison between design and execution. It explores color-coded geometry overlay and real-time geometry scanning interfaces. The deployment process is then illustrated in the design and fabrication of pottery pieces with both the traditional sequenced approach and the integrated design-make process. Results showcase a detailed comparison between physical and virtual designs, evaluating the guiding system's effectiveness. The discussion acknowledges system limitations and emphasizes the importance of design values during making, advocating for synchronized design and construction processes. The research aims to contribute to a paradigm shift in architectural design, fostering collaboration between designers and makers through innovative digital tools.

Introduction

The Experience as an Architect of Record and the Motivation of the Thesis

Prior to this thesis and my graduate school journey at Carnegie Mellon, I was working as a technical designer at an Architect of Record office focusing on construction documentation and construction administration. It is from the daily interaction with both fellow designers and architects and the construction crew that gave me the understand of how design intents are translated to drawing then to physical buildings. At the juncture between the design team and the execution team, the role of designers and builders began to converge and the boundary blurred. It is the first time my drawings are interpreted by non-architects for the purpose of not to only understand my design, but to translate that into construction materials and techniques that realize the notations on drawing to physical reality.

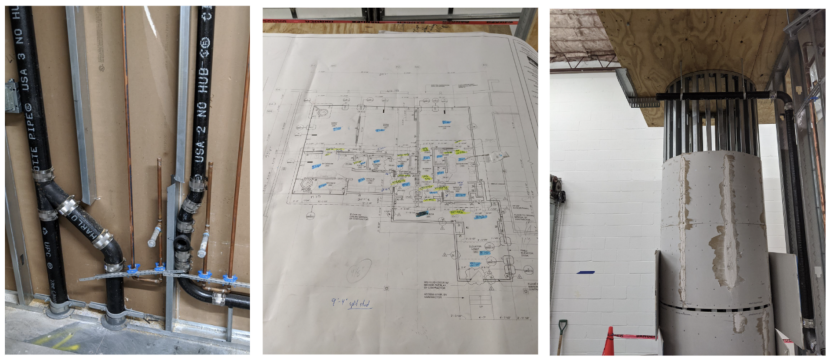


Figure 1: Observation at construction sites, credit to author.

As seen from the photos above, this process is not always smooth and reinterpretations are made by builders. There are sometimes mistakes that caused by the conflict of material and design intent, like plumbers cut away the studs for piping. Although most of the time I will see improvised construction methods that deviated from the drawing but still get the jobs done, like bending flat gypsum

boards as column wrapper instead of ordering customer curved boards.

The architect of record are well aware of these on-site improvisations so much so that there are deliberate omission of construction detail and techniques on the construction drawings usually denoted by a cloud with the comment of "Resolve on-site" or "Contractor to coordinate". These gestures represent passing the design agency to the contractors and builders on site by trusting their expertise in both understanding the design intent and the specific construction method that achieves it. Compared to letting the construction crew blindly follow drawings and cut holes of the revision cloud, a balanced relationship between the designer and builder on site has countlessly proven to be the optimum solution to architectural design and construction. It is the desire to understand, to appreciate, and to pursue this balanced relationship that motivated this thesis, which aims to conceptualize and clarify a balance relationship between designer and builders in the decision-making process of the art, architecture, engineering and construction industries.

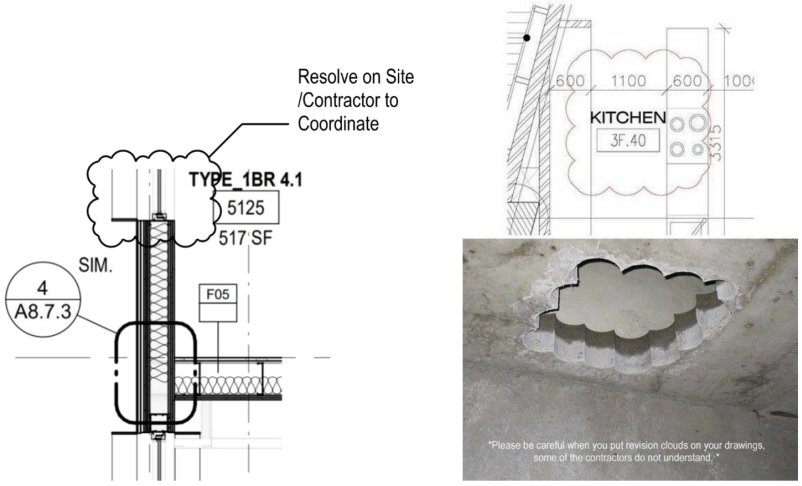


Figure 2: Construction Documentation and the execution. Left: Architects delegate the detail to contractors, credit to author. Right: Construction failure meme, credit to (Hurley, n.d.)

How to Read this Thesis - An Outline

The above introduction is simply my personal reflection and occasional sparks that accumulated throughout my early school and career experience. The thesis will follow a much more rigid structure and academic approach starting with the background chapter. In which the thesis will identify the gap in the existing literature and practice that this research aims to address. The background chapter will explain and exposit the historical development and the existing efforts around the relationship between not only architects and builders, but between designers and makers in general. This chapter will discuss key concepts and terminology relevant to design agency, the split between form and matter, concept and reality, ensuring that readers have a foundational understanding of the subject matter. This part will clearly state the purpose and objectives of this thesis study, explaining why it is important and how it contributes to advancing knowledge or practice in the field of design.

Besides the theoretical argument, two case study projects: InnixAR (Adriaenssens & Al Asali, n.d.) (Oval et al., 2024), an arch construction with augmented-reality guided brick layering, and Computational Clay (Obuchi Lab, 2017) (Lopez, 2016), a digitally-guided construction exercise to build a pavilion with custom-molded clay panels, will be introduced and analyzed. They are presented to inquire about the possibility of mitigating this relationship and facilitate a design-via-making approach using digital technology without the use of drawings. Digital technology like smart devices and mixed-reality headset will be introduced together with an elaboration of the implication and relevance of these technology development.

To inquire about a balanced relationship between designer and maker, this thesis hypothesizes a new guiding system with the aid of digital display technology to display relevant design information to replace conventional drawings that mainly use notation and abstract two-dimensional representation of three-dimensional designs. This thesis will develop this digital guiding system to aid not the fabrication and construction industry in general, but to focus on a specific trade of craft: pottery throwing. The relevance of this craft in the contemporary design, art and architecture industry and its significance in representing the relationship between designer and maker will be argued in detail in the Methods chapter. Furthermore, the Method chapter will also provide detailed scope of theorizing, developing, and assessing the guiding system.

The next part of the thesis will document the deployment and results. The results section starts with a detailed comparison among the

physical fabricated object, the virtual original design, and the virtual updated design. It then evaluates the effectiveness of the guiding system by two main criteria: How effective the guiding system is in helping the maker achieve the original design intent? How effective is the guiding system in capturing the maker's improvisation and deliberate deviation from the original design? More importantly, detailed documentation of the improvement of the guiding system will be presented and diagramed. Before drawing any conclusions of the system, it is more important to present the documentation of the refinement process of the guiding system in tandem with the making of the installation.

Last but no the least, The discussion section highlights the limitations of the guiding system and issues during the deployment process. It highlights the significance of design values during the making process and promotes a synchronized development of design and making. Tying back to the hypothesis, this section reinforces the importance of a synchronized relationship between design and construction, particularly focusing on enabling the development of design methodology. It concludes with potential future works and a broad environ of the art, architecture and design industry.

Background

An Architectural Designer's Reflection

As an architectural designer first stepping into the industry, the materiality and physical manifestation of architectural design has been deeply fascinating to me. It is always a different feeling to witness the buildings in person compared to studying the drawings and representations from textbooks. I could not resist the temptation to touch and feel the materiality on site, and as an architect of record, it is even more exciting to witness the construction process. Naturally, during the design process, I draw a significant amount of inspiration from precedents that draw that reference this crafting process. Renzo Piano, an architect who pays particular attention to craft and the fabrication of buildings, integrates the idea of craft and expresses such elements explicitly in the office's design. The Tjibaou Cultural Center (Langdon, 2015), one of RPBW's early works, drew inspiration from the traditional Kanak architecture and building techniques. However, a closer examination of the building details reveals that despite the resemblance in form of local traditional crafting practices, the building is constructed with modern construction techniques with bolts and nuts. In essence, the form of the building still follows a contemporary design and construction process where each construction detail is meticulously designed before being executed on site. Such a relationship between design and construction has been constantly developing and deviating from the traditional architecture practice where the architect also plays a crucial role in the physical construction process on site.



Figure 3: Craft-driven design based on forms. Credit to Langdon (2015)

The Status Quo: A Gap between Design and Construction

As Alberti wrote in Momus, Momus argues that thinking and action should be kept apart. This "Albertian split" has been widely recognized and debated in architecture (Carpo, 2011) (Cardoso Llach, 2015), and it has become increasingly evident in the contemporary architecture, engineering, and construction (AEC) industry. Under such influence, designers, who distinguish themselves from the traditional role of master builders, distance themselves from material execution and privilege the mental over the material. This distance, or gap, could be best reflected in the way of communication and expression of the architects' design intent. Drawings, a set of mutually agreed sets of notations, act as the communication medium between designers and makers. The information entailed in these drawings has also shifted from referential and suggestive to prescribed and instructional. The communication is usually strictly uni-directional where the makers are the audience who are supposed to understand the design intent and translate graphical drawings to physical actions. In fact, to further widen the gap between and execution, not all makers read the drawings, they merely execute specific tasks from the command of contractors and sub-contractors. As a result, the construction crew, who has always been a group of dexterous craftspeople, gradually lost their decision-making power and became mere assemblers who followed the instructions.



Figure 4: Change of roles of the construction crew. Up: the "master builder", credit to Cardoso Llach (2015), Down: the assembler, credit to IKEA (2020)

When the agency of design, control, and decision-making shifted away from builders and makers, their independent judgment on site could be considered as deviation from the original design and designers are in constant pursuit to fine grain their drawings and specification as detailed as possible to achieve a level of total design.

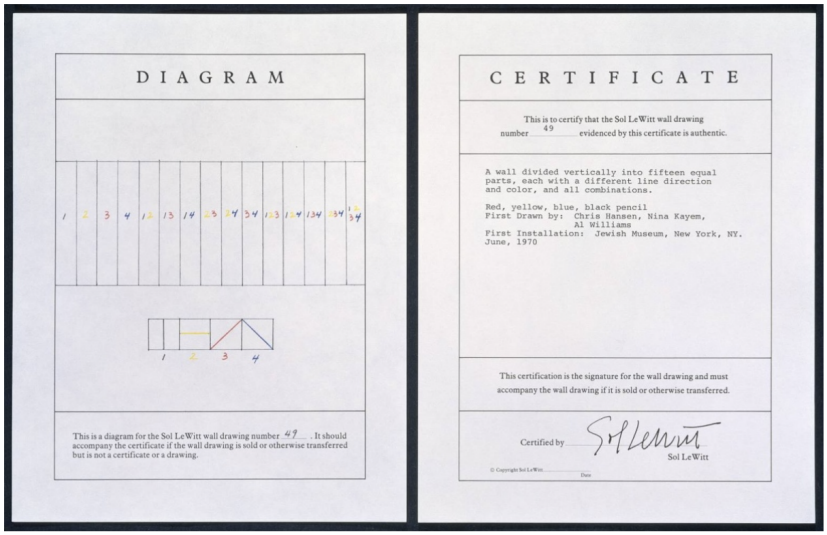


Figure 5: Sol LeWitt concept instructions as the legitimate form of art over art itself. Credit to DOM PATRUNO (2016)

This relationship, prevalent in wider fine art practices, is best summarized by artist Sol LeWitt, the founder of conceptual art, in his essay Paragraphs on Conceptual Art in 1967. LeWitt claimed,

> "When an artist uses a conceptual form of art, it means that all the planning and decisions are made beforehand, and the execution is a perfunctory affair." (Alberro & Stimson, 1999)

However, I would argue that the process of making and execution is not *perfunctory* nor straightforward. The technical trade and techniques processed by each agent in the execution phase have tremendous value that is being ignored with the dividing design and execution relationship. Furthermore, there is also the intangible aspect of craftsmanship, a unique understanding of the project during the making, which could become an essential factor influencing architectural design.

From another perspective, designers have to realize that even though there is zero-variation machinery that autonomously replicates digital design into physical buildings, the architects have to design every single construction detail to eliminate deviation. As a junior architectural designer who witnessed tens of thousands of pages of construction specifications of a single office tower, the sheer amount of design effort is simply impractical. We, as designers, have to accept the fact that, as argued by David Pye,

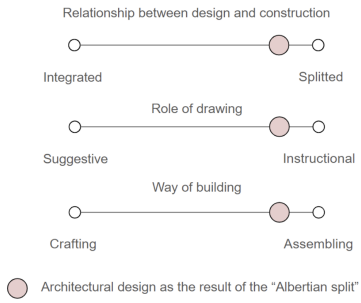


Figure 6: Diagram of the impact of the *Albertian split*, credit to author

> "Something can only be designed, or at any rate be designed in detail, by the workman himself." (Pye, 2008)

So instead of investing major effort in developing more autonomous construction robots, why couldn't we rethink the relationship between designers and makers, and the agency of design in architecture?

Design-via-making

There are various design approaches where designers could design via making. The design-via-making methodology has a long history in various art and design practices, and there has been extensive study on the design process. One example is by Knight (Knight & Stiny, 2015) (Knight, 2018), who studied Kolam, a traditional pattern-making practice in detail and theorized the concept of making grammar. Making grammar is defined as follows:

> "the computational theory of making based on the improvisational, perception, and action approach of shape grammars and the shape algebras that support them." (Knight, 2018)

This concept generates physically manufactured objects that are defined by a set of making rules. Her approach to analyzing crafting and decision-making events is based on *a (spatial and) temporal segmentation of motions into discrete, primitive actions* (Knight & Stiny, 2015).

The design and execution gap is mitigated and the two processes are synchronized in the context of Kolem practice. There is no doubt that Kolem practitioners are both designers and makers at the same time. If their decision-making process during the design-make process could be externalized and rationalized in a computational manner, it is worth inquiring how could such process be augmented by newer communication mediums powered by digital technology instead of paper and drawing on an application level. This thesis aims at investigating an explicit guiding system that provides the necessary means for a designer to design via making.



Figure 7: Traditional Kolam practice, credit to Knight (2018)

Furthermore, there is also the intangible aspect of craftsmanship, a unique understanding of the project during the making, which could become an essential factor influencing architectural design. There are academic efforts that brought these extraordinary skills and values in craftsmanship back to people's attention with the aid of computational design. Bard's research (Bard, 2014) on hand-craft skill transfer captures the physical and tangible movement of such activities. In his paper, workers' actions are recorded and captured for robotics training and digital fabrication. There is no denying that

with adequate training and modeling, machines could replicate, or even improve to accomplish the same action as a human. However, the embodied know-how or internal sense of understanding of the task, the design, and the controlled actions can hardly be captured by motion tracking.

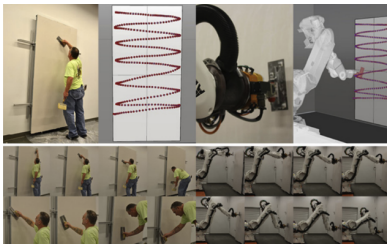


Figure 8: Skill transfer and capture, credit to Bard (2014)

Human-centered Guiding System in Construction

In order to facilitate the synchronized relationship between designer and maker, and letting the construction process better inform the design, we will need a more interactive communication medium compared to drawings. Luckily, this intent collides with the interest to utilize digital graphics to better guide the construction crew. InnixAR (Adriaenssens & Al Asali, n.d.) (Oval et al., 2024), a project developed by IE University and Princeton is an exemplary project that provides an alternative answer to paper drawings with the aid of an augmented-reality-powered guiding system for construction. A non-planar brick arch is considerably challenging to represent and specify using traditional two-dimensional projection on drawing. Instead of developing a complex placing system and commanding the workers to follow complex indexing, the construction process is facilitated by digitally marking the shape of the arch on a heads-on display calibrated by QR codes. More importantly, the guiding shape does not dictate the brick-laying pattern but remains as the design intent by showing only the UV mesh curves. By illustrating the design form at a schematic level, the worker has the autonomy to lay down the bricks to best align with the arch, and the agency of design is balanced between designers and workers.



Figure 9: The construction process of the InnixAR Project, credit to Oval et al. (2024).

A Initial Attempt towards Guiding System - A Pilot Study

The Chip-n-Dip project was an initial attempt to implement the guiding system using augmented reality as the communication medium. This project uses a digital guiding system to better facilitate the making process as an alternative to drawings as instructions. The design prompt was straightforward: using spontaneously painted transparent chips to create an installation that resembles a complex form.

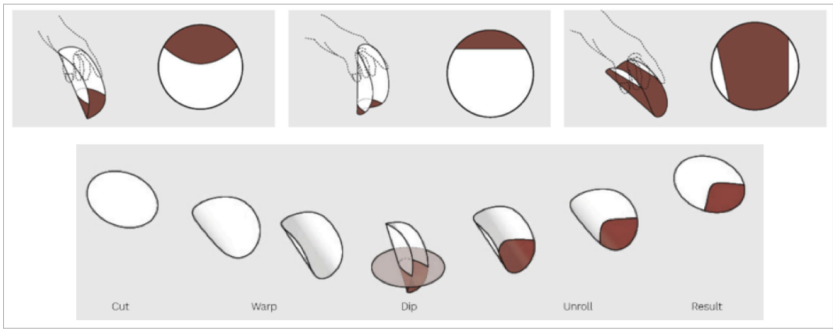


Figure 10: The dipping process, credit to author.

This project consists of two parts, the first one is to spontaneously handcraft each chip and let the computer determine the best location of each chip. The crucial aspect to investigate is how this guiding system could integrate a certain level of freeform and improvised artistic creation during the design-making process. Instead of predetermine the paint area and exact location of each chip, I improvised and hand-dipped each fragment in paint to achieve a level of randomness and unexpectedness. Each chip is then photographed, and its position on the final installation is then calculated. The algorithmic calculations provided me, the craftsperson, guidance on what type (crescent or full) of chip to produce. This information greatly improved the hand-dip crafting process because I would purposefully produce crescent shape paints around the neck and shoulder area, and full paint shapes around the face and head area.

The second part of the project is an AR-guided fabrication process after the calculation concludes. Each chip and its desired location is displayed virtually. This display also uses the camera to integrate the physical object on the same screen. The maker's job is to follow the AR guidance and place the chip in the required position. However, the guiding system took no consideration of the deviation from reality to the original planned form. Each chip is deformed and bent under gravity when more weight is added on. The guiding system, with no awareness of the difference between digital design and physical reality, could provide little informational guidance to the making

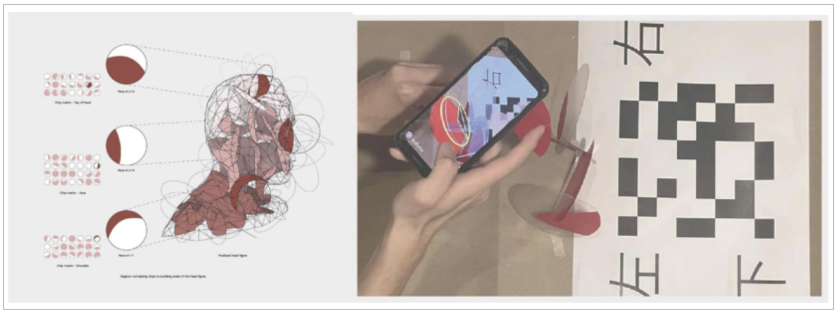


Figure 11: The calculation and guiding process, credit to author.

and became rather counter-productive for makers to follow. In the end, chips that are higher in position have to be manually decided and placed to achieve the intended form and physically support each other without falling. It is not to hard to conclude that the fabricated object failed to resemble the desired shape, and this proves that a successful craft-driven design does not simply guide, but requires adjustments from the makers.

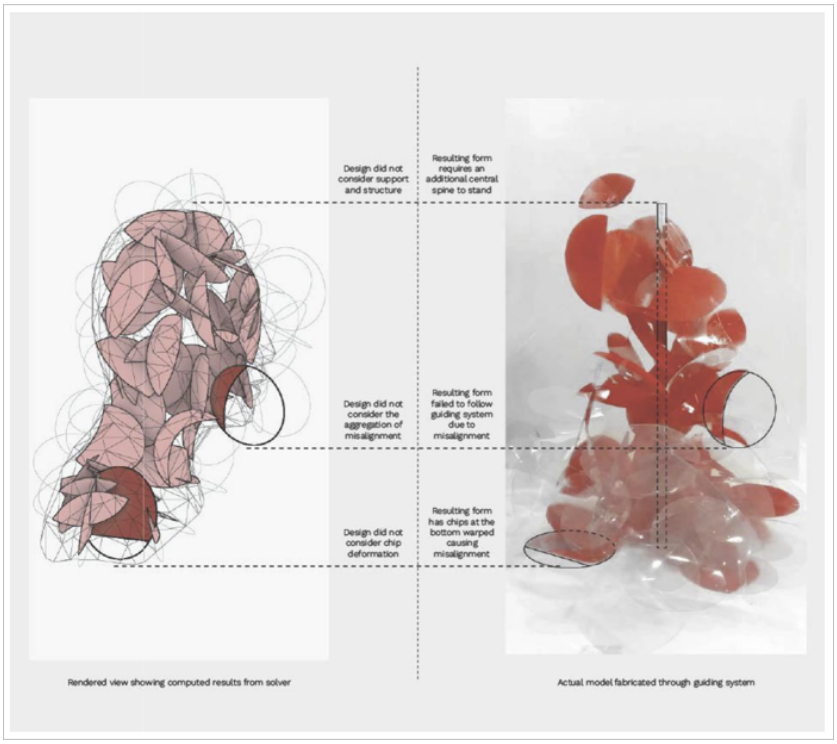


Figure 12: The comparison between digital and physical model, credit to author.

A More Synchronized Human-centered Guiding System as Precedent

The Computational Clay Pavilion done by the Obuchi Laboratory (Lopez, 2016) (Obuchi Lab, 2017) led by Prof. Yusuke Obuchi at the University of Tokyo is one contemporary project that empowers the skillful workforce behind the execution process to play a more meaningful role in influencing design decisions. The pavilion is an onsite fabricated structure with the intent to magnify the influence of makers in impacting design. In the beginning, the pavilion's form is designed and subdivided into individual pieces. What differentiates this project from other parametric designs is each panel is not pre-fabricated according to the design model. They are computer-guided, hand-crafted pieces whose form is determined by the maker and builder.

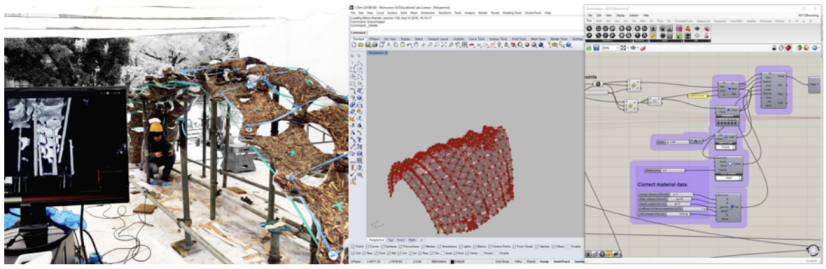


Figure 13: The Computational Clay Pavilion, credit to Obuchi Lab (2017).

During the fabrication process, there is no drawing telling nor tools measuring the exact bending angle. Instead, each panel is curved by hand-pressing under the guidance of a proximity sensor and color-coded projection. As expected, builders who are mainly students and researchers, would need extra effort to handle this new fabrication technique. They will make mistakes by putting too much or too little force on one panel, or by pressing the location inaccurately. Any of the above-mentioned issues could be a nightmare on modern construction sites, and these are the exact issues digital and robotic fabrication are trying to avoid. However, the pavilion design team took the opposite approach by fully embracing imperfections with the help of a computerized "master builder". The construction guiding and design optimizing agent is an inheritance from the traditional craftsperson system. After each panel is installed, the guiding system will capture and recalculate the pavilion shape based on the existing structure. It plays the role of both contractor and designer to train and guide its workers to best align with the original intent. With the new design in mind, the guiding system would not force-

fully dictate the construction process but just like an experienced craftsperson providing advice. The builders, on the other hand, have visual guidance projected on the panel if the position, direction, and force are incorrect. They will actively adjust their movements and technique in real-time and gain a better understanding of the task they were working on. This feedback loop eventually makes the workers the designer of the pavilion and the guiding system does not prescribe the design but simply optimizes and advises as a mentor. The Computational Clay illustrates a viable design-build system that bridges the gap between design and execution, and it also revives the lost charm and significance of craftsmanship.



Figure 14: The fabrication and crafting of Pavilion Panels under the guiding system, credit to Obuchi Lab (2017).



Figure 15: Scanning and recalculation of pavilion structure after panel installation, credit to Obuchi Lab (2017).

The Computational Clay pavilion, at first glance, is another example of parametric architectural design. However, it is inherently different since a parametric design would require a complicated and detailed set of instructions that maps every piece of prefabricated elements to its designated location. I would argue the pavilion is a craft-driven design that recognizes and responds to the maker's deviation from the original design during the fabrication process. More specifically, by monitoring and analyzing the existing status of the execution process, the design could adjust itself in real-time to reflect the maker's purposeful and site-specific decisions. The level of uncertainty and flexibility of hand-bending is crucial to the craft-driven design. Workers have no specific reference nor measurement, and they must develop a sense of craftsmanship, the ability to estimate and adjust based on tactile and visual feedback. Craft-driven design should not have hard-coded specifications, but a coexisting system

that involves the execution workforce.

Guiding System User Interface: an Introduction and the Decision to choose Mixed Reality

One of the most obvious limitations of the smartphone based guiding system from the previous section was that the maker gets interrupted during the making process when they are holding the phone for position guidance. Although the device is able to update the location of the next assembly piece in realtime, the maker cannot take advantage of this guiding system during the making process. This limitation challenge the thesis by adopting another medium of visualization which can free the hands yet provide location-aware guidance from the perspective of the maker.

Mixed Reality (MR) is a term that has less definitive meaning comparing to the other two more established concepts, namely augmented reality and virtual reality. Defined as a large spectrum of *Reality-Virtuality (RV) continuum* (Milgram et al., 1994), mixed reality encompasses all RV displays that have differences in form and medium. This thesis was seeking a prototype that aligns more towards augmented reality which only enhance and supplement the real world views with additional information. Microsoft HoloLens is a competent choice until the release of a series of immersive virtual headsets with powerful spatial computing capabilities like the Meta Quest 3 and the Apple VisionPro at the beginning of this thesis.

The HoloLens which projects virtual information on transparent glasses, which means the display falls closer towards reality on the RV continuum. However, the new wave of headsets are more categorized to *augmented virtuality (AV)* devices which are *head-mounted see-through and monitor-based video AR displays* (Milgram et al., 1994), due to the fact that the real world is observed via a reconstructed video stream from a set of outward facing cameras.

Although both AV and AR devices are capable of overlaying virtual geometry on top of real world environments, the main deciding criterion for choosing the guiding system medium is still affordability. One of the main considering factors of the guiding system is accessibility. By keeping the guiding system affordable, it ensures that individuals from diverse backgrounds can participate in different crafting activities without facing significant financial barriers.

Instead of relying on official development kits, a cheaper display system often encourages more open-source and broader forum of developers. A great example is the Meta Quest 3, which have accumu-

lated significant amount of professionals and enthusiasts to develop and pose tutorials which in turn encourages faster development cycle and more functionalities of the Meta MR developer kits.

From the arguments above, the ideal display system of the guiding system should provide an affordable mixed reality display that allows the maker to see both the virtual and real environment hands free. The detailed equipment and developing environment choices will be discussed in the Methods chapter.

Design and Craft in Ceramics and Pottery

With the prototype direction established, this thesis requires a specific type of craft and making form for deployment, testing, and analysis. This choice is pivotal as it will not only determine the practical application of the prototype but also significantly influence the depth and breadth of insights gleaned from the subsequent experimentation. Considering the myriad options available, it is prudent to delve into a craft that encapsulates both historical significance and contemporary relevance. Among the plethora of crafts, ceramics emerges as a compelling choice.

Ceramics is one of the oldest crafts. Since Prehistoric ages, the material and methods of ceramics and its making have evolved with advancements in technology and culture. The earliest form were primitive and improvised by hand-molding to make rudimentary shapes that serve the most fundamental purpose of containers. Each piece of pottery done in the most primitive fashion is unique, because it is a carefully balanced and improvised decision-making process that the artisan is responsible. From finding readily available materials to firing the pots with open-air flames, the artisans could only strategize and "design" in a generic manner with a open-mind. Previous pots could be referenced, but there will always be contingency and discoveries from making a new piece. The artisans or craftspersons are responsible for the entire process, and the making of each piece embodied the design process.

As civilizations developed, so did ceramic techniques and tools. Artisans refined their craft, mastering wheel-throwing, glazing, and firing methods. These advancements allowed for greater precision in shaping vessels and decorating them with intricate designs and motifs, showcasing both artistic expression and technical skill. At different stages of the evolution of clay-making, the mergence of supportive tools and machinery function is an important step the artisans took to sacrifice certain level of malleability and manual techniques in exchange of higher consistency and efficiency.

Pottery wheels is an excellent example of such tools that created lasting impact on ceramics crafting. Early pottery wheels were simple devices consisting of a rotating platform or turntable, often powered by hand or foot. The potter would shape the vessel by placing a lump of clay on the rotating wheel and then using their hands and tools to mold it into the desired form. The rotation of the wheel allowed for smoother and more uniform shaping, enabling potters to create vessels with greater symmetry and precision. Together with the pottery wheel comes the prefabricated template. These templates are used to produce the same design with higher consistency and standardization at the cost of personal touches when making each pot.

Similar to other trades of craft, the adoption of supportive tools, machinery and streamlined processes also meant labor specialization. Skilled artisans who were proficient in using these tools often took the controlling roles, while less skilled workers might be assigned to tasks that required less training or expertise. For instance, more skilled worker can design and create the template for less-skilled workers, taking the agency of design and separating the execution.

Methods - Towards Craft-driven Design

Hypothesis

As discussed in the previous chapter, a drawing-based design and construction lifecycle deprives the decision-making autonomy and on-site improvisation of the workforce which deviates the construction from the design. It is the interest of this thesis to study the effect of such spontaneous improvisation in depth via a custom-designed guiding system. This guiding system projects the design intent instead of enforcing it, and this guiding system guides construction instead of instructing and dictating the process. By deploying this system in designing and constructing a furniture scale installation, each step will be carefully documented and the maker's feedback analyzed. Through such a feedback loop, I am also aiming to adjust the guiding system's interface and methods of guiding.

My Hypothesis in this thesis is that compared to a traditional and split design and construction lifecycle, the new guiding and updating design process could encourage more *workmanship of risk* (Pye, 2008). Both the designer and maker could gain more situated knowledge of the design and the making of the design. Moreover, such design will be more diverse, slightly deviating from the original design intent but in a better on-site finished product.

Methods Overview

The Method chapter begins by introducing the subject of study for this thesis: pottery on wheel. It then emphasize on relevance of this craft in the contemporary design, art and architecture industry and its significance in representing the relationship between designer and maker. This chapter then outlines the process of reality capturing and the development of a guiding system for pottery making. In reality capturing, a digital copy of a pottery object is created over its formation using two capture cameras for plan and elevation views. The captured curves define the shape, and edge detection with Canny Edge Detection is employed. The guiding system involves an immersive display headset for makers, with translucent and color-coded mesh layers providing guidance on shaping the pottery. The color-coded mesh indicates correctness, areas needing compression, and areas requiring expansion. The guiding system's crucial aspect is consistent color coding, and it also explores hand-specific guidance through gestures and verbal instructions. The deployment of the guiding system extends beyond pottery making to complex ceramics installations, including architectural cladding, with an emphasis on spontaneous design and spatial variance. The process involves fabricating circular units and stacking them to form ceramic columns, introducing diversity through slight variations in each unit. The section concludes by indicating an on-site try-out for the guiding system development.

Pottery on Wheel: Subject of Study

The preceding discussion delineates the divergence between design and making in ceramics akin to many other trades like architectural construction and conceptual art. However, unlike other trades, pottery throwing practice does not end up as perfunctory in comparison to conceptualize a design. In fact, I would argue that pottery designs are "sculpted", it cannot separate itself from the making process. This denotes that an integrated craft-driven design method could benefit both the design and making process.

This claim is supported by the following reasons:

Firstly, ceramic art making requires distinctive skills that could not be displaced by mass-produced fabrication technology. In order to resemble the common understanding of pottery, the making process needs to follow a similar phased manufacturing process disregarding the extent of automation. As a result, these gaps necessitate the coordination of various production stages. As seen from the manufacturing processed above, despite the presence of complex molding, manual fine-tuning in the form of trimming is required before firing. The paining and texturing tasks at the end of the manufacturing process are also always performed by workers to give the pottery its esthetic touch. Here, the indispensable role of craft skills becomes apparent, acting as a bridge between each phase of the process. Craft skills offer the flexibility and adaptability required to adjust the original design intent as needed, thereby facilitating the creation of the most optimal solution as a hybrid of both design and making.

Secondly, despite advancements of autonomous fabrication techniques like 3D-printing, there are still limitations of computer-aided technology in achieving a seamless transition from digital design to finished physical artifact. Additive fabrication has managed to exclude all aspect of manual interference by translating the morphing action of clay-making to layering. The resulting pottery has completely different tectonics from conventional pottery.

Last but not least, pottery design has little awareness and control of materiality. The integration of craft skills into the design process fosters a deeper connection between the designer and the material, and this connection and the following hands-on exploration cannot be reflected at the design stage. This essentially deprived the design agency from designers who attempt to confine the form and exact dimension of their work. This prompt another perspective of craft-driven design which the design process only concludes when the final piece of clay is made. At this stage, the original design, digitally modeled or mentally envisioned, requires an update to con-

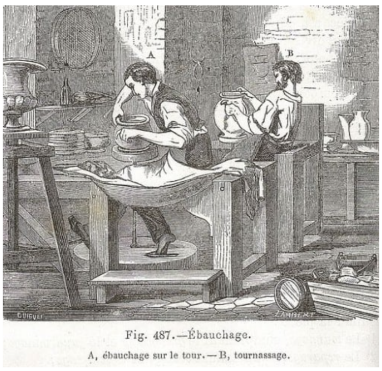


Figure 16: Pottery wheel in history, credit to Girard (1864).



Figure 17: Up: molding in mass-produced pottery process, down: custom trimming after mold removal, credit to Jahanbani (2018).

solidate with the final form. Digitally capturing the physical piece is an crucial aspect of the guiding system. Scanning the existing shape to produce a digital twin which will be discussing in the following chapters.

All of the above factors lead to the same conclusion that pottery makers and their craft skills are indispensable in perfecting the design and the resulting artifact. Pottery craftspersons across different staged of making still maintains the design agency with the autonomy of deviating from design. As a result, this thesis determines to select pottery throwing as the subject of study of craft-driven design and the next chapter will discuss the methods of augmenting the makers' skill and their decision-making impact by developing and deploying a guiding system for making.

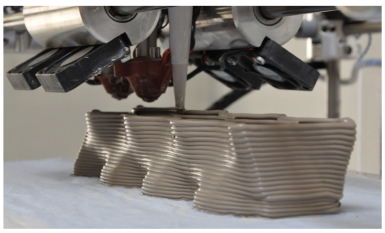


Figure 18: Pottery wheel in history, credit to Girard (1864).

Guiding System Setup: Reality Capture

For reality capturing, the goal is to grasp the volume of the real-life pottery object over the making of it. In other words, the unit would make a digital copy of the shape of the ceramics over time from a piece of clay to the final product. The setup consists of two capture cameras focusing on the object: one for plan and one for elevation. They are used to capture the plan view and side profile respectively. A three-dimentional virtual construction is obtained by lofting the side profile along the main vertical axis. The setup is diagrammed below.

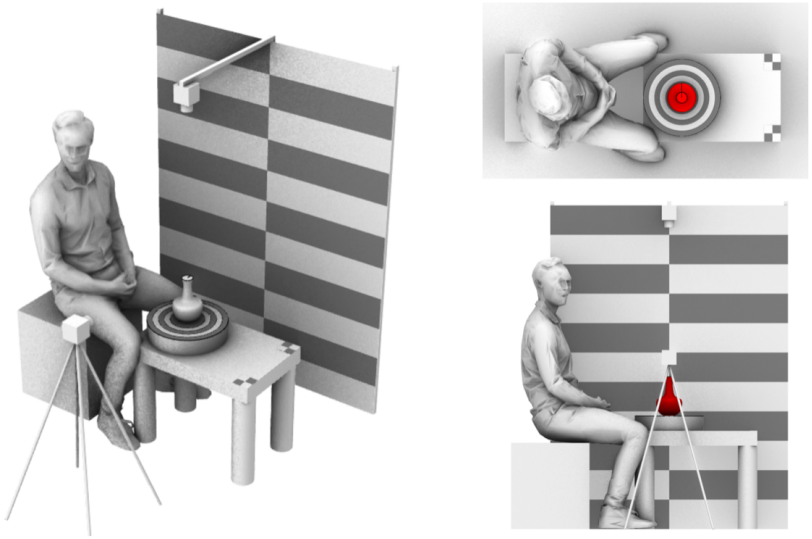


Figure 19: Setup diagram, credit to author.

In the setup, two cameras are not used to scan the entire shape but

just to capture the contour and profile as curve geometries so that the data communication between the camera and the AR device has minimal data transfer size. From the diagram below, we can see the curves that could define the shape of the vase in real life.



Figure 20: Capture diagram, credit to author.



Figure 21: Environment setup result, credit to author.

The capture process, uses Canny Edge Detection from openCV. Canny Edge Detection is one of the most widely used edge detection algorithms developed by John F. Canny in 1986. It works in four stages: Noise reduction, Finding the intensity gradient, Non-maximum suppression, and Hysteresis thresholding. (pawan_kumar_gunjan & simmytarika5, 2023) The captured curve is translated to Scalable Vector Graphics format and stored on the server for further processing.

Guiding System Architecture: Frontend and Backend

The headset communicates with the camera setup via network shown by the diagram below. The curve data connected by the camera setup is composed as a geometry file and uploaded to a server. The headset quarries the curve from the server and reconstruct the physical shape by lofting. This virtual representation of reality could then be used as the base object for comparison to the intended design.

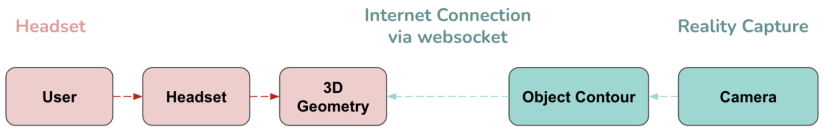


Figure 22: Data transfer pipeline, credit to author.

Guiding System Backend: Reconstruct scanned geometry

In order to produce an accurate digital representation of the pottery in reality, this thesis utilize Rhinoceros, an established NURBs based 3d modeling software to process the SVG file to construct 3d objects. Specifically, The server backend is consists of technology stacks with Rhino Compute, a stateless REST API that provide code-level Rhino geometry commands and SDKs. The server backend reads the SVG file by extracting the x and y pixel coordinate value and translate into a 3d geometry points. Each point maps the original y-axis to z-axis in a z-up geometry space and appends a zero-value y coordinate. A rhino polyline connects each point in sequence forming a vertical profile of the scanned pottery. This profile is then rotated eight times each at 45 degree forming a 3d-wireframe. The last step of geometric operation is to loft the wireframes to construct the final solid 3d geometry. Lastly, This 3d geometry is further translated to a mesh file in .obj format which is used by the server to transfer to the mixed-reality headset when requested via a websocket connection.

Guiding System Backend: Coordinates Calibration

In the context of mixed reality (MR) headset technology, one of the critical challenges lies in seamlessly integrating the virtual and physical worlds to provide a coherent and immersive experience for users. A key aspect of achieving this integration is calibrating the coordinates between the physical environment captured by the headset cameras and the virtual world rendered in software platforms such



Figure 23: Edge detection sample. Left: camera feed, middle: edge detection, right; reconstructed geometry, credit to author.

as Unity.

The main technique of this calibration process is done by using spatial anchors. Spatial anchors serve as the bridge between the physical and virtual worlds in MR applications. These anchors are reference points that match the coordinates of specific locations in the physical environment with corresponding positions in the virtual world. By aligning these coordinates, spatial anchors enable virtual objects to appear anchored in the real world, maintaining spatial consistency and enabling interaction between virtual and physical elements.

In the context of this project, the physical world is represented by a passthrough immersive environment captured by the headset cameras. This immersive environment provides users with a live video feed of their surroundings, allowing them to see and interact with the real world while wearing the MR headset. In the meantime, The headset cameras capture the real-world environment, generating a spatial map that represents the geometry and layout of the physical space.

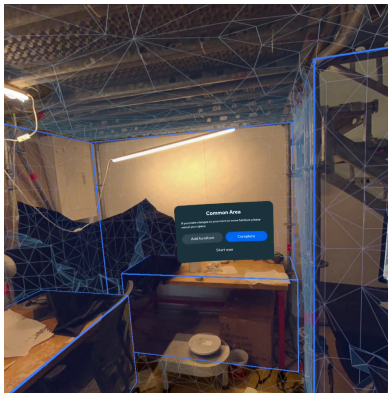


Figure 24: Spatial map of the physical environment visualized, credit to author.

The spatial map records detected objects and their corresponding locations, as shown from the screenshot above, the Quest 3 provides customizable object edit capability within a scanned space. This spatial anchor coding is implemented in Unity, using Meta provided extended reality SDKs (OVR). [1] The anchors are *transforms*, a coordinate class in unity, that represent fixed physical locations in the real world. It will be fixed on top of the pottery wheel regardless of the headset movement. In turn, the reconstructed 3D geometry will be generated, positioned, and projected accurately on top of the real world pottery wheel, hence overlapping with the real world clay object. By assigning and adjusting the material and display layering, this juxtaposition forms the core display mechanism of the guiding system.

[1] For more info on Meta Quest Unity SDKs and Spatial Anchors, https://developer.oculus.com/documentation/unity/unity-spatial-anchors-overview/

Guiding System Frontend Functionality One: Immersive Guide and Display

The pottery maker will mainly interact with the display unit. As ceramics novice makers, they will be guided over the entire making process by wearing an immersive display headset. On the screen, the main interactive object is the clay piece the maker is making. There are several layers of information to assist the maker in making the vase as close as the intended shape.

The first layer is a translucent shape indicating the designed piece. This is illustrated by the translucent gray volume in the diagram below. This layer serves the purpose of constantly reminding the maker what their final objective looks like. There is no active guiding on this layer as it simply functions as a reference layer. Technically, this layer is directly imported from any 3D software the maker or the teacher designed them in.

The second layer is a color-coded transparent mesh on top of the real-life volume. The volume resembles the real-life form on a one-to-one scale. This is the digital copy of reality that is updated in real-time to match the ever-changing vase on the wheel. There are three colors used: green is used when the real-life form aligns with the designer form, this is to say, this part of the making is correct. Red-colored area means the maker needs to compress on this area. As shown in the diagram below, the designer neck is thinner and the maker needs to pinch on that area. Last but not least, the blue-colored area means the vase needs to expand to match the intended shape. For example, the maker needs to pull the top of the vase out to match the plate shape at the top. Technically, this mesh layer is obtained by the contours and profiles using the reality-capture system.

Juxtaposing these two layers together, we have a subtle overlay of information on top of reality, which can provide crucial shape information to ceramic maker. This functionality is the first step to inform the maker on keeping the design in mind while making.

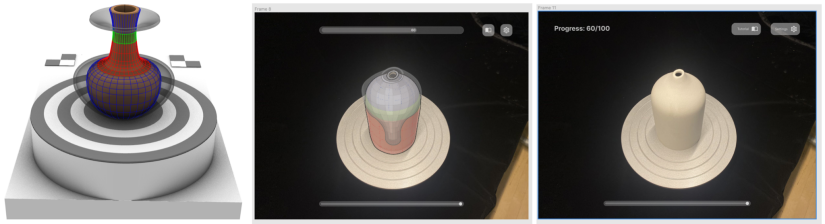


Figure 25: Guiding system color coding and UI/UX design, credit to author.

The diagram above presents the intended version of the user inter-

face design. The left interface represents the guiding shape overlay on top of the real-life object. The user has the option to turn off virtual guidance and view their object in an isolated view shown on the right. The development of immersive virtual display empowers a low-latency and high-resemblance of the reality when the user is wearing an immersive display headset.

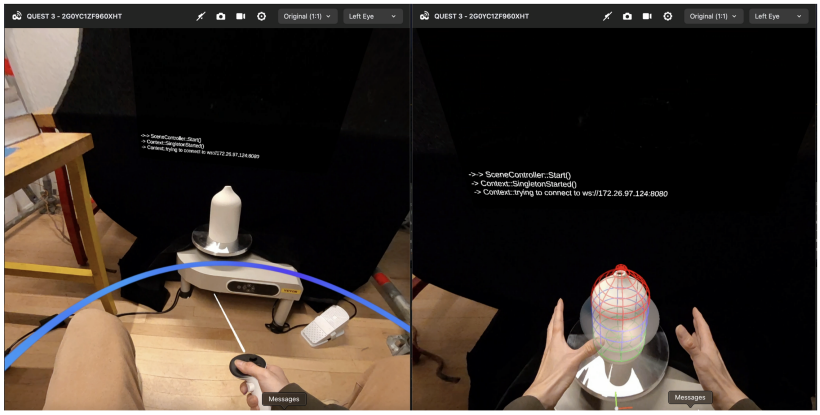


Figure 26: Deployed guiding system, credit to author.

As the guiding system initiates, the user will see the physical reality via the headset with no virtual information. If the user decides to turn on the guiding system and any virtual information overlay, the person will use the controller to calibrate the virtual space with reality. This step ensures any digital assets displayed will be at the corresponding position in relationship to the captured object in reality. The user points a preconfigured point in reality with the extending light ray projected from the controller. After calibration, a GET request is sent to the server querying the scanned object and design object.

After receiving the result mesh objects from the server, the guiding system will render the digital design intent with a colored mesh wireframe indicating the current differences between the current pottery and the design intent. The user then can turn the guide off or keep working on throwing the pottery with real-time comparison and color-coded overlay.

Guiding System Frontend Functionality Two: Realtime Pottery Capture and Panel Display

Besides a virtual overlay on top of the clay object during the making process, the frontend of the guiding system also provides real-time pottery capture displayed on virtual panels to enhance the maker's experience and facilitate the making process. This functionality, compared to a color-coded overlay, aimed at optimizing user interaction and minimizing visual interference while providing valuable information and guidance.

On the other hand, unlike still images on printouts, the panels in the immersive environment are dynamic and capable of updating themselves in real-time. This ensures that makers have access to the latest information, feedback, and guidance throughout the making process. Whether displaying real-time scan data, virtual overlays, or additional reference materials, the panels provide makers with up-to-date information that can adapt to their progress and needs.

The same dynamic effect could be achieved by other screen-based devices like tablets, screens and 3D viewing panels. However, makers have to break away from their making process by holding these devices and move them around. The immersive environment of the guiding system frontend allows for hands-free interaction. Makers can access and interact with the panels without the need for additional devices, freeing up their hands to focus entirely on shaping the clay object. Furthermore, the headset offers flexibility in panel placement, allowing panels to be positioned anywhere within the maker's field of view.

To reduce visual interference and streamline the user experience, the virtual environment can project the digital design model and real-time scan by the side of the pottery object. This positioning ensures that the maker can easily reference these digital assets without obstructing their view of the clay object or impeding their ability to shape it. The digital design model provides a reference point for the intended form and structure of the pottery object, while the real-time scan offers immediate feedback on the progress and quality of the shaping process.



Figure 27: Guiding system display panel UI/UX design, credit to author.

Guiding System User Interface: Controller Functions and Immersive Display Control

Both controller are primarily used during the setup phase of the application, ensuring minimal user input during the pottery throwing process. The right controller is responsible for placing the spatial anchor and switching between different guiding modes. On the other hand, the left controlled are primarily used for checking system information to ensure correct back-end functionality and Internet connection.

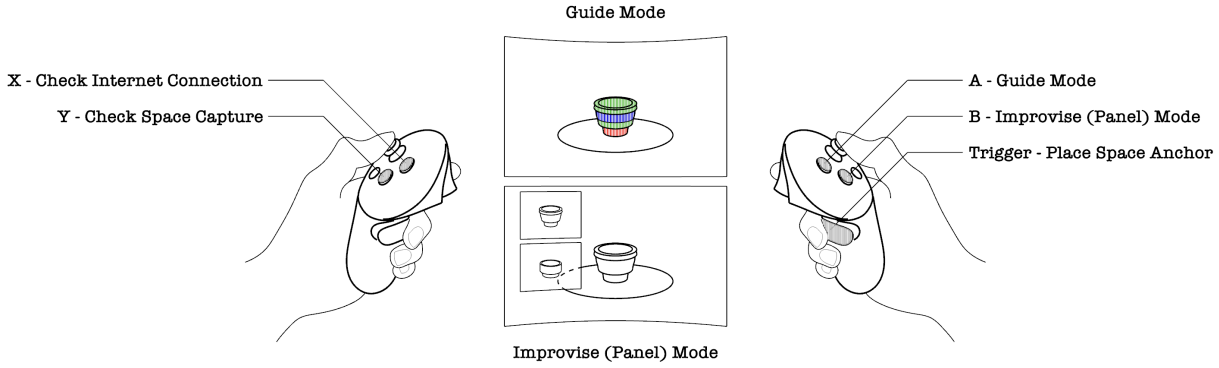


Figure 28: Controller button functions, credit to author.

The main point of control is still the paired controller instead of hands for the following reasons:

Precision and Accuracy: The paired controller offers precise and accurate control over interactions within the immersive environment. For example, when using the trigger button to place a spatial anchor, the projected light ray from the controller offers much better accuracy with little flickering compared to hand control. As mentioned from the previous section, the accuracy of the spatial anchor is essential for virtual space project.

Consistency and Reliability: Using the paired controller ensures consistency and reliability in user interactions. Unlike hand control, which requires complex and specific gesture detection, the controller can register unambiguous button click. Also, hand gestures lacks the consistency under the influence of factors such as lighting conditions and user dexterity. Furthermore, the controllers can be put aside after setting up the user interface, while the hand gesture detection might register false commands when the user is actively engaging in pottery throwing.

Guiding System Device

The Meta Quest 3 virtual reality (VR) headset will be utilized as the guiding system display device. It offers several advantages that make it well-suited for guiding participants through the pottery-making process:

- Affordability:

  The Meta Quest 3 is known for its relatively affordable price point compared to other VR headsets on the market. This accessibility makes it an attractive option for educational and creative purposes, allowing more individuals to experience immersive virtual environments without breaking the bank.

- Good Pass-Through Capability:

  The Meta Quest 3 is equipped with advanced pass-through technology, which enables users to seamlessly transition between virtual and real-world environments. This feature is particularly useful for pottery-making exercises, as participants can easily switch between virtual guidance and hands-on practice without removing the headset.

  Developer-Friendly Environment:

  The Meta Quest 3 provides a developer-friendly environment with robust tools and resources for creating immersive VR experiences. This flexibility allows instructors to tailor the guided experience to suit the specific needs and objectives of the pottery project, whether through interactive tutorials, virtual demonstrations, or collaborative exercises.

Pottery Design

Before embarking on the making exercises for the pottery project, it is crucial to establish a shared design concept that will serve as the basis for comparison between each approach.This section outlines the design process, considering various inspirations and references, to conceptualize a pottery object that balances aesthetics and crafting complexity.

Embracing minimalism as the overarching theme, the design concept prioritizes simplicity, clean lines, and understated elegance. This approach aligns with the desire to create a pottery object that exudes a sense of tranquility and harmony while showcasing meticulous craftsmanship.

Drawing inspiration from minimalist aesthetics, a variety of online sources were explored to inform the design process:

- Pinterest:

  A popular platform for artists and enthusiasts alike, Pinterest offers a vast repository of pottery-related images and ideas. Various boards and pins were explored to gather inspiration, covering a wide range of styles, techniques, and artistic expressions.

- Online Pottery Shopping Websites:

  In addition to Pinterest, online pottery shopping websites were also consulted for inspiration. These websites showcase commercially available ceramic wares, providing insights into the latest trends, popular styles, and consumer preferences in the ceramic industry.

The design specification will follow the visual references found, sketches of the design size, dimensions will be presented in the Results chapter.

Matetial, Tools, and Equipment

Choice of clay material Amaco is chosen due to its ideal plasticity and texture for throwing that align with the objectives of the project. This clay does not require firing in a kiln for curing, making it ideal for simple and straightforward projects where firing is not considered or feasible. This aligns with the scope of the thesis, which focuses on exploring different making approaches without the need for kiln firing. By using the same clay material for all making exercises, consistency is maintained throughout the project. This ensures that any variations in the making approaches can be attributed to the techniques and methods employed, rather than differences in clay properties.

Choice of tools and equipment For the making exercises, a standard set of tools and equipment will be utilized to facilitate the pottery-making process. The primary tools and equipment include:

- 10-Inch Turning Wheel:

  A 10-inch turning wheel will serve as the primary equipment for wheel-throwing exercises. This turning wheel provides a stable platform for shaping and molding the clay, allowing for precise control and manipulation of the pottery object's form.

- Common Throwing Tools:

A set of common throwing tools, including ribs, trimming tools, wire cutters, and throwing sponges, will be used to shape, trim, and refine the pottery object on the wheel. These tools are essential for achieving smooth surfaces, clean lines, and balanced proportions in the final piece.

Additional specific tools and equipment required for each making exercise will be detailed in the corresponding sections. These may include hand-building tools, carving tools, texture tools, brushes, and other specialized equipment necessary for shaping, decorating, and finishing the pottery object according to the chosen approach.

Making Approaches: Techniques, Methods, and Workspace Setup

In this section, three distinct approaches will be outlined for the making exercises: conventional, guided, and improvised. Each approach offers a unique perspective on the pottery-making process, with varying levels of structure and experimentation to test the proposed immersive guiding system and design processes.

Conventional Approach: Design followed by making with a physical template

In the conventional approach, once the design is finalized, the maker proceeds to the making stage, firstly by making a physical template resembling the shape of the clay. This template provides a reference for achieving consistent dimensions and proportions in the final object. The maker relies on their skill and experience to execute the design, shaping the clay using wheel-throwing followed by limited extent of hand-building. The finished object is then left to dry and set the form.

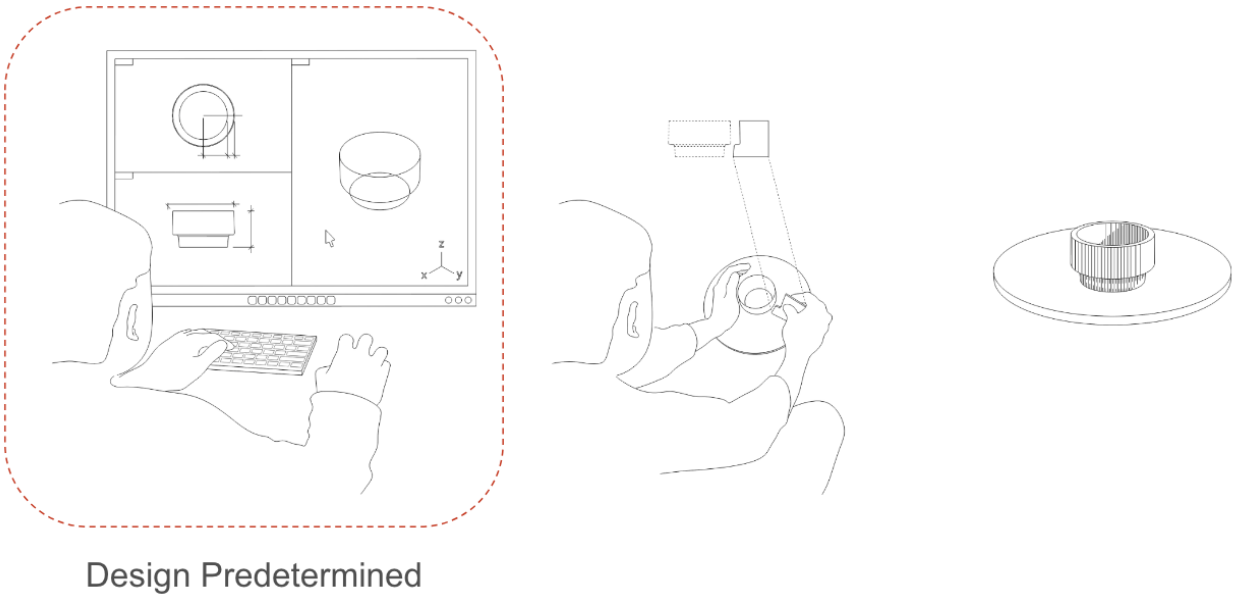


Figure 29: Conventional Approach diagram, credit to author.

Detailed Procedures of Pottery-making in the Conventional Approach

- Design process:
  1. Conceptual design (shared between all exercises)
     Aforementioned design intent formalized.
  2. Digital modeling
     Once the concept is finalized, it is translated into digital form using Rhino 7 as the primary modeling software. Digital modeling allows for precise adjustments to proportions, shapes, and details, ensuring accuracy in the design.
  3. Template Production
     The vertical profile of the digital design is extracted and a piece of plexiglass is laser-cut to the exact shape and scale of the profile
- Making process:
  1. Preparation (shared between all exercises)
     Standardized clay preparation in pottery-throwing that includes pottery wheel and clay material setup, centering the clay on wheel, opening clay in a cup topology, and pulling the cup to desired height.
  2. Shaping with template
     Once prepared, the physical template will be used to shape the clay. Using the template as a guide, the clay is carefully shaped

and molded to realize the design concept. Attention is paid to achieving clean lines and smooth surfaces throughout the shaping process

3. Trimming with template

   After the initial shaping, excess clay is trimmed away using the template as a reference. This step helps to refine the form and ensure consistency in dimensions.

4. Finishing up (shared between all exercises)

   Cutting and detaching the clay from wheel and left to dry.

Guided Approach: Design followed by virtual guiding geometry in MR

In the guided approach, the design process also begins with conceptualization, but with the added element of virtual guiding geometry in mixed reality (MR). Using the developed pipeline, the maker export the same digital file as the first approach and the guiding system will import the shape and visualize the form as described in previous sections. The maker then follows these virtual color-coded guides while shaping the clay, using XR technology to visualize and adjust the design in real-time. This approach allows for greater control and less constrains over the making process, as the maker can refine the design iteratively without the binding force of the template. Once the object is shaped, it will be scanned one last time for digital archiving before proceeding to the drying stage.

Furthermore, it's essential to note that the guiding system will be deployed separately in the shaping and trimming stages of throwing. This separation allows for two distinct exercises to be conducted, testing the effectiveness of the guiding system at each stage. By comparing the user experience and resulting pottery object in both exercises, insights can be gained into which stage the guiding system performs best, informing future iterations and improvements. These comparative analyses will be further explored and discussed in the results chapter, providing valuable insights into the efficacy and practicality of integrating MR technology into the pottery-making process.

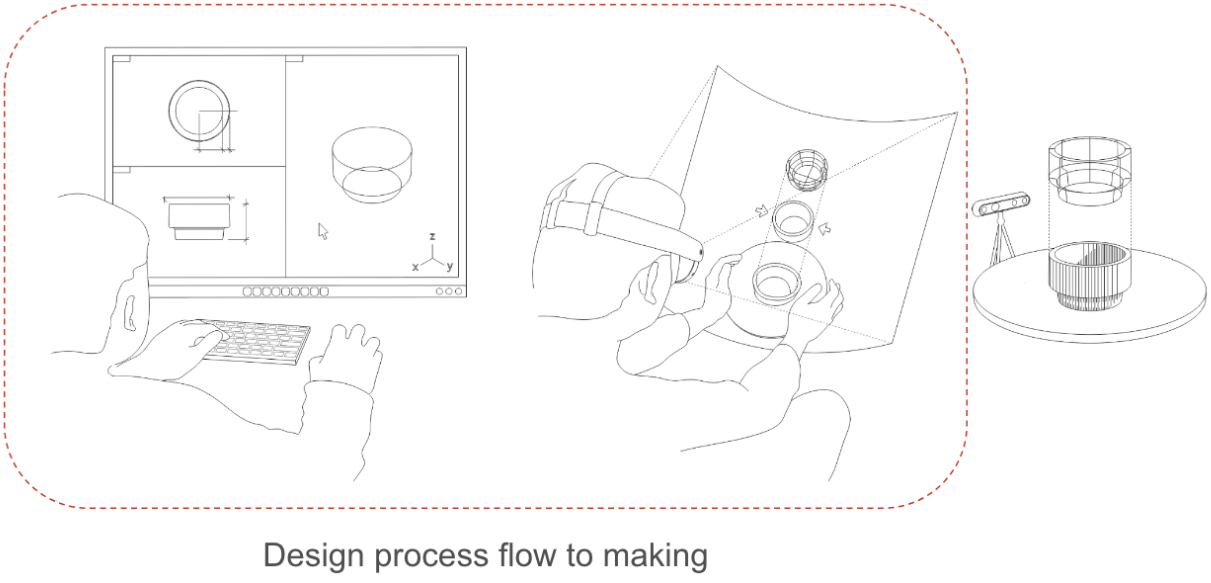


Figure 30: Guided approach diagram, credit to author.

Detailed Procedures of Pottery-making in the Guided Approach

- Design process:

  1. Conceptual design (shared between all exercises)

     Aforementioned design intent formalized.
  2. Digital modeling (shared between the conventional and the guided approaches)

     Once the concept is finalized, it is translated into digital form using Rhino 7 as the primary modeling software. Digital modeling allows for precise adjustments to proportions, shapes, and details, ensuring accuracy in the design.

- Making process: (immersive guiding system deployed at the shaping stage)

  1. Preparation (shared between all exercises)

     Standardized clay preparation in pottery-throwing that includes pottery wheel and clay material setup, centering the clay on wheel, opening clay in a cup topology, and pulling the cup to desired height.
  2. Immersive guiding system setup

     Wear the Oculus 3 headset and open the immersive guidance application. In the application, the user will perform the following actions to get the device ready for real-time guiding:

     – Check Internet connection on the information panel
     – Check if the headset recognize the surrounding environment
     – Use the right controller to place a spatial anchor
  3. Shaping with the immersive guiding system

     Keep the headset on. Once the clay and the immersive guiding system are both prepared, the maker can proceed to shape the clay. Using the digital guide as a progress tracker, the clay is carefully shaped and molded to realize the design concept as close as possible by turning all sections of the color-coded guide to green.
  4. Trimming

     After the initial shaping, take the headset off and trim away the excessive clay using common throwing tools.
  5. Finishing up (shared between all exercises)

     Cutting and detaching the clay from wheel and left to dry.

- Making process: (immersive guiding system deployed at the trimming stage)

  2 Shaping

  The make will perform initial shaping of the pottery with hands and common crafting tools provided without wearing the headset. The goal of the step is to achieve a rough shape similar to the design form instead of matching the two as close as possible.

  3 Immersive guiding system setup

  Follow the same steps of the shaping exercise but only after the shaping step

  4 Trimming with the immersive guiding system

  Keep the headset on. After the initial shaping, the same set of common crafting tools are used to refine the pottery. The goal of this step is to trim the pottery as close as possible to the original design by turning all sections of the color-coded guide to green.

Improvised Approach: improvised making followed by digital capture of the final artifact

In the improvised approach, the design process takes a more spontaneous and experimental path. Rather than starting with a predetermined design, the maker begins with an open-ended exploration of the material, allowing the clay to guide the making process. This approach embraces improvisation and serendipity, allowing for unexpected discoveries and creative expression. The maker may work intuitively, shaping the clay by hand without the use of templates or guiding geometry. As the object takes form, the artisan may make adjustments and refinements based on intuition and aesthetic judgment. Once the object is completed, it is digitally captured using the same setup to create a digital record of the final artifact. This digital capture preserves the unique qualities of the improvised making process and allows for further analysis or manipulation in the digital realm.

Similar to the previous making approach, it's important to note that the guiding and capturing system will be deployed separately in the shaping and trimming stages of throwing. This separation also allows for two distinct exercises to be conducted, testing the effectiveness of the capturing system at each stage. These comparative analyses will also be further explored and discussed in the results chapter.

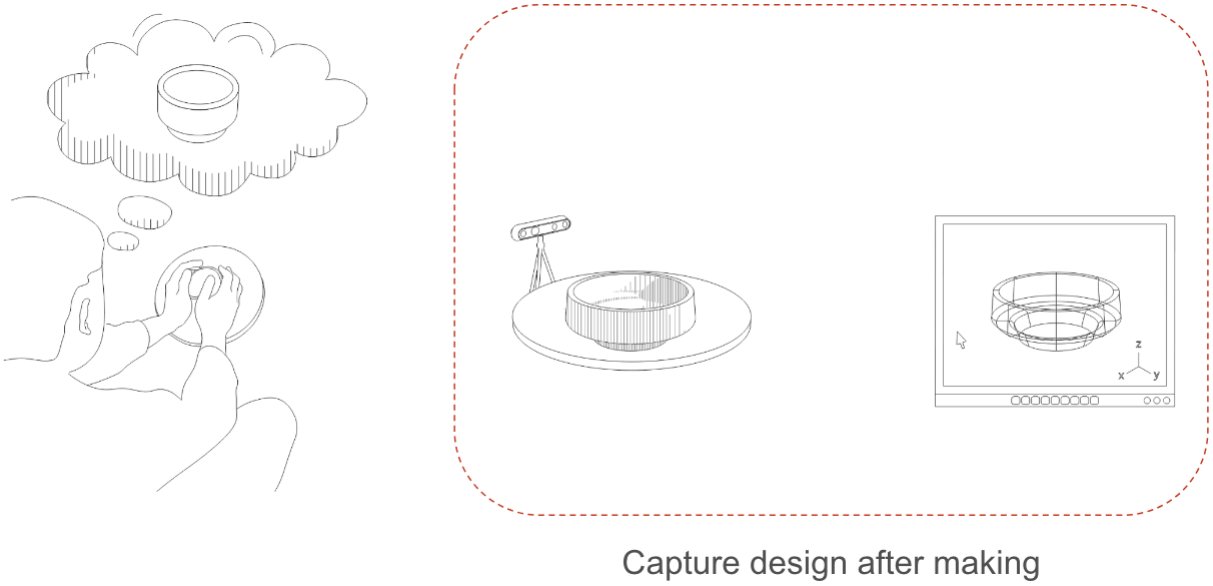


Figure 31: Improised approach diagram, credit to author.

Detailed Procedures of Pottery-making in the Improvised Approach

- Design process:
  1. Conceptual design (shared between all exercises)
     Aforementioned design intent formalized.
- Making and capturing process: (guiding and capturing system deployed at the shaping stage)
  1. Preparation (shared between all exercises)
     Standardized clay preparation in pottery-throwing that includes pottery wheel and clay material setup, centering the clay on wheel, opening clay in a cup topology, and pulling the cup to desired height.
  2. Immersive guiding system setup
     Wear the Oculus 3 headset and open the immersive guidance application. In the application, the user will perform the following actions to get the device ready for real-time guiding:
     - Check Internet connection on the information panel
     - Check if the headset recognize the surrounding environment
     - Turn on the guiding panel using the left-hand controller
  3. Shaping with the guiding and capturing system
     Keep the headset on. Once the clay and the headset are both prepared, the maker can proceed to shape the clay by improvising with the common throwing tools. The clay is carefully shaped and molded to realize the design concept as long as the maker is **satisfied**.
  4. Shape capture with the capturing system
     Keep the headset on. Press the secondary button on the left-hand controller to save the existing pottery's shape as a OBJ file.
  5. Trimming
     After the initial shaping, take the headset off and trim away the excessive clay using common throwing tools.
  6. Finishing up (shared between all exercises)
     Cutting and detaching the clay from wheel and left to dry.

- Making process: (guiding and capturing system deployed at the trimming stage)

  2 Shaping

  The make will improvise initial shaping of the pottery with hands and common crafting tools provided without wearing the headset.

  3 Immersive guiding system setup

  Follow the same steps of the shaping exercise but only after the shaping step.

  4 Trimming with the immersive guiding system

  Keep the headset on. After the initial shaping, the same set of common crafting tools are used to refine the pottery. The goal of this step is to improvise and trim the pottery by referencing the design and real-time scan in the headset. This step terminates as long as the maker is **satisfied** by the existing shape.

  5 Scan the result with the capturing system

  Follow the same steps of the shaping exercise but only after the trimming step.

Results

Results Overview

The Results section of the thesis begins by delving into the personal journey of pottery-throwing, which started at the beginning of this thesis development. This section lays out some of the major techniques for pottery-throwing. I will draw from subjective reflections on learning these techniques and steps at different stages of pottery throwing.

The section is followed by detailed documentation of the three proposed making methods from both a qualitative and quantitive approach. I will document my thought process, physical actions, and observations on designing and making each clay piece. There will also be quantitive measurements like how much time is taken at each step. Analysis of the making process from video screenshots will highlight the mistakes, unexpected scenarios, and technical contingencies that happened overtime. This documentation will also reflect the responding measurements I took, which could be some crucial design decisions made during the process. Furthermore, each finished piece from different making methods will be documented and evaluated based on the level of finish, aesthetic appeal, structural integrity, and most importantly, its relationship to the original design.

Last but not least, the section features a summary in the form of a table documenting the setup, and the user experience at each step of making for the comparative analysis in the next chapter.

Pottery Throwing: an Initial Encounter

The pottery-throwing classes comprise three two-hour working sessions aimed at providing makers with a brief yet comprehensive introduction to the entire pottery-throwing process.

The following diagram illustrates a summary of different steps in different stages of pottery-throwing learned from the classes. There are a total of six stages which focuses on different skills sets and one functions as a preparation of the next step. The diagram also includes a subjective scoring system for each step in three categories: craft difficulty (level of skills required), design influence (how much dos this step determines the form of the pottery), and improvisablity (how much freedom and agency does the maker have in following their hands at each step). The last two factors will be used to determine the usability and effectiveness of the guiding system this thesis proposes.

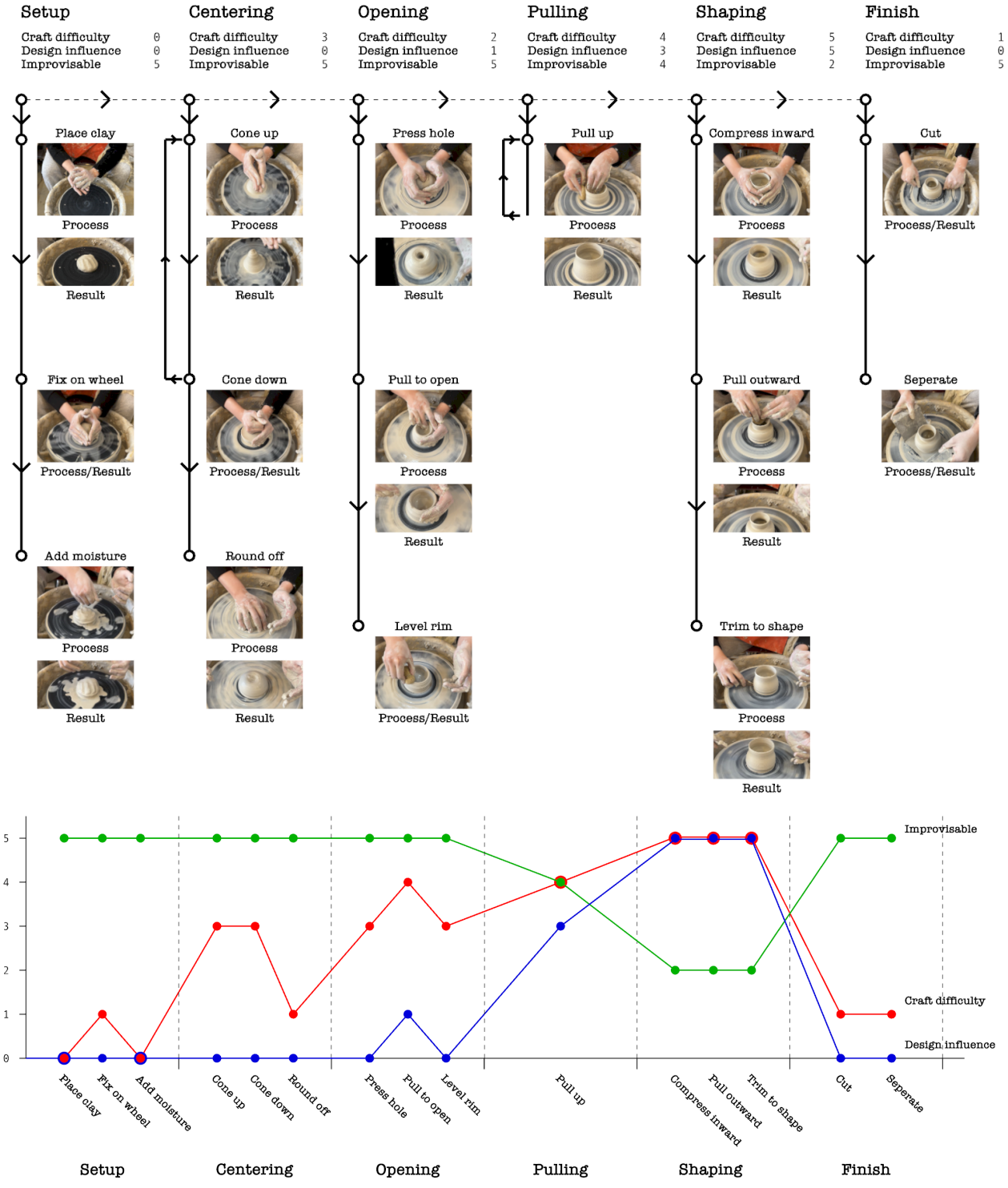


Figure 32: Pottery-throwing process and assessment, credit to author.

Session 1

Date: 03/07/2024 3pm - 5pm

Objective:

The first session aims to familiarize participants with basic pottery-making techniques by focusing on the creation of simple objects, with the mug serving as a key introductory piece due to its relatively straightforward construction.

Processes:

The session began with an overview of the pottery-throwing process, covering clay preparation, wheel operation, and object formation. Instructors guided participants through each step, emphasizing proper techniques and safety measures. Participants then prepared their clay and learn to center it on the wheel, followed by gradually building up the clay to create the desired height for their mugs. Techniques for pulling, smoothing, and trimming the clay are demonstrated and practiced under the guidance of instructors.

Results:

By the end of the session, participants have successfully created their own mugs, gaining practical experience in the initial stages of pottery-throwing. They have developed an understanding of basic pottery-making techniques and processes, setting the stage for further exploration and skill development in subsequent classes.

Session 2

Date: 03/12/2024 3pm - 5pm

Objective:

In the second session, participants continue to build upon the foundational skills acquired in the first session. However, unlike the first session, participants are challenged to design a rough shape of their piece before beginning the making process. This class emphasizes the use of techniques such as compression and horizontal pulling across different sections, which is a set of more advanced shaping skills. Instead of creating mugs, participants in this session are tasked with making vases, requiring them to adapt their skills to a different form and level of complexity.

Processes:

At the beginning of the class, the instructor gave an overview of the class and gave references of different vases as inspirations of design. The participants drew their intended vase shape, and prepare the clay accordingly. The making session begins with a review of the

pottery-throwing process, covering clay preparation, wheel operation, and object formation. The key difference in the making process is between pulling and finish the throwing. After adding height via pulling, participants then slow down the wheel and hold the clay with both hands from the bottom. They begin the compressing action to gently push part of the clay inward according to their design.

Results:

By the end of the session, participants have successfully created their own vases, demonstrating their ability to apply and expand upon the skills learned in the previous class. They have gained experience in shaping clay into more intricate forms and have honed their ability to design and execute their pottery pieces. The session builds upon the foundation established in the first class, providing participants with the opportunity to further develop their pottery-making skills and explore new techniques and challenges.

Session 3

Date: 04/18/2024 3pm - 5pm

Objective:

The objective of the final session is to complete the pottery-making process by trimming the pieces created in the previous two sessions, as well as crafting caps for cups and bases for leveling all previous pieces. Participants will refine the exterior shape of their pottery pieces, ensuring smoothness and symmetry, while also creating functional components to enhance the usability of their creations. This session serves as the culmination of the pottery-throwing classes, providing participants with a comprehensive understanding of the entire pottery-making process.

Processes:

The session begins with a review of the trimming process, emphasizing precision and attention to detail in shaping the pottery pieces. Instructors demonstrate various trimming techniques, including using trimming tools to remove excess clay and refine the form. Participants then apply these techniques to their own pieces, working under the guidance of instructors to achieve desired results.

Following the trimming process, participants proceed to craft caps for cups and bases for leveling. Instructors provide instruction on forming and attaching these components, ensuring proper fit and functionality. Participants apply their newfound skills to create caps that fit securely onto their cups, as well as bases that provide stability and balance for all previous pieces.

Throughout the session, participants have the opportunity to ask questions, seek feedback, and refine their skills through hands-on practice. Instructors offer guidance and support as participants work to complete their pottery pieces and functional components.

Results:

By the end of the session, participants have successfully trimmed their pottery pieces, crafted caps for cups, and created bases for leveling. Each piece exhibits a refined exterior shape, smoothness, and symmetry, reflecting the skills and techniques learned throughout the classes. Participants leave with a sense of accomplishment and confidence in their ability to create beautiful and functional pottery pieces. The session concludes with a reflection on the journey of pottery-throwing, highlighting the progress made and the skills acquired.

Pottery Throwing under the Context of the Guiding System

After an introduction to pottery-throwing skills, a series of unsupervised throwing sessions is conduced to evaluate the guiding system prototype. There are three distinct making exercises scheduled. There is one common design intent conceptualized to regulate the resulting pottery for comparison. The first exercise is a traditional making approach that follows the lessons learned at the workshop. I will conventionally design and execute this design with the help of a physical template. The making process and the pottery made will be documented as the control group to evaluate the guiding system prototype. The second exercise is a digitally guided pottery throwing wearing the MR headset. I will follow the color-coded guidance projected immersively to craft the same design without the help of the template. The last exercise is an improvised pottery making session also wearing the MR headset. The difference is that no explicit guidance will be provided. I can only reference my design intent and check the 3d reconstruction of my current pottery piece by the side. By comparing the outcomes of throwing sessions conducted using each approach, I will evaluate the effectiveness of the guiding system prototype in enhancing the pottery-throwing experience.

Pottery Design Intent

In order for a parallel comparison between each making approach, a shared pottery design is conceptualized before any making exercises. By reference online images for inspiration, this figure of a tapered-bottom cup is chosen at a balance between aesthetics and crafting

difficulty.

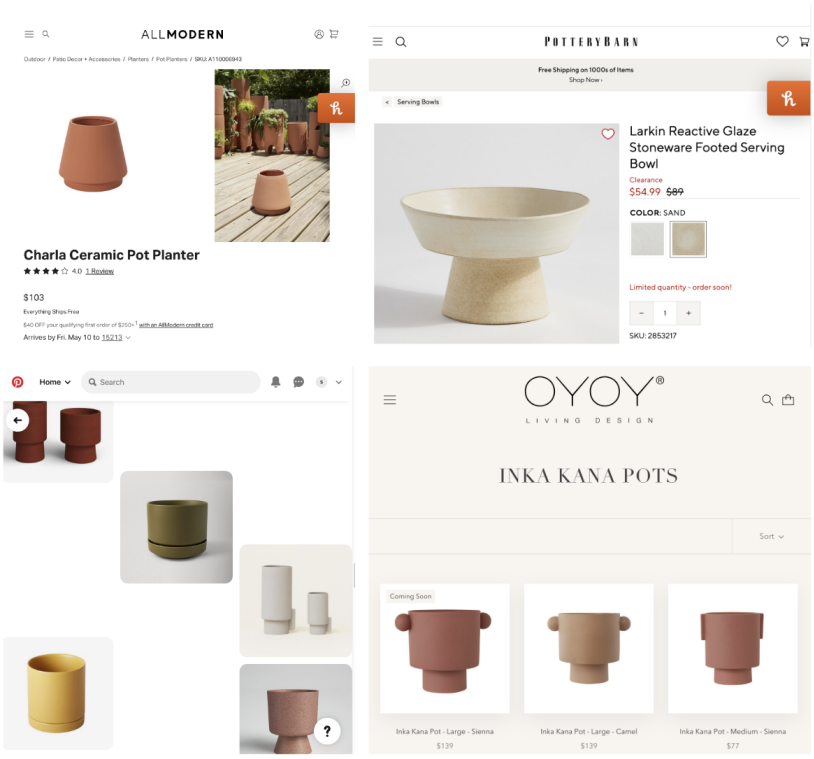


Figure 33: Collages of reference images of the pottery to make, credit to author.

Pottery Throwing in the traditional approach

Before diving into the detailed processes of this crafting exercise, there are some details and explanations about the physical template need to be foregrounded.

The traditional approach to pottery throwing represent the common practice of pottery-crafting adopted by most crafters and artist. With the existing design intent, a more detailed digital model is constructed to formalize the intent with concrete dimensions. A physical template is then laser-cut to the profile of the shape for easier execution to replicate the design. During the making process, all steps would follow the aforementioned procedures until the pulling step where the cup takes its rough shape. During the shaping section of the making process, the template will be used to shape and trim the initial clay piece to the design form.

Compared to the hand-crafting shaping process, the physical template provides a solid guide for me to achieve the intended design. As observed from the photo above, holding and pressing the tem-

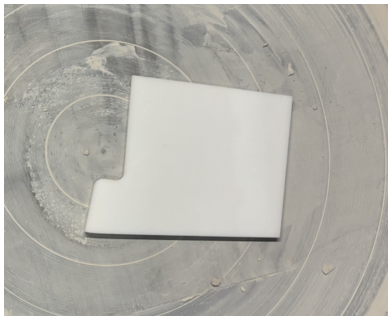


Figure 34: Shape template during the making process, credit to author.

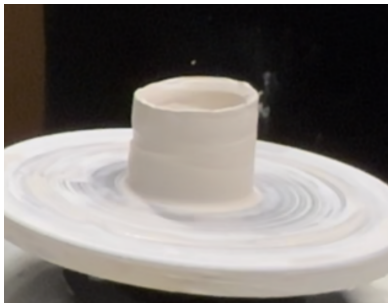


Figure 35: Rough shape before shaping, credit to author.



Figure 36: Rough shape before shaping, credit to author.

plate will automatically trim the clay to shape. The level of craft difficulty took a drastic drop and the result is unsurprisingly close to the original design. During the shaping process, I would only pay attention on smoothing the surface and watch out for excessive trimming. On the other hand, little attention was given to the design of the cup because the template has taken entire control of shaping the cup. In total, three rounds of template shaping were taken, with the first two rounds trimming the clay to shape and the last round smoothing the surface. The result, shown in the image below, resembles the original design to a high extent.



Figure 37: Final result of the first shaping exercise, credit to author.

In the traditional approach, the physical template was able to shape and trim the exterior of the clay at the same time. As a re-

sult, the final result of trimming exercise with the physical template yielded a very similar result.



Figure 38: Final result of the first trimming exercise, credit to author.

Pottery Throwing in the guided approach

The preparation stage of this crafting is identical to the previous approach. I prepared and pulled a clay piece to roughly the same shape as the last cup. At this point of the crafting process, this making exercise involves wearing the MR headset with the digital guiding system turned on. Operations on the clay is paused while setting up the guiding system. The same digital model from the first exercise is used and automatically imported into the headset. The guiding system is tuned to tolerate a plus/minus 3mm deviation from the original design to categorize the profile as green/matching the design.



Figure 39: Shaping results in clay collapsing, credit to author.

The shaping section resumes with the headset clearly visualize a color-coded representation of the existing clay piece highlighting the area needs attention. Unlike the first exercise, this making approach did not succeed in the first attempt. While shaping the clay to match the design, too much and uneven pressure caused the clay to collapse resulting in a invalid clay making exercise.

The second attempt resumes the guiding system at the shaping stage. As observed from the screenshots below, the first step I took is to trim the excessive top area which is marked in the res section. The color-coded representation can accurately pinpoint the exact height to cut. By holding the pin at the boundary between the red and blue section, the cup is cut to the correct height within tolerance.

The next phase of shaping the cup is more complex. Unlike the previous exercise, there is no physical template to trim the clay and I have to compress and expand the cup with my hands. As shown from the screenshot below, I stated pulling with a sponge to expand



Figure 40: Shaping results in clay collapsing, credit to author.

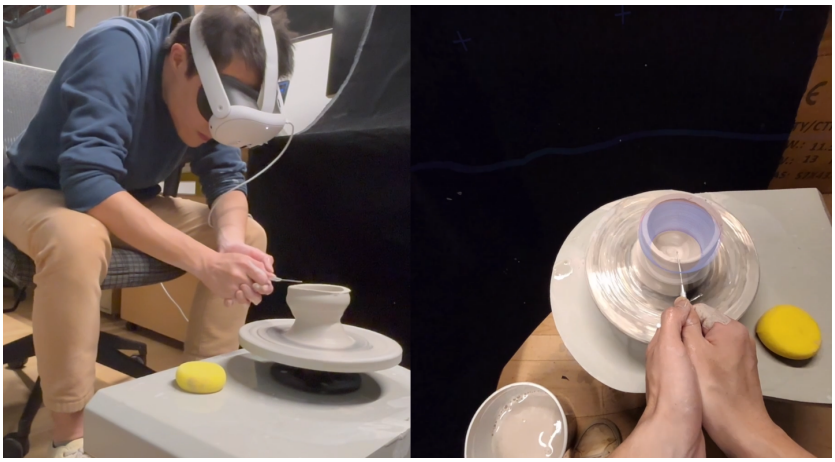


Figure 41: Shaping results in clay collapsing, credit to author.

the upper blue section to match the original design. This action is considerable more challenging compared to using a template. The shaping took five rounds in total, each lasting considerable longer than a shaping round from the previous exercise. The first 3 rounds was intended to match the original shape and turn the guiding color green. The last two rounds were used to fine-tune and rounding the clay to refine the design at my own discretion and within the tolerance of the guiding system.

The photo below shows the resulting piece of the successful attempt.



Figure 42: Final result of the second shaping exercise, credit to author.



Figure 43: Final result of the second trimming exercise, credit to author.

Pottery Throwing in the improvised approach

The setup and preparation are identical to the previous two exercises. Before shaping the rough cylinder to the design, this making exercise involves wearing the MR headset with the digital referencing system turned on. Operations on the clay is paused while setting up the guiding system. The same digital model from the first exercise is used and automatically imported into the headset. This time, instead of turning on the color-coded guiding overlay, the real-time reference is turned on, which displays two view windows at the top left corner of the immersive environment. The top panel shows a representation of the existing clay in 3D, and the bottom panel shows the imported design shape. Instead of a guiding system directly overlaying on the pottery, the design object and real-time scan are presented by the side as references. Varies tools and handcrafting can be improvised to achieve the design with no restrain. The pottery is updated in realtime to update the design form.

Without a direct overlay in the guiding system, there is no direction comparison between the design and the pottery I was making. The shaping process also takes five rounds, each rounds lasting about the same time as the previous exercise. What different from the previous exercise is that there is no clear distinction between each round in term of objectives. There is no color to match and no exact shape to achieve, and hence each round of shaping relies the on-site judgement from the previous one.



Figure 44: Shaping the cup, credit to author.

The photo below shows the resulting piece of the successful attempt.

The improvised approach also actively scanned and saved the clay



Figure 45: Viewing design of the cup, credit to author.



Figure 46: Final result of the third shaping exercise, credit to author.



Figure 47: Final result of the third trimming exercise, credit to author.

during the shaping and trimming phase of throwing. The screen-shots below details the shape change after rounds of shaping and trimming, and the existing shape at that moment is also saved at the backend for design archives. These design archives are exported and displayed.

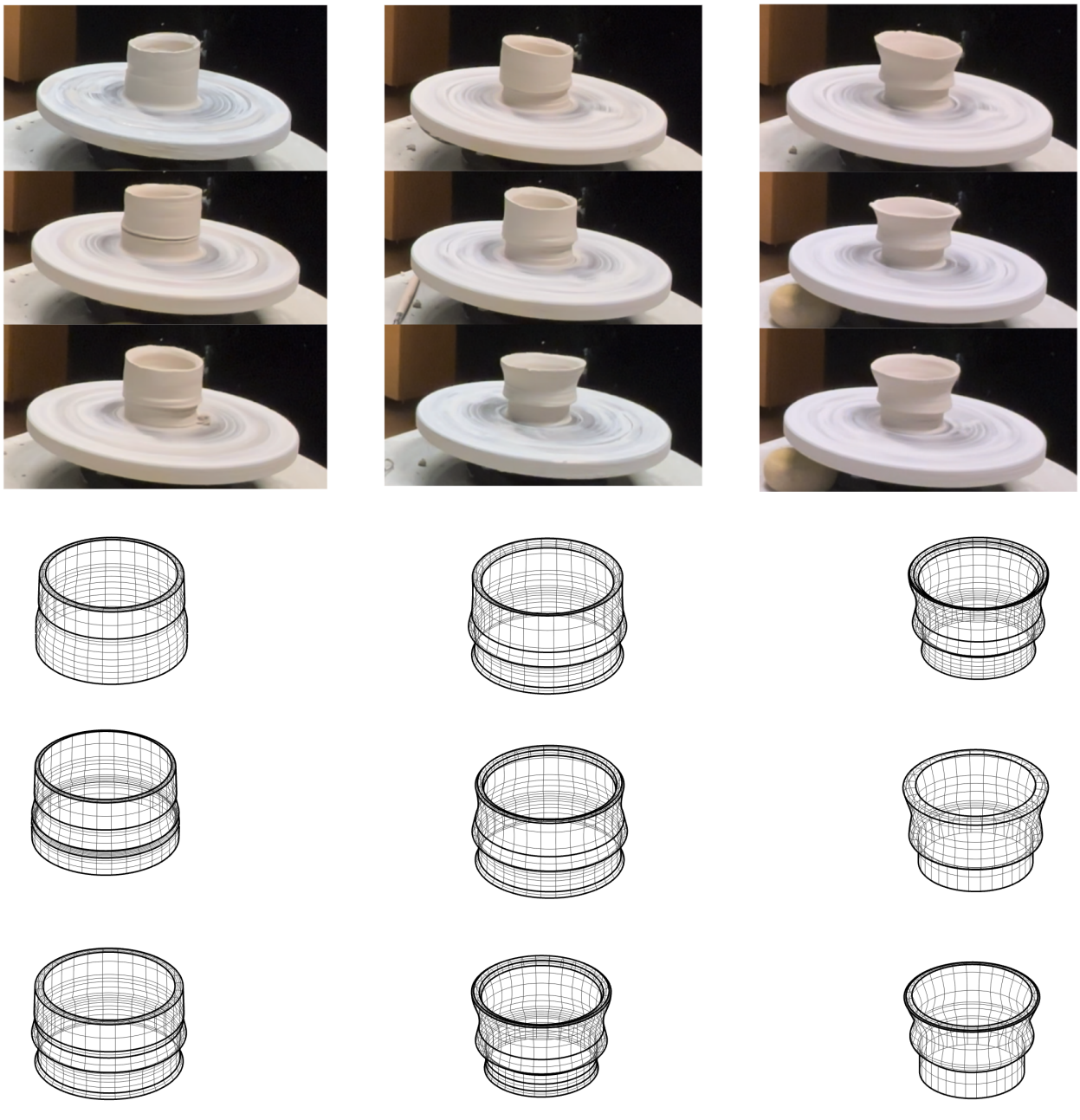


Figure 48: Up: Change of shape captured by camera. Down: change of shape captured by scanner , credit to author.

A Comparison of the Three Making Methods

After all six exercise are completed, the clay potteries made are documented together with the original design intent and the final design model saved at the backend. As shown from the table below, each column represents a different approach and the initial design, pottery photos, and final design captures are listed from top to bottom.

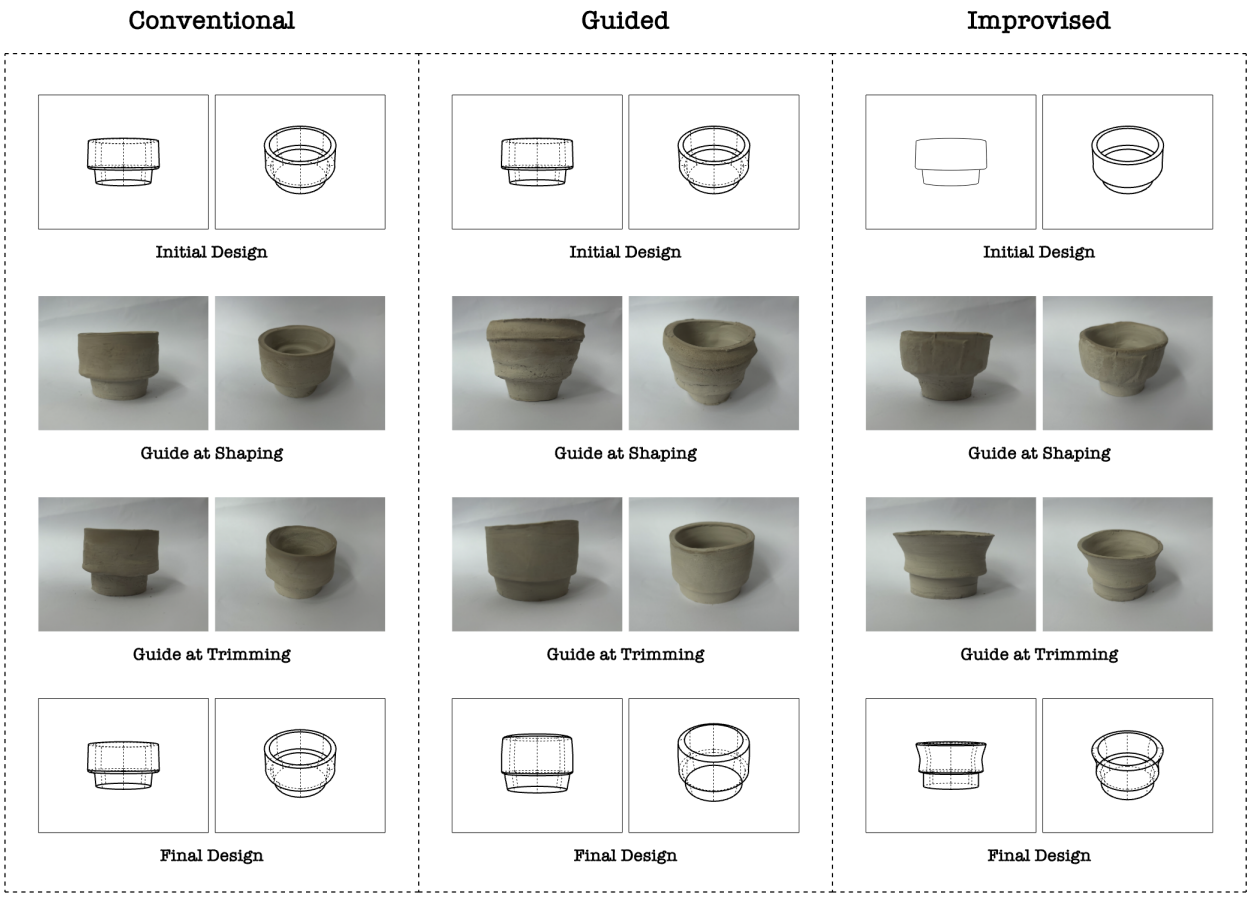


Figure 49: A comparison between three approaches, credit to author.

Discussion

Discussion on the Guiding System Prototype

This section of the discussion chapter focuses on reflecting the comparison summary of the three different making approaches: the conventional approach with a physical template, the guided approach with a mixed reality headset, and the improvised approach with a scan of the design shape at the end.

Firstly, the conventional approach with a physical template relies on traditional methods and tangible tools to guide the pottery-throwing process. Overall, the throwing process was the easiest with least amount of time taken. The making procedures were also simplified since no other tools than the template was required to shape and trim the clay after preparation.

While this approach provides a familiar and tactile experience for potters, it may limit creativity and flexibility due to the fixed nature of the physical template. From the results of the two exercises using the physical template, the pottery made had the smallest variation and the closest resemblance to the modeled design. In this case, the potters may feel constrained by the template's design, hindering their ability to explore new shapes and forms.

In contrast, the guided approach with a mixed reality headset removes the restraining template by letting the maker using hands and more generic tools. By overlaying digital instructions and visual cues onto the physical workspace, the mixed reality headset allows a certain level of tolerance for maker to deviate their execution. However, the presence of technology may pose challenges for potters who are less familiar with digital tools or prefer a more hands-on approach to pottery making. During the exercise where I was using hands to shape the clay, I noticed significant difficulty in eye–hand coordination because there is a slight latency between the shape change I felt from hands compared to the change I saw from the screen. As a result, the shaping exercise results in a few failures when the clay collapsed while I was trying to change the shape too drastically.

However, these failures might not all be attributed to wearing the headset, my crafting skills as a pottery novice also contribute to the occasional mishaps. During the second phase of the exercise, I experienced a lot less inconsistency while wearing the headset during the trimming phase of the pottery making process. As seen from the comparison between the two result cups, the digitally guided trimming cup has smoother edge and higher level of finish. Holding additional tools like the metal scraper and wood ribs provides extra support and stability which in turn enhanced the making experience. As a result, I would still conclude that the mixed reality headset offers significant potential for enhancing the pottery-throwing experience by providing real-time feedback and guidance to potters and allowing higher extent of decision making during the crafting process.

Finally, the improvised approach with a scan of the design shape at the end represents a departure from conventional methods and processes, emphasizing creativity and experimentation in pottery throwing. This approach allows potters to create their designs freely, without the constraints of a physical template or digital guidance. The results produced aligned with my expectation as they differentiate the most from the original design by exhibiting unique features and forms. One of the unique feature is the inner-curved body as the result of bending the metal scraper which forms a natural curve while trimming. However, the reliance on digital scanning and replication may introduce challenges related to accuracy and fidelity to the original design. During the exercise involving the scan of the design shape at the end, I encountered difficulties in accurately replicating the existing clay due to variations in clay consistency and interference of hand when detecting clay edges. Despite these challenges, the improvised approach offers a unique opportunity for potters to explore new shapes and forms, pushing the boundaries of traditional pottery-making techniques.

Discussion on Mixed-reality

The discussion of the limitations of mixed reality (MR) in pottery throwing reveals several challenges that affect its usability and effectiveness compared to other tools and methods.

Firstly, the distortion issue poses a significant challenge when using MR headsets for pottery throwing. Distortion occurs when the digital overlays or visual cues projected onto the physical workspace do not accurately align with the real-world environment. This can result in discrepancies between what the potter sees through the

headset and the actual shape and position of the clay. Furthermore, the Quest 3 headset has some area of "blind spots" where the immersive view distorts because of reconstruction inaccuracy between the edge of the cameras. As a consequence, achieving precision and consistency in shaping the clay becomes difficult, leading to potential errors and inaccuracies in the final pottery pieces.

Additionally, the battery issue presents a practical limitation of MR headsets in pottery throwing. Prolonged pottery throwing sessions drained the battery quickly, necessitating frequent recharging. These exercises were conducted as the Quest 3 consistently plugged in which resolved the power issue but make the makers movement and choice of venue limited or inconvenient.

Furthermore, besides the tangling of the power cord, the inconvenience issue arises from the bulkiness and weight of the Quest 3. I was able to wear the headset for only rounds of pottery throwing without feeling fatigue and reduced dexterity, which might be an issue for further participants. The most inconvenient aspect of wearing the Quest 3 device lies in the setup stage of the guiding system. It is practically impossible to put up/down the headset and press the controllers in the middle of throwing with dirty hands. Even though part of the setup has been migrated to voice command, there are necessary steps like recalibrating the spatial anchor after drifting which still need the controller. Furthermore, the need to adjust and readjust the headset to ensure optimal fit further adds to the inconvenience, disrupting the flow of work and impeding the my focus and concentration.

Lastly, the less user-intuitive nature of MR compared to other more handy tools presents a barrier to adoption and acceptance among crafters. As taught by the instructor during my introductory sessions, we use clay caliper, and height measuring gauge to ensure accurate and concrete measurement. On the other side, other hands-free projection tools could also be more user-friendly and solve most of the questions above.

Discussion on Maker's Design Agency

In evaluating the the maker's agency for the three different approaches to pottery throwing—conventional with a physical template, guided with a mixed reality headset, and improvised with a scan of the design shape at the end—it becomes evident that each approach offers unique implications for the agency and creativity of the maker.

In the conventional approach with a physical template, the maker's design agency is the most constrained by the fixed nature of the template. While the template provides a clear structure and guide for shaping the clay, it also limits the maker's ability to deviate from predetermined designs. Consequently, makers may feel restricted in their creative expression, as they are confined to the parameters set by the template. Within these constraints, makers just retain agency in their choice of materials, techniques, and finishing touches, allowing for some degree of personalization and customization in their pottery pieces.

The guided approach attempted to provide more opportunity for the maker to improvise and deviate from the design. The digital guiding system substitutes the restraining template with a soft guide. I was able to use common tools to shape and trim the clay with more interaction with the material and took a more active role in the decision making process. However, one of the limitation is the rather ambiguous role of the guiding system, which simply provided additional tolerance but still functioned as a mentally restraining factor that instruct the decision and action of the maker. Or specifically, with the only presence of the original design intent as a direct overlay, I was tempted to follow its guidance and focused on making the shape so every part of the guide turns green. The limitation of the exercise resides in the fact that it lacks additional design constrains or other design influencing factors that the maker can get a hold of. When there are additional design factors presented, the balancing between different or even conflicting design requirements is the key aspect that granted the maker agency to make improvised and on-site decision.

The improvised approach with a scan of the design shape at the end offers the greatest degree of freedom and agency for the maker. By allowing makers to create their designs freely and then scan the final shape for replication or modification, this approach empowers makers to explore their creativity without constraints. Makers have full control over the design and execution of their pottery pieces, with the scan serving as a tool for validation rather than limitation. However, the reliance on digital scanning and replication may introduce challenges related to accuracy and fidelity to the original design, requiring makers to balance their artistic vision with the capabilities of the scanning technology.

Discussion on Relationship to Architectural Design and Future Works

So how does this pottery-throwing guiding system relate to the craft-driven design method of architectural design and its relationship to architecture?

The pottery-throwing guiding system could shine some light on the continuous development of the craft-driven design method in architectural design, particularly in its emphasis on craftsmanship, iterative processes, and the integration of traditional techniques with modern technology.

Firstly, ceramics, as a critical construction material, holds a distinct position in architectural elements. Take, for instance, ancient Roman vaulting tubes, which not only utilize ceramics but also mirror similar form and fabrication methods of this thesis. This historical example underscores the enduring relevance of ceramics in architectural design and construction. The pottery-throwing guiding system, by embracing technology while upholding traditional craftsmanship, could facilitate the reconstruction, preservation, and even modern adaptation of similar architectural elements and construction techniques. The scanning and archiving system could also be used for an on-site creation and identification of new ceramic modules that the construction crew customized.

This lead to the first potential direction of the future works of the thesis. The first avenue of exploration involves using the guiding system to recreate historical architectural elements that rely on ceramics. By combining traditional craftsmanship with modern technology, researchers could replicate ancient Roman vaulting tubes or other similar architectural features with a high degree of accuracy and authenticity. This process would not only contribute to the preservation of cultural heritage but also provide valuable insights into ancient construction techniques and materials. Specifically, a pavilion-scale project similar to the Computational Clay reference project. At this scale, the potential of craft-driven design would be fully explored due to the presence of more design constrains and coordination between different clay modules. Creating and improvising the pottery fabrication to balance between these new requirements and constrains will in turn cause design variation, this feedback loop could then be activated and the true potential and contribution of craft-driven design could be assessed.

The second connection and potential contribution to the field of architectural design and construction lies in rethinking the role of the building information modeling (BIM). The role of BIM in the existing architecture, engineering and construction (AEC) industry is primar-

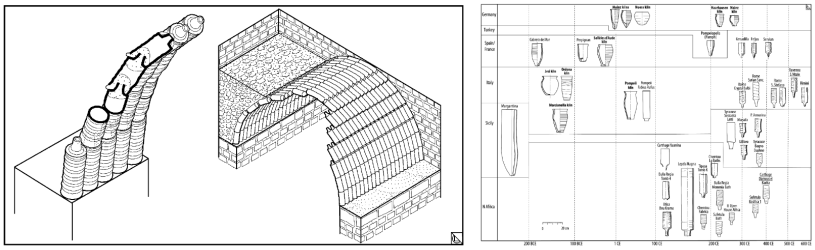


Figure 50: Ancient Roman Vaulting construction and modules, credit to Lancaster (2009) "Vaulting Tubes" (2015)

ily collaborative for the designers and engineers, and instructional for the construction crew. Without the agency of editing and modifying BIM information makes the contractors and workers incapable of updating their construction instruction and guidance according to what is actually happening on site. There are pipelines that can reflect the construction changes for further coordination. However, this always requires the builders to initiate a request and the rights of modifying design documentation and BIM information is always reserved by designers.

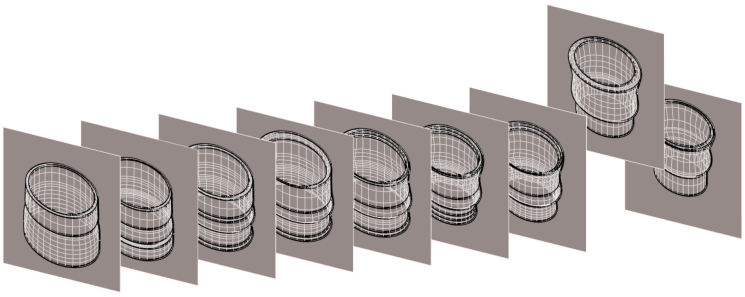


Figure 51: An illustration of BIM diary, credit to author

However, the pottery-throwing guiding and archiving prototype could provide a new perspective on how BIM is utilized between AEC parties. The consistent documentation of the existing project in digital models forms the concept of a BIM diary contributes valuable insights into the advancement of digital twins. Much like pottery-throwing guidance systems provide real-time feedback and assistance to potters, building information model diaries could document the development and refinement of the construction site and reflect that in the digital models, shedding light on the complexities involved in creating accurate digital representations of physical structures. This parallels the iterative and collaborative nature of craft-driven architectural design, where designers and the builders together engage in continuous refinement and experimentation to achieve optimal

outcomes. Through these parallels, we see how the pottery-throwing guiding system and craft-driven design methods in architecture share common principles of integrating technology with tradition to push the boundaries of creativity and innovation.

Conclusions

In conclusion, the journey through the exploration of and comparison between different approaches to pottery throwing reveals the dynamic interplay between tradition, technology, and creativity. As noted by the Tim Ingold in his book Being Alive: Essays on Movement, Knowledge and Description, "Any formal resemblance between copy and model is not given in advance but is rather a horizon of attainment, to be judged in retrospect," the process of pottery making is not merely about replication but about the evolution of the maker's vision over time.

Proposing an alternative design-making pipeline for an improvised yet guided making process that allows makers to make on-site decisions that impact the design is essential. This approach enables the digitalization of improvised physical artifacts for archiving and referencing, fostering a system that records and uncovers the continuous corrections that differentiate from the traditional design drawing and restriction instruction and assembly menus. The guiding system and the creative processes "gradually yield to a network of lines that close in on the drawing and pull the net tight, immobilizing the design." Through such a process, makers have the freedom to experiment and innovate while still benefiting from guidance and support.

In essence, the exploration of different approaches to pottery throwing, craft, and design underscores the importance of embracing innovation while honoring tradition. By combining the best of both worlds, we can create a rich and dynamic landscape for the art and architecture industry, where makers are empowered to express their creativity freely, guided by the wisdom of the past and the possibilities of the future.

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