FABRICATION OF COMPLEX CLAY STRUCTURES THROUGH AN AUGMENTED REALITY ASSISTED PLATFORM

JIAXIANG LUO[1], EFTHYMIA MASTROKALOU[2], RAHAF AL-DABOUS[3], SARAH ALDABOOS[4] and ALVARO LOPEZ RODRIGUEZ [5]
[1,2,3,4,5] *University College London*
[1]*luojiaxiang0610@foxmail.com, 0000-0002-6982-3692*
[2]*efimastrokalou@gmail.com*
[3]*rahafaldabbous@gmail.com*
[4]*skaldabbous@hotmail.com*
[5]*alvaro.rodriguez.14@ucl.ac.uk, 0000-0002-5561-1365*

Abstract. The relationship between clay manufacturing and architectural design has a long trajectory that has been explored since the early 2000s. From a 3D printing or assembly perspective, using clay in combination with automated processes in architecture to achieve computational design solutions is well established. (Yuan, Leach & Menges, 2018). Craft-based clay art, however, still lacks effective computational design integration. With the improvement of Augmented Reality (AR) technologies (Driscoll et al., 2017) and the appearance of digital platforms, new opportunities to integrate clay manufacturing and computational design have emerged. The concept of digitally transferring crafting skills, using holographic guidance and machine learning, could make clay crafting accessible to more workers while creating the potential to share and exchange digital designs via an open-source manufacturing platform. In this context, this research project explores the potential of integrating computational design and clay crafting using AR. Moreover, it introduces a platform that enables AR guidance and the digital transfer of fabrication skills, allowing even amateur users with no prior making experience to produce complex clay components.

Keywords. Computer Vision, Distributed Manufacturing, Augmented Craftsmanship, Augmented Reality, Real-time Modification, Hololens.

1. Introduction

Digital craftsmanship describes the involvement of the digital aspect in the process of making (Parisi, 2019). Craftsmanship on its own leaves us at the mercy of individual talent and skill. With the introduction of machine logic, the fundamentals of making have shifted into a more in-depth understanding of the matter (Wang, 2009). The

HUMAN-CENTRIC, Proceedings of the 28th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2023, Volume 1, 413-422.

certainty represented by the machine and the physical skill of the creator is combined through digital craftsmanship by developing a harmonious dialogue between them (McLuhan, 1964). Based on this concept, this paper will explore Augmented Reality as a tool that engages the maker in the fabrication process, builds a stronger relationship between creator and matter, and strengthens their interaction.

This study argues for an Augmented Reality assisted crafting process focused on both the fabrication of single components and on the generation of bigger assemblies. The components are developed through an innovative method of ceramic making that proposes a skeleton of sticks and woven rope to which clay is applied.

From the beginning, it was determined that this system would be accessible to all whether they were high-skilled workers, designers, artists, or users enthusiastic about ceramic making. As a result, a digital platform (ceARamics) was created that was divided into parts: "design" and "make". In the design section of the application, the designer/architect can import a volume, control specific data inputs, generate clay parts, choose among weaving styles and control the overall density. When the process is finished, a request for fabricating one's design can be made. In the "make" section of the application, users can implement clay components by following simple holographic instructions. Those instructions are embedded in the platform from other users that have recorded their weaving styles and techniques, thus transferring their skills. The whole idea of the ceARamics application is based on distributed manufacturing, enabling users with only the use of their phones and 3d printed nodes (which can either be 3D printed locally or be delivered to them) to fabricate without the use of expensive gadgets. The process is multidisciplinary and expands the production chain allowing for a fully democratised manufacturing process that is enabled through AR technology.

2. Methodology

This research aims to find an accurate and fast method for manufacturing and assembling complex clay structures. Under the guidance of holographic introductions, a method of making and assembling clay model structures is developed for users of various skills, from inexperienced to experts.

Material testing preceded digital model simulations. After studying different clay moisture ratios and structural options, the research team established a material workflow that allows for rapid modelling that does not produce cracks and affect firing, as well as a template system that allows for guided assembly using AR tools. The AR system was developed based on Hololens2 and mobile devices, making it accessible.

To enable large-scale model stitching, the geometrical representations that CeARamics works with are polyhedrons that can be replicated in an infinite number of stitches. The generative logic is provided by the Grasshopper© plugin WASP©. Components can be stitched together according to custom rules. Growth simulations that were used include growth along curves or surface constraints and aggregations through point clouds. The defined rules can be changed at any time during the procedure. These geometries can be replaced by digital clay models using computer simulation, so that designers can get a real-time simulation of the result via AR.

In terms of applying the system in architectural design, the research was mainly focused on the development of ceramic building facades such as shown in Figure 1.

Figure 1. Facades

Although ceramic facades exist today they are limited in terms of form and volume. Therefore, a system is introduced that can produce volumes and elevations defined by their complexity and plasticity, which is possible by the ceramic manufacturing method proposed in this paper.

3. Digital and Augmented Craftsmanship

After the industrial revolution, technology was introduced into the manufacturing process, changing the norms of crafting (Carpo, 2017). Even though automation processes in manufacturing reduce production time to a certain extent, there are cases where digital tools can become a burden due to the weakness they demonstrate in tasks that include human-like movements. A robot or an automated function may sometimes lack the ability to handle or manage an object in settings that require fine muscle control (Dellot and Wallace, 2017). Although specific tasks of production can be automatable, machines demonstrate inability to undertake a complete process because it is challenging for them to shift between tasks. In this context, human presence is required to oversee this shift or to complete the rest of the process.

Augmented craftsmanship is an approach to digital crafting that combines both digital tools and physical craftsmanship. Augmented craftsmanship can be seen in newly developed tools (such as HoloLens) that overlap virtual and real environments. It provides the opportunity to include more of the human factor within the fabrication process by broadening the creator's experience and developing further connections between the designer and the fabricated matter.

Subsequently, AR technologies may be the next step toward digital crafting by establishing a dialogue between automated processes and craftsmanship. Nowadays, more and more designers and architects are implementing AR technologies in their projects. Such an example can be seen in the woven steel pavilion implemented in the CAADRIA 2018 Workshop. The pavilion represents how designers can be holistically engaged in the process of making, by developing a digital platform that enables them to create interactive holographic instructions that translate design models into intelligent processes enabling unskilled construction teams to assemble complex structures in short time frames and with minimal errors (Jahn et al., 2018).

In the fabrication process presented in this paper, weaving through the frame of the components was an essential step. However, because of the scale of the components and the small distance between the sticks weaving as a task was too complex to be performed by a robot (robotic arm) so the human factor needed to be involved. Furthermore, for the success of the physical models, the maker was required to have a good understanding of their form and materiality. At the same time, it was important to generate a discipline through which the components could be mass-produced while maintaining their highly customisable features. Augmented Reality was selected as the tool that would enhance the user's natural crafting abilities and would accelerate the manufacturing process by facilitating mass production and customisation using human labour guided by HoloLens.

On the weaved frame of the components, sprayed clay was applied. This method, as opposed to using moulds or 3d printers, allowed the clay element to maintain its organic features and unpredictability. The idea was to be true to the matter and to generate a method that best represents its identity by respecting and testing its limits (Picon, 2019).

4. CeARamics Application

The components that were explored in this process were based on geometries of tetrahedrons and pentahedrons because compared to orthogonal shapes they provide numerous possibilities for combinations in all three axes and can be attached by all their faces. In order to establish the fabrication method presented, material testing was implemented as well as a trial-and-error process for the development of a rigid and feasible substructure that could be removed during the firing phase. As illustrated in Figure 2, for each component, nodes are placed on the corners of the polyhedrons that hold the sticks in place. These nodes are open from both sides, making it possible to pull away the sticks once the clay is dry. Weaving in patterns between the positioned sticks follows, creating the faces of the polyhedrons. After that is completed, clay is applied.

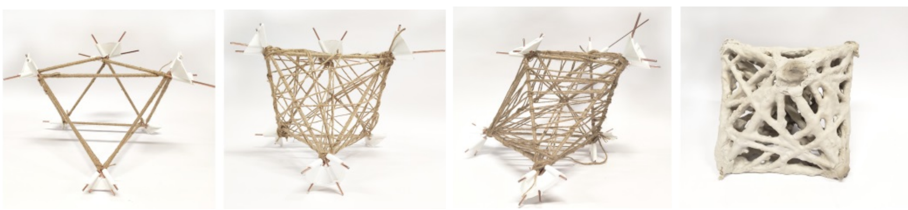

Figure 2. Component fabrication

4.1. AUGMENTED REALITY FOR THE DEVELOPMENT OF COMPONENTS

In the "make" section of the application dedicated to the manufacturing of components, users are able through their phones or Hololens to launch the Augmented Reality simulation displayed in Figure 3, that positions the outline of the component in space as well as where the sticks and nodes should be. After the user has assembled the frame, weaving zones with lines within them appear so that it is easy to follow the weaving patterns with the rope. This simplifies the process of assembling the component and makes it faster, even for someone who is doing it for the first time. After having assembled and weaved the total number of components that each user was assigned to, the users collaborate with designated ceramist workshops to apply clay and glazes.

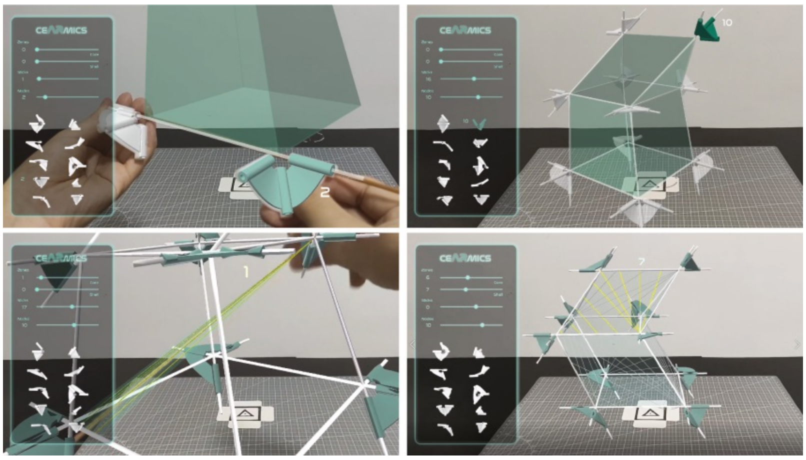

Figure 3. AR simulation for component manufacturing

4.1.1. Application of weaving styles

Computer vision is a field of artificial intelligence that trains computers to interpret and understand the visual world by replicating parts of the complexity of the human visual system. Using digital images, machines can accurately identify and classify objects — and then react to what they "see." (Jahn et al., 2019).

In this research, computer vision was explored as a way to identify weaving patterns-styles that would then become digitised and easily followed by users. In a scenario where different people weave on the same physical component, it is understandable that each individual would intuitively weave differently. Therefore, in the design part of the app, the option of weaving styles was incorporated. This option was crucial for architectural applications such as facades, where the components must exhibit some degree of uniformity. Two methods were explored. The first was movement tracking and the second was drawing curves on a physical model with the guidance of AR. The goal for both cases was for the information to become digital and be incorporated into the application so that the users could follow their desired weaving styles.

Object tracking is a field within computer vision that tracks objects as they move across a series of video frames (Wang, 2019). This works by creating a unique ID and specifying a position for the object which will be identified in each frame. Tracking was used as a way to determine weaving motion, by placing a sphere of distinguishable colour at the end of the rope as shown in Figure 4. This process generates the coordinates of the sphere while it moves, thus composing the "weaved" curves. However, this process wasn't entirely successful because when a person weaves, their hands or even the rope are very likely to interfere, disrupting the process.

For the second method, the faces of a component are unfolded digitally so that it becomes 2-dimensional. This is because the application allows drawing on each face only in 2D. Figure 5 demonstrates how the user is enabled through AR to virtually draw "weaving lines" through the screen of a mobile phone on the physical model.

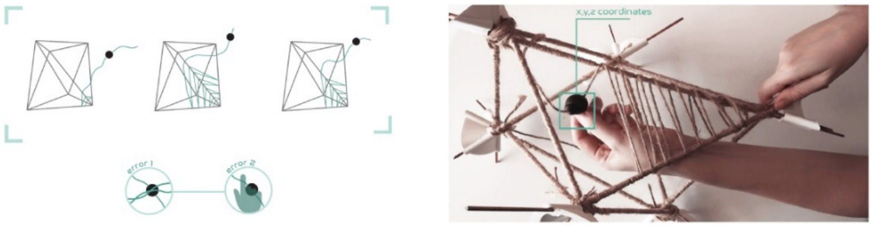

Figure 4. Sphere tracking

Those lines are directly transferred as curves to the design program and can then be attached to the unfolded 3D model through the app. This allows users to rapidly decide on the weaving style they prefer and instantly have the digital model of it.

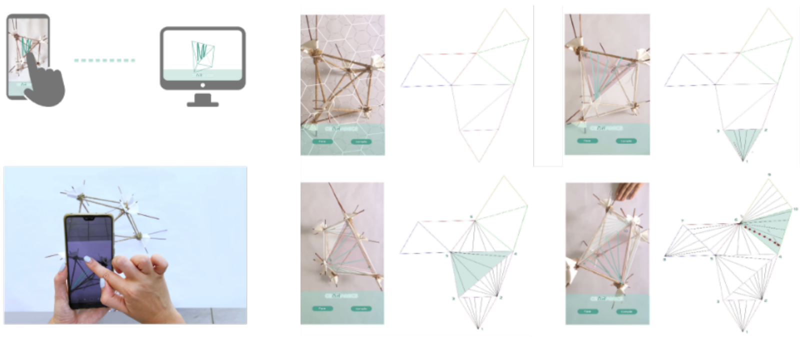
Figure 5. Weaving style recognition

Nine basic weaving styles were developed for the style catalogue, from which users can select one for their design. In the making part of the app, users are guided through AR to weave based on the specific style the designer has chosen.

4.2. AUGMENTED REALITY FOR ASSEMBLY

The assembly of components to create bigger parts was studied both physically and digitally. Augmented reality through the application supported both and one was dependent on the other. The design section of the ceARamics platform allows the population of digital clay elements based on a generative algorithm. The generative logic of component growth is based on custom rules and includes all information necessary for the aggregation process (geometry, location of connections, and orientation). Therefore, the type of components and their position when producing a bigger aggregation is determined by this algorithm. The types of components used were:

- The basic tetrahedron and pentahedron named Type-V + Type-T displayed in Figure 6.

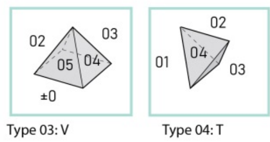

Figure 6. Type-V and Type-T

- Geometrical representations of orthotetrahedrons and pentahedrons named Type-L and Type-S, displayed in Figure 7. These types allow for a faster and more random generation of aggregations compared to the basic tetrahedron and pentahedron since they contain more faces that enable a wider variety of connections. However when the growth simulation was performed, it was found that the results performed directional convergence. The main reason is that due to the specificity of the geometry there is only a 20% possibility to change the growth direction of the components. In order to apply directional variety it was necessary to add Type V and T as a transformation medium.

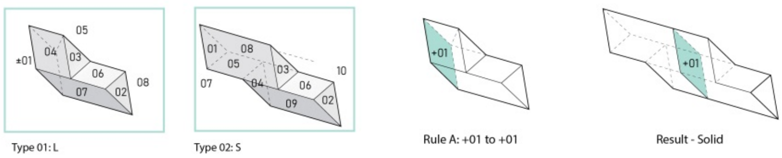

Figure 7. Type L and S combination

In the end, four sets of rules that used all types of components were selected to generate different discrete design results. For example, the wall generation results displayed in Figure 8 are the outcome of these different set of aggregation rules.

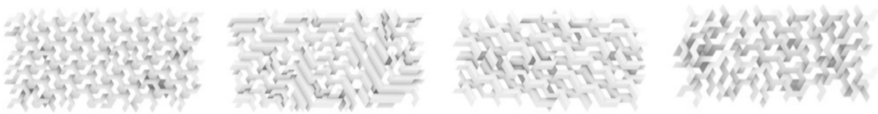

Figure 8. Walls according to sets of rules

In the design section of the platform, designers can import their geometries (surfaces, voxels) to the app and generate solid components on them based on the generative algorithm. Using the WASP© replacement algorithm, the solid components can be replaced by digital clay parts of varying weaving densities. This process relies on mechanical simulation analysis as well as functionality. Depending on the type of space the geometries will enclose (public, semi-public, private) the porosity of clay parts is adjusted accordingly. In terms of mechanical analysis, the generated part obtains the corresponding force areas, which are replaced by clay modules of relevant strengths to obtain a reasonable design result. This process is described in Figure 9 below.

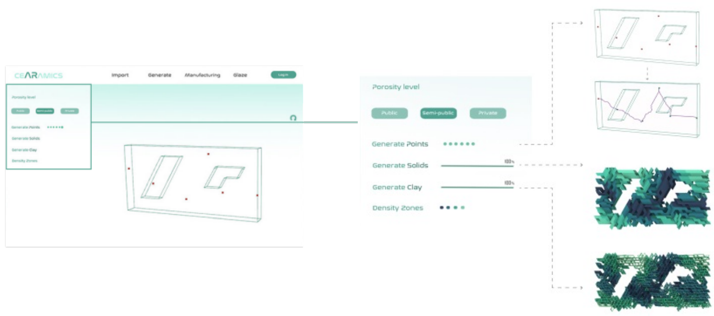

Figure 9. Replacement of solid components with clay parts

Users can finally choose from a variety of weaving styles for their design and then view the glazed version of it by selecting a colour from the palette. The designer can then apply through the application for the generated part to be manufactured. The clay elements will be assigned to manufacturers worldwide that will produce them guided by the application. Once fabrication is complete, the components are shipped to the building site. Construction workers can use AR to view the digital aggregation within the real environment. They can then select a portion of the aggregation to assemble and begin construction. The prospect for this platform is that it is meant to be accessible on different devices (Hololens, tablet, phone). Thus, on their chosen device, manufacturers can view the aggregation in segments consisting of three different colours of solid components as shown in Figure 10. Each colour corresponds to a different density of components. The combination of clay parts is a cladding system positioned on special panels that are attached on a building like a curtain wall. The components themselves are non-structural. In the occasion when the edges of the components are too irregular because of the organic form that clay produces, they are sanded and smoothened in order to be well-adjusted and fixed on the panel.

Figure 10. Assembly of aggregations

5. Making the platform accessible

When digital tools were first developed, they were handled in a way in which users could process, alter and communicate information individually rather than in a joint effort (Carpo, 2011). However, design and production started to overlap at the turn of the 21st century with the emergence of digital tools that allowed for generative and automated processes through information modelling and contemporary fabrication methods (Carpo, 2011). Modern technology allows architects through digital communication to control what is being implemented and cultivates solid connections between the different disciplines involved in the process of making (Celanto, 2007). Furthermore, digital architectural software has evolved in a way that emphasises its participatory nature and, except for the professionals involved, creates platforms for citizen and community participation as well (Carpo, 2011).

The digital era brought the shift from mass production to mass customisation, which entailed variability and a process of specialist and social involvement in all stages. Therefore new models of shared ownership and authorship are developed (Michalatos, 2016). An important part of the holistic system that was introduced is open-source networks that allow interaction and citizen participation (Sanchez, 2017).

Within this context of a holistic system, the process that is analysed in this paper aims to create a platform that offers the tools and means for decentralised forms of production within a system that enables social empowerment.

When it comes to manufacturing through the ceARamics application for the building industry, it was critical to invent a way for mass production. Instead of following a centralised manufacturing procedure, it was questioned whether Augmented Reality could activate a system of distributed manufacturing. In that context, the application users are assisted throughout all the needed steps with an AR simulation which they can launch through their phones. Whether fabrication is implemented by specialists, workshops that engage communities, or even individuals fascinated by ceramic making, the aim is definitely for a decentralised procedure that expands the production chain and democratises the process. The nodes, sticks and rope that are needed for component assembly are shipped as a kit to the users, and then as illustrated in Figure 11, users only need their phones to operate. The fact that this process does not require expensive equipment to function adds to its accessibility and makes it more inclusive.

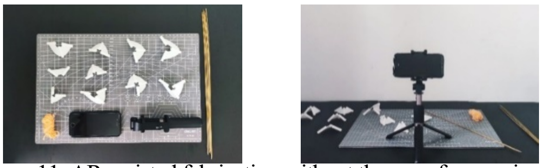

Figure 11. AR assisted fabrication without the use of expensive gadgets

In addition, it is understood that since the fabrication process could be implemented with the participation of people that could be anywhere on the planet, what was previously introduced by Michalatos (2016) about shared authorship is also applied here. The outcome is a collaborative effort of various contributors which also adds to the development of a genuine democratised system.

6. Conclusion

The use of clay as a building material has been a constant throughout architecture history. In recent years, its integration with digital and automated technologies has collaborated to keep it as one of the more relevant materials, as well as sustainable. By introducing Augmented Reality assisted manufacturing into the process, the catalogue of possibilities is expanded, and traditional and new techniques, can now be combined together with the prevalent industrial manufacturing of the material.

This paper presents the idea of a platform that allows for an AR-assisted crafting method to develop clay components and their assemblies. The platform has the potential to guide the fabrication process with holographic instructions and allows for component population through a generative algorithm that provides various design options. This solution for merging physical craftsmanship with the efficiency of technology allows non-skilled workers to participate in the process, enabling a larger community to access and share manufacturing skills and preserve them on a database.

Although the project is still in the development phase, and more research and testing would be required, the capacity to record and deliver skills to untrained users has been tested through prototypes that show the potential of this AR assisted crafting system. In contrast to other mainstream automated manufacturing processes, the physical crafting characteristics of clay enable this method to be more intuitive, participatory, and community conscious while preserving the heritage of clay craftsmanship, demonstrating how craftsmanship can continue to adapt to future technologies. The presented manufacturing system is a model seeking to explore the limits of a concept like this and stimulate thought about how it can be applied to other production models as well.

Acknowledgements

The research was developed in The Bartlett School of Architecture, UCL 19/20, within the Research Cluster 9 Agenda of the B.pro AD M.Arch. The project was supervised by the cluster leaders Alvaro Lopez Rodriguez and Igor Pantic (0000-0001-8802-5592).

References

Carpo, M. (2011). The alphabet and the algorithm. Mit Press

Celento, D. (2007). Innovate or perish: new technologies and architecture's future. Harvard Design Magazine,26(Spring/Summer).

Dellot, B., & Wallace-Stephens, F. (2017). The age of automation. *Artificial intelligence, robotics and the future of low-skilled work*, 44.

Driscoll, T., Farhoud, S., & Nowling, S. (2017). Enabling mobile augmented and virtual reality with 5G networks. *AT&T: Dallas*, *TX, USA.*

Jahn, G., Newnham, C., & Beanland, M. (2018). Making in Mixed Reality. Holographic design, fabrication, assembly and analysis of woven steel structures, DOI:10.52842/conf.acadia.2018.088

Hahm, S., Maciel, A., Sumitiomo, E., & Lopez Rodriguez, A. (2019). *FlowMorph-exploring the human-material interaction in digitally augmented craftsmanship*. *CAADRIA 2019* (pp. 553-562). The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), https://doi.org/10.52842/conf.caadria.2019.1.553.

Laing, R. (2018). *Digital participation and collaboration in architectural design*. Routledge.

McCullough, M. (1996), Chapter 7: Medium. In: *Abstracting Craft, The practiced digital hand*, Cambridge, Massachusetts, London, England, pp. 191-220, https://doi.org/10.4324/9781315161488.

McLuhan, M., & Fiore, Q. (1967). The medium is the message. *New York, 123(1)*, 126-128.

Michalatos, P. (2016). Design signals: The role of software architecture and paradigms in design thinking and practice. *Architectural Design,86(5)*, 108-115. https://onlinelibrary.wiley.com/doi/abs/10.1002/ad.2096

Parisi, L. (2019). Media ontology and transcendental instrumentality. *Theory*, *Culture & Society,36* (6), 95-124, https://doi.org/10.1177/0263276419843582.

Picon, A. (2019). Digital Fabrication, Materiality and Nostalgia. In *Robotic Building* (pp. 112-116), DOI:10.11129/9783955534257-024.

Sanchez, J. (2017). Combinatorial Commons: Social Remixing in a Sharing Economy. *Architectural Design*, *87* (4), 16-21.

Wang, X. (2009). Augmented reality in architecture and design: potentials and challenges for application. *International Journal of Architectural Computing*, 7(2), 309-326, DOI:10.1260/147807709788921985

Yuan, P. F., Menges, A., & Leach, N. (2018). *Digital Fabrication,* Tongji University Press