FEDERICO GARRIDO
KARLSRUHER INSTITUT FÜR TECHNOLOGIE

JOY SAMUEL
RODRIGO BRUM
CHRISTIAN SCHMITT
GERMAN UNIVERSITY IN CAIRO

Digital Imperfection

Earth brick construction supported by mixed–reality technologies

Abstract

Digital Imperfection was a temporary installation at the German University in Cairo (GUC) that combined the use of mixed-reality tools and earth as a sustainable and multifaceted material. The project involved two separate processes that came together during the final montage procedure: on the one hand, the design of handmade earth bricks, and on the other, the design of a parametric wall and the coding of the montage procedure on the mixed-reality platform.

The project aimed to reconnect both students and a wider audience with a traditional craft through the use of modern digital tools. Hand-crafted bricks were stacked to create a wall with the help of a HoloLens device, which overlaid a digital four-dimensional model over the physical world. Despite the mediation of digital apparatus, the aim was to engage participants in a comprehensive workflow that involved aspects of both handmade production and interactive assembly, rather than promoting a mere robotic process. During the research phase, we investigated the relationship between high-tech and low-tech tools through the following questions:

- How can we incorporate digital technology without losing human interaction?
- How can we measure and account for manufacturing imperfections?
- How can we minimise those imperfections within the design and its montage?
- What benefits and opportunities are offered by the combination of low- and high-tech techniques?

The process accounted for various imperfections and height irregularities (resulting, for example, from differences in mortar thickness or manufacturing), sustaining a constant loop with real-time feedback: the physical model was updated with new bricks while the digital model was updated with height corrections.

The research offers multiple benefits. Firstly, it introduces students (and a broader academic public) to the use of sustainable materials in combination with parametric design. Secondly, it produces a digitally-designed installation (of relative complexity) without the need for printed documentation. Finally, it demonstrates a resource-saving method in which both building procedure and instructions are entirely virtual, eliminating the need for framework or printed plans.

Digital Imperfection puts humans at the centre of the digital assembly process; humans are not replaced by robots or algorithms

but instead collaborate with them in ways that maximise the advantages they offer.

Introduction

Earth is no longer a peripheral material phenomenon. Circularity, lifecycle and cradle to cradle are finally dominating architectural debates and conferences about sustainability. The architectural world is developing a new awareness and a sustainable conscience around architecture and construction. Recognising and reflecting this growing awareness, and seeking to further develop it, a workshop was held at the German University in Cairo (GUC) in 2021. The workshop was organised as a collaborative event between two elective courses, "Unplugged Matter: Earthen Material" (UM:EM) and "Introduction to Robotics in Architecture" (IRA). It considered the use of earth as a building material from a range of perspectives, including ecological, economic, social, participative and aesthetic. These considerations are all important for the development of a holistic approach to sustainable activity.

The present research aimed to combine perspectives specific to each of the elective courses, and thus to integrate, at every stage, knowledge and understanding particular to both material responsible design and digital/parametric design. While it is already almost impossible to avoid digital technologies in contemporary architectural discourse, the collaboration also proposed to augment not only the capacities of each sub-discipline, but also the perception (and auto-perception) of them by associating low-tech building techniques with hi-tech design procedures. Given the focus of the IRA elective course, one key priority of the collaboration was to expose students to some of the most complex tools currently available for design and construction. This is a highly relevant concern within contemporary architecture given the relative absence of mixed reality technologies such as Augmented reality (AR) and Virtual reality (VR) in design and construction contexts despite these same technologies rapidly becoming ubiquitous in other areas of everyday life (for example, in the form of real-time image and video filters on social media platforms such as Snapchat and Instagram).

The research used Microsoft's HoloLens, a smart glass projection system that uses a complex array of sensors and cameras in order to 'sense' its environment. The device is able to interpret its position in a given environment and project information seamlessly onto a transparent glass, creating the impression of "holographic" projection, that is, the superposition of digital imagery over reality. The HoloLens is Microsoft's take on "mixed reality", (Speicher, Hall, and Nebeling 2019, 1-15) a combination of technologies that fosters interactions between real and virtual environments by using instinctual interfaces such as precise motion detection and environmental sensing. Mixed reality is designed as a blend between physical and digital worlds, a form of technology that enables the user to operate seamlessly in both physical and virtual spaces. According to Microsoft, the developer of HoloLens, Mixed Reality can be thought of as a spectrum, with the physical world at one end and the digital world at the other (Wen et al. 2022). Within this spectrum, AR is often understood as being closer to the ‘ physical world,’ while VR is closer to the ‘digital world.’

The scope of the present research does not include consideration of the many and complex functions of mixed reality technologies, such as motion sensing or cloud computing. The focus instead will be on using the HoloLens as a location and projection device. This will involve tracking the user in three-dimensional space while overlaying graphics and precise visual feedback.

Objectives

The main objective of this research project is to explore possible relationships between handmade craft techniques and digital tools. The research installation was designed as a collaboration between two courses, one dealing with earth construction and the other with robotics and parametric design, and for this reason, the intention was to find common topics and concepts in order to cross-fertilise each field of expertise with the other.

The possible fields for collaboration between the two courses, UM:EM and IRA, were defined by the different stages of a design, either analogue or digital. These stages were defined roughly as:

- Conceptual design
- Constructive/detail design
- Design procedure
- Design of construction procedure
- Construction process

The concept behind the collaboration was to hybridise these stages, to the extent possible, blending both analogue and digital techniques. As previously noted, while most contemporary design procedures include more or less of a digital component, we intended to maximise this feature by using parametric design or remote sensing instead of just using three-dimensional modelling or CAD drawings. For example, when designing the final pieces, or ‘bricks,’ the student did not only model them in 3D but also parametrised their design, exploring different formal and size variations of the same design. In the conceptual design stage, we evaluated the possibilities of building two distinct types of object: either, on the one hand, a sculpture or a bench, or else a wall. The possibilities of digitalisation allowed us to parametrise a shape, for example, a bench, and then the formwork that would limit the rammed earth. The parametric wall was designed by considering two parametric variables: the brick and the wall itself. Design research explored both, testing different dimensions and geometries of forms and their interactions. At this point, before any material input, this conceptual design stage was limited only to the decision to build either a wall or a sculpture.

The constructive design phase was carried out by students from the UM:EM course. They explored several brick types using different earth construction techniques, such as for compressed earth bricks (CEB), adobe and rammed earth. As each student group tested and developed their own ideas, there was significant diversity in the shapes of the resultant bricks, ranging from 'tileable' shapes like hexagons or traditional bricks to other, more complex forms, featuring interlocking shapes and Tetris-like geometries (Figure 1). This stage was carried out entirely with analogue tools such as sketches and models, while also trying to take into account material qualities and characteristics such as resistance, rigidity, overall load bearing capacity and other visual features, such as textures or colours.

During this semester, teaching was influenced by Covid 19. Lockdown forced us to reconsider the manufacturing process, leading to a switch from CEB bricks to the use of a wooden frame that could be exchanged among students. Students *rammed* the bricks by hand at home, then let them dry until the assembly day. The increased number of imperfections resulting from this procedure forced, and indeed inspired, us to come up with a digital solution – one that could effectively address the issue of bricks of varying heights and could be integrated into the digital design and build setup.

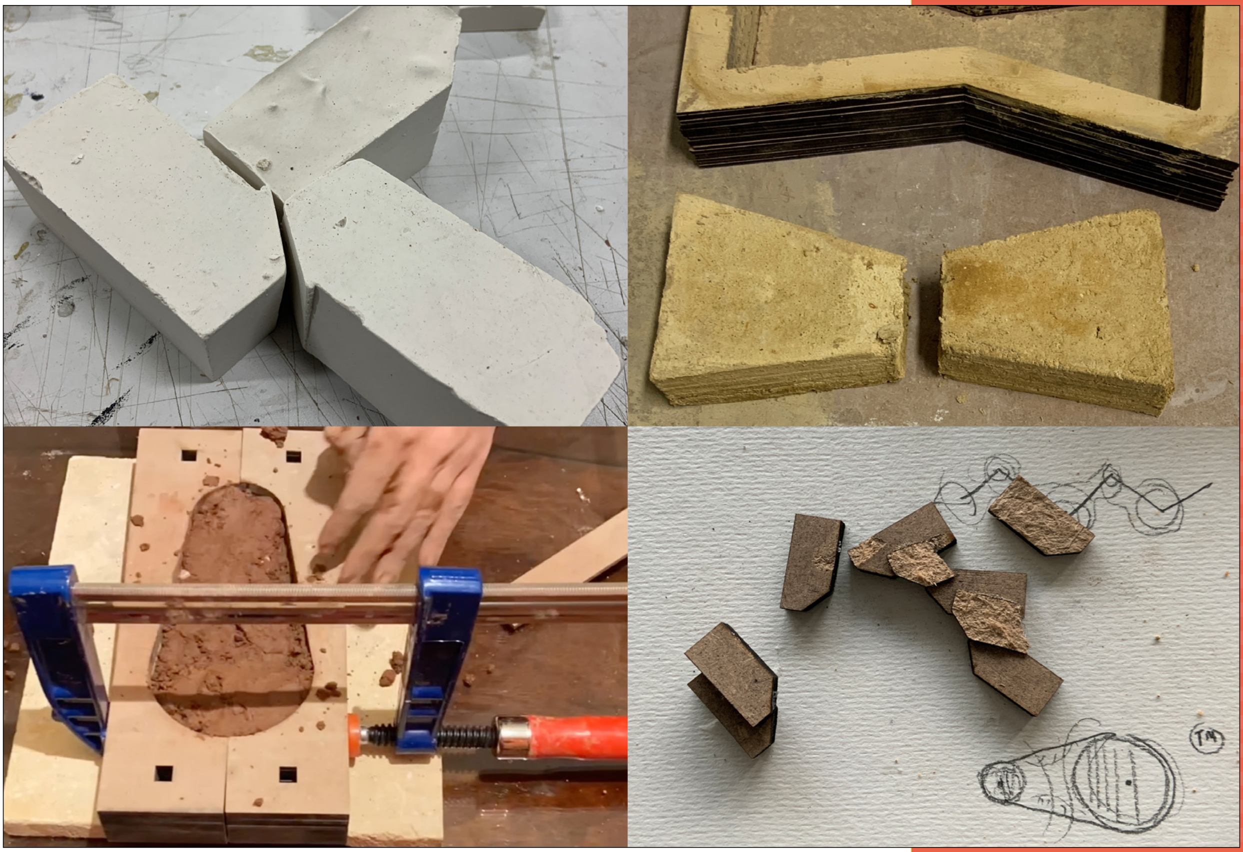

Figure 1. Student work. Early sketches and models for brick design and interlocking possibilities

In parallel to this work, students from the IRA course carried out the design procedure for a wall composed of single bricks. It was allowed for the wall to take any shape, both in section and floorplan, including the possibility of slope, inclination or curvature in any plane. The solution for the wall definition was quite simple. A surface is defined by two curves or polygons (top and bottom). If both curves have the same dimensions and are displaced in vertical, the wall will be perfectly vertical. If they are misaligned or offset, rotated or scaled in any direction, then the wall or parts of it will be sloped. Finally, the wall is ´sectioned´, or ´sliced´, in horizontal lines: these will be the guiding lines for the bricks. Each brick will be located over these horizontal lines, either aligned to it or re-oriented according to other criteria.

Lastly, the construction procedure was designed by students from both teams, who negotiated the particularities of the material and construction technologies and translated them to the digital project. The assembly procedure needed to be embedded with the final design of the wall, as did brick size and the unique positions of each brick in the wall. Since the procedure was to be performed with the HoloLens device, a certain differentiation between the different bricks had to be defined, for example, between the bricks in the wall, the bricks in the pick-up area and the ´current´ brick, the one being carried by the user.

The intention was to create a seamless workflow that would allow the user to visualise any change in the design of the wall (either its overall shape or the position or type of bricks) in real-time, on a one-to-one scale and superimposed on the actual site. It was also intended to account for various imprecisions, such as geometric inaccuracies due to the manufacturing process, mounting mistakes or discrepancies in the thicknesses of materials, for example, in the ´mortar´. Since these types of errors are embedded in the material and the construction procedure itself, the purpose of this research was also to create a design process that could effectively account for them.

Rammed Earth: Material and Technique

The use of rammed earth construction methods stretches back through centuries-long traditions, with the technique evolving from generation to generation through orally transmitted experience reports among master-builders (Guillaud 1997, 5). Rammed earth is made from a mixture of loam and granulated stone that can frequently be found in nature. During the ramming process the loose earthen material is turned into a solid mass (Kapfinger and Sauer 2015, 157). Humid earth is poured into a formwork in thin layers and then rammed to compress the material and increase its density. By increasing the density, the compressive strength and water resistance of the material are also increased. Traditionally, the ramming process was done by hand with a heavy stomp, but in recent decades, ramming has been done mechanically using a pneumatic tool. Current research projects are attempting to partly automatise the process using robotic manufacturing technologies (Bonwetsch, n. d.).

Rammed earth is not homogeneous around the world. In fact, as compared to adobe and compressed earth bricks, rammed earth is considered particularly susceptible to variation in quality due to differences in soil quality and homogeneity (Houben and Guillaud 1994; Standards Australia 2002). Due to their enhanced durability, buildings constructed from both rammed earth and compressed earth bricks are considered less costly to maintain compared to those constructed from adobe.

Use of prefabricated rammed earth blocks is a technique that sits somewhere between rammed earth and compressed earth bricks. They are usually manufactured by hand or with very little mechanisation. Apparently, the first attempts in creating rammed blocks were made in France during the nineteenth century by Francois Cointeraux. Cointeraux fabricated pre-cast small blocks of rammed earth, using hand rammers to compress humid soil into small wooden moulds, which were held in place with the feet (BASEhabitat 2018). The present research was carried out using a similar technique, the compressing of small brick-type blocks on a wooden frame.

Clay types: The case of Egypt

Although earthen materials are available worldwide, Egypt offers two main subtypes of clay: one originates in the sedimentation of the Nile, another in the desert. As the former subtype is important for agriculture, its use has been restricted over time. The bricks for this project belong to the latter subtype: desert clay.

The soil for this project was obtained from Tunis Village, in the Fayoum governorate. This soil is a desert clay soil, suitable for earthen construction, and its use does not cause desertification of agricultural land. A series of tests were carried out in order to determine the composition of the clay. For example, one of the tests employed was the sedimentation test. This test is conducted by filling a transparent bottle one quarter full with soil and three quarters with water. The bottle is shaken vigorously and left to settle until, after a period of around eight hours, the water on top is clear, gravel and sand fill the bottom of the bottle, with silt above this, then clay, and finally organic components on the top of the excess water. This test can be used to approximately tell the percentages of each component in the soil, which is then was plotted on the United States Department of Agriculture (USDA) textural classification chart to determine the type of the soil. In this case, a lab test established the percentages of each material: clay 15%, silt 50%, and sand 35%. According to the USDA chart, the soil type is a loamy soil. Further compression lab tests yielded 8.36 kg/cm^2 as a result for unconfined compressive strength (Maher 2020) (Figure 2).

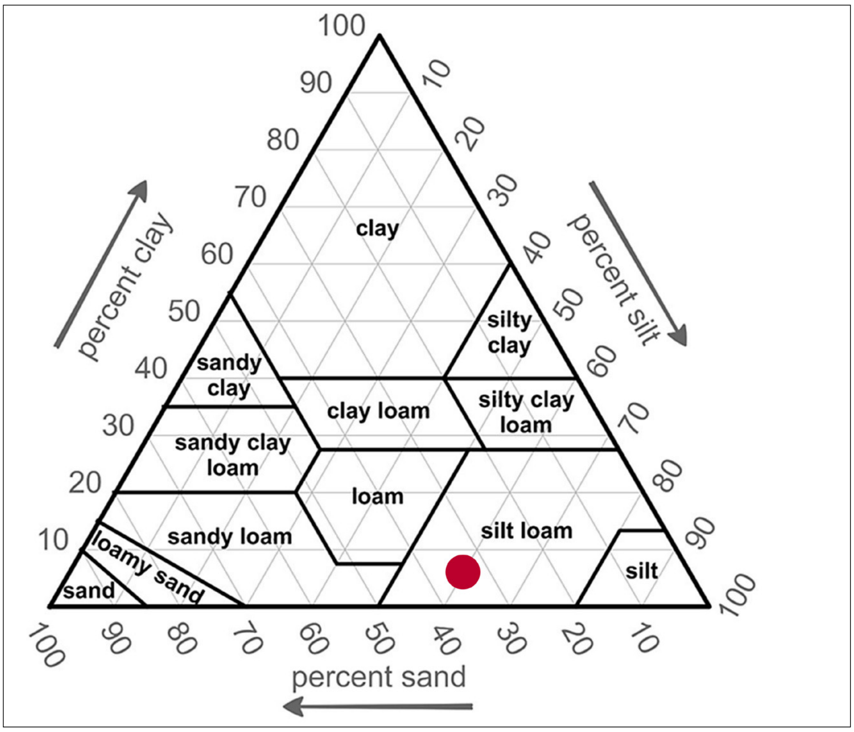

Figure 2. USDA textural classification chart

Brick design

The design of the rammed earth bricks was an integral part of the UM:EM course. The students were divided in teams, and each group designed and manufactured several brick types, first in a digital medium, later as models and finally in real scale with actual earth. The bricks were formed manually by students, without mechanical assistance, to conform to set dimensions. Each brick needed to be formed of a number of flat sides, such that they could be stacked or recombined horizontally, vertically or in any other possible combinations. Similarly, the geometrical characteristics of each brick were required to be such that they were able to ´lock´ to their vertical or horizontal neighbours.

Within the bounds of these geometrical constraints, the students experimented with various designs and techniques. Several kinds of brick were employed to test different types of walls, starting from straight, vertical walls and then experimenting with other designs, such as zig-zagging and curved walls. The teaching team and the students eventually decided on a final design for the brick to be used (Figure 3): an isosceles trapezoid with curved edges. This shape allows the brick to be ‘articulated’ and rotated incrementally without exposing edges, which might otherwise present points of structural weakness.

Once this brick design was established, several wall designs were tested, taking into account the number of rows, overall weight, number of bricks and structural resistance. Given that the wall was to be built without any physical reference or measurement, the final design of the wall was limited only by its material characteristics (Figure 4).

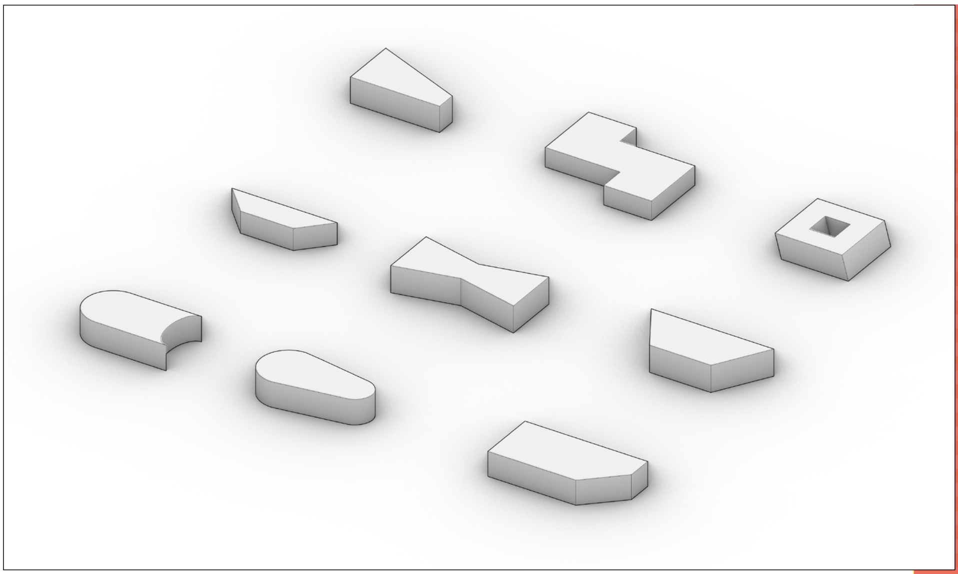

Figure 3. Different brick types designed by the students

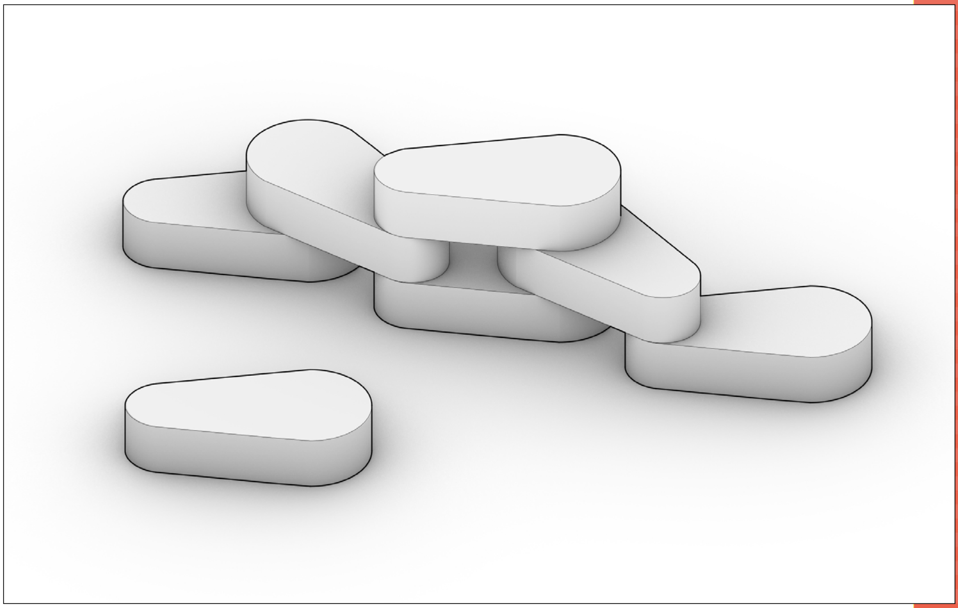

Figure 4. Selected brick

Design Procedure

The wall was designed with a parametric design software (Rhinoceros Grasshopper), while simultaneously, a real-time procedure was streamed to the HoloLens device in the field. The parametric definition takes two curves (one on the bottom and the other on top) and creates a surface between them. If both curves are straight parallel lines, the resulting surface will be a straight surface. If they are not parallel, the result will be a ruled surface. Finally, if one or both curves are curved, Rhinoceros will interpolate a surface connecting them, resulting in any number of complex surfaces, like hyperboloid or paraboloid patches, among other irregular surfaces.

In the next step, this surface is ‘divided’ in rows according to the height of each brick row (calculated as the thickness of the brick and the mortar combined), resulting in a series of stacked curves that are parallel to the ground. On each of these curves, a line of bricks will be laid, separated by a user-defined parameter (Figure 5).

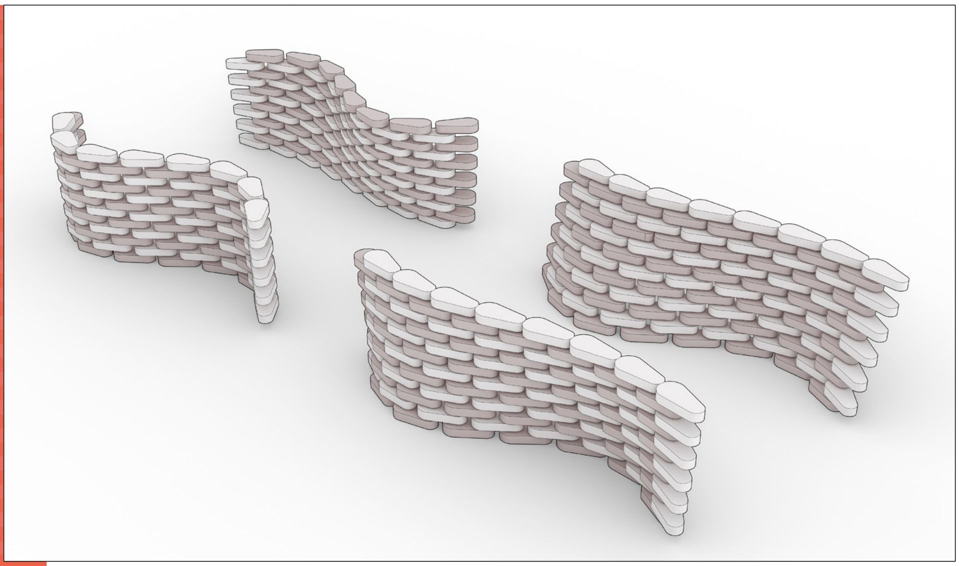

Figure 5. Parametric wall compositions

Because of the design of the brick, the relevant characteristic is that the centres of the curved parts are aligned. This way, the relative rotation angle between each brick can vary without compromising its structural capacity. Also, the separation between bricks remains constant, but the relative rotation may change while adapting to the wall geometry. Furthermore, the position of each brick is precisely defined in a three-dimensional space, as is its angle in the XY plane (parallel to the ground).

Assembly Procedure

The position and rotation angle of each brick is pin-pointed in space, and this information is transmitted to the HoloLens device. Due to fabrication issues, there were two different brick types, of two different thicknesses. Due to the need to maintain a regular height, the user must be able to identify them easily. Since the difference in height was sensible but not easily noticeable, two different piles of bricks were defined, one with each brick type (A and B). The parametric procedure indicated to the user where to pick up the bricks (either pile A or B) and then where to locate them with precision.

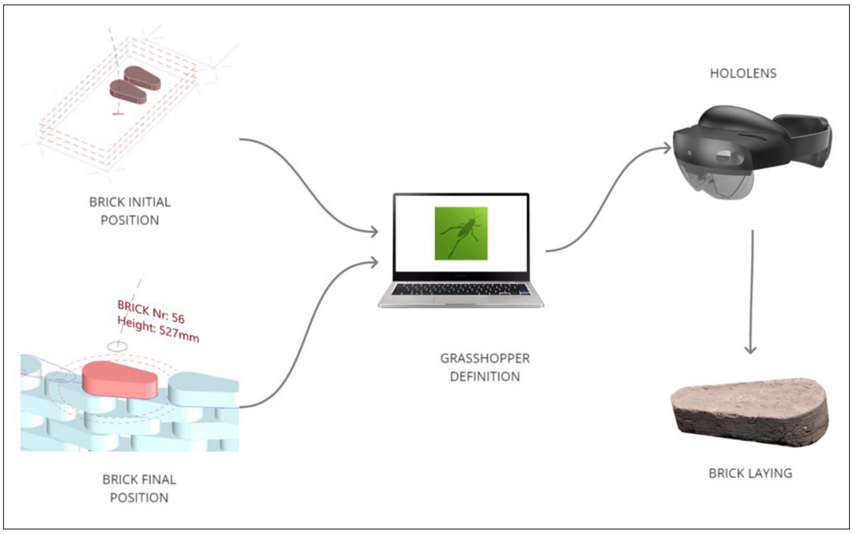

Figure 6. Assembly procedure, from parametric design to bricklaying

The assembly process required two persons: a user or brick layer using the HoloLens device, and an operator on the computer. The operator controlled the overall procedure and selected the 'active brick', that is, the brick that is highlighted in the wall composition and streamed to the HoloLens device (Figure 6).

The bricklayer receives the 'active brick' location (either pile A or B) and also the final position in the wall. The HoloLens device highlights the location of the brick pile by projecting a dotted line from the brick to its final position on the wall (a video of the installation assembly process can be seen here: https://vimeo.com/714403348) (Figure 7- 9)[1]. The final position of the brick in the wall, as well as its rotation, is highlighted in red. The bricklayer then matches the position of the physical brick to its position in the HoloLens projection. Once the brick is located in its final position, the operator moves on to the next brick: a new 'active brick' is designated, and the process is repeated.

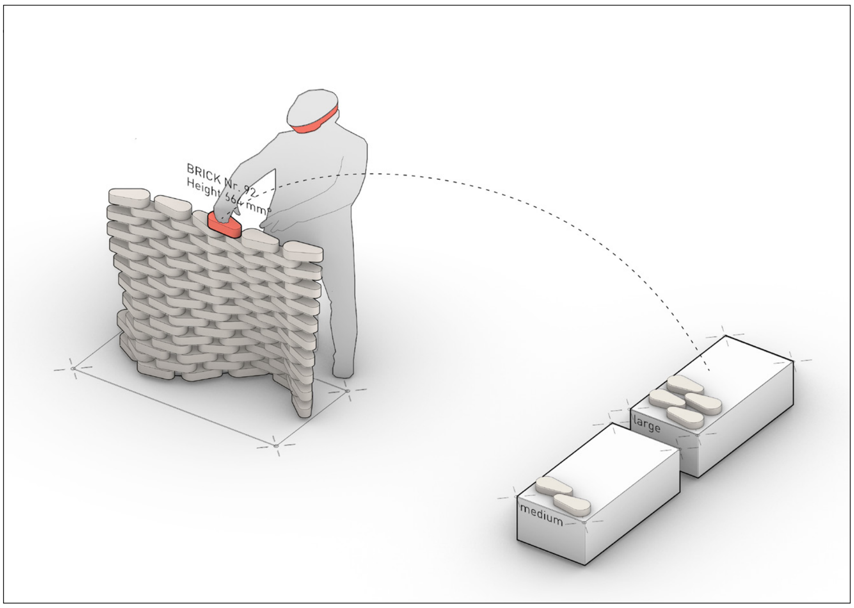

Figure 7. Brick type location and assembly procedure

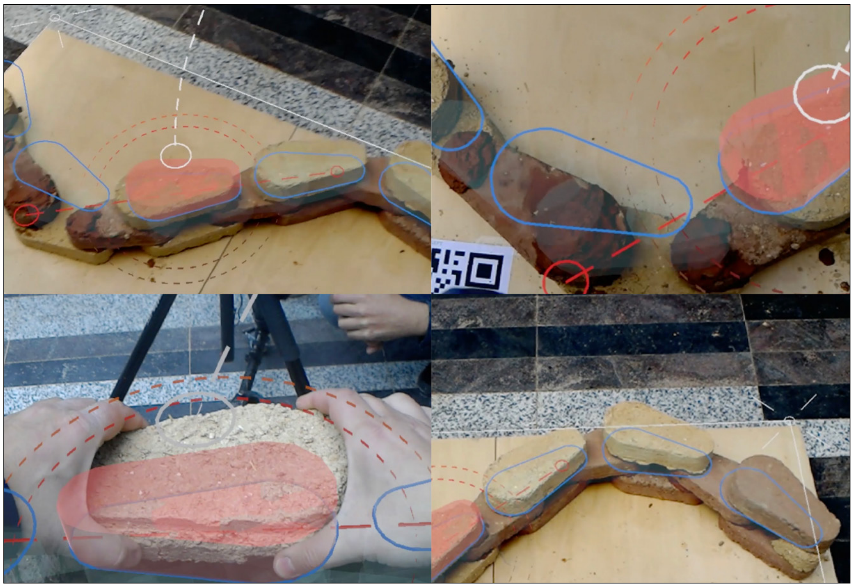

Figure 8. Assembly procedure through HoloLens

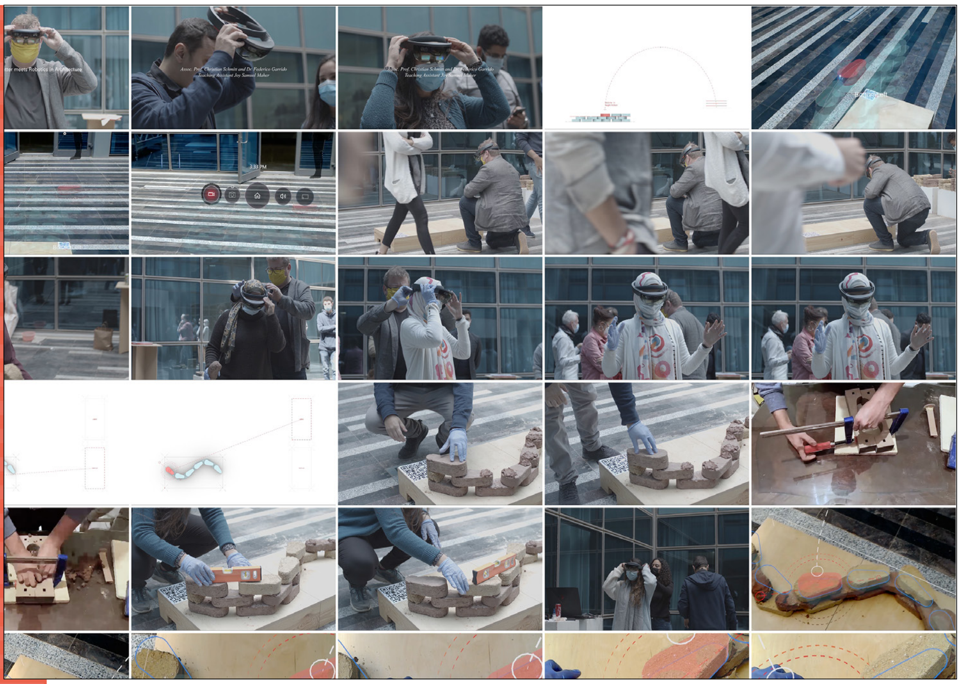

Figure 9. Assembly Process (https://vimeo.com/714403348)

Height Compensation

One of the key difficulties of this research arose through differences in precision between the three main components of the procedure. The parametric model was obviously the most precise of all, as it is mathematically perfect. The HoloLens device, however, introduces minor errors due to its positioning sensors. Most importantly, the bricks themselves have manufacturing ‘imperfections’, resulting in differences in their geometries. Finally, the application of mortar also adds yet another source of discrepancies (Figure 10).

Figure 10. Bricklaying with earth mortar

In order to compensate for these errors, the parametric definition allows the operator to readjust every brick row in order to match the actual position of the physical bricks. This error compensation mechanism is performed after each row of bricks has been laid, with the necessary feedback provided by the HoloLens user via visual aids projected by the parametric definition. Once the operator makes the corresponding adjustments, the bricklayer should see the next row of virtual bricks exactly positioned on top of the last real brick row.

This feedback procedure proved to be fundamental to the whole process, and it was used every two or three rows, thus adjusting the virtual brick wall to the dimensions of the real one. Both walls were thus built simultaneously, each one continuously informing the other.

Conclusions and Further Research

The benefits of mixed reality devices in the field of construction are mostly related to the display of spatial and geometrical data, providing users with useful contextual information, for example for assembly or maintenance operations. In this case, mixed reality technologies were combined with low-tech construction materials (earth bricks), speeding up the design process and removing the need for traditional construction documentation (i.e., plans or sections).

This research questioned the relationship between high-tech and low-tech tools, measuring and accounting for variations in manufacturing, montage and design. It also attempted to compensate for and/or minimise discrepancies within the design and its montage by establishing extra parameters and a feedback loop between the operator and the bricklayer.

The process accounted for various imperfections and height differences (such as those caused by differences in mortar thickness and manufacturing), sustaining a constant loop with real-time feedback: the physical model was updated with new bricks, while the digital model was updated with corrected heights. The imperfection of adobe or earth bricks is often understood synonym with low-tech construction and deprived communities. These materials remain a simple, cheap and often a perfect resource with which to build in many parts of the world. With Digital Imperfection, we wanted to underline that earth is much more than a vernacular material, and how by combining its use with innovative digital tools, we can augment the use of rammed earth bricks in a contemporary, elegant way.

Using digital technologies to enhance and to promote locally sourced materials presents exciting possibilities. Particularly in countries in the global south, ‘technical’ or ‘digital’ enhancement can help communities to identify with their own material traditions and projects, as well as encourage participation in the planning and construction process.

REFERENCES

BASEhabitat. 2018. “Work in progress.” *BASEhabitat Summer School handbook* 29.

Bonwetsch, Tobias. n. d. “Disruption of concrete floor slabs with highly innovative, scalable and sustainable earth-timber elements”. Accessed July 15, 2022. https://www.rematter.earth.

Groenendyk , D. G. (n.d.). P.A. Ferré, Ty; R. Thorp, Kelly; K. Rice, Amy (2015): USDA Soil Texture Triangle.. PLOS ONE. Figure. https://journals.plos.org/plosone/article/figure?id=10.1371/journal.pone.0131299.g001

Guillaud, H., 1997. *Les carnets de lárchitecture de terre. Une grande figure du pâtrimoine Rhône-Alpes, François Cointeraux (1740-1830). Pionnier de la construction modern en pisé.* Grenoble: CRAterre-EAG.

Heringer A., Howe L., and Rauch M.. 2019. *Upscaling Earth: Material, Process, Catalyst.* Zurich: gta Verlag.

Houben, H., and Guillaud H. 1994. *Earth Construction, A comprehensive Guide.* London: Intermediate Technology Publications.

Jahn, G., Newnham, C., van den Berg, N., Iraheta, M., and Wells, J. 2019. “Holographic construction.” *Design Modelling Symposium Berlin*, 314-24. Cham: Springer.

Kapfinger, Otto, and Sauer, Marko. 2015. *Martin Rauch, refined earth: construction & design with rammed earth.* Translated by Lindsay Blair Howe. Munich: Detail.

Loporcaro, G., Bellamy, L., McKenzie, P., and Riley, H. 2019. “Evaluation of Microsoft HoloLens Augmented Reality Technology as a construction checking tool.” *19th International Conference on Construction Applications of Virtual Reality*, 44-53.

Maher, J. 2020. “Earth Architecture in Rural Egypt.” Unpublished Master's diss., German University in Cairo.

Mitterberger, D., Dörfler, K., Sandy, T., Salveridou, F., Hutter, M., Gramazio, F., and Kohler, M. 2020. “Augmented bricklaying.” *Construction Robotics* 4(3), 151-161.

Speicher, M., Hall, B. D., and Nebeling, M. 2019. What is mixed reality? 2019. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1-15.

Standards Australia. 2002. *The Australian earth building handbook.* Sydney: Standards Australia.

Wen, Qian, et al. 2022. “What is mixed reality?” Accessed July 15, 2022. https://docs.microsoft.com/en-us/windows/mixed-reality/discover/mixed-reality.