Mobile Augmented Reality for Aided Manual Assembly of Compressed Earth Block Dwellings

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This paper investigates how augmented reality (AR) can instruct and assist in assembling an earthen structure consisting of a limited set of geometrically different interlocking blocks. By adapting a visual-inertial object tracking software, to the assembly process of a mortarless, compressed earth block (CEB) dome, the construction site no longer needs physical templates and manuals. This enables the builders to have real-time tracking with visual feedback to actively adjust according to the optical guidance during the course of assembly. Two identical dome structures are built with the same set of earth blocks, one with AR and one without. The results show that using AR can significantly improve construction efficiency for complex, dry-stacked structures as it acts as assembly guidance and provides insight into the limits of the tracking tolerances. Further, this paper discusses the limitations and challenges and can provide an outlook for further research scaling up the production to construct a habitable dwelling. Starting with just a pile of dirt and a mobile phone, the demonstrator exhibits the compatibility of local, sustainable materials and digital, efficient processes.

Keywords: *Compressed Earth Blocks, Augmented Reality, Interlocking Blocks, Earth Building, Dry-Stack Assembly, Sustainable Construction*

INTRODUCTION

In the current state of the climate crisis, there is a need for all industries to reevaluate their impacts on the built and natural environment. The building sector alone contributes 37% of CO_2 emissions and is currently not on target to meet the 2050 decarbonization goals of the Paris Agreement (United Nations Environment Programme, 2022), making it imperative to explore sustainable building materials and processes. Reducing the number of new buildings is not an acceptable solution to reduce emissions because there is a pressing need for safe and resilient housing worldwide. (UN General Assembly (UNGA), 2015). Changes away from materials sourced with high-embodied carbon and optimizing structures to use only the material needed are essential to reduce the building sector's footprint and to keep up with the growing demands of accessible housing.

This project builds on the research and development of using interlocking Compressed Earth Block (CEB) geometries to create mortarless, CEB dwellings (Zhang, 2023b). It serves as a case study to investigate the advantages of using object-based augmented reality (Sandy and Buchli, 2018) to aid in the assembly of a CEB dome demonstrator.

However, challenges arise with the complexities of assembling such a dome with a set of five bespoke block types designed with a tolerance of two millimeters. The following research explores using

AR as a digital tool to build a demonstrator on-site to find, for example, the tolerance limits. Quantifying the results provides insight into the efficiency of assembly, error tolerance, and redundancies.

Background

The beginnings of augmented reality (AR) are rooted in overlaying information from the digital world onto the physical for human-operated fabrication. Coined in the 1990s, AR began to flourish with the proposal to visualize AR on a head-mounted display (HMD) for aircraft manufacturing, forgoing the need for physical guidance like templates and diagram boards and instead superimposing the information to a fixed object in space (Caudell and Mizell, 1992).

They hoped to implement the AR system to help increase the production and efficiency of building airplanes. Still, they found the biggest challenge in the "real-world registration system" (Caudell and Mizell, 1992). A topic that continues to have research dedicated to it as an essential AR component, to correctly overlay information onto the physical world (Sandy and Buchli, 2018; Mitterberger *et al.*, 2020; Yan, 2022). The automation of airplanes could not be realized with robots like in some industries; it requires human dexterity. In the Architecture Engineering and Construction (AEC) field, many have also begun to challenge when fabrication requires human touch rather than mechanical automation (Sandy and Buchli, 2018; Mitterberger *et al.*, 2020; Yang *et al.*, 2022).

The visualization of AR as a digital tool can be overlayed through digital projections (Mitterberger *et al.*, 2022), HMDs (Song, 2020; Jahn, Newnham and van den Berg, 2022; Yang *et al.*, 2022), external monitors (Mitterberger *et al.*, 2020) and handheld mobile phones (Yan, 2022). Each display method has economic, physical, and technological advantages and disadvantages. These physical and digital costs should be considered when developing the framework of the AR experience for fabrication.

Research on AR has grown exponentially since the introduction of the smartphone. Competing tech companies heavily invested in improving mobile technology and the capacity of processing power as each new generation decreases in cost (Arth *et al.*, 2015), resulting in high-powered tiny computers in the hands of more and more consumers. Now with almost half the world's population owning a smartphone, there is potential for this group of smartphone users to tap into the powerful computers in their pockets as a digital tool for building (Silver, 2019).

Motivation

Building with earth has a long history as a sustainable building material because of its availability and malleability. Around 30% of the world already has established traditions in earth construction (CRAterre, 2021). One of the most significant challenges with the adoption of earth building is education and perception of the material as a modern way to build. Many argue against earth as a building material because of its water solubility. However, that exact property provides thermal comfort for a stable interior climate through capillary absorption (Heringer, Howe and Rauch, 2019). Despite its stigma as fragile and dated, earth has yet to be surpassed by any material that can be used and reused repeatedly without degradation of performance (Bruno *et al.*, 2020).

To those most in need of adequate housing, the cost and availability of materials can hinder their ability to sustain shelter. CEBs offer numerous benefits as a low-cost sustainable building material. They have low embodied energy and can be made on-site, reducing transportation costs and associated emissions while also providing thermal comfort and resilience against fire and pests. With its easy accessibility and non-toxic nature, this material is kind and forgiving to those without construction experience.

The tradition of building in a mono-material persists across the world, often due to a scarcity of resources. Climate change now further disrupts once relied-on resources. The roof alone usually assumes more than 50% of total building costs in earth construction (Pérez-Peña, 2009). This has led some to use loose earth and metal sheets as a quick fix, but the consequences in earthquake zones have been catastrophic, and such a solution can heat the interior like an oven. This project hopes to contribute a straightforward application of AR-assisted manual assembly of interlocking CEBs to the catalog of earth building.

MEANS AND METHODS

The following section discusses the means and methods of the project, starting from the block geometry to the production and assembly of the two CEB domes.

Geometry

The design built is a modular, single-story dome-shaped structure transitioning from a square-base footprint to a circular roof zone using five, distinct block types using the development of Zhang et al. (2023a) as a case study (figure 1). Interlocking block features enable both aligned and offset dry stacking and eliminate the use of mortar and formwork. Every other layer in the dome consists of a unique pattern of the five blocks, creating double-stacked layers. The double layers are essential for structural performance and keeping the interior space usable while minding the CEB fabrication and assembly limitations.

The five bespoke blocks used in this project have two sets of interlocking groves and protrusions that integrate tangential and radial offsets to link layers (figure 2); this allows for the transition from the wall to the roof. Within the five-block types, only one, “RC,” has no top or bottom joint, a feature that makes it susceptible to misplacement. As shown in figure 2, “RA” has one top joint and bottom groove, “CB” has one bottom groove, “CA” has one top join and two bottom grooves, and “RB” has one top joint and three bottom grooves. The varying interlocking levels on the top and bottom faces significantly increase the complexity and understanding of assembly.

The dome can be split into two building components, the wall and the roof (figure 1). The walls are stacked with “RA” in alignment up to the tenth layer to maximize usable space, with slight overhangs in the corners (figure 3). Once at the roof layer, the geometry jumps to cantilever about a third of the block to further the transition to the top circle geometry.

Further segmenting the dome into different components shows the repetitive nature of the design (figure 1). The pattern of blocks has rotational and mirror symmetry. As a result of the side interlocking joints, the blocks follow a counter-clockwise direction; this feature gives only pattern symmetry along the corner axis because, if mirrored, the direction of the joints would face the wrong direction. However, the designed pattern symmetry helps with block identification and ensures a correct assembly of the dome. If just an eighth of the layer is built, that is all the information needed to complete the pattern for the rest of the layer.

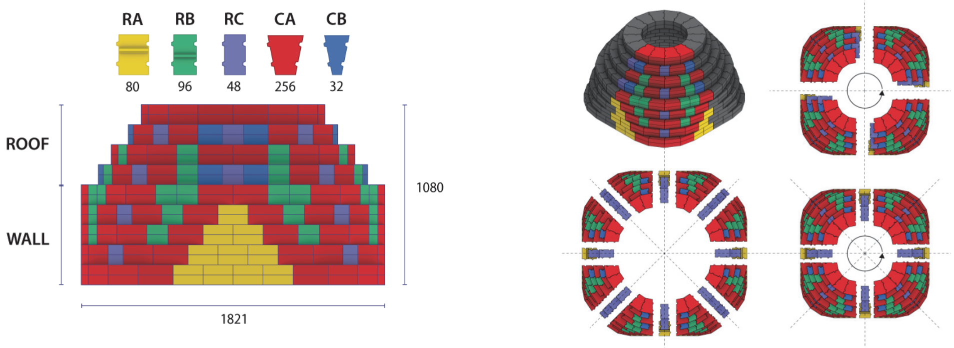

Figure 1
Dome Elevation (unit: mm, left)
Interlocking top and bottom blocks (right)

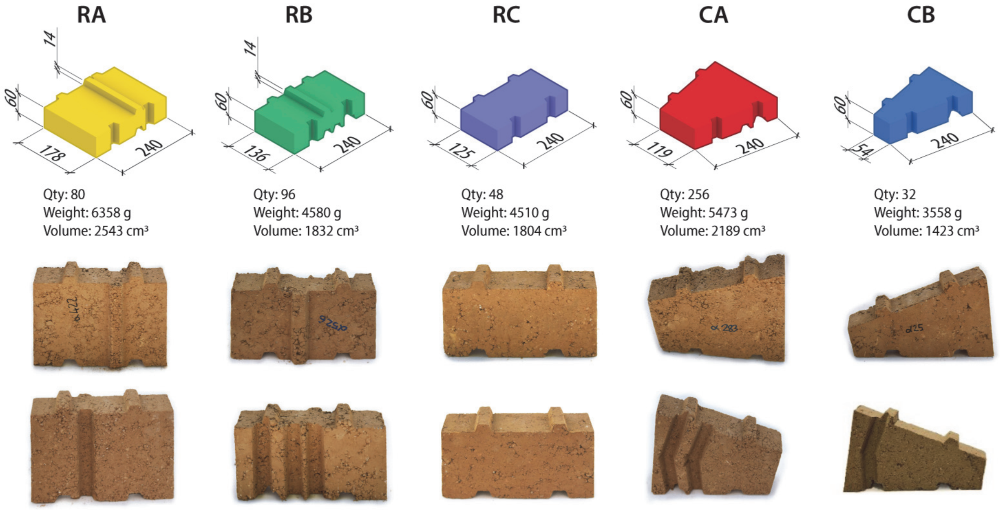

Figure 2
Block typologies

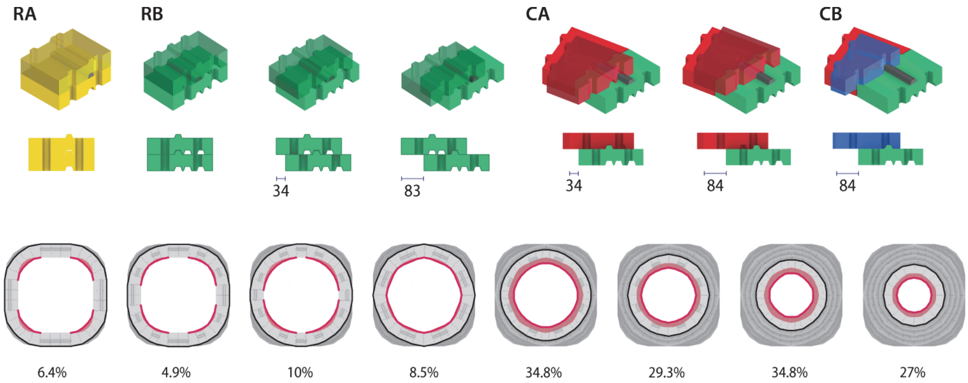

Figure 3
Blocks with interlocking protrusions and groves (unit: mm, top) Percentage of each layer's overhang (bottom)

Methodology

Setting up the project began with collecting the resources, developing the data workflow, and executing the build sequences (figure 4). The earth mixture and production equipment were procured and provided by the lab. To realize the AR visualization, there was a choice between a head-mounted display (HMD) or a mobile phone. While having both hands available during assembly would be beneficial, using an HMD did not fit the larger goals of making this means of assembly available to an audience with limited resources.

To realize the project using AR in a short timeframe, this project partnered with (*incon.ai*, n.d.), an AR guidance platform. They have developed an object-based tracking system that can reach within three millimeters of tolerance of the input geometry (Sandy and Buchli, 2018). This object-based tracking allows a better understanding of the

Figure 4
Overview of the resources, framework, and method

block geometry and provides a digital overlay for the accuracy and efficiency of the overall assembly.

The data framework was organized in (*Grasshopper*, n.d.), starting with the initial script of the block geometry. It was then sorted for the assembly sequence and metadata to be displayed in AR. The reformatting also required translating the geometry from an Euler to a quaternion grid system for compatibility with the AR application.

Once the workflow was up and running, testing began on the 3D-printed 1:10 scaled blocks while the full-scale blocks were being produced. Testing with the scaled blocks helped inform the full-scale demonstrator's building setup. Several tests with spatial tags identified the number of tags needed for coverage on site and the display of information required during construction.

The final stage of the project required evaluation by scanning the physical demonstrator to compare the results to the expected outcome and determine if the system could adapt in real time. The results are analyzed, discussed, and further remarked upon for future research on this method.

Figure 5
Production of CEBs used for the project (photo credit to Anastasia Skorik)

Production

The fabrication process for the unstabilized CEBs is based on an existing work (Zhang, 2023b), where embedded 3D-printed molds are used in a manual CEB press chamber to make bespoke blocks. The layout of the block production space has 25 m^2 of a dedicated area for mixing, measuring, and pressing (figure 6). The production ran on a typical day, with three people making an average of 50 to 60 blocks daily over three weeks. One person would oversee the mixing and measuring while the other two ran the CEB press, tracking, and stacking. Since the space was limited, the material was screened by hand as it was filled into the press chamber. Each batch mixed was enough volume to press five blocks. Across batches, the ratio of water to earth was tracked as it varied daily with weather conditions. As shown in figure 5, the production sequence led to a total of 522 blocks with contingency.

Assembly

Following the block production, the first dome was built with a physical manual and template. First, a template was made from printed paper as a stencil to draw an outline of the footprint on the building platform. Three people familiar with the project worked together with a set of diagrams to aid the block sequence during the dome assembly. This was used to gather empirical data about the potential for AR assistance and observe how the overall geometry works together as a structural system. After the completion of the first dome, the structure was disassembled and restacked on pallets until the building of the final demonstrator.

For the final assembly of the demonstrator, two people with firsthand knowledge of the project assisted, and one person unfamiliar with the design joined in the assembly (figure 6). The first layer was laid out block-by-block to ensure the base was evenly set out (figure 7). The AR overlayer guided the two other builders to the sequence of blocks (figure 7). To familiarize inexperienced people with the project, they controlled the smartphone and AR visual data until the third course.

After the third course, AR guidance for the duplicate layer is not used and shows an entire layer at a time rather than the block-by-block sequence. All hands are used during the double layer, placing the blocks in any order as long as they match the layer below. Once the dome section was reached, the blocks cantilevered inward (figure 7). As observed in the first dome, compression started to build up on the eleventh layer, and again there was not enough space to fit the last block. AR guidance is used to identify where some shifting and lifting of the blocks were needed to fit the final piece. Once in place, the compression ring of the dome is engaged.

At the top layer, the accumulation of errors in the blocks led to an uneven top layer. The final three layers consist of blocks without vertical interlocking between layers, which made for easy assembly, but they did not display the same compression level as the layers below.

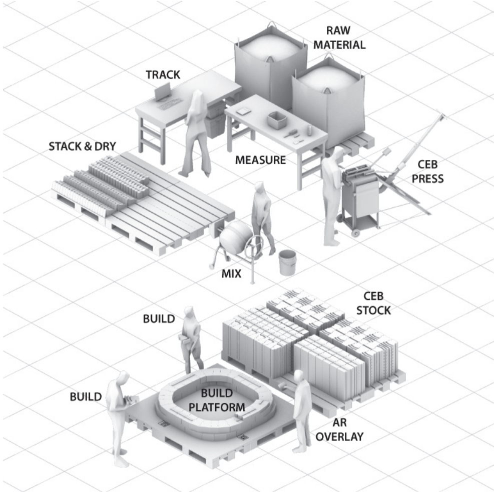

Figure 6
CEB production and assembly site

Figure 7
AR guided assembly of CEB dome. First layer layout (top), cantilever level check (middle), AR interface guiding roof assembly (bottom) (photo credit to Anastasia Skorik)

RESULTS

Comparing the data collected from each dome assembly, there were some significant improvements to the total time it took to complete the demonstrator using AR. However, because the same set of blocks was used for both domes, there were similar issues with the tolerance accumulation as it grew to completion.

The first dome (without AR), from start to finish, took 4 hours and 9 minutes to complete. However, this does not account for the time it took to produce the template and manuals. Which required a few additional hours of preparation not included in the assembly time to format the drawings, print them out, tape together the stencil, and mark the initial footprint.

Analyzing further the timelapse video footage, and removing 44 minutes of unrelated activities, the net assembly time of the first dome was 3 hours and 25 minutes (without AR), with an average time of 11 minutes per layer. The average assembly time reduced per duplicate later was 25% of the layer below.

The AR assisted assembly of the second dome, from start to finish, took 3 hours and 10 minutes. The net assembly time, analyzed by timelapse video footage, was 2 hours and 14 minutes, additional measurements and documentation added to the excess time. The AR assembly resulted in an average of 7 minutes and 4 seconds per layer. The average assembly time reduced per duplicate later was 45% of the layer below. The AR assembly, on average, is four minutes, or 36%, faster per layer to complete than without the AR guidance.

Up to the third course, each layer's completion time was around the same for both domes. This could be accounted for by the time it took the builder unfamiliar with the project to identify block types and understand the assembly. Looking at the assembly time per layer in figure 8, the double course of the layer always took less time to assemble.

The data from the number of rescans and the assembly time shows a correlation between the time it took to complete the layer and the higher amount of rescans during the assembly build (figure 8). Since the tags are placed on the ground as anchors, the higher the build, the further away the anchors are, and they are more likely not to be in the frame. However, the object-based visual-inertial tracking (Sandy and Buchli, 2018) allowed us to build without the tag in the frame because the virtual geometry was locked to the physical blocks. Still, the mobile phone's sensors could get lost if someone passed in front of the cameras or moved around the dome too quickly.

Due to human error in producing the set of blocks, the most occurring block, "CA," was, on average, +4 mm taller in the Z direction. Since there was no time or labor available in the schedule to reproduce the defective blocks, this known imperfection had to be considered in the next phase of testing with AR. However, the (*incon.ai*, n.d.) platform proved robust and error-tolerant in comparing the 3D scan of the built dome in figure 9.

The built dome stood 74 mm taller than designed, more than one layer of blocks taller than intended. The 3D model produced in (*Grasshopper*, n.d.) was not adjusted for this aggregated inconsistency; instead left as designed. Despite the accumulated height discrepancy, the AR guide for placing the blocks remained accurate and helpful for positioning.

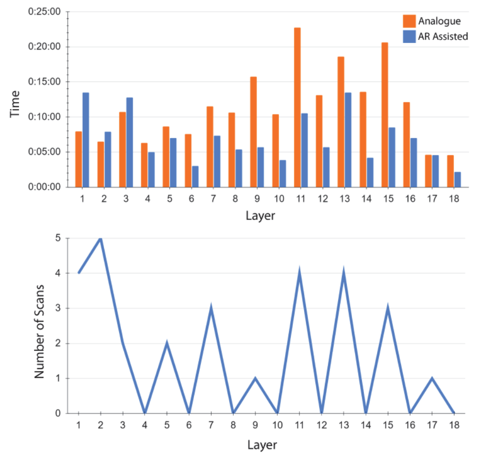

Figure 8
CEB assembly time comparison (top)
Amount of spatial tag rescans per layer (bottom)

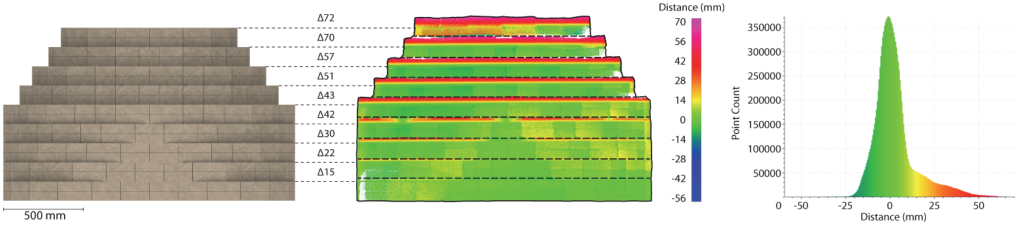

Figure 9
Comparison of the designed dome with the built dome from a 3D scan (left) distances between mesh and point cloud (right)

DISCUSSION

Comparing the first build to the AR-assisted assembly, the most helpful points in increasing the efficiency and accuracy of AR guidance were at the initial footprint layer and reaching the "roof" layers. The first layer is critical to set the base for the successive layers as the potential for tolerance build-up increases with size and complexity. Laying out the CEB block-by-block with AR was substantially a faster and easier setup than the manual route of physically building a template. Once at an even larger building scale, setting the dome's base as designed will be even more critical for completion.

It was observed that the counterclockwise sequence of assembling the blocks is not required after the initial layer. It is faster to display the entire layer in AR and have the two builders work out from the same point, benefiting from the symmetrical pattern. At the same time, the AR overlay follows around the full layer to help correct block placement.

After the third course, the pace increased by not using the AR guidance for the duplicate layer. This allowed even quicker assembly because more hands were available to stack, and the placement did not need to follow a prescribed sequence. The builder unfamiliar with the project by the fourth layer could understand the block identified and could easily use the AR overlay to help identify placement and if adjustments were needed.

On the first "roof" layer, the blocks begin to cantilever, an important place to check for the correct interlocking level. This use case was observed during assembly as a block was placed on the wrong interlocking level and could be quickly identified and corrected on the spot.

Based on the observations during the two builds, there is still more potential to optimize the building sequence with a larger team and scale. The series of instructions should be displayed layer-by-layer once the base is set. It would also make sense to split the group into halves or quarters with a larger building team, depending on the availability of labor and smartphones. The geometric sequence of the blocks per layer has rotational symmetry every quarter, allowing a group of even builders and AR operators to synchronize the assembly of the same block types. This would require less movement of one phone around the building site and could help reduce the number of rescans of the spatial anchors.

The CEBs, produced by first-time builders, enabled the testing of the AR object tracking to update with the geometrical inaccuracies as each layer was stacked to completion (figure 10). This helped to keep the momentum of the assembly going. In a fixed AR system, location updates must be manually relayed into the program to update the deviation. Without this feature, someone with programming know-how would have to be on-site to fix the visualization for each successive layer, which would slow down the whole process.

This feature allowed the AR assembly to continue without interruption and prevented further delay by staying on site and not returning to the computer for adjustments. However, to further mitigate the compounding tolerance, building in additional AR feedback from the true geometry could help to indicate which blocks are incompatible with the designed tolerance and allow them to be replaced or repositioned to reach the aims as designed.

Figure 10
Completed dome (left) with AR overlay (right)

CONCLUSION AND FURTHER RESEARCH

The project's outcome has demonstrated a well balance of high-tech digital tools with minimal and sustainable resources. Paring the interlocking CEB design with AR assembly allowed for a building site without paper plans or manuals and increased efficiency by more than 36%. AR was not needed at every moment, and running through the entire build sequence identified redundancies in guidance that could be improved for future studies of this system.

Further research into adding architectural elements, i.e., fenestration, ventilation openings, and electrical runs, would provide insight into whether this system could adapt to more complex assemblies or where the limit in error tolerance hinders the use of AR guidance. This could further introduce a new strategy for spatial tags for real-world registration as the building scales up in size and complexity.

The simplicity of assembly and positive environmental aspects of the project allows for further research into the more significant social impacts of such a building model outlined in this paper. Since it is a labor-intensive process resting on the shoulders of established earth-building knowledge aided with digital tools, this model could provide a shift in where local funds are invested. Instead of buying highly embodied materials or high-tech proprietary equipment, building from local materials, utilizing mobile phone based technology, and investing resources in local labor pools can give communities in need an alternative for resilient housing.

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