Developing Feedback Based Robotic Manufacturing Method for Earth-Based Materials

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Although earth-based materials have the advantage of being locally sourced and have low embodied emissions, they can have an unpredictable material behavior due to their heterogeneous composition which potentially limits their use in manufacturing. As a result, it becomes challenging to standardise and maintain quality outcomes. Moreover, current industry methods are labour-intensive and require a high level of traditional knowledge. This research explores and develops a fabrication methodology for earthen materials that is location-agnostic. It involves an array of fabrication approaches, including the development of a robotic 'Impact Printing' setup using a UR10 robot and a custom tool to pick, place, and mechanically compact earth blocks. The 'Feedback System' employs Kinect 2.0 to scan the deformation of earth materials observed during fabrication and a computational algorithm to generate accurate and adapted toolpaths for the position and compaction of earthen blocks in real-time. To push the boundaries of architectural design for traditional building materials, the study investigates the construction of a closed Nubian vault using the aforementioned techniques and tools. Through the optimization of material behavior and manufacturing processes, the research opens up a pathway for automated onsite earth construction.

Keywords: *Robotic Fabrication, 3d Scanning, Adaptive Feedback System, Earth Building.*

INTRODUCTION

The construction industry is increasingly turning to sustainable alternatives with Earth-based materials gaining popularity due to their low environmental impact, specifically lower embodied and operational emissions (Gomaa *et al.*, 2021), lower cost and require locally sourced and minimally processed materials (Ben-Alon *et al.*, 2019). Based on utilising local materials, local skills and local needs, it has proven to be a robust method of construction, demonstrated by some of the earliest known standing structures dating back over 5000 years (Dethier, 2020). However, Earth-based materials are high varied in composition its subsequent material behaviour, which making it challenging to ensure consistent quality across different projects and locations. The extent of standardisation in Earthen Construction relies heavily on specialized workers with experience and knowledge, which is slow and labour intensive. (Hamard *et al.*, 2016).

To address the labour and standardization challenges, this paper develops and proposes a methodology for automating Earth-based construction.

IMPACT PRINTING

Large scale Additive Manufacturing (AM) has been a major research focus for the last 20 years, with concrete the main material of interest. Combined with advances in computational tools like Finite Element Analysis, has enabled the realization of highly efficient structures with minimal material use. Materials used for traditional mass earth-based construction usually comprise of a mix of clay, sand, aggregates and sometimes straw. 'Computing Craft' developed at the Welsh School of Architecture (Gomaa *et al.*, 2021) and Tecla House by Wasp (Moretti, 2023) have demonstrated Additive Manufacturing printing of Earth-based materials. However, fibrous and granular aggregates have been shown to lead to clogging and equipment damage(Gomaa *et al.*, 2019). Also, most large-scale AM relies on liquid deposition modelling, where reliably controlling the flowrate is a major challenge. Controlling rheological parameters for large scale process like AM requires a high degree of control of the viscosity, where the material prepared has to be highly homogenous in particle size as well as high water content for it to behave with a more predictable steady state flow. These strategies present 2 limitations: maintaining the homogeneity of the material mix, and secondly, the more fluid the material mixtures are, the higher the potential for shrinkage and cracking during drying, compromising the strength of the structure (Reyes et al., 2018, Eugenin et al, 2022).

Impact printing offers a unique solution to this rheological conundrum, where discrete elements or bullets composed of earth can be picked, where the working range of the material viscosity observed is at a much lower water content ratio, and therefore will exhibit less shrinkage. Unlike Liquid Deposition Modeling where layer adhesion is achieved upon the solidification of the liquid mixture, Impact Printing relies on compressive forces to achieve layer adhesion. (Ming *et al.*, 2022) realized this approach by leveraging projectile physics, where 'bullets' of material deposited at the same target location were bonded upon impact. Remote Material Deposition by Dorfler et al, 2017 also used a similar methodology to construct forms on a larger scale. The forms in both projects made with clay did achieve layer adhesion, however, there was little control over the form and surface geometry.

'Clay Rotunda' used a lance technique to pick clay cylinders and compress them using as a pneumatically actuated plate attached to a robot (Jenny *et al.*, 2022). Layer Adhesion and a more consistent surface geometry was observed (in comparison to the projectile-based methods).

Research for impact printing of cob, a mixture of sand, clay, straw and water, was explored in our previous research 'Variable Aggregate Impact Printing of Cob'. The research explored fabrication of a curved nonplanar cob-wall (refer to Figure 1) (Hetherington *et al.*, 2023). Similar to Clay Rotunda, the methodology relied on a compression system leveraging pneumatic actuation to achieve layer adhesion. At the micro level, the bonding between adjacent bullets during drying is controlled by the clay and water content of cob. At the macro level, compacted bullets interlocked with each other through local deformation to form bonds. Although higher pressure led to stronger particle adhesion,

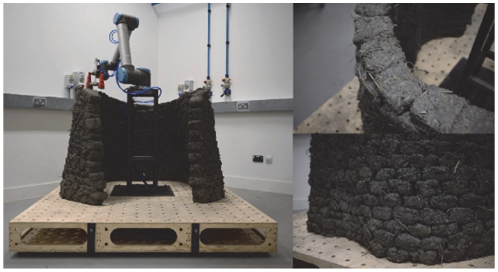


Figure 1
Impact Printing of Cob

excessive lateral deformation resulted in overlapping and uneven layer height. To address this problem in our current research we propose and develop a feedback system via 3d scanning.

DESIGN PROPOSAL

The aim of the research is to explore construction of closed habitable structures using mass-earth. Vault geometry does not require columns or walls for support, making it an excellent candidate for exploring innovative structural designs and an ideal subject for experimentation of closed structures. The successful construction of vaults requires understanding of various factors including material properties, load-bearing capacity both during wet construction and after drying, as well as geometry, making it a crucial test in architectural design. In general, constructing vaults often involves using extensive formwork.

However, to reduce waste from formwork and explore ways to automate the process through impact printing, alternative methods for constructing closed structures that do not require supporting formwork were explored, such as the Nubian method of vault construction, developed by Hasan Fahy. With this method, earthen blocks are laid at an angle, using the previous blocks as support (Granier *et al.*, no date).

MATERIAL OPTIMISATION

A significant aspect of the project is investigating, comprehending, and devising a procedure for utilizing earth-based materials for impact printing. Since earth is not a standardized construction material (Quagliarini *et al.*, 2010), it is necessary to discern the features of specific loam compositions through experimentation. Loam is a mixture of sand, clay, silt, and larger aggregates such as stones or gravel, with clay being the most crucial component for finding the appropriate earth mixture for construction. Initially, a series of tests were conducted to gain a better understanding of material compositions and mixtures. The first set of experiments focused on testing the printability and binding outputs of soft earthenware and coarse stoneware. The following mixtures were tested: a) 100% Earthenware, b) 50% Earthenware, 50% Stoneware, c) 100% Stoneware, d) 70% Earthenware, 30% Stoneware, and e) 30% Earthenware, 70% Stoneware. The most effective combination was found to be 70% Vulcan Black Stoneware Coarse and 30% Red Earthenware, as anything higher than 70% of coarse stoneware could not be picked up by the end effector due to the minimal amount of clay asbinding agent,. Furthermore, Hackney Marshes was identified as a suitable location for potentially sourcing localmaterial resources

The first test was the Cohesion Test (Cigar Test) (German Appropriate Technology Exchange. and CRAterre., 1995), was used to test whether a soil was acceptable for earth construction. This included rolling a ball of moist soil into a cylindrical shape that was 30 mm in diameter and 300 mm long, and gently pressing on the cylinder until it broke and fell. For more precise findings, the test was repeated twice after measuring the falling portion of the cylinder. To find out how much clay was in the soil and how strong it was, another test known as the "biscuit test" (German Appropriate Technology Exchange. and CRAterre., 1995), was carried out. A smooth paste made by combining the soil with water was formed into a disc with a diameter of 30 mm and a thickness of 10 mm. The disc was manually fractured after being allowed to dry for 24 hours in the shade. It was discovered that our soil has a very high clay percentage since breaking the disc by hand proved difficult. Furthermore, the percentages of silt, sand, clay, and gravel per volume were calculated as part of the "sedimentation test" (German Appropriate Technology Exchange. and CRAterre., 1995), which was used to examine the soil composition. For this test, half of the sieved sample of on-site soil is placed in a bottle, and water is then added. The mixture is then allowed to settle after the bottle has been intensely shaken to fully incorporate the soil and water. To determine the amount of gravel, sand, silt, and clay, measurements were made at various intervals. According to the results, the soil has a high clay concentration, with roughly 30% gravel, 15% sand, 20% silt, and 50% clay. Finally, the adhesion test was performed to gauge how adhesive the soil was. In this experiment, water was added to the sieved soil to make it more mouldable. Two cylinder-shaped bullets were then created, impact printed together, and allowed to dry completely.

The adhesion was then evaluated by manually pulling apart the bullets. The two bullets proved to be difficult to pull apart, and even when they did, they did not deviate from the adhesion line, indicating that our soil has outstanding layer adhesion without the use of any additional binders. This discovery is encouraging for the project since layer adhesion is important to take into account while impact printing and because poor layer adhesion might lead to structures that are too weak to support themselves and may collapse.

To create a recipe suitable for impact printing, the elemental composition was first determined, and shrinkage of the soil was further tested. To avoid cracking and decreased structural strength, multiple tests were conducted with various water contents, aiming to keep the water content percentage as low as possible. For the main recipe, 15% water content mix was proven to be optimal as it allowed for good structural strength, sufficient layer adhesion between bullets, minimal observable cracking and enabled infinite material reuse and does not require any binders. Moreover, it was ensured that the majority of the material is used after sieving aggregates larger than 3mm. The samples were then tested on a Zwick Roell AllroundLine Universal Testing Machine (UTM) for compressional strength.(refer to Figure 2A)

To address the deformation issue in vault prototypes in the bottom layers of structures, a modified recipe was developed for the base layers to make them denser, heavier, and less prone to deformation. Additional aggregates can be added to the recipe to achieve this. For the final design, which involves printing a closed arch structure, it was found that found that lighter bullets were necessary and conduced test with adding straw and a straw

B

Composition	Compressional Strength (mpa)
15% Water Content	1.35
15% Water Content + Straw	1.59
40% Aggregate Content	1.58

Figure 2

a) Structural Test Setup
b) Compression strength results of various material compositions

and sand mix to the 15% water content base recipe in order to achieve a lighter bullet. The key requirement for these bullets is weight, rather than adhesion. Our experiments with straw showed promising results in achieving this goal. Straw, or other inert long strand fiber, is often added to mass earth mixes built without the use of formwork, to provide initial linking strength between blocks of wet material, and after drying provides torsional strength in walls, similar way to steel rebar in reinforced concrete. (refer to Figure 2B)

DESIGN STRATEGIES

For the enhancement of support and to withstand the impact generated during printing, a decision was made to opt for a 45-degree angle despite the traditional inclination angle of 65 to 70 degrees for building Nubian vaults. Figure 3A illustrates this alteration.

Further the print angle of the bullets was gradually increased as the height of the vault, the width of the vault, and the size of the bullet changed, as depicted in Figure 3C. Another strategy employed included using higher bullet density at the base to ensure better strength and minimise deformation when printing upper bullets (refer to Figure 3B). However, during the prototyping process, it was observed that the compression of the bullets and adhesion between the layers were unpredictable. To tackle the issue of unpredictable compression, a scanning feedback system was developed. For enhancing adhesion between the layers, the material composition was optimised for various layers, and multiple compressions were implemented for the same bullet based on the layer and material used.

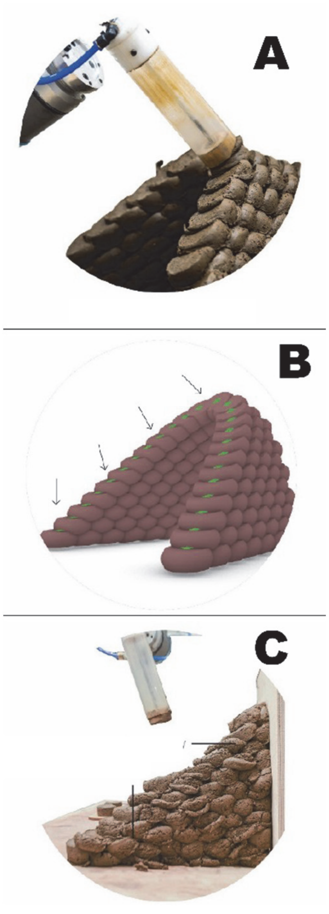


Figure 3
a) Printing at 45degrees, b) bullet density variation across the structure, c) gradual increase of print angles

FEEDBACK SYSTEM

The robotic manufacturing process consists in the sequential pick, orient, place and compaction of soft bullets. A UR10 collaborative robot with a custom built end-effector, comprising of a cylinder with a pneumatic piston was used to pick and place the earth. By using a collaborative robot for material handling within its working envelope, it becomes feasible to fabricate structures on-site with the involvement of both human and robotic collaborators (Burden, Caldwell and Guertler, 2022). Bullets are loaded into the cylinder; the robot manipulator is used to position and orient each bullet into a specific target determined by the designed toolpath. Finally, the pneumatically actuated piston compresses the bullet. Particles in the malleable state behave in a complex, unpredictable manner during sequential compression steps. Despite efforts to homogenize material composition, bullet size and geometry, compression with constant pressure could be observed to affect individual bullets at varying rates. Offsets in layer height can be accommodated by the tolerances afforded by the material and construction logic.

However, in larger structures, these variations can accumulate, and lead to significant deviations from the goal geometry and ultimately lead to the failure of the fabrication process and the collapse of the structure. (Brion and Pattinson, 2022) and (Nicholas *et al.*, 2020) have integrated scanning in the manufacturing processes of their projects to address panel shrinkage, substrate distribution, variations, error detection and correction in 3D printing. However, limitations include potential workflow disruptions due to panel size and substrate distribution variations and the risk of collision and limited printing of curved forms. In order to accomplish repeatability and accuracy of positioning independently of the size of the structure similar approach using a 3D scanner-based feedback system was implemented to dynamically calculate the position and orientation of particles in real-time and generate adaptive toolpaths for every layer. 3D scanning is used to derive the position of the previously deposited bullets. The recorded point cloud data is used to accurately position the following layer and effectively compensate for layer height deviations due to irregular material compression (refer to Figure 4). This adaptive workflow allows for a dialog between the structure being manufactured and the 3D model and robotic toolpath. In this manner, material composition properties are integrated into the deterministic, top-down approach given by the geometric data and robotic toolpath to accomplish a material-informed computer-aided manufacturing process.

A 3D scanner Azure Kinect DK was used to capture point cloud data of the workspace of the robot manipulator after the deposition of each layer. To collect the data the scanner was mounted on the wrist of the robot manipulator. Capturing the structure as a point cloud from the top view allows the simultaneous recording of layer height as well as the stepover of individual bullets on the previous layer. The captured 3D data is subsequently input into a custom script in the Grasshopper environment for Rhinoceros 7 for further processing to re-calculate the position of the next layer.

To align the coordinate system of the scanner to the coordinate system of the robot a calibration step was necessary. To accomplish this, three markers were placed on the work object. The position of the three markers was captured by approaching each with the tool center point (TCP). The coordinates x, y and z were recorded and served as reference points to align the coordinate systems. The distance between the scanner and the workobject is crucial in determining the precision of the scan. A series of scans were captured at distances of 200, 300, 400, 500 and 600 mm between the markers and the scanner lens. The optimal scanner distance was experimentally determined to be 300 mm.

To derive the position of the next set of bullets, the point cloud data of the entire workspace environment needs to be processed. Initially, a rectangular perimeter is defined around the deposited layer on the scanned workspace. The remaining point cloud data, which corresponds to the deposited bullets, is filtered based on the Z value. The target position and orientation of the next layer are determined by finding the centroid of the top surface of the previous layer. To find the centroid, the point cloud of each bullet is isolated from the rest of the layer. For planar deposition, the centroid is calculated by averaging the maxima and minima for x and y values of the points with the

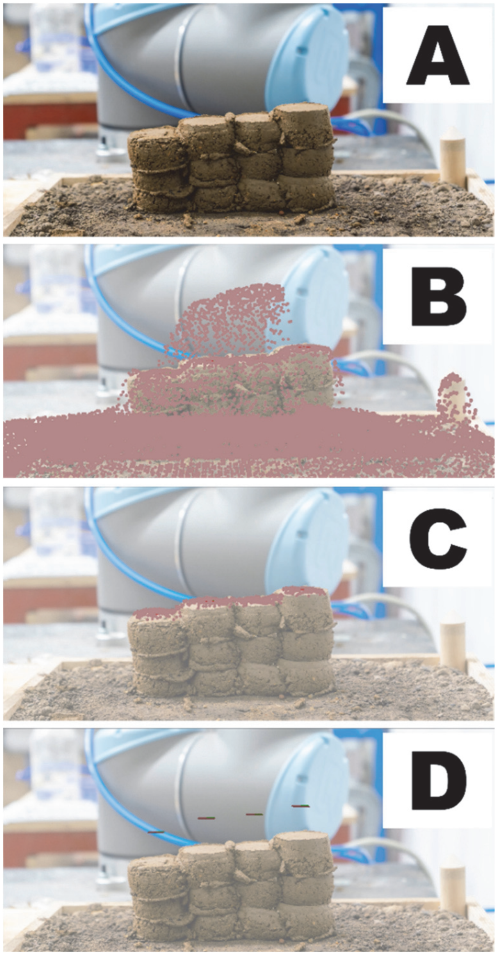
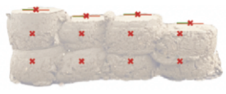


Figure 4
a) unequal layer height, b) scanned point cloud, c) isolated top layer, d) offset planes for next layer.

Table 1
Deviation of place position with scanner

Layer	Compression points comparison (with scan vs without scan)	Deviation (Bullet no: x, y, z) in mm
1		B1: 9.4, 6.5, 2.9 B2: 7.8, 5.6, 6.4 B3: 5.2, 4.1, 8.9 B4: 2.0, 3.7, 10.2
2		B1: 10.4, 4.9, 2.0 B2: 7.6, 4.3, 9.0 B3: 4.7, 3.4, 9.4 B4: 1.2, 3.2, 16.4
3		B1: 11.2, 4.1, 1.4 B2: 7.9, 2.1, 10.8 B3: 3.8, 2.9, 11.0 B4: 0.4, 2.3, 20.4
4		B1: 14.1, 7.6, 6.0 B2: 9.7, 4.1, 17.2 B3: 4.9, 2.4, 15.3 B4: 0.5, 1.9, 24.4

highest z values, which correspond to the top surface of the bullet.

However, for non-planar deposition, an additional step is required. The points corresponding to the maxima and minima for the z values are isolated, and a line is interpolated between them to derive the subsequent bullet orientation. The centroid is selected as the point closest to the line. An additional recursive step is added to accurately determine the position of the centroid. This adaptive workflow has been successfully implemented to accomplish multiple layer aggregations. A comparison of the target position with and without the implementation of the adaptive workflow can be seen in Table 1. The error measured between the plane generated using exclusively geometric data and the plane generated by the feedback script was between 12 to 27 mm. Although, the feedback system paves a methodology and a technique for addressing deformation, the accuracy needs improving and further investigation for large scale onsite construction.

POST PROCESSING

In the final stage of the project, the team explored whether post-processing could enhance the impact-printed surface. Drawing inspiration from traditional practices in arid regions like Mali and Cameroon (Zune *et al.*, 2020), where patterns created by hand enhance and control the thermal and structural performance of structures such as Mousgoum huts, the team sought to achieve a similar effect. Mousgoum huts are sustainable and constructed entirely of locally sourced materials such as mud, thatch, and wood, they also collect and channel rainwater, a precious resource in the arid Far North Region of Cameroon. The sculpting of Mousgoum huts is crucial to their design, with the conical shape achieved through layering mud bricks in a spiral pattern, creating natural ventilation and air circulation that keeps the interior cool. The sculpted mud walls also provide insulation from heat and cold, making the huts comfortable to live in year-round.

To achieve a similar effect, the team developed a manual sculpting process similar to the strategies using by (Varela *et al.*, 2022 that recorded lead-in and lead-out angles, intermediate angles, sculpting paths, and depth. Hand movement was traced based on an Aruco marker (Figure 5B) using Hololens (Figure 5A) that created a sculpt plane each time the tool moved. The setup included a UR10, tool, material set, and QR code to align digital and real setups (Figure 5C).

Multiple tests were conducted on clay and soil (Figure 5D), and a composition of 30% clay to 70% soil was found to be optimal. The prototypes successfully demonstrated the potential of robotic sculpting and the adaptation of sculpted paths to control the facade's depth (Figure 5E). Future steps include exploring how patterns can be adapted to more complex geometries, controlled parametrically according to required environmental performance, and exploring the potential of craft-performance-driven vernacular.

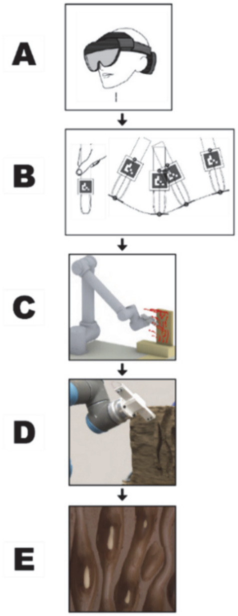


Figure 5
Post-Processing Workflow
a) HoloLens Motion Capture
b) Manual Toolpath
c) Transformation into Robotic Trajectory
d) Robotic Fabrication
e) Prototype

PROTOTYPE

To demonstrate the developed workflow, a specific design exploration was analyzed. This exploration involved a radial tri-vault structure, an innovative and intricate design that presents unique challenges during fabrication (refer to Figure 6). The base of the tri-vault structure was 1200mm in diameter and maximum height of 450mm. One notable aspect of this design is that each vault serves as a formwork for the subsequent construction. This means that each vault is not only a structural component but also plays a crucial role in supporting and shaping the construction of the next vault. With the tri-vault structure the complexities of building at the intersection of the vaults especially using automated fabrication. Reachability and collision with the robot were tested using a reachability map. To ensure that the construction process is successful, the limits for the length of the cantilever were tested for each vault.

This involved determining the point at which the vault could no longer support its own weight without collapsing or deforming. Through these tests, it was possible to optimize the material composition and print angle for each layer, ensuring that the construction was structurally sound and visually appealing. Optimizing the material composition and print angle for each layer is essential for ensuring that the final product is strong and durable. By carefully selecting the materials used in each layer and adjusting the print angle, it is possible to achieve the desired level of strength and stability. The prototype was exhibited as part of the Fifteen Exhibition show.

Figure 6
Prototype Tri-Nubian Vault

CONCLUSION

The research presented here demonstrates a novel methodology for the aggregation of mass earth materials, creating opportunities to expand the options for traditional and vernacular materials. Integration of material properties, manufacturing and digital scanning suggests the possibility of adapting the process to the specific location, ensuring that the resulting building exhibits the required structural integrity and durability.

Through the established feedback system, this research addresses the main challenge of material deformation during fabrication for using earth-based materials. The construction of a vault with minimal formwork made with recipes that enable reuse of the material, and combining the established construction techniques with modern manufacturing tools is a significant milestone in the field of architecture and construction. This technique has opened new possibilities for exploring various geometries for non-planar and complex walls that offer improved structural efficiency.

The construction method developed in this paper could be used to build low-rise structures, particularly in regions with low rainfall, where Earthen Architecture is already widespread, like South America, Europe, West Africa, South Africa, Middle East, India and China. The fabrication methodology developed in this paper lends itself primarily to onsite construction as prefabricating specific building elements and transporting such large masses would be a major challenge and be a significant contributor to the environmental performance of the structure. A promising area of exploration is to examine the viability of this methodology for In-Situ Resource Utilization.

Furthermore, another promising area of research is the use of the materials recipes as substrate for growing biome or even utilizing biome to improve the performance of a structure. The use of fibrous materials (like hemp or agricultural waste) or xanthan gum to improve layer adhesion are promising avenues of exploration. The post-processing workflow developed suggests a methodology where vernacular texturing practices can adapt to an architectural context, where instead of replacing these practices, this manufacturing method could serve as a conduit to continue the practice of these rich vernacular traditions.

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