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Robotic 3D printing with earth: A case study for optimisation of 3D printing building blocks

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Abstract

The interest in 3D printed earthen buildings in developed countries has increased due to the demand for healthy, comfortable and sustainable buildings constructed with low carbon materials and labour-saving methods. However, the amount of research about this field is still limited. Our research aims to contribute to this field by optimising the robotic 3D printing process by investigating issues such as buckling while printing, adequate soil mix recipe for printing, print and extrusion speed calibration. This paper illustrates the process and the results of the temporary research project and the Robotic Cob Printing Workshop with MSc Computational Methods in Architecture (CMA) students at the Welsh School of Architecture, Cardiff University, in March 2022. The project aims to achieve structural stability with less material by using the geometry and the infill of the building block while exploring the role of computational design, robotic extrusion and material understanding in robotic 3D printing with earth as a low-carbon novel building method.

Keywords: earthen architecture, 3D printing, robotic automation, material-based design computation, sustainability

1. Introduction

The UN World Urbanization Prospects Report states that by 2050 68% of the world's population is expected to be living in urban areas, adding another 2.5 billion people to the urban population (United Nations World Urbanization Prospects [1]). Half of Asia will be urbanised and China alone will be adding one "New York" to the planet every two years with 40 billion m^2 of construction demand over the next 20 years (Dobbs [2]). Manufacturing of industrial construction materials such as concrete and steel contributes up to one-third of all carbon dioxide emissions emitted by the construction industry (UN Environment Programme [3]). For energy-efficient buildings, the impact of the emissions created by manufacturing building materials is much higher while the energy consumed by the operation of the building is lower (Habert *et al.* [4]). Using earth as a construction material presents a promising alternative for reducing the environmental impact of the construction industry. Unlike industrial materials, unfired earth does not require energy intensive processes while it is readily available and reusable. In fact, unfired earth saves between 1 to 5 GJ of energy (per tonne of material), principally in the drying and the firing process - this represents an up to 95% reduction in embodied energy, as well as use of fossil fuels (Hamed *et al.* [5]). Earthen buildings balance humidity and regulates indoor temperatures, eliminating the need for mechanical heating and cooling systems, further reducing the carbon footprint of the building (Minke [6]). The hygrothermal and non-toxic nature of earth also provides thermal comfort, especially for climates that have extreme heat variations between night and day temperatures (Houben and Guillaud [7]). Humidity, indoor air quality and temperature affect well-being and physical reactions of people. Hence earthen buildings also provide psychological comfort (Altomonte *et al* [8]).

On the other hand, conventional earthen building methods such as cob and adobe are labour intensive, expensive and slow, making them incompatible with the mainstream construction industry in developed countries. Automation in construction has been increasingly favourable in developed countries, especially in buildings constructed with 3D printed cementitious materials. 3D printed earthen materials demonstrate a better environmental performance than 3D printed cementitious materials due to the energy-intensive manufacturing of cement (Alhumayani *et al* [9]). Moreover, this process uses less material than conventional earthen building methods by placing material exactly where needed. Enabling complex geometries and automation by computational design and robotic printing improves the positive qualities of an earthen building, such as thermal regulation and eliminates the disadvantages such as labour-intensive construction and structural weaknesses (Izard *et al* [10]). Steel and concrete became mainstream construction materials in the 20th century, causing earth to be perceived as primitive or rural material. The introduction of digital design and fabrication techniques in earthen architecture can eliminate this bias, creating a contemporary image of the material relevant to the architecture in the 21st century (Schweiker *et al.* [11]).

1.1. Earth as a construction material

Earthen building techniques have been known for at least 9000 years, dating to the Neolithic Era (Minke [6]). The start of earthen construction coincides with the beginning of agricultural societies, as the same clayey and sandy alluvial soils that led the communities to settle down also inspired the creation of the mud-brick (Houben and Guillaud [7]).

Unstabilised, unfired earth can be considered as natural concrete, with clay providing cohesion instead of cement. Unfired earth, however, is susceptible to erosion, water and moisture, requiring regular maintenance. The strength of unfired earth is generated by the adherence between soil particles due to the loss of water; therefore, exposure to water undermines the adherence, and rather, affords reversible plasticity. Protecting earthen walls with a water-resistant roof and foundation in wet and rainy zones is common. Lime plasters are also used in vernacular earthen architecture to protect earthen walls from rain and reduce erosion. Adding stabilisers to the soil can increase compressive strength, tensile strength, and durability by binding the soil particles, reducing the number of voids to prevent water absorption, and eliminating shrinkage and swelling (Uzoegbo [12]).

The most common stabilisers are Portland Cement, asphalt emulsions, hydrated lime, calcined gypsum (plaster of Paris), supplementary cementitious materials like silica fume, fly ash, and ground granulated blast furnace slag or other pozzolans (Van Damme and Houben [13]). However, when admixtures like cement or lime are used, stabilisation may cause a loss of reusability and permeability; increase the material's embodied energy, and reduce the thermal performance and indoor air quality (Fabbri and Morel [14]). Hence, it is essential to investigate using natural admixtures to stabilise unfired earth structurally while maintaining its hygrothermal and ecological qualities. For example, the use of biopolymers (guar- and xanthan-gums) as stabilisers is a promising natural alternative for the stabilisation of earthen materials (Muguda *et al.* [15]). Alginate seaweed is another interesting biopolymer that gave promising results as a stabiliser (Perrot *et al.*[16]).

When mixed with water, earth behaves as a fluid material, making it ideal for extrusion. However, unlike concrete which gains strength as it cures, unstabilised earth gains strength as it dries, so increasing water content also increases the drying time. Clay provides cohesion for earth, but large amounts of clay in the mix also cause extreme shrinkage and cracks while drying. Adding fibres like straw, sisal or hemp to the earthen mix reduces cracking through fibre bridging mechanisms when a wall is drying or is subjected to rain and wind erosion.

There are several methods of building with earth, but the most common traditional methods are adobe, rammed earth, wattle and daub, clay straw, cob and compressed earth blocks (Minke [6]) (Houben and Guillaud [7]). Cob is a technique of mixing clayey earth and fibres such as straw or grass and then applying them by hand by pushing them to create a monolithic wall. With these characteristics, cob can be described as manual additive manufacturing. For our 3D printing experiments, we based our earth mix on this traditional building method because of its fluid and ductile characteristics.

1.2. Computational design and the extrusion (3D printing) of earthen mixes

Digital fabrication can be classified under three main categories: subtractive fabrication (such as computer numeric control (CNC) milling), formative fabrication (such as robotic bending) and additive manufacturing, which creates forms by adding material in layers (Beorkrem [17]). Additive manufacturing introduces a novel kind of materiality, where the additive use of the same material can define nature-like structures such as a cave or a termite mound. Oxman indicates that nature's "material first" approach is efficient because materiality guides structure and form whereas “form first” or “structure first” approach of the conventional design process is often wasteful (Oxman [18]). With additive manufacturing, placing the material precisely where it's needed makes it possible to increase the structural and thermal efficiency of building elements and avoid material waste (Paoletti [19]). With local materialisation and fully automated fabrication, additive manufacturing does not require assembly and shipping of building parts, reducing the need for labour, cost and waste while allowing an unprecedented speed of prototyping (Claypool *et al.* [20]). Additive manufacturing enables short supply chains and localised fabrication, catalysing the establishment of `micro-factories`. Fisher predicts a future where local industry replaces global companies and economies (Fisher [21]).

Earth is ubiquitous, low-cost, and does not require shipping like concrete. Instead of shipping the industrialised materials that are expensive and carbon-intensive, local soils can be used for robotic extrusion. The digital fabrication tools can be brought to the site, reducing the construction process's carbon footprint. Earth mixes void of any chemical stabiliser are infinitely reusable for additive manufacturing. Depending on the size and complexity of the robotic construction, various automated processes with cranes, cable systems, robots attached to rails or mobile platforms to 3D print can be set.

Form and geometry of the building block have not changed significantly over the past centuries and were standardised during the Industrial Revolution to fabricate affordable building blocks with mass production. However, additive manufacturing and computational design have revolutionised this process by enabling mass customisation at no additional cost. These advanced technologies enable designers to design and fabricate customised earthen blocks that vary in size, form, and infill at no additional cost. In addition, combining computational design and digital fabrication enables the architects and engineers to optimise the building block structurally by using form and geometry. Block infill strategies developed with computational design, instead of using solid blocks, help save material while ensuring structural stability.

1.3. Off site vs On site automated extrusion of earthen mixes

Automated extrusion of earthen mixes can be either realised on site as monolithic structures, like TECLA by World's Advanced Saving Project using cranes and bespoke extruders (WASP and MCA [22]) or can be fabricated as blocks off site with an industrial robot arm to be later assembled on site such as the Terraperforma Project by the Institute for Advanced Architecture of Catalonia (IAAC [23]). While on-site construction has a smaller carbon footprint, by eliminating the transport of building parts or building materials using local soil, off-site construction is not dependent on weather conditions, enabling an all-year-round production of earthen building parts. Earthen buildings are not water resistant unless coated with a water-resistant layer and need protection from water and humidity, especially during construction. Another major challenge is the deformation of the form and dimensions of earthen structures due to shrinkage while drying, which can be estimated and controlled in a climatically regulated environment during off-site fabrication. Moreover, an earthen wall can only be printed up to a certain height in one printing session to enable the drying of the structure and avoid collapsing, which can make the on-site construction process long and complicated. On the other hand, prefabricated earthen blocks can be printed continuously and set aside for drying, accelerating the process and avoiding mistakes caused by craftsmanship on site, which is essential for the uptake of this fabrication in the mainstream construction industry. For example, rammed earth wall blocks of Ricola Herb Centre were fabricated off-site by automated production system developed by Lehm Ton Erde, accelerating the adoption of this vernacular building technique by the mainstream construction industry in Europe (Lehm Ton Erde [24]). This approach is significant in showing that it is possible to benefit from the advantages of prefabrication while using local soil with lesser transport requirements to the site. The main challenge of off-site fabrication of earthen blocks is transporting and assembling blocks on site. Earthen blocks are heavy to transport. Also, careful consideration of connection geometry and a mortar recipe is required to maintain the low-carbon and reusable nature of the material. Furthermore, protection from damage during transportation is essential if the 3D printed blocks have elaborate forms. Although the fabrication of blocks is automated, the assembly is labour intensive and requires craftsmanship. Our research project examines these challenges during the printing and assembly of prefabricated earthen blocks.

2. Robotic cob printing research and workshop

2.1 Equipment

Kuka KR 60 six axis high accuracy industrial robot was used during the research project and the design and fabrication workshop at the Welsh School of Architecture, Cardiff University. The custom-designed dual extruder at the Architectural Robotics lab enabled continuous printing (Gomaa *et al.* [25]). The extruder was connected to the nozzle held by the robot with two 50 mm diameter pressure hoses. The Y shape steel end effector connecting the hoses to the nozzle was custom-made for the dual extruder. 25 mm and 35 mm in diameter, two nozzles were 3D printed in advance.

The robot and the extruder were calibrated for X,Y,Z coordinates and the location of the printing bed before running experiments. The calibration process was initiated by calculating the height of the printing platform, the nozzle dimensions and the layer height for the Z axis. X and Y coordinates for the home position for printing were set by measuring the size of the printing platform and its distance from the centre of the robotic arm. Once the calibration process was finalised, robotic arm controller calibration values were imported into KUKA|prc plugin in Rhinoceros® Grasshopper®. Through test prints, the exact home position of the printing was confirmed.

Figure 1: KUKA KR60 six axis high accuracy industrial robot, the dual extruder (Gomaa *et al*. [25]) and the custom fabricated steel end effector connecting 3D printed nozzle to the pressure hoses.

2.2 Material

Local subsoil from Cardiff was ordered from a local construction company to use for the project. When delivered, subsoil was wet, and high in clay content with plenty of stones, so it was not suitable for extrusion. The goal was to be able to print with the 25 mm nozzle, hence stones larger than 20 mm in diameter needed to be removed from the soil to avoid any blockage.

Figure 2: Delivered subsoil was not workable for extrusion, too clayey, wet and included large stones. This soil was spread and dried as chunks for a couple of days and then crushed into smaller pieces to sieve and eliminate larger stones.

First, the soil was spread in chunks to dry for a few days indoors to avoid exposure to rain and accelerate the drying process. Once dry, it was crushed and sieved to eliminate larger stones. This fine soil with stones smaller than 20 mm in diameter was mixed with water and straw and then kneaded thoroughly to produce a homogenous mix. The first mix recipe consisted of 69% clayey soil, %27 water and % 4 straw by weight. This recipe's viscosity was suitable for extrusion as it was fluid enough to flow through the system but solid enough not to buckle during printing. However, later during the prototyping phase, this recipe put too much pressure on the extrusion system and was revised.

Figure 3: Soil mixing process: Sieving soil to eliminate larger stones, adding water, straw and kneading until reaching a homogenous mix. After the viscosity check, the cartridges were filled with the soil mix and sealed to keep the mix humid.

2.3 Computational Design and Materiality

The workshop task given to the MSc CMA students was to design the form and infill pattern of the blocks to be 3D printed and assembled into a wall. The goal was to ensure structural stability with less material by using geometric optimisation and parametric design. Each block could have a maximum 10 000 cm^3 in volume which was equivalent to the amount that can be printed with two cartridges. Students were also asked to consider the interlocking strategy for the blocks. During the first week of the workshop, students explored the block geometry and infill patterns while defining the main parameters for their block design. Four options were developed: a growth algorithm approach, an interlocking block strategy with polygonal blocks, curved, undulating infill patterns, and splines. These options were 3D printed in PLA to test the geometry. Subsequently, we explored the possibilities and constraints of 3D clay/soil printing and robotic fabrication with a set of lectures and short trainings. These explorations revealed the materiality of the process and limitations that should be considered related to the drying time of soil mixes and buckling while printing. It was also noted that the printing bed was limited to 450x450 mm and a 25 mm nozzle would be used for printing. Based on these inputs, students revisited their undulating curved block option and optimised their design by developing several alternatives based on wall thickness, number of wall layers, layer height, number of undulations, and width and length control. After the drying period, the blocks were to be assembled into a tapering and rotating wall.

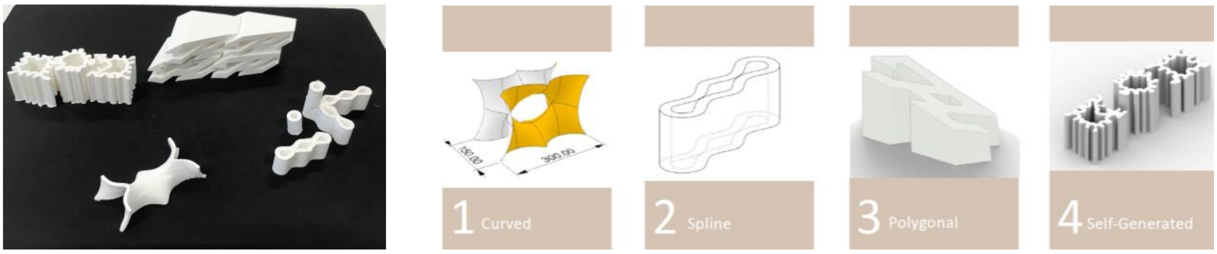


Figure 4: Initial block design explorations, 3D printed in PLA to test the form and geometry. Images courtesy of MSc CMA students, Cardiff University, 2022: Afnan Aldulaijan, Ashley Vias, Dorsa Boroujerdifard, Darshan Chavan, Deval Ambavi, Louai Jaber, Mohammad Omar Eqbal, Sapta Sunusae and Selda Pourali Behzad.

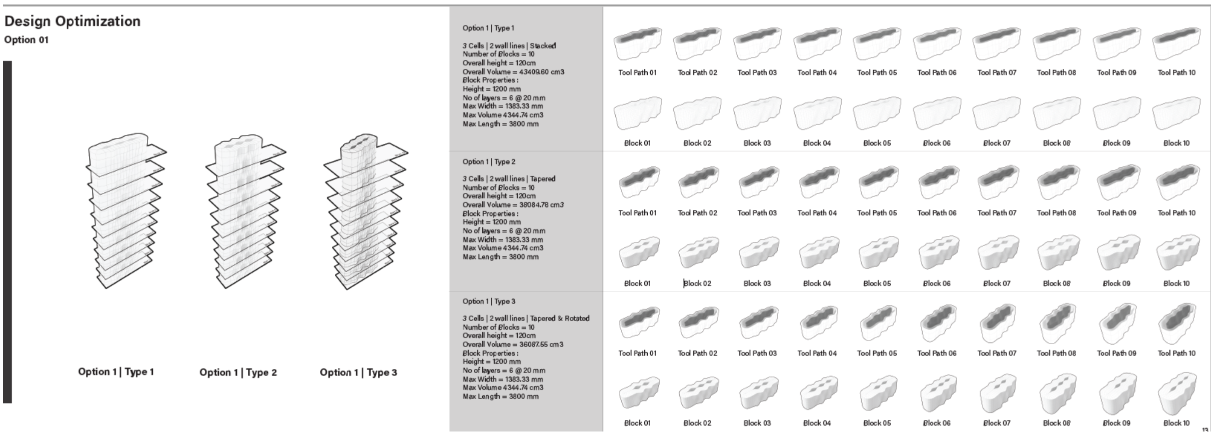


Figure 5: Design development and options for optimising the spline block with parameters based on wall thickness, number of wall layers, layer height, number of undulations, and width and length control. Images courtesy of MSc CMA students, Cardiff University, 2022: Afnan Aldulaijan, Ashley Vias, Dorsa Boroujerdifard, Darshan Chavan, Deval Ambavi, Louai Jaber, Mohammad Omar Eqbal, Sapta Sunusae and Selda Pourali Behzad.

2.4 Robotic extrusion and prototyping

The print quality is defined by the careful calibration of robot speed, extruder speed, and the soil mix viscosity. During the prototyping phase, several tests were made to find the optimum balance between these parameters to enable an accurate printing result. The initial soil mix recipe has put excess pressure on the extruder to push soil through the 35 mm nozzle, so we did our first calibrations with a 50 mm nozzle instead.

Our goal was to print with the 25 mm nozzle to be able to print the infill design developed to create a sturdy block with less material. Our initial recipe of 69% clayey soil, 27 % water and 4% straw was too sticky and dry to be able to print with the 25 mm nozzle. We tried several recipes to reach the ideal viscosity and coherence to work with the extrusion system and the desired nozzle. These recipes were documented with slump tests, and extruder cartridges were labelled with the same numbers to follow the performance of each mix recipe during the extrusion.

It was essential to develop a recipe that would be solid enough not to buckle during printing and fluid enough not to put pressure on the extruder while printing with the 25 mm nozzle. After several trials and experiments, we revised our recipe to 61% soil, 0.3%straw, 22% sand and %17 water. The addition of sand was necessary to make the mix less sticky and more fluid, while the reduction of straw ensured a more fluid mix with less water, easing the flow of the material along the extruder and the hose. Once the ideal soil mix was confirmed, the prototyping and calibrations were focused on the fine-tuning between robot speed, extrusion speed and layer height. Based on this experimentation, the final parameters were set as 0.1 m/s extrusion speed, 0.09 m/s robot speed and 10 mm layer height for the optimum results. The nozzle height from the bed was set as 10 mm, to ensure adherence and stability of the first layer to the printing bed for subsequent layers to be built on without buckling.

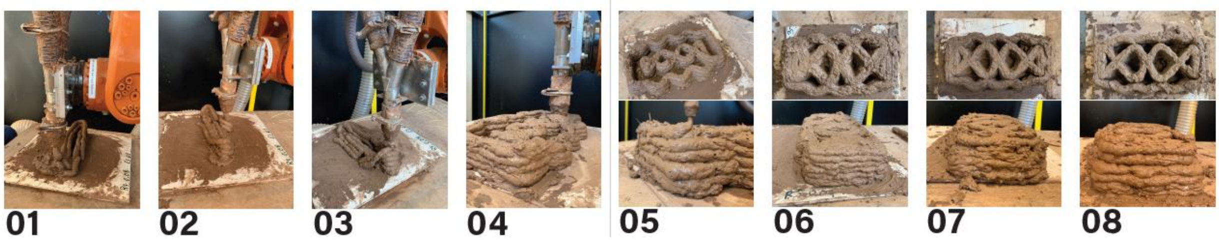


Figure 6: Trials with various robot speeds and layer heights while keeping the extrusion speed at 0.1 m/s and printing with the 25 mm nozzle.

2.5 Design optimisation, parametric design process and 3D printed blocks

After the prototyping phase, block designs were optimised once more based on the feedback collected during the prototyping phase. With the confirmed soil mix, a maximum number of 7 layers could be printed without buckling, with each layer height set as 10 mm. In order to gain better structural stability and avoid buckling while 3D printing, the block form was updated with more significant undulations, and interlocking waves were added to the infill geometry to work as buttresses. During the prototyping phase, overhangs collapsed, so for the final printing, each block is divided in two to be printed upside down and flipped for assembly once dry.

From the early design iterations until the final design, students have optimised and developed their block and wall designs with a parametric design approach developed using Rhinoceros® Grasshopper®. This approach gave them the control over the main parameters such as layer height, layer width, number of undulations and interlocking infill waves. Furthermore, the empirical nature of the 3D printing earth required a significant amount of trials with different block geometries. Hence, controlling these parameters enabled us to quickly test new design iterations based on the fabrication and material feedback.

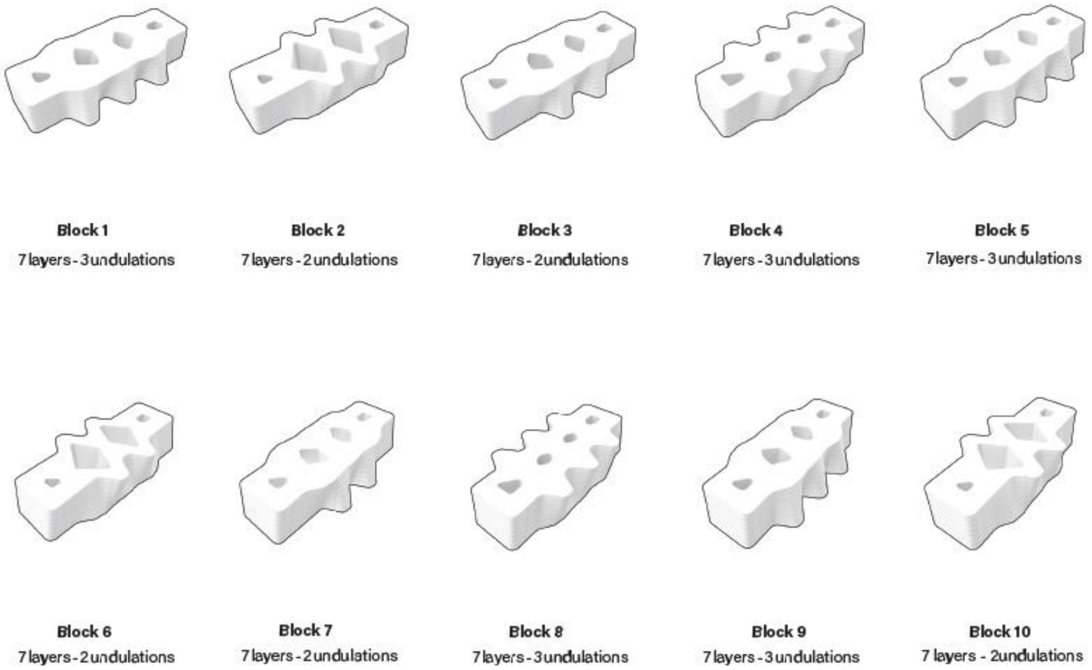


Figure 7: Final design optimisation and blocks to be printed with undulations and infills blending into the wall form. Images courtesy of MSc CMA students, Cardiff University, 2022: Afnan Aldulaijan, Ashley Vias, Dorsa Boroujerdifard, Darshan Chavan, Deval Ambavi, Louai Jaber, Mohammad Omar Eqbal, Sapta Sunusae and Selda Pourali Behzad.

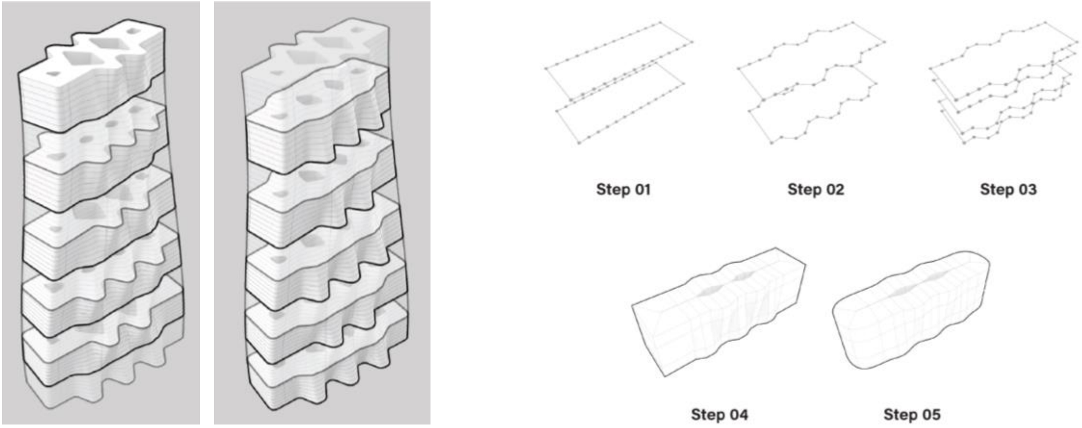
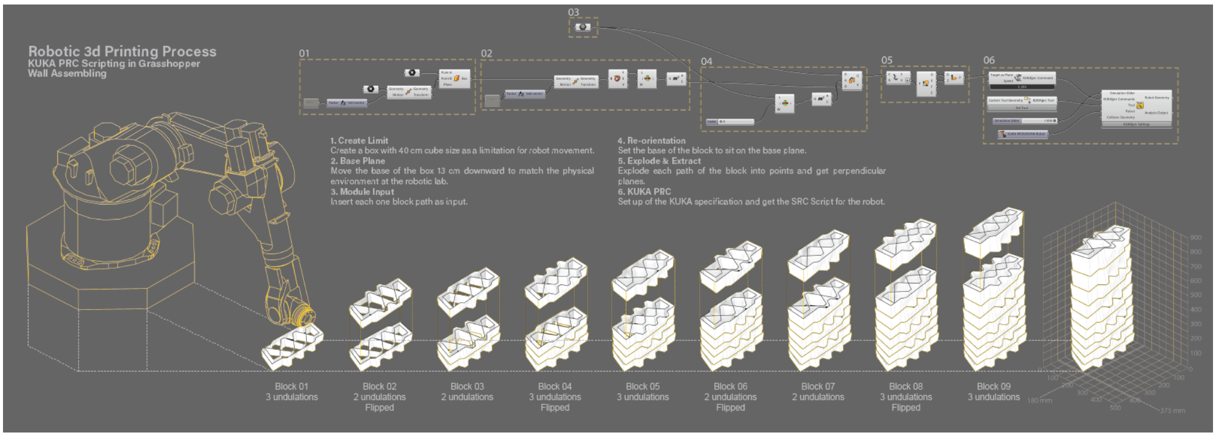


Figure 8: Final wall design illustrating the wall`s printing sequence, parametric design sequence, and the control over the number of undulations (cells) . Images courtesy of MSc CMA students, Cardiff University, 2022: Afnan Aldulaijan, Ashley Vias, Dorsa Boroujerdifard, Darshan Chavan, Deval Ambavi, Louai Jaber, Mohammad Omar Eqbal, Sapta Sunusae and Selda Pourali Behzad.

Once the parametric design in Rhinoceros® Grasshopper® was finalised, a system reference code (SRC) was generated for printing the block geometry, with each printing layer divided into 50 polylines. The design process was completed by creating printing limits, locating the base plane, inserting each block, and exploding the blocks into perpendicular planes. Finally, the SRC script was extracted to run the robot.



1. Create Limit
Create a box with 40 cm cube size as a limitation for robot movement.
2. Base Plane
Move the base of the box 13 cm downward to match the physical environment at the robotic lab.
3. Module Input
Insert each one block path as input.
4. Re-orientation
Set the base of the block to sit on the base plane.
5. Explode & Extract
Explode each path of the block into points and get perpendicular planes.
6. KUKA PRC
Set up of the KUKA specification and get the SRC Script for the robot.

Figure 9: Robotic 3D printing process, developed with KUKA PRC plugin for rhinoceros. Image courtesy of MSc CMA students, Cardiff University, 2022: Afnan Aldulaijan, Ashley Vias, Dorsa Boroujerdifard, Darshan Chavan, Deval Ambavi, Louai Jaber, Mohammad Omar Eqbal, Sapta Sunusae and Selda Pourali Behzad.

Eight blocks varying in size, form and infills based on the final design were printed and left to dry for a month at the Architectural Robotics Lab at the Welsh School of Architecture. Each block took less than five minutes to print, proving the potential for fast-track prefabrication.

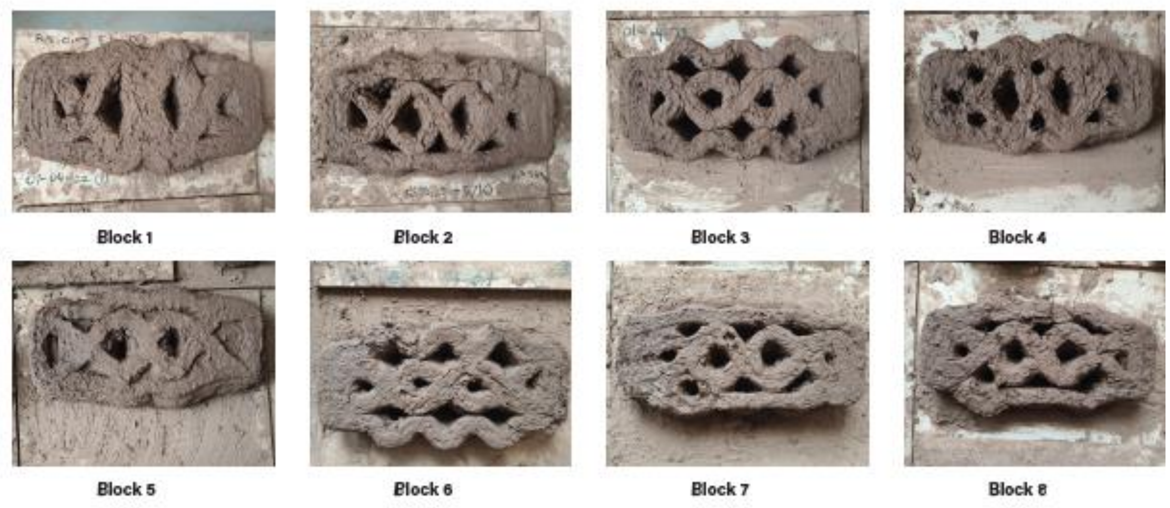

Block 1 Block 2 Block 3 Block 4
Block 5 Block 6 Block 7 Block 8

Figure 10: Robotic 3D printed earthen building blocks before leaving to dry.

3. Drying, shrinkage and the assembly of blocks

The blocks were weighed before and after the drying period. 15% weight loss has been observed during this time due to the evaporation of water. Because of the controlled indoor temperature and humidity, blocks dried homogeneously, and significant deformations in block forms were avoided. Nonetheless, the blocks required sanding before the assembly to ensure strong connections between each block. After sanding, the stacking surface of the blocks was sprayed with water to increase the adhesion between blocks. The same soil mix used for 3D printing blocks was also used as a mortar to combine the blocks. The surface was levelled with a spirit level to ensure a horizontal surface on top before stacking the subsequent blocks. After completion of the assembly, gaps on the surface were filled with the same soil mix and the wall was left to dry.

Figure 11: Assembled wall and the assembly process

4. Conclusion

This paper acknowledges the potential of prefabricating 3D printed earthen blocks and presents challenges such as the unstandardised nature of soil mixes, shrinkage while drying, assembly process and fine tuning between the robot speed, extrusion speed and the viscosity of the soil mix. Several blocks were printed with various soil mixes during the prototyping process to determine the adequate soil mix recipe, printing speed and extrusion settings. In addition, multiple block infill geometries were tested to successfully print earthen blocks using less material while avoiding buckling during printing. The parametric design approach has proven crucial for the feedback loop between design and fabrication to optimise the geometry of the block form and infill, enabling us to generate several options efficiently by changing parameters such as layer height, layer width, block width, number and the size of the undulations. The research project and workshop have shown that a holistic and thorough understanding of the material, design, fabrication potentials and constraints is essential, emphasising a material-driven computational design and fabrication approach. Further experiments will help investigate the effect of different infill strategies on the structural stability of the block and the printing process. In addition to physical tests, virtual simulations with Rhinoceros Grasshopper can accelerate the process. Straw was added to the soil mix for this project; however, the effect of fibres such as hemp or sisal on preventing cracking during shrinkage and supporting stability is another issue worth investigating. Developing innovative interlocking strategies for blocks can result in more robust walls. However, the discrepancy between block design and 3D printed blocks due to inconsistencies during printing and drying should be addressed. A precise and predictable outcome is essential for the uptake of this process by the mainstream construction industry. Further research and prototyping can resolve these challenges to optimise this innovative and sustainable building method with earth.

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References

[1] United Nations Department of Economic and Social Affairs, *2018 Revision of World Urbanization Prospects*, Available at: https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html. (Accessed: 13 April 2022)

[2] Dobbs, R., 2010, *Prime numbers: megacities*. Available at: https://foreignpolicy.com/2010/08/16/megacities/ (Accessed: 20 May 2022)

[3] UN Environment Programme, *2019 Global Status Report for Buildings and Construction Sector*. Available at: http://wedocs.unep.org/bitstream/handle/20.500.11822/30950/2019GSR.pdf?sequence=1&isAllowed=y (Accessed: 15 January 2022).

[4] Habert, G., Castillo, E., Vincens, E. and Morel, J.C., Power: A new paradigm for energy use in sustainable construction. *Ecological Indicators*, 23, 109-115, 2012.

[5] Hamed, N. *et al.*, "Life cycle assessment of earthen materials for low-cost housing, a comparison between rammed earth and fired clay bricks", *International Journal of Building Pathology and Adaptation., 2021*

[6] Minke, G., Building with Earth. Design and Technology of a Sustainable Architecture. (6th ed.) Basel; Boston: Birkhauser-Publishers for Architecture, 2009.

[7] Houben, H. and Guillaud, H. *Earth Construction. A Comprehensive Guide*, London: Intermediate Technology Publications., 1994.

[8] Altomonte, S. *et al.*, "Ten questions concerning well-being in the built environment", *Building and Environment*. Elsevier Ltd, 180, 2020.

[9] Alhumayani, H., Gomaa, M., Soebarto, V. and Jabi, W., Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete. *Journal of Cleaner Production,* 270, 2020.

[10] Izard, J.B. *et al.*, Large-scale 3D printing with cable-driven parallel robots. *Construction Robotics,*1; 69-76, 2017.

[11] Schweiker, M. *et al.*, "Ten questions concerning the potential of digital production and new technologies for contemporary earthen constructions", *Building and Environment*. Elsevier Ltd, 206(August), 2021.

[12] Uzoegbo, H. C. "Dry-stack and compressed stabilised earth-block construction", in: Harries, K. A., Sharma B. (eds.) *Nonconventional and Vernacular Construction Materials. Characterisation, Properties and Applications.2nd ed*. Cambridge: Woodhead Publishing, pp. 305-348, 2020.

[13] Van Damme, H. and Houben, H. "Earth concrete. Stabilisation revisited", *Cement and Concrete Research.* Elsevier Ltd, 114, pp. 90–102, 2018.

[14] Fabbri, A. and Morel, J. C., "Earthen materials and constructions", Nonconventional and Vernacular Construction Materials, pp. 375–401, 2020.

[15] Muguda, S. *et al.* (2020) 'Durability and hygroscopic behaviour of biopolymer stabilised earthen construction materials', *Construction and Building Materials.* The Authors, 259, 2020.

[16] Perrot, A., Rangeard, D. and Courteille, E, "3D printing of earth-based materials: Processing aspects", *Construction and Building Materials*. Elsevier Ltd, 172, pp. 670–676, 2018.

[17] Beorkrem, C. (2013). *Material Strategies in Digital Fabrication.* New York: Routledge, 2013.

[18] Oxman, N., "Structuring Design Fabrication of Heterogeneous", *Applied Physics Letters*, 80(4), pp. 78–85, 2010.

[19] Paoletti, I., "Mass Customization with Additive Manufacturing: New Perspectives for Multi Performative Building Components in Architecture", *Procedia Engineering*, 180, pp. 1150–1159, 2017.

[20] Claypool, M. *et al.*, `Print`, in: Claypool, M., Garcia M. J., Retsin G., Soler V.(eds.) *Robotic Building. Architecture in the Age of Automation.* Munich: Detail Business Information GmbH, pp. 38-47, 2019.

[21] Fisher, T., "Welcome to the Third Industrial Revolution: The Mass-Customisation of Architecture, Practice and Education", *Architectural Design*, 85(4), pp. 40–45, 2015.

[22] WASP and MCA, *3D printed house TECLA - eco-housing* Available at: https://www.3dwasp.com/en/3d-printed-house-tecla/, 2021 (Accessed: 20 May 2022)

[23] IAAC, *TerraPerforma project- Institute for advanced architecture of Catalonia. Open Thesis fabr.* Available at: https://iaac.net/project/terraperforma/, 2017 (Accessed: 20 May 2022)

[24] Lehm Ton Erde, *Ricola Herb Centre,* Available at: https://www.lehmtonerde.at/en/projects/project.php?pID=87, 2012(Accessed: 15 June 2022)

[25] Gomaa, M. *et al.*, "3D printing system for earth-based construction: Case study of cob", *Automation in Construction*. Elsevier B.V., 124(January), 2021.