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Robotic 3D printing with earthen materials as a novel sustainable construction method

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Abstract
Additive manufacturing is revolutionising architecture and design by enabling the manufacture of data-driven complex forms created by computational design, which could not be realised by conventional ways of craft and making. Robotic 3D printing with earth presents a promising alternative for the future of earthen architecture. Building with earth is a time tested environmental construction method which can be enhanced with digital fabrication. This paper presents the opportunities and challenges of ongoing research integrating robotic 3D printing with conventional earthen building techniques.

Keywords: earthen architecture, additive manufacturing, robotic 3D printing, sustainability

1. Introduction
The construction industry was responsible for 39% of energy and process-related carbon dioxide emissions in 2018; 11% of those emissions were caused by manufacturing building materials like cement, steel and glass (United Nations World Urbanization Prospects [1]). The rising demand in construction is widely supplied by concrete and steel, exacerbating the impact of the construction industry on the environment. To mitigate the impact of the construction industry, the low-carbon, ubiquitous and reusable nature of earth as a construction material can contribute significantly.

Recently there has been a growing interest in understanding material behaviour and researching ways of enhancing the use of the material in architecture with computational design and digital fabrication. By placing the material exactly where it's needed with precision provided by machines, it is possible to increase the structural and thermal efficiency of building elements and avoid material waste with additive manufacturing (Paoletti [2]). 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 quick prototyping and testing (Claypool *et al.* [3]).

The conventional construction process is slow, wasteful and carbon-intensive. Unlike other sectors, the construction industry has not increased its productivity in the past 20 years (Barbosa *et al.* [4]). Automated construction has the potential to improve the process by making it faster, low-carbon and more efficient while the multi-axis robotic arm removed the geometric limitations of fabrication. By attaching different effectors to robot arms mounted on movable platforms, various applications could be automated on-site such as painting walls, assembling bricks or spraying concrete (Delgado *et al.* [5]). Artificial intelligence and machine learning help designers to develop behaviours of robots for fully automated construction processes.

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2. Earth as a building material

Earth as a building material is referred to as loam, soil, mud and dirt. Loam is used scientifically to mean a mixture of clay, silt, sand, and sometimes larger aggregates such as gravel or stones (Minke [6]). For this paper, "earth" is used as a collective term. Building with earth has several advantages. It is a reusable, ubiquitous, affordable, energy-efficient and low carbon material which creates healthy and pleasant indoor environments by balancing the humidity and storing heat due to its thermal mass (Minke [6]). Conventional materials like steel and concrete have high embodied energy because of the energy required to provide high temperatures necessary for their production or recycling (Habert *et al.* [7]). In contrast, unfired earth requires no industrial processing and it is generally available at the excavation site or nearby, eliminating the need to transport materials to the site. If there is no chemical additive, earth is reusable indefinitely by adding water and mixing.

Hygrothermal performance of earth, (its change in functional properties when exposed to various heat and moisture conditions) is better compared to conventional building materials such as fired clay and cement (Luizzi *et al.* [8]). Experiments done by the University of Kassel showed that, unfired clay bricks absorbed 30 times more humidity than fired clay bricks when exposed to a sudden 30% rise in humidity (Minke [6]). In contrast to baked bricks and tiles which require high temperature and energy for their production, unfired earth only needs solar heat to dry. Unlike industrial materials, unfired earth is nontoxic and non polluting while easy vapour exchange with its breathable nature creates comfortable and healthy indoor environments. Moreover, it can delay thermal variations, making it a favourable material for climates with extreme heat change between day and night (Houben and Guillaud [9]). This quality also diminishes the need for mechanical heating and cooling systems such as air conditioners, reducing operational energy costs.

3. Construction industry, robotic automation and additive manufacturing

3.1. Construction industry and digital fabrication

The industries that have profited greatly from automation and more recent advances in production technology, such as Additive Manufacturing technologies have one thing in common: they rely on manufacturing processes in which the workpieces can be moved around a manufacturing plant (International Federation of Robotics [10]). Thus, the value chain of additive manufacturing has been tested in small scale applications such as product and industrial design. Its impactful benefits to the design and construction industry, since they require applications at larger scales, remained a less explored area of development. Beside the challenges related with scale, the construction industry has been also slow to adopt digital (fabrication) processes (Agarwal [11]) due to its unstructured work environment and it relies heavily on standard components and building systems.

The implementation of computational models integrating design and fabrication procedures provides customized design solutions. Digital fabrication represents a stand against standardization and mass production. In contrast to the subtractive and formative fabrication methods, additive manufacturing allows and embraces the production of non-standard objects and components, providing a high level of customization and formal freedom. The level of customization allows reciprocity between the overall form of a component or spatial installation and the external shell and the internal pattern for additional performances.

Amongst the techniques such as sintering, laminating, binding, or curing the material; welding, melting, and depositing the material are the additive manufacturing methods explored in the construction industry. Thus, the range of material expands from plastic pellets to wood chips, from earth to liquid or pasty materials. Conventional three axis gantry systems have an inherent limitation of one-way deposition along the Z-axis, whereas an industrial robot that offers a multi axis fabrication possibility allows an approach from various angles and provides greater geometrical freedom.

3.2. Best practice selection of robotic 3D printing

In this section, we focused on the investigation of fabrication procedures and methodologies for robotic 3D printing utilizing various materials, and how the early experiments and related challenges provide a road map for robotic earth printing.

One of the initial promising experiments of additive manufacturing in construction is Mesh Mould, pursued between 2012 and 2014 at ETH Zurich. The first phase of the research was based on Fused Deposition Modeling (FDM), that was not only a scaled up spatial polymer extrusion but also a combination of formwork and reinforcement. This single procedure of robotically fabricated construction system allows fabrication of geometrically complex concrete structures. The experiment provided the interrelationship of mesh topology, cell size, and the rheological behavior of the fresh concrete within the mesh. Informed with these findings and to scale up the research to be applicable in the construction industry, the team pivoted from spatial polymer extrusion to a methodology which employed an end-effector that could cut and weld specific lengths of metal rod to construct a metal framework doubling as the reinforcement (Hack *et al* [12]). The second phase utilized an in-situ fabricator (IF) framed within a feedback-controlled environment to build a partition wall in DFAB house (Buchli *et al* [13]). Since earth printing requires a manufacturing setting onsite, the localization (robot itself, work area, extruder/stock material connection and other items of interest) strategy of IF utilized for Mesh Mould could provide a road map. This means determining the robots' own position in a 'world' coordinate system, the mutual position of the stock material and work zone, orientation, and other state information of the workpiece. The challenges would include sensory fusion, scene understanding, context interpretation.

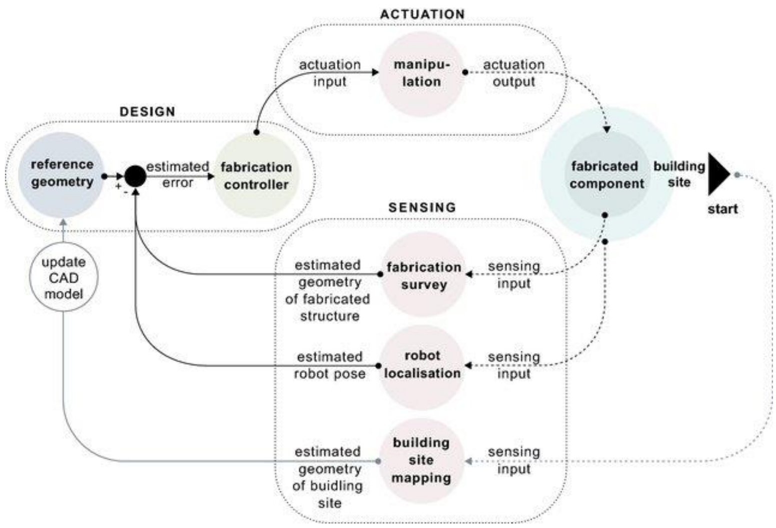

Figure 1: Diagram of the sensor-integrated adaptive fabrication strategy: the geometric-based closed-loop control allows the robotic system to deal with uncertainties related to the (1) building site, (2) the robot localization, and (3) the material behaviour. The diagram also shows the close entanglement of design, actuation, and sensing in robotic in situ fabrication (Dörfler *et al.* [14]).

Image courtesy of Dr. Kathrin Dörfler, Technische Universität München, Germany, all rights reserved.

The MX3D bridge by Joris Laarman used Wire and Arc Additive Manufacturing (WAAM) that enables large components to be built with reasonable geometric accuracy, costs and build times (Williams *et al* [15]). Printing was carried out using a 6-axis ABB industrial robot mounted on the ground, fitted with a MIG welding machine that has a vertical build direction. As opposed to the intentions of the winning proposal, building on the Oudezijds Achterburgwal with the robots sliding across the bridge as they built, the design had to change significantly due to regulatory, engineering, and practical reasons. The bridge was printed in four main pieces, plus the four corner swirls, which were then manually welded together. Verification of the bridge involved a combination of traditional structural design calculations, full scale physical testing and nonlinear finite element modelling (Gardner *et al* [16]). This comprehensive testing and modelling were deemed necessary for the safety verification of structures fabricated using any innovative technique until the quality control measures and standards are developed for each method. The lack of legislation regulating 3D-printed structures is problematic for the additive manufactured structures.

The differences based on the material properties results in the following changes of the robotic additive manufacturing methodology:

- The offline path planning strategy. Planar slicer based on contouring the geometry, curved slicer for printing on an existing surface or an overhang, user defined path for complex geometries.
- The feedback mechanism to identify the amount of material deposited accordingly adjust the material flow and printing speed as well as the movement speed, extrusion flow to adapt the specific printing process to the characteristics of the material.
- Level of automation.

4. Robotic 3D printing with earthen materials

4.1. Conventional earthen building methods in comparison to 3D printing with earth based materials

Conventional building methods with earth such as cob, adobe and rammed earth are labour-intensive, which is expensive and slow in high-income countries (Van Damme and Houben [17]). Robotic 3D printing with earth presents a promising alternative for the future of earthen architecture as it is a fast and labour-saving process which does not need scaffolding and is mostly waste-free (Rael and San Fratello [18]). Additionally, conventional earthen building methods consume excessive amounts of earth. Compared to the conventional earthen building methods, robotic additive manufacturing uses less earth and provides geometric freedom to fabricate advanced forms. Institute for Advanced Architecture of Catalonia (IAAC) Researchers argue that positive qualities of an earthen building (such as thermal regulation) can be enhanced while the disadvantages (such as labour-intensive construction and structural weaknesses) can be eliminated by combining computational design, material science, additive manufacturing and robotic fabrication (Dubor *et al* [19]). After several tests, “a straight face for the internal wall finish, a dense infill for structural performance, ventilated infill for thermal performance, and a curved face exposed to exterior for solar performance” was introduced with a parametric design approach (Izard *et al* [20]). Robotic 3D printing is faster than working by hand, provides higher freedom of form and enables higher precision. Earth mixes without any chemical stabiliser are reusable forever.

Recently, transdisciplinary research on the juxtaposition of the latest robotic 3D printing technology with conventional earthen building techniques has accelerated. Cob especially, has been a preferred conventional wet earthen building method to integrate with this technology because of its ductile nature which enables it to be fed into the extruder and printed. Cob is an energy efficient earthen building technique which consists of mixing clayey earth and fibres such as straw or grass and then applying them by hand with pushing them to create a monolithic wall (Minke [6]). Ben Alon et al. compared the LCA of a cob wall and conventional systems such as a concrete masonry block wall from cradle to construction site stages, based on embodied energy and air emissions (CO2, CO, SO2, …). It was observed that “the production of cob decreases energy demand by 62–82%, global warming potential by 75–82%, air acidification by 89–95%, and air particulate pollution by 96–98%, compared to conventional assemblies.” (Ben Alon *et al* [21]). There are at least 200 000 cob buildings in Europe, which have proven their durability for up to 300 years with the correct maintenance (Hamard *et al* [22]). Because of these qualities, cob has been gaining interest from researchers as a promising sustainable building technique for contemporary architecture. CobBauge is an international research project led by the universities in France and the UK, aiming to develop a novel low-carbon cob building technology and subsequently get it registered in building codes (Goodhew *et al* [23]). Hence this paper considers cob as promising contemporary building technique instead of a traditional one.

Figure 2: Traditional wet earthen building (Minke [6])

Figure 3: Cob Building, Devon England, 1410 (Minke [6])

Images courtesy of Prof Gernot Minke, all rights reserved.

Figure 4: CobBauge wall sample (Goodhew *et al* [23]) Image courtesy of Llyod Russell and Steve Goodhew, University of Plymouth, all rights reserved.

Figure 5: IAAC Terraperforma (IAAC [27]) Image courtesy of Gabriel Frederick, IAAC, all rights reserved.

4.2. Earth mix for 3D printing

Generally accepted traditional mix of cob includes 20% water, 1.4 to 1.75 % fibre and clayey earth to be stirred with forks, picks or hoes several times to create a consistent and plastic mix where water and clay is evenly distributed (Hamard *et al* [22]). For 3D printing, a more fluid mix is required for assuring the flow of material efficiently through the feeding hose and into the nozzle (Veliz Reyes *et al* [24]). A dry mix also puts more pressure on the extrusion motor and the cartridge causing damage to the equipment and disrupting the smooth flow of the material. The increased water content however, causes shrinkage and cracking while drying which needs to be taken into consideration. For example, research has shown that 3D printed curved lines that do not self-intersect has proven to perform better while drying compared to straight lines of 3D printing (Izard *et al* [20]). The water content also effects the structural integrity of the printed object as each printed layer should be robust enough to support the subsequent layer during the printing process. IAAC researchers developed a custom-built drone with a thermal camera to check the drying of clay for defining the printing speed of the robot to avoid collapse (Dubor *et al* [19]). Fibre contents that strengthen the earth mix should be added in smaller pieces compared to conventional cob building to avoid creating blockages along the hose and at the nozzle. 20-30 mm wide nozzles were installed for the latest experiments while printing speeds were set as 5mm/sec for cob and 15 mm sec for clay (Veliz Reyes *et al* [24]). Extrusion rate, layer height and extrusion speed need to be tested and adjusted for each prototype based on the size of the nozzle and the ratio of the earth mix.

4.3. Extrusion system

3D printing system primarily consists of an extrusion system based on the type of material and a motion controller for creating the form. Electromechanical and pneumatic systems are the two main extrusion systems used for printing clays and earthen materials.

The pneumatic extruder uses a pneumatic pump while the electromechanical system uses a stepper motor which is connected to a worm gear reducer to push the clay along a cartridge into the extruder. The extruder utilises an auger screw to transport and compress the material to the nozzle. It was observed that the electromechanical system performed better than the pneumatic one in terms of extrusion rate and consistency (Veliz Reyes *et al* [24], Gomaa *et al* [25]).

The size of the container within the extrusion system limits the size of the printable object. A 200x200x60 cob unit could be printed with a 4000 ml clay container which approximately accommodates 4.5 kg of cob (Veliz Reyes *et al* [24]). The need to replace and relocate the containers during the printing process disrupts the continuity of the printing and requires extra labour force. Gomaa M. et al designed a bespoke extrusion system with dual cartridge with 8000 ml material capacity each to ensure a continuous printing process. They have also suggested a secondary robot for reloading cartridges to fully automate the system in the future (Gomaa *et al* [25]).

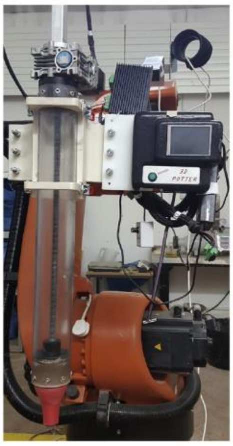

Figure 6: 3D printing earth with electronical linear ram extruder (Gomaa *et al* [25])

Images courtesy of Dr. Wassim Jabi, Welsh School of Architecture, Cardiff University, all rights reserved.

4.4. Robotic 3D printing

The geometries of prototypes are generally modelled in Rhinoceros software via Grasshopper plug in, and KUKA|prc as the inverse kinematics solver when the prototypes are printed by a 6-DoF KUKA KR20-3 robotic arm (20 kg payload, 1611 mm reach, KRC4 controller).

Firstly, the generative model of the prototype that includes the external shell and the internal pattern is created. Depending on the geometry, a slicer methodology is identified to create a toolpath for the robotic arm to follow via KUKA|prc. This solver works based on the planes along the toolpath and the type of movement between consecutive planes. The curves generated by slicing the geometry are divided into equally distanced planes and the toolpath will be created based on these planes. The extrusion path and additional traveling paths of non-extruding movements are integrated with a microprocessor to start and stop the motor for extrusion.

This generative model allows to re-iterate the toolpath based on the findings of the printing process. By printing a series of specimens from the same digital model and by varying the parameters that control the printing process, it is expected to clarify the settings of these parameters that result in more significant deviations between the digital and printed models. Such parameters would include the velocity along the extrusion path, speed of additional traveling paths (non-extruding movements), distance between consecutive planes.

4.5. Geometric limitations

Keeping the form stable during the extrusion process is challenging due to the increase in loads. Similar to the conventional wet earthen building methods, a drying period should be considered at intervals for the material to settle and gain strength. Although creating overhangs is hard with 3D printing earthen materials, recent research has demonstrated that it is possible to achieve 40 degrees of straight inclination with 3-axis 3D printing while 45 degrees of radial inclination is achievable with 6-axis 3D printing (Gomaa *et al* [25]). After designing the dual cartridge extruder system, researchers has also observed that separating the extruder from the robotic arm provided a greater geometric freedom (Gomaa *et al* [25]).

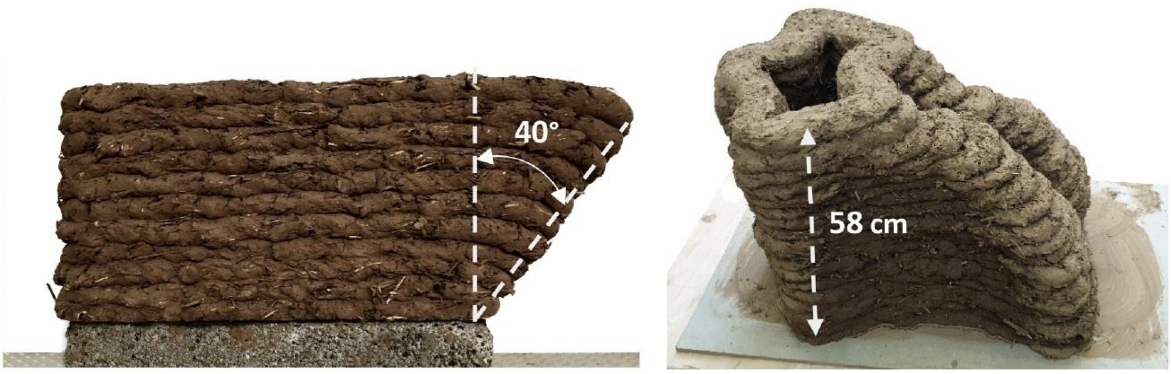

Figure 7: Inclination tests with 3-axis 3D printing (Gomaa *et al* [25])

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4.6. Environmental performance

Recent research has shown that 3D printed cob has achieved better environmental performance compared to 3D printed concrete because of the carbon intensive process to manufacture the cement. Conventional cob demonstrated better environmental performance compared to the 3D printed cob, mainly because of the use of electricity in 3D printed construction that compromises 83% of its environmental impact. Conventional cob however, uses more subsoil compared to 3D printing cob which is a scarce natural source (Alhumayani *et al* [26]).

5. Conclusion

As the paper has presented within the above sections, there are several opportunities and challenges for integrating robotic 3D printing with conventional earthen building techniques.

Robotic 3D printing with earthen materials is a promising novel sustainable construction method in the field of construction robotics. Using local soils and excavation soil where possible for onsite robotic printing suggests an energy efficient and affordable construction process for the future of construction. Concrete 3D printing has been gaining interest in the construction industry, however 3D printing with earthen materials is a more sustainable option. There is no post processing requirement such as firing for 3D printing for earthen materials. The low level of geometric freedom of earthen materials could be improved by using a combination of other structural materials, such as timber which is stronger in tension.

In addition to the opportunities, there are also several challenges to be addressed. Unlike concrete, earth is not a standardized material. The properties of subsoil varies based on the location and needs to be tested in each occasion. Material mix ratios and fiber sizes requires adjustments based on the extrusion system and nozzle diameters. It is essential to monitor flow rate, flow speed, geometric performance and the drying speed during the printing and enhance these parameters subsequently to ensure an optimum printing process. Strategies are expected be developed for introducing fenestrations, overhangs and connection to foundations. As the continuity of the printing depends on the capacity of container, continuous feeding systems should be designed based on the size of the building. Correspondence between the scaled prototype and real-life implications of on-site robotic additive manufacturing along with the change in scale, machinery and material should be carefully considered. Considering the cost of industrial robots and complexity of the software to operate them, developing affordable robotic printing systems and accessible software can accelerate adoption of this system as a mainstream construction method.

Although mass customisation, additive manufacturing, robotics and automation in construction are currently not mainstream and doing it with earth is even less so, it is still a promising alternative for the future. Yet the amount of research on using these technologies with earth is limited. Our ongoing research aims to contribute to this field and its adaptation to the industry considering the opportunities and challenges presented in this paper based on the recent research in the field.

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