2021-04

3D printing system for earth-based construction: Case study of cob

Gomaa, M

10.1016/j.autcon.2021.103577
Automation in Construction
Elsevier BV

Article published in

Journal of Automation in Construction, Vol. 124 (2021) 103577

https://doi.org/10.1016/j.autcon.2021.103577

3D Printing System for Earth-based construction: Case Study of Cob

Mohamed Gomaa[a*], Wassim Jabi[b], Alejandro Veliz Reyes[c] and Veronica Soebarto[a]

[a] School of Architecture and Built environment, Horace Lamb Building, University of Adelaide, Adelaide SA5005, Australia.
[b] Welsh School of Architecture, Bute building, Cardiff University, Cardiff, CF10 3NB, United Kingdom.
[c] School of Art, Design and Architecture, Roland Levinsky Building, University of Plymouth, PL4 8AA, United Kingdom.

*Corresponding Author: mohamed.gomaa@rmit.edu.au ;

Abstract

Despite the dramatic development in digital manufacturing technologies in the recent years, 3D printing of earth materials, such as cob, still presents several challenges to the market-available 3D printing systems. This paper describes the development process of a 3D printing system for cob that fits the contemporary requirements of digital construction. The study first described the methodology of producing a revised cob recipe for the purpose of 3D printing. Then, the study conducted thorough investigations into the properties of three types of extrusion systems using both electromechanical and pneumatic methods, leading eventually to the development of a new bespoke dual-ram extruder. The study then explored systematically the relationship between the new 3DP system and the rheological properties of cob, followed by an exploration to the new geometric opportunities the new system offers. The study findings show that the new extrusion system improves greatly the 3DP process of cob in terms of extrusion rate, continuity, consistency, and mobility. The findings are expected to bring 3D printed cob construction closer to full-scale applications. On a broader scale the study contributes to the disciplines of architectural design and construction by providing a framework capable of bridging the knowledge gap between vernacular modes of building production and contemporary digital practice.

Keywords

3D printing; Additive manufacturing; Robotic construction; Digital fabrication; Extrusion systems; Cob; Earth-based material.

1. Introduction

An increasing amount of research on implementing 3D printing (3DP) systems for large-scale formats has exposed multiple potential applications for architecture and the construction industry (Tay et al. 2017; Wu, Wang, and Wang 2016). Concurrent research highlights the advantages of 3D printing in construction to achieve a higher degree of process optimisations (e.g. financial, construction time, staffing resource), the emergence of new digital processes associated to Building Information Modelling and potential for mass customisation, and environmental benefits towards the life cycle of 3D printed objects and building elements (Wu, Wang, and Wang 2016). Additionally, research such as the review paper by Tay et al. (2017) outlines environmental benefits of 3DP in construction as a result of a reduced use of formwork (Kothman and Faber 2016).

Cob stands as one of many types of earth construction methods and it had been utilised historically all over the world. Its mix consists of subsoil (earth), water, and fibrous material (typically straw). However, similarly to related construction methods, cob buildings embody a material mix, as well as its associated construction method. Cob walls are typically built using hand-made material deposition on top a plinth, then corrected (e.g. correction of vertical planes) with material added or removed before or after drying (Hamard et al. 2016). As a result, building elements can comprise a variety of geometries, yet the builder is required to constantly negotiate the execution of an intended design with ever-changing material properties (e.g. water content, drying speed) necessary to achieve the design goals without the need for formwork or any mechanical compaction method (Figure 1). As a result:

- Cob provides a high degree of design freedom and adaptability throughout the construction process, where the builder negotiates with the material (and its properties) as the building process proceeds (Veliz Reyes et al. 2019), challenging the normalised view of robotic 3D printing as a linear process from design to production.
- Cob can be reutilised throughout the construction process, providing the opportunity for testing and prototyping design solutions (Kennedy, Smith, and Wanek 2015), reducing the amount of waste material and enabling low-cost project corrections and modifications on-site.
- Recent research demonstrates that cob complies with modern regulations such as UK building performance standards (Goodhew and Griffiths 2005).
- When compared to other massing construction materials and methods (e.g. concrete), cob has lower CO_2 emissions, low embodied energy (Benardos, Athanasiadis, and Katsoulakos 2014) and requires a lower degree of depletion of natural resources (Goodhew and Griffiths 2005).

These criteria suggest that a 3D printing system of cob warrants further investigation as a potential pathway toward more sustainable 3DP practices, with a lesser environmental impact when compared to concrete 3D printing (Alhumayani et al. 2020). Recent evidence supports this observation; an early study conducted on small material samples (Gomaa et al. 2019) provides evidence that 3D printed cob elements have competitive thermal performance standards when compared to other materials such as concrete, brickwork, and conventional cob construction.

Figure 1. Exposed cob construction in Totnes, UK.

Hamard et al. (2016) and Agustí-Juan et al. (2017b) highlight that the integration of digital fabrication techniques with vernacular modes of architectural production can reveal sustainability potentials for construction applications as compared to other cement-based 3D printing methods. This, mainly due to existing forms of cob knowledge production (e.g. vernacular construction techniques), emerges from long-lasting local environmental, material, social and skills contexts of construction practice. This research recognises the potential of developing building technologies associated with vernacular knowledge and building practices, generating a research and development process highly grounded on responsible innovation by leveraging local industries and technologies, utilising local materials and workforce (Garrett 2014). Moreover, the study challenges normalised models of design-to-fabrication research by incorporating local, vernacular and material knowledge as a methodological consideration and engagement process throughout the study. This negotiation between disparate frameworks of material practice (detailed in Veliz Reyes et al, 2019), established both in R&D research and in vernacular construction, not only results in emergent material opportunities within a standard design-engineering professional delivery framework but also enables novel methodological approaches to architectural tectonics, local materials and skillsets, digital discourses and building technologies.

A substantial share of recent research on 3DP for construction addresses 3D printing of cement and mortar-like materials. As a result, there has been a huge development in 3D printing systems for cement-based materials in recent years (Geneidy, Ismaeel, and Abbas 2019; Shakor et al. 2019). Different types of extrusion systems are currently used for 3D printing; varying from pneumatic pumps and electromechanical ram extruders. In spite of these developments, 3D printing of earth-based materials, such as cob, still presents several challenges to the market-available 3D printing systems such as material granularity, material properties and mix ratios, or the use of local organic fibres, which must addressed through extensive experimental research before delivering a feasible construction method (Veliz Reyes et al. 2018). These requirements highlight the opportunities of vernacular knowledge as a source of digital innovation, as it has already tested, iterated and perfected mix ratios and earthen architecture production typologies around the world.

Following early studies of cob 3DP technology (e.g. Veliz Reyes et al, 2018) the sensitivity of the printing process to the material mix is currently a major limiting factor in the development of construction-scale 3D printing with cob. The hardening property of the material mix creates a critical constraint on the speed of the 3D printing process (Perrot, Rangeard, and Courteille 2018; T. T. Le et al. 2012). The interrelation between hardening time and printing velocity must be monitored carefully, as each printed layer must be hard enough to support the weight of the successive layers. At the same time, the material mix must sustain a certain rheological behaviour that enables it to be extruded smoothly through the 3DP printing system (Perrot, Rangeard, and Pierre 2016; Veliz Reyes et al. 2018), despite its irregular granularity and addition of organic material. Moreover, effective design of material delivery systems may offset some irregularities that may be unavoidable in a commercial application, particularly considering the effect of specific geological, environmental or geographic conditions on the quality of 3DP cob mix.

Panda and Tan (2018) demonstrated the importance of establishing a clear understanding of the rheological behaviour of highly viscous 3D printed materials such as concrete. One of the major issues with 3D printing of such materials is to balance between the fluidity level and sufficient viscosity simultaneously in a way to ensure smooth flow of material through the extrusion system without clogging while maintaining the extruded material shape during the printing process. In concrete 3D printing, the developed mixtures must be thixotropic in nature, which means it should have high yield stress and low viscosity (Panda, Unluer, and Tan 2018). Other studies by Lipscomb and Denn (1984), (Le et al. (2015) and Choi, Kim, and Kim (2014) also highlighted the critical influence of mixture components, such as particle size, gradation, surface area and paste/aggregate volume on the flow property of the material as they govern the yield stress and viscosity. In his study, Perrot et al. (2016) proposed a theoretical framework for the structural built-up of 3DP of cement-based materials. His proposal showed the correlation between vertical stress acting on the first deposited layer with the critical stress related to plastic deformation that is linked to the material yield stress.

In earth construction, the rheology of the material is the key to control the quality of the structures. Historically, adjusting the consistency of cob mixtures depended greatly on the on the local know-how, simply though controlling the water to soil ratios, or by adding other ingredients such as fibres or lime (Perrot, Rangeard, and Lecompte 2018). As the construction industry shows a growing interest in earth materials via 3D printing, the need to develop simple and rapid testing for estimating earth material workability and rheological properties has increased (Bruno et al. 2017; Khelifi et al. 2013). According to Perrot, Rangeard, and Lecompte (2018), field-oriented tests can be leveraged to estimate material parameters such as the yield stress, which will provide important information to describe the rheological behaviour of the earth material. Weismann and Bryce (2006) demonstrated in their book "Building with cob: a step-by-step guide" detailed the methods for simple field tests of subsoil and cob characteristics. The recommended testing procedures were established on historical methods for building with cob, all aiming to provide clear understanding of the subsoil workability and rheology properties.

This research leverages the qualities of cob construction to utilise it as a groundwork for digital innovation through robotic 3D printing of building elements. This line of research has maintained the craft quality of cob as a source of innovative knowledge, often developed outside the boundaries of professional and academic frameworks - a "vernacular" understanding of the material usually communicated through making and practice instead of standard academic communication pathways (Niroumand, Barceló Álvarez, and Saaly 2016).

This evolutionary approach of vernacular architecture as a driver for novel environmental, technological and cultural discourses is exploited in this study through an iterative design research method, which has developed a material mix for cob 3D printing applications, an innovative extrusion system for cob 3D printing applications, and a series of tests attempting to outline emerging large-scale design opportunities resulting from this technology.

2. Methods and Material

2.1. Material

In cob constructon, printing material properties must be considered and formulated carefully according to both its wet and hardened states. Wet properties are those related to the material in its fresh, or 'green' state, i.e. the state that the material is in from initial mixing to the point at which it is deployed on site, before drying or hardening (Perrot et al. 2018a). According to Le et al., (2012), three basic criteria must be met to ensure a successful 3D printing process; extrudability, buildability, and workability with time. This means that the material must flow efficiently through the system without excessive force and be deposited in layers with minimal deformations. At the same time it must be able to support the loads of subsequetnt layers before hardening and reaching some degree of structural integrity. The transition from printing to hardening must occur within a time frame considering the material hardening rate while meeting the overall construction requirements such as tolerances for deformation. A similar process is conducted during hand constructed cob, as the builder must skillfully negotiate water contents, structural integrity and building design throughout the construction process.

In the context of this study, mix ratios have been reached through an iterative process of testing and material characterisation. Weismann and Bryce (2006) and Hamard et al. (2016) recommended that the composition of a cob mixture (averages) to be 78% subsoil, 20% water and 2% fibre (straw) by weight. The recommendation for the subsoil formula itself is 15-25 % clay to 75-85 % aggregate/sand. This mix, however, requires adaptation for 3D printing applications that maximises its fluidity, while maintaining printability properties (e.g. layer definition) and structural cohesion (e.g. layer height). This study used subsoil sourced from a farmland near Cardiff, UK, for the cob specimens. Subsoil specimens were examined according to the recommended testing methods in the literature (Steve Goodhew, Grindley, and Probeif 1995; Weismann and Bryce 2006): shake test, brick test, sausage test, ball drop test. These tests utilized simple deposition tests in order to acknowledge typically utilized on-site tests as well as to eventually simplify the material characterization process should this method be used in different contexts with little or no access to material testing facilities (Figure 2).

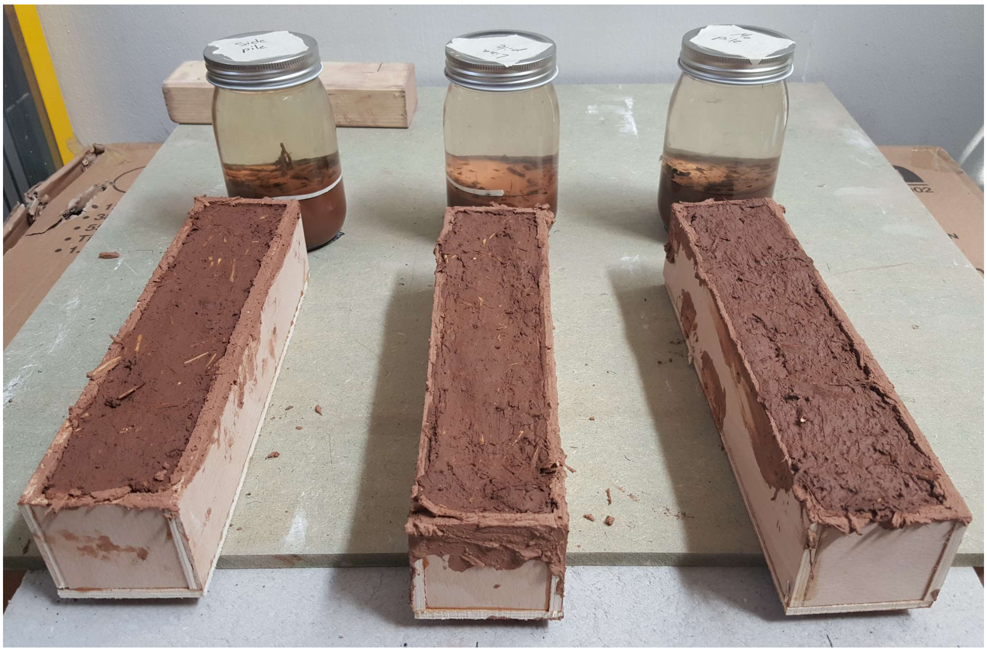


Figure 2. Shake and brick tests to the three subsoil samples from Cardiff.

However, as cob is traditionally mixed in a nearly dry state, the recommended compositions above do not necessarily fit the purpose of 3DP applications where a less viscous rheology is required. Lower water content in the mix leads to higher friction between the material and extrusion cycle parts, creating massive pressure on the extrusion mechanisms, resulting in increasing wear rate of the parts and reduce the long-term efficiency and printing quality. Gomaa et al. (2019) conducted a number of systematic tests to reach suitably modified proportions of cob mixtures for 3D printing purposes. The testing process included systematic alteration of several factors. Water contents of 22, 24, 26, and 28% were tested. The study concluded that the water content in the 3D printed cob mixture should be increased to an average of 25% while straw remains at 2%, resulting in a subsoil percentage of 73% (by weight).

It was anticipated that the increase in the water content will alter the rheology of the cob mix during and after the extrusion process. Therefore, it was important to examine the behaviour of the cob mix under the extrusion force. This examination seeks a systematic understanding of the variation in the printed path size in relation to the extrusion rate through the nozzle and motion speed on one side, and nozzle size and layer height on the other. Extrusion rate is usually used to express the volume of material passing through a given cross sectional nozzle area per unit time (mm^3/sec). Linear extrusion rate, on the other hand, represents the passing length of the material over unit time (mm/sec) (Khan Academy 2015; Zareiyan and Khoshnevis 2017). The study at first examined the synchronization process between linear extrusion rate and motion speed. Linear extrusion is chosen so that changes in the cross sections of different nozzles will not alter the outcome. Yet, the study focused on understanding the vital relation between the layer height and nozzle size, and their impact on the printed outcome. Understanding this relation is essential during the process of transforming the designed geometry into accurate contours and path lines for the 3D printing framework. The correct, and accurate, estimation of the 3D printed size of path lines and the geometry in total increases the quality of the outcome.

A series of tests were conducted to define this relationship mathematically. The tests set the nozzle diameter and the motion speed as constants at 45 mm and 80 mm/sec respectively, with a synchronised linear extrusion rate at 105 % of the nozzle motion speed (approximately 85 mm/sec). The printed file consisted of five path lines. Each line had a different layer height, starting from 15 mm and ending at 35 mm with 5 mm intervals. Each printed line was then measured and assigned to its respective height. This test was repeated three times to observe any possible variation to the outcome and increase credibility of estimations.

2.2. Equipment

A complete 3D Printing (3DP) system consists of two separate devices: a motion controller and a material delivery system. The two must be designed in coordination to realise the final 3D printed outcome: the weight of the extrusion system can affect the motion controller, or the accuracy of the motion controller can affect the tolerance and deformation of the final printed element. The study used a 6-axes KUKA KR60 HA robotic arm as the motion controller. The computer software package for robotic control was Rhinoceros via Grasshopper and KUKA PRC®. The material delivery system is the part of the printer setup which stores, transports, and deposits the print medium. The design of the material delivery system is vital to successful printing, as the material must be layered with enough accuracy, at a consistent and synchronized extrusion rate with the robot motion. Not meeting these needs can easily jeopardise the resulting print quality, which could significantly affect the shape and the structural integrity of a printed element. The material delivery tool (i.e. the extrusion system) replicated commercial clay extruders that exist in the market, which usually use both pneumatic and electromechanical techniques. The study then developed a new bespoke extrusion system which will be detailed later in the paper.

2.3. Extrusion system

Two types of material extrusion methods were tested in this research; 1) Screw-pump, and 2) Ram extrusion. The screw pump is a method that utilises an auger screw in order to transport and compress the material to a specific point, which in the case of 3D printing is the nozzle. Upon rotation, the screw acts as a type of rotational positive displacement pump, transporting material in the axial direction of the screw (Figure 3). Auger extrusion systems may be vertically or horizontally oriented. The screw sits within a material hopper, which is filled with material to be extruded. The rotating screw then pulls the material through the system. This method is used by the WASP Company in their Delta 3MT and 12MT printers, which they used to experiment with 3D printing of earth-based materials (Figure 4) (3D-WASP 2020).

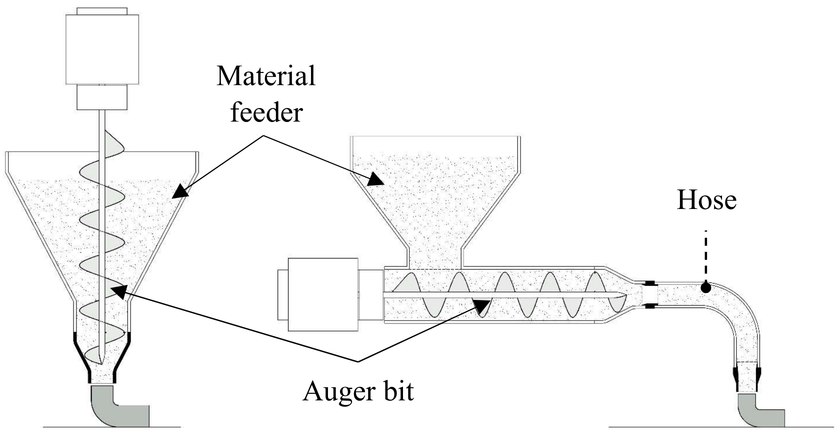


Figure 3. Two types of the screw pump: vertical screw (left) and horizontal screw (right)

Figure 4. Screw pump extruder by WASP

In ram extruders, a linear force is applied on a piston inside a cylinder ram filled with the material. The generated pressure then forces the material through the nozzle once a threshold of pressure is reached. These systems are also commercially known as linear actuators. The exerted force in linear actuators is generated by two methods (Figure 5);

1) Pneumatic, using air/gas, by increasing the pressure on one side of a pneumatic cylinder, leading to linear motion and an applied force on the plunger of the extrusion device.

2) Electromechanical, using lead screw or screw-jack, which translates circular motion from a motor into the linear motion and force exertion required to extrude the material.

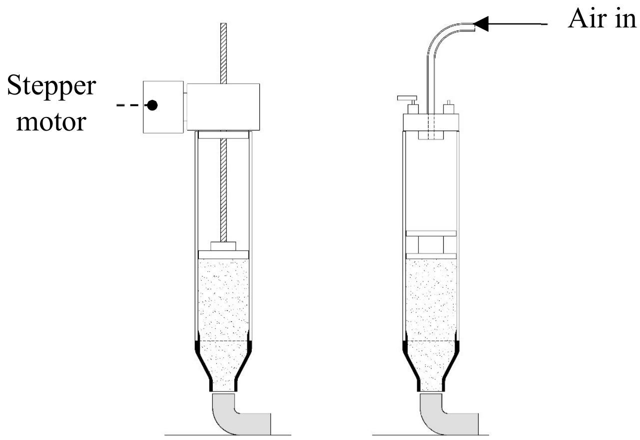


Figure 5. Scheme of the Pneumatic (right) and electromechanical (left) ram extruders.

2.4. Prototyping and Geometry

The prototyping process included two stages; the first stage is the calibration of the 3D printing settings, and the second stage is geometry prototyping. The calibration of settings is an important step to enhance the relationship between the robotic arm and the extrusion system. The calibration process was designed as a set of 3D printed path lines with variable layer heights and speeds. An understanding of the material behaviour is pursued through observing the relationship between the layer height, extrusion rate and nozzle dimension. The applied changes in the layer heights varied from 15 to 35 mm. These heights are chosen to represent a range of ratios in relation to the nozzle size, which has a diameter of 45 mm.

The second stage of prototyping focused on the geometry potentials and limitations. The main aim of this step is to examine several geometrical challenges that encounter the robotically assisted 3D printing of cob such as the inclined surfaces, arch based shapes and maximum height per printing period. The maximum height per printing period reflects the achieved geometry height before pausing the printing process until the printed geometry gain structural strength through the transformation process from wet to dry state (3D WASP 2016). Additionally, it must be acknowledged that cob can be reutilised after printing, either through the modification of a printed object (while still wet) or through trimming excess cob from already set built elements. As a result, the geometric and prototyping processes of cob 3D printing comprise an iterative quality which facilitates testing.

3. Results and Discussion

3.1. Extrusion System

3.1.1. Bespoke Screw pump

Inspired by the vertical screw extrusion system in the commercial Delta12MT WASP® (Figure 4), the research team developed a screw pump based on an auger bit device. The initial concept was to create a more robot-friendly extruder, where the material feed point was stationary and the extruded material was delivered to the robot arm end-effector point through a hose. This design concept aimed to provide a higher freedom of movement for the robot, besides an improved practicality of material feeding technique as compared to the available cob and clay extrusion system in the market, which requires regular human interference with the extruder for material feeding while on the move.

The used device for this testing was a repurposed auger conveyor, originally designed to transport sand. Alterations were made in order to make it suitable for cob extrusion (Figure 6). The initial testing of the device showed remarkable improvement in terms of extrusion rate, consistency and scale of the printed outcome. It was able to achieve a maximum extrusion rate of 80 mm/sec with a 50mm nozzle diameter. However, this system revealed several major shortcomings that required further stage of developments:

- The extruder jammed consistently due to the build-up of straw and rough aggregate at two points in the system; one at the interface between the auger tip and the nozzle and another at the interface between the hopper (feed point) and the auger.
- It still required constant human interaction to feed the material through the hopper.
- The whole mechanism was heavy and relatively large, which compromised the freedom of movement of the robot, and consequently limiting the complexity level of the geometry designs.
- The attempt of making the screw device stationary and install a hose at the screw end (as shown in Figure 3- right) was unsuccessful. Installation of the hose increased both the load and the material travel distance beyond the auger direct contact surface. The increase in hose length has an inverse proportional relation with the extrusion rate, accompanied by noticeable material retraction at the feeding point.

Figure 6. The prototype of the bespoke screw pump.

3.1.2. Pneumatic

The experimentation of this extrusion type was inspired by most of the industrial clay and concrete extruders, which are based on exerting linear force by using pneumatic pumps. The study used a pneumatic linear ram extruder, in which the pressure was manually controlled. The ram cylinder had a maximum capacity of 4000 ml and the used nozzle size was 30 mm Figure 7. The system was compact enough to be mounted easily on the robot arm and enable remote control of system at the same time. Despite the acquired strength from this extruder, the use of pneumatic system for a dense material like cob revealed a series of challenges in terms of controlling the extrusion rate, quality and consistency of extrusion. Furthermore, it required consistent human interaction throughout the print process to adjust the extrusion rate, fix faults and prevent collapses.

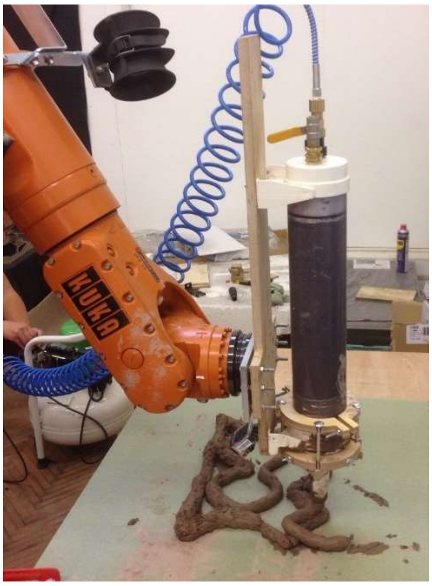


Figure 7. The pneumatic linear ram extruder

3.1.3. Electromechanical

In order to overcome the drawbacks of the pneumatic system, the study switched again to the use of the electromechanical extrusion method in its third phase. This phase used a commercial small size screw-jack extruder provided by 3D potter ® (Figure 8). The benefit of a screw-jack is that it includes a gearbox, providing extra torque at a lower speed. The new system provided a better control over the extrusion rate and consistency due to the use of a stepper electric motor, which resulted in a higher print quality. However, this extruder by 3D potter is designed to execute small-medium size porotypes of clay-based materials, as the standard maximum nozzle size was 16 mm. The system had to be modified by attaching a larger 25mm bespoke nozzle to be more suitable for cob extrusion. Despite the dramatic increase in the printing quality, the new system suffered from a slow printing speed limited to 5 mm/sec due to the increased nozzle size. This rate of 3D printing had restricted the progress of the experimentation, while it also restricted the scale of the printed outcome which may represent actual wall in a building. Furthermore, the capacity of the material container was too small (3000ml) for a large print to be made without refilling, and the process of refilling the device was slow as it required almost a partial disassembly of the whole extruder (Veliz Reyes et al. 2018).

Figure 8. The electromechanical linear ram extruder and its 3D printed outcome.

3.1.4. Bespoke electromechanical dual ram extruder

All the previous experimentations of different extrusion methods have led to the development of a completely new extrusion method that can accelerate the creation of prototypes, leading to an increased productivity and greater research potentials. The previous three experimentations have exposed five critical challenges that face robotically assisted 3D printing of cob:

1) Continuity of printing process.
2) Maximum extrusion rate.
3) Consistency and quality of outcome.
4) The freedom of movement.
5) Reduction of human interaction (remote control).

Each tested extrusion system exhibited a number of advantages and limitations. Table 1 summarises the efficiency level of each tested extrusion system based on the five previous criteria. The efficiency levels are expressed as Low, Medium and High, where low refers to limitations and high refers to advantages.

Table 1. Efficiency level of the tested criterions of each extrusion systems

	Continuity	Extrusion rate	Consistency	Movement Freedom	Human interaction
Screw pump	Medium	High	Medium	Low	Low
Pneumatic	Low	Medium	Low	Medium	Medium
Electromechanical	Low	Low	High	Medium	Medium

These criteria are crucial challenges to improve the workability and productivity of 3D printed cob research and practice. The successful encounter of these issues will open the window for more sophisticated explorations on both the 3DP cob mix properties and the geometry design aspects. Out of all the previous three introduced extruding systems, the electromechanical linear ram has shown promising potentials in overcoming the five challenges. However, it suffered mainly from the slow extrusion speed and the lengthy process of material reloading. Therefore, it has become important to build a new -off the shelf- extrusion system, inspired by the core concept of electromechanical screw jacks and capable of tackling the limitations of the previous systems.

The design process of the new system went through different iterations of trials and failures before reaching the final design. The initial concept started with the aim of building a simple upscaled version of the existing electromechanical screw jacks, shifting it from a single 2000ml cartridge to a single 8000ml, while adding a quick release system to accelerate the refill process. However, while this partially solved the issue of material quantity, it did not solve the continuity issue as the system still required to be on hold while the cartridges were being replaced. To solve this problem, an auxiliary cartridge was added in order to cover the hold time for the main cartridge to be replaced, but with the two cartridges working sequentially. The concept was inspired by small scale PLA and ceramic dual extruder by Leu et al. (2011) and 3D-WASP (2020). The first trials were proofs of concept, where preliminary prototypes of the system were made in 1:4 scale using 3D printed plastic parts. These trials used the standard 2000ml cartridges from the existing 3D potter electromechanical screw jack (Figure 9). The dual joint tested two different angles (45° and 22.5°) to ensure a smooth merge of the material between the two channels. The lower angle (22.5°) showed a smoother merge, hence it was selected to be applied in the full-scale prototype.

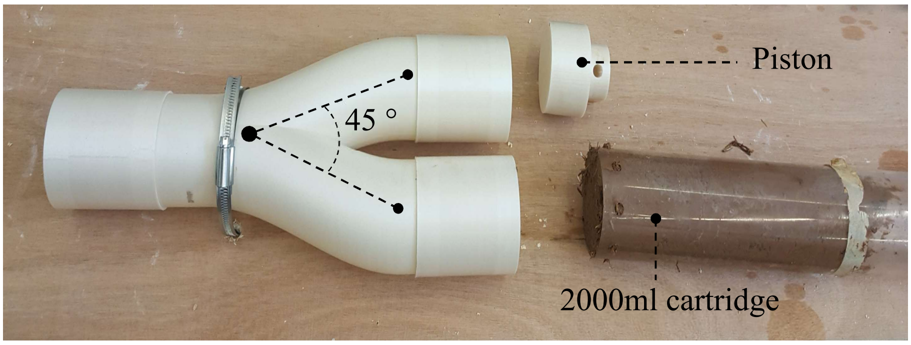


Figure 9. Initial proof of concept of the system in 1:4 scale using the 45 degrees dual joint.

The full-scale prototype initially used 3D printed plastic joints and fixtures. The whole system was then fixed on a mobile plywood platform (Figure 10). The first set of tests of the prototype showed success in terms of proving the workability of dual extrusion concept, yet it revealed two critical flaws which affected the extrusion process. The plastic parts were receiving a huge amount of pressure externally from the screw jacks and internally from the material flow, which eventually led to a quick wear and destruction of the parts at the mounting points (Figure 11-left). In addition, the accumulating pressure along the axis between the screw jack mounting point and the dual joint mounting point made the plywood platform buckle from the middle. This buckling forced the cartridge to bend, leading to a material leakage then eventually a massive crack in the plastic cartridge (Figure 11-right and Figure 12). Therefore, to avoid these flows in the final prototype, it was obvious that the system components must be fabricated from stronger materials such as aluminium, whereas the platform must be reinforced with a metal structure to prevent bending. The extrusion system can then be mobile by mounting the whole platform on a mobile table.

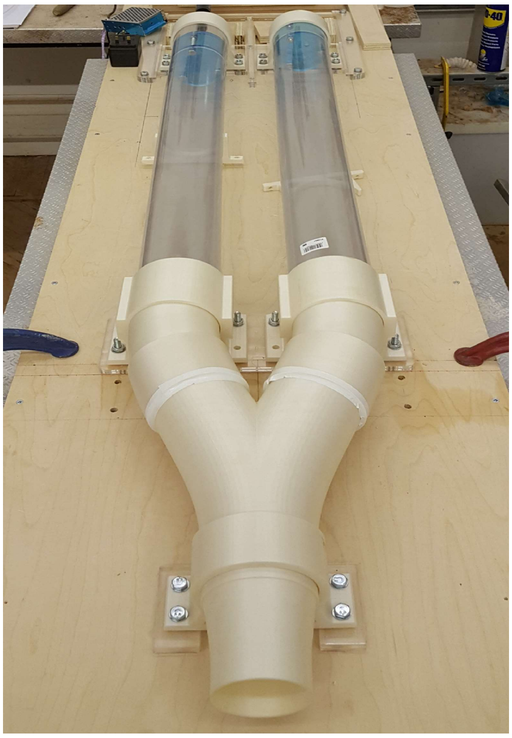


Figure 10. The initial full-scale prototype using 3DP PLA joints and fixtures on a plywood platform.

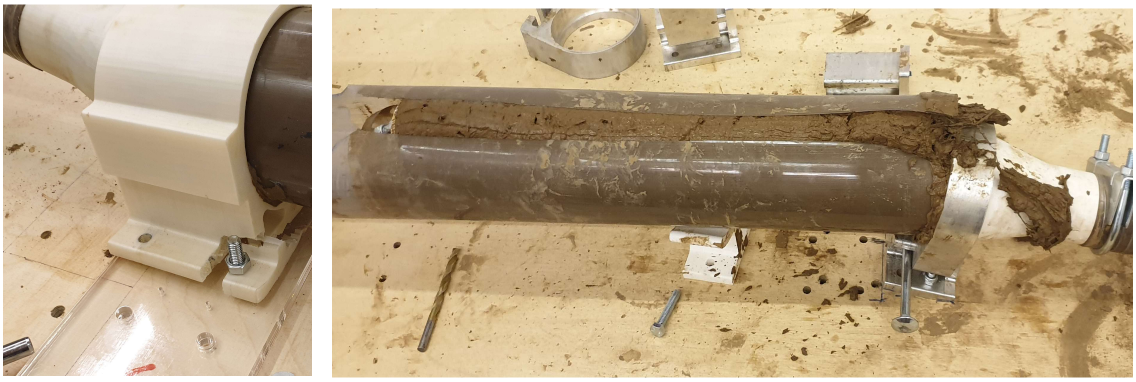


Figure 11. Destruction of the 3DP PLA joints due to pressures caused by the cob mix (left) and the destruction of the cartridge due to pressures caused by the bending plywood platform (right).

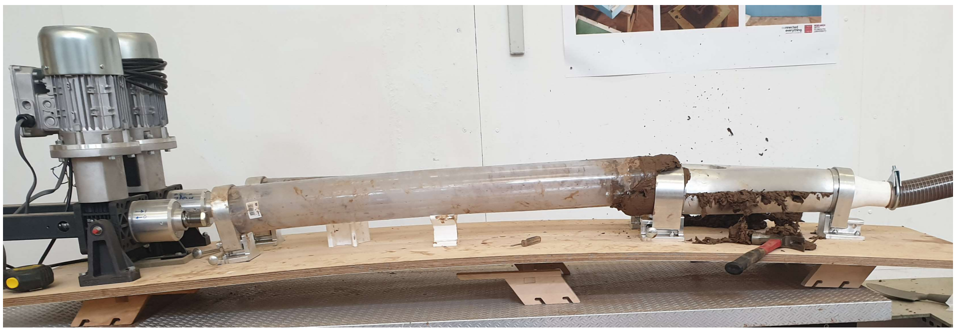


Figure 12. Buckling of the plywood platform due to accumlitated pressures on mutnig points

The final system prototype introduces a bespoke extrusion system with a unique dual-cartridge design (Figure 13, Figure 14). Each cartridge has a capacity of 8000 ml (total of 16000ml both) and powered by a heavy-duty electric screw jack. The screw jacks are supplied by ZIMM®

with 25 kN nominal capacity, leveraging a 1000 mm stroke and capable of delivering 80 mm/sec operating travel speed. The screw jacks are powered by two 3-phase motors, 0.75kW each. The motors combine electromagnetic braking system that ensures immediate stop to the stroke, which minimizes the dynamic response. These specs were specially requested based on calculations of the expected loads in the system, considering factors such as the material weight inside the system and the desired extrusion rate. As budget was limited, some adjustment to the system design were applied to simplify the manufactured parts and reduce the cost without affecting the targeted efficiency. Figure 13 shows a scheme of the bespoke dual extruder different components.

Material cartridges and screw jacks are connected together by bespoke aluminium parts, which are designed to provide smooth and fast reloading process. The most distinctive aluminium part is the Y-shaped joint that merges the material dual flow from both cartridges into a single flow then feed it to a hose. The used hose is 3-meter-long, made from PVC with a steel-wire reinforcement. The complete system is mounted on a mobile platform, allowing transitions around the robotic arm.

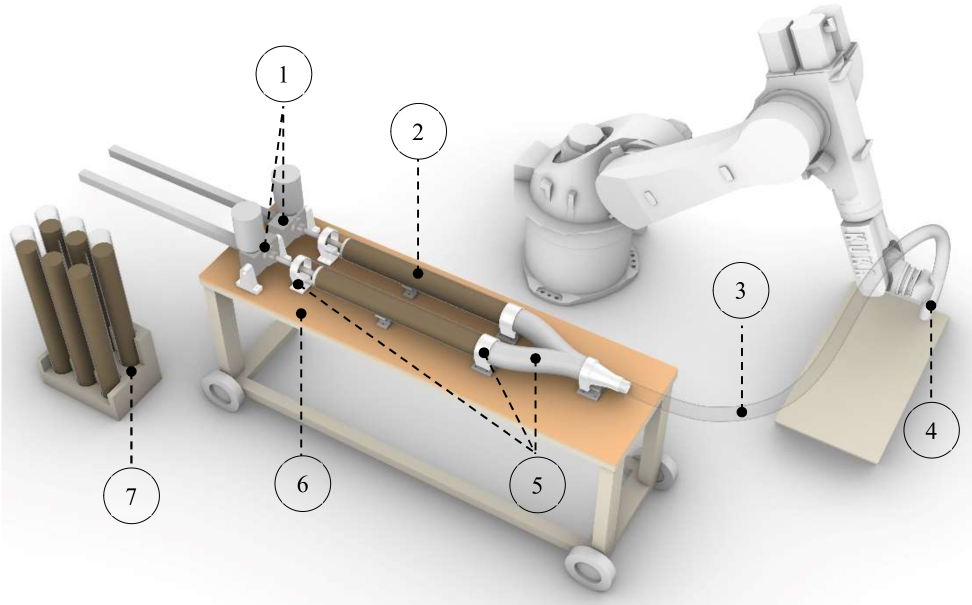
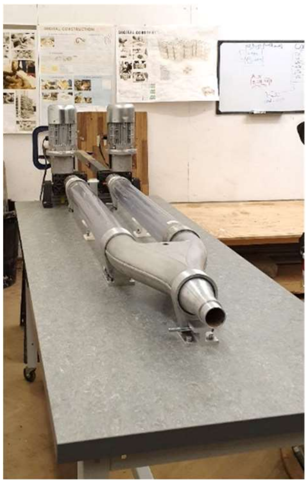


Figure 13. Scheme of the new bespoke dual extruder components: 1) Screw jack, 2) Cob Cartridge, 3) Steel-wired PVC hose, 4) Nozzle, 5) Aluminum parts, 6) Mobile platform, 7) Cartridges Rack.



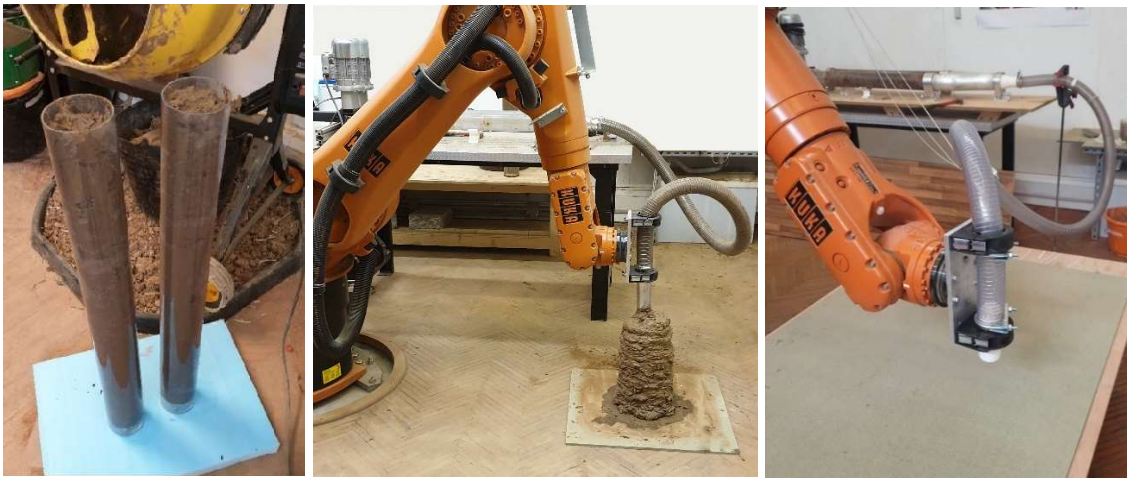


Figure 14. The components of the bespoke dual extruder.

The new system was tested extensively through sequence of calibrations and prototyping process, which took place as part of an experiential studio on 3D printing of cob at the Welsh School of Architecture in Cardiff University. The system proved to be successful in overcoming the five previous challenges as follows:

1- Continuity of printing process:

The new system adopts a sequential process of extrusion based on dual lines of cartridges. This process can be described in 6 steps as shown in Figure 15:

Step 1: The process preparation starts by loading two filled cob cartridges on the platform. Each cartridge, with its attached screw jack, form a line of extrusion. Few other cartridges are filled with the required amount of cob for the whole print and kept in a rack, ready to be loaded on the system later.

Step 2: The printing process starts by pumping cob through one cartridge at a time using one screw jack (line 1), simultaneously with initiating the robotic arm motion to exert the required design.

Step3: As the operating screw jack on line 1 reaches its stroke end, it stops and immediately triggers the second screw jack to start pumping cob through the second cartridge on line 2 while the first screw jack is retracting. After the complete retraction of the first screw jack, the empty cartridge is removed and a full cartridge is reloaded.

Step 4: By the time the first cartridge is reloaded, the operating cartridge will be reaching its end of stroke, which then releases the stopping brakes and triggers the first screw jack to start pumping cob through the first cartridge while the second screw jack is retracting.

Step 5: After the complete retraction of the second screw jack, the empty cartridge is removed and a full cartridge is reloaded on line 2.

Step 6: The process then repeats sequentially until the end of the required 3D printed outcome.

It is recommended to estimate the whole required amount of material before the printing process, then preparing either the exact number of cartridges (for small tasks) or just a few extra cartridges and store them in a rack. This will create a buffer margin between the process of refilling and reloading, which will ensure continuity of the process and constant flow of cob throughout the whole process, with no need to interfere, stop or slow it down. The special design of the aluminium parts also enhances the continuity of the process as they combine rails with latching mechanism, offering smooth reloading of cartridges on the platform.

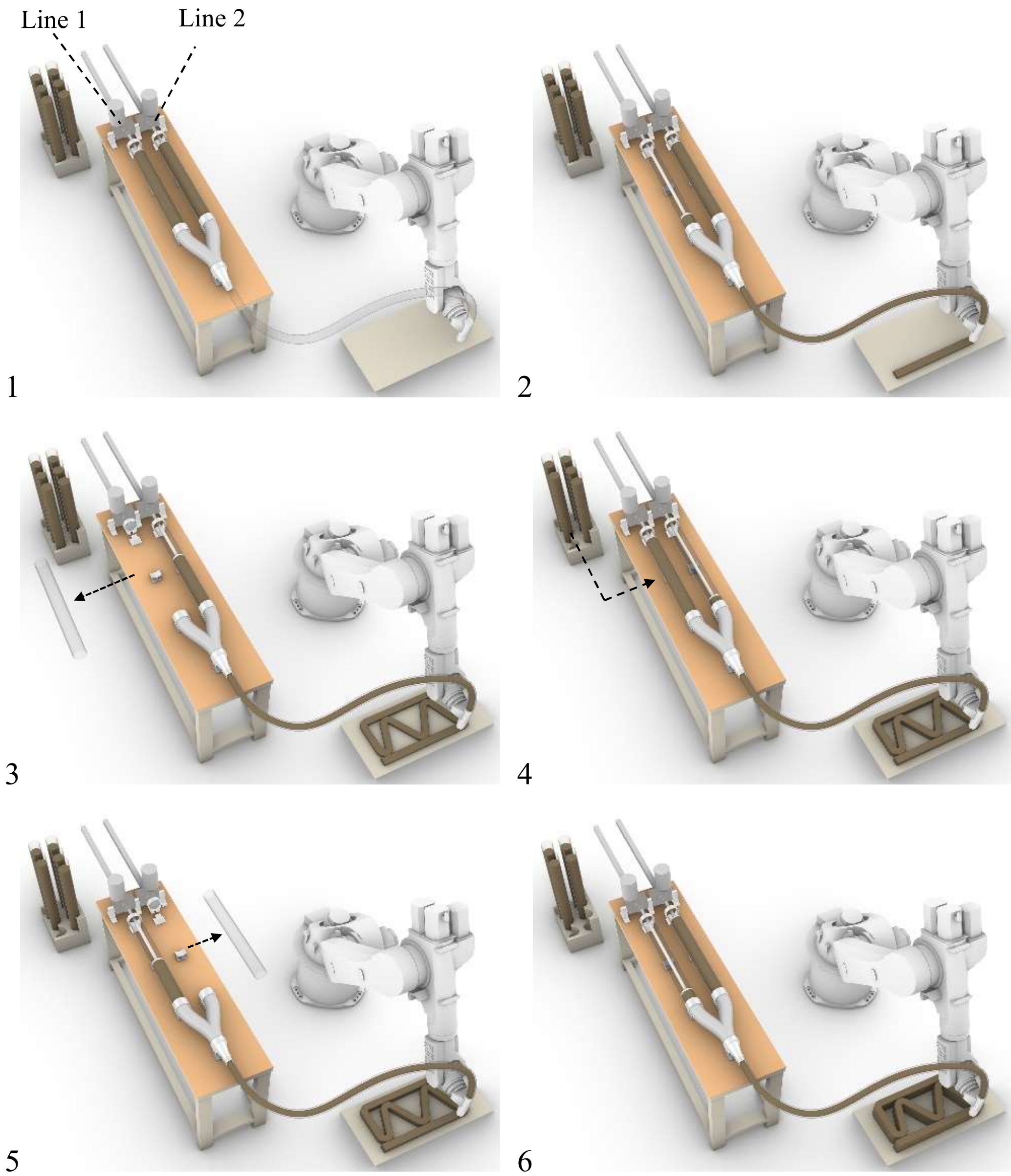


Figure 15. The six steps of the extrusion process in the bespoke dual extruder.

2- Maximum extrusion rate:
The upgraded screw jacks can deliver up to 80mm/sec operating travel speed. Using this travel speed with a 45mm diameter nozzle elevates the extrusion rate of cob on the nozzle to 120mm/sec, which is nearly 20 times faster than the previous small linear ram extruder with 30 mm nozzle. However, based on calibration tests, it was found that 50 to 80mm/sec extrusion rate is sufficient for most of the geometry testing in this project. Moderate speeds offer a relaxed reloading process and gives time to extruded layer of cob to strengthen slightly before receiving the subsequent layers.

3- Consistency and quality of outcome:

The new screw jack by ZIMM leverages a 25KN ball screw gearbox and 3-phase motor controlled by variant frequency driver (VFD). This enables a steady operational torque and an accurate control over travel speed, which provides a consistent flow of cob. This consistent flow dramatically improves the quality of the printed outcome as compared to the previous extruders.

4- Freedom of movement

The new system uses a hose to link between the main body of the extruder on the platform and the nozzle point. This minimises the mounted mass/ load on the robot's end-effector, as now it only carries the nozzle joint with the hose instead of carrying the whole extruder as in the previous pneumatic and small electromechanical linear ram extruders. Minimising the contact size between extruder and robot enables more degrees of freedom for the robot to move, resulting on broader complexity levels in the geometry design if needed. Moreover, the platform itself is mobile and can be easily moved around the robot if required to compensate the possible limitation in the hose length.

5- Reduction of human interaction (remote control)

The new system is designed to separate between the material feeding point on the platform and the extrusion point on the robot's end-effector. This separation enables the reloading of the cartridges without the need to interrupt (stopping or slowing down) the robot movement. The cartridges system and the simple latching mechanism of aluminium parts also minimise the time required for reloading and reduce human interaction time consequently.

3.1.5. Remarks on the dual extrusion system

Besides the five previous advantages, the simple, yet innovative, design of the new extrusion system made it replicable and also affordable to build as compared to the available commercial options. Moreover, the design enables the system to operate either as a single or dual extruder with different nozzle sizes. This facilitates the 3D printing process for small and medium size prototypes without the need to operate the full system. In addition, the new system has potential for successful implementation into full autonomous large-scale 3D printing process. The study suggests leveraging two on-site 3D printing concepts for that purpose; first one is inspired by mobile crane 3DP system by Contour Crafting (2020) Figure 16-left, where the robotic arm and the extrusion system can be combined in the crane system. The second is inspired by the mobile robotic vehicles which is presented in a study by Zhang et al. (2018) Figure 16- right. A revised design for mobile robot vehicle that can combine both the extruder and the collaborative robotic station is suggested as in Figure 17.

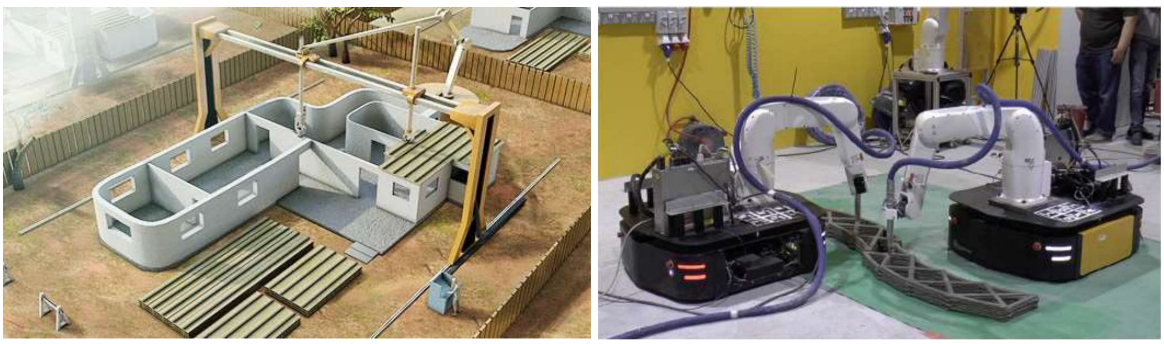


Figure 16. Mobile crane system for 3DP by Contour crafting (left), mobile robotic vehicles by Zhang et al (2018) (Right)

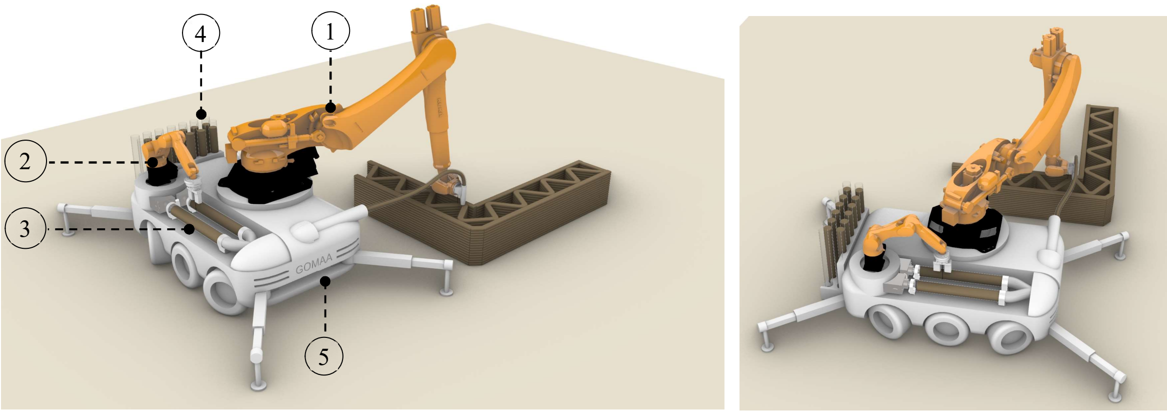


Figure 17. Design of mobile robot vehicle combining both the cob extruder and the collaborative robotic station. 1)Primary robot for printing. 2) Secondary robot for cartridges reloading. 3) Cob extruder. 4) Cartridges rack. 5) Autonomous robotic vehicle.

It is however important to state that the system is an initial prototype that also requires some enhancements and future upgrades. The current design still depends on human interaction to initiate and terminate the 3D printing process, in addition to preparing the cob mixtures, refilling and reloading the cartridges on the platform. It also very important to follow good practice while filling the cartridges to avoid air pockets and inconsistency, which causes high dynamic response. Also, the current material capacity is limited to 12.0 kg/cartridge, which forces large number of refills to print a real scale wall. For example, 1×1×0.5 m cob wall would require nearly 45 cartridges. Another current limitation is associated with the hose length. Increasing the hose length over 3 meters was found to be harder to mount on the robot and creates higher resistance towards moving and bending. Longer hose is also harder to be cleaned from cob leftovers after each printing process. Therefore, several planned upgrades will involve:

- Connecting the VFDs (controllers) of the screw jacks directly to the Robot controller unit, where the extruder will be operated simultaneously with the robot using the same code file.
- Increasing the material capacity of the system through upgrading the screw jack power and the cartridges volume. Moreover, the current dual-piston design could be redesigned to combine four pistons, capable of accommodating four cartridges at a time.
- The introduction of a collaborative robotic process, where a smaller robot arm will be part of the extruder platform to execute the cartridge reloading task. The required amount of material will be calculated ahead of the process, then translated into a number of cartridges. Another machine will be dedicated for mixing and refilling the empty cartridges while the prefilled cartridges are being used in the extruder.
- Implementing a shutter mechanism over the main dual Al connections can add extra layer of controllability as it will prevent any possible backflow of material during the cartridge reloading process. The current system design, however, does not suffer from material backflow due to the acute angle (45 degrees) of the dual Al piece and the relatively high viscous nature of the cob mix.

3.2. Material mix properties

The increased water content to 25 % in the new 3DP cob composite, instead of 20% for conventional cob composite, has shown satisfactory extrusion in terms of consistency and quality of extrusion. It was naturally anticipated that the increase in fluidity has proportional relation to the rheology of the cob mix during and after the extrusion process. First set of tests explored the synchronization process between extrusion rate and robot motion speed. It was clear from the start that the extrusion rate must be synchronised with the motion speed of the robotic arm on a 1:1 rate at least. Slower rate of extrusion will result in an intermittent printed outcome as can be seen in Figure 18-left. On the contrary, increasing the extrusion rate in relation to the robot motion speed (using a constant layer height) will result in a more consistent print and wider path lines. In Figure 18-right, the path lines A and B reflect a ratio of 1.15:1, while path lines C and D reflect a ratio of 1.05:1. The increased ratio of extrusion rate to motion speed results in wider path lines under a constant layer height. Table 2 below describe the relationship between extrusion rate and robot arm motion speed.

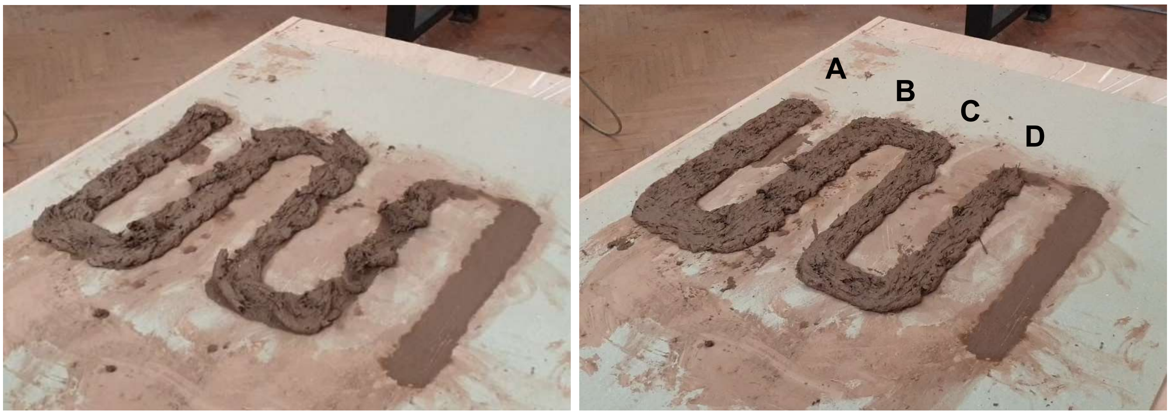


Figure 18. Explorations of the synchronization process between extrusion rate and robot motion speed (left & right)

Table 2. Relationship between extrusion rate and robot arm motion speed

Path line code	A-B	C-D	Unit
Nozzle diameter (D)	45	45	mm
Layer height (h)	15	15	mm
Extrusion rate	92	85	mm/sec
Robot motion speed	80	80	mm/sec
Path width (w)	88	70	mm
Extrusion rate to motion speed ratio	115	105	%

The study concluded after several trials that 3D printing with a liner extrusion rate of 105-110% of the robot motion speed (1.1:1) considered favourable due to the nature of the cob mix, where there are chances of having inconsistent sections of materials inside the cartridges that cause slight interruptions in the extrusion rate from time to time. It is possible to overcome this issue by installing an extrusion rate sensor at the nozzle end that can give live feedback to the variant frequency driver (VFD) of the actuator to make the proper adjustments to power. Worth mentioning that the study also observed that the slightly higher extrusion rate has a "ramming effect” on the printed outcome, where the printed path lines becomes denser and gain more structural strength with each new printed layer.

The second set of tests on the relationship between the layer height, nozzle size and path line width has improved the understanding of their influence on the 3D printed outcome and printing process in general. As can be seen in Figure 19, each printed path line (A to E) is designed to reflect the relation between a specific layer height and its respective path width, where the extrusion rate to robot motion speed ratio is set to 110% as advised previously, and the nozzle size is fixed at 45mm. The layer heights started with 15 mm at path line A, then the heights were increased discretely with 5 mm increment per each path line, ending with 35 mm layer height at path line E. Each increase in the layer height exhibited a decrease in the path line width. These relationships between the change in layer heights and path line width has been recorded and described as the expansion factor in Table 3. This test eventually resulted in a model that can estimate the path line width in accordance to the layer height and the nozzle size (Figure 20).

The linear relationship presented in Figure 20 can be described using the following equation:

$$\text{Estimated path line width (mm)} = \text{Nozzle size (mm)} \times \text{Expansion factor}$$

where the expansion factor can be obtained from the chart. To explain further; for example; under a synchronised motion speed and linear extrusion rate, with a 45mm in diameter extrusion nozzle and 25mm layer height (layer height is 56 % of the nozzle size) and an expansion factor of 1.6, :

$$\text{Estimated path line width (mm)} = 45 \times 1.6 = 70 \text{ mm}$$

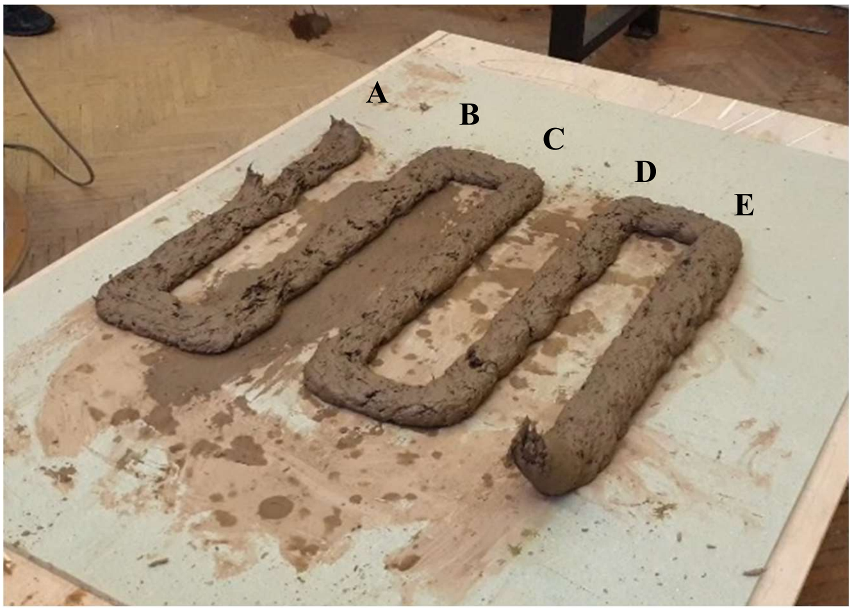
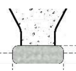
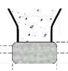
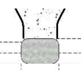


Figure 19. Exploring the relationship between layer height and nozzle size

Table 3. Description of the testing on the relationship between layer height, nozzle size and path line width.

Path line code	A	B	C	D	E	Unit
Scheme of path line cross section						--
Nozzle diameter (D)	45	45	45	45	45	mm

Layer height (h)	15	20	25	30	35	mm
Path width (w)	88	79	70	62	52	mm
Layer height to nozzle D ratio	**33**	**44**	**56**	**67**	**78**	%
Path width multiplication factor	1.96	1.76	1.56	1.36	1.16	--

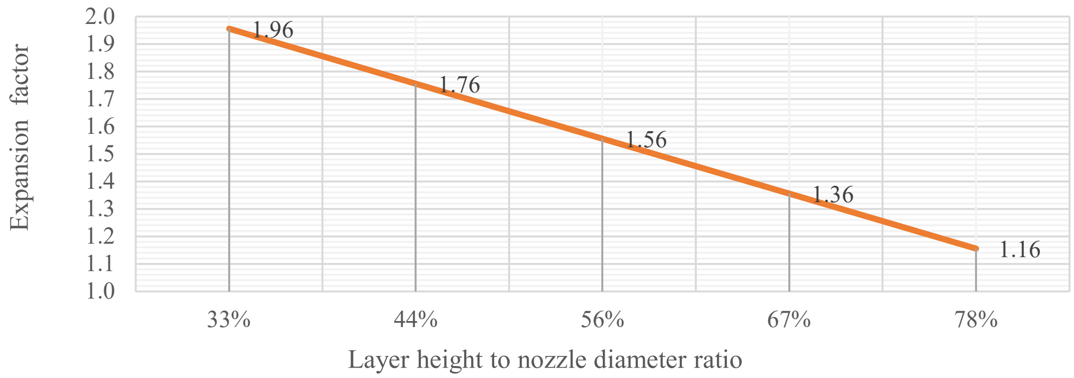


Figure 20. Path line width estimation chart

The early estimation of path line's printed width has enabled the study team to implement a code in the Grasshopper definition as part of the 3D model files to estimate the printed outcome to provide informed decisions for geometry planning. For example, when planning to print a cob wall that has a thickness of 500 mm, using a layer height of 25 mm would require a distance of 430 mm between the two path lines creating the inner and outer sides of the wall. Increasing the layer height to 30mm (while using the added definition in the 3D models) will then automatically update the distance between the wall path lines to 448 mm.

In addition to the previous changes in path line width due the extrusion process and the forced height by the nozzle, 3D printed cob encounters another cause of lateral deformation due to the accumulative loads of each added layer. As the 3D printing process continues, more printed layers accumulate on top of each other to create the desired height of the geometry. This increase in loads leads to further slight lateral and longitudinal deformation as compared to the original virtual model, where it is mostly seen in the bottom layers (Figure 21, left & right). It was observed during all experiments that the level of deformation depends primarily on the water content in the cob mix, as lower water content minimises the deformation to a negligible level (Figure 21- left), which was an early prototype with 22% water content. The higher water content of 24-25% leads to a noticeable deformation as in Figure 21- the prototype to the right, where the gradual increase in layer heights is slightly noticeable from the bottom to the top layers. Further exploration for the deformation aspects will be tested and presented in future work.

Figure 21. Prototypes showing the longitudinal deformation due to accumulative weight of layers (lower water content to left, higher water content to the right).

3.3. Geometry exploration

An exploration of various geometries was conducted to examine the capabilities of the 3D printing system. The study experimented with three types of geometries. The criteria of geometry selection were established on exploring the geometrical challenges that face the robotic 3D printing of a simple cob wall with an opening. Figure 22 suggests a traditional cob wall with arch-shaped opening to represent possible challenges while 3D printing cob walls, without using form work to create the openings. The challenges were found to be as follow:

A. Lift height (Max. height of continuous 3D printing)

B. Inclined 3-axis 3D printing (horizontal corbelling)

C. Inclined 6-axis 3D printing (radial corbelling)

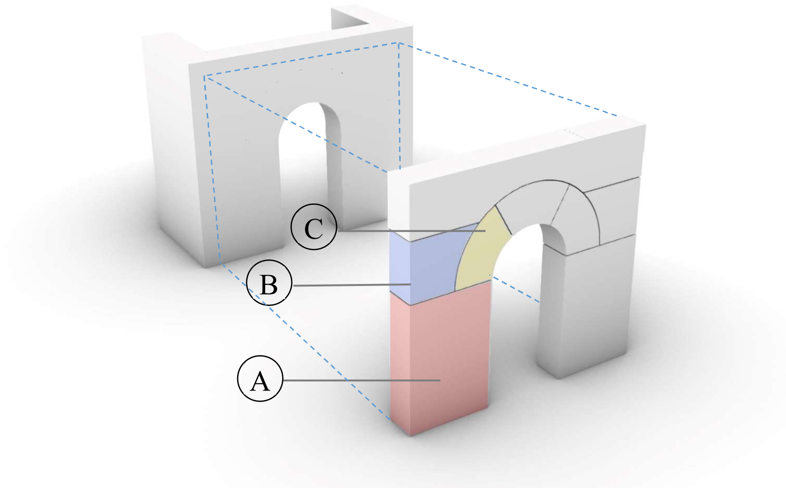


Figure 22. Geometry challenges in a regular cob wall with an opening. 1) Lift height- 3 axis 3D printing; 2) Inclined 3-axis printing (corbelling); 3) Inclined 6-axis 3D printing.

3.3.1. Lift height.

Cob walls are conventionally built of successive monolithic layers of earth called lifts. Each lift must be dry enough to a degree that enables it to bear the loads from the subsequent lifts. Lift height has an average of 60 cm. (Hamard et al. 2016; Weismann and Bryce 2006; Snell and Callahan 2005). Hence, the first geometry exploration aimed to examine the maximum height per lift (Figure 23). The geometry footprint was designed to have a rectangular footprint of 60x40 cm, with a serpentine printing path line that creates the inner pattern of the wall. A serpentine path line was selected for two reasons; first is to improve the structural performance of the wall (Emmitt and Gorse 2005); second is to extend the printing time per each path line as this should give more time for each layer to start drying and gain rigidity before receiving the successive layers.

This test showed that the maximum stable height of the lift was 58 cm, very similar to the traditional cob method. Exceeding this height increasingly jeopardised the stability of the geometry and it starts showing toppling signs. This finding is also supported by the prototypes by WASP (3D WASP 2016). This finding highlighted the importance of pausing or reducing the 3D printing speed to give a chance to the freshly printed layers to settle properly and gain more structural strength throughout the drying process.

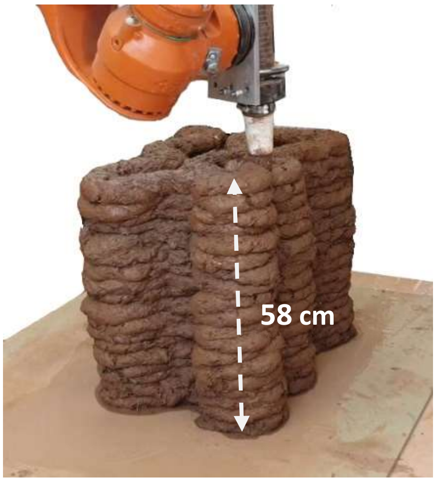


Figure 23. Testing the maximum height per printing period.

3.3.2. Inclined 3-axis 3D printing (horizontal corbelling)

The Second geometry exploration aimed to examine inclined 3-axis 3D printing, where the corbelling happens in the horizontal XY plane only The study examined two main approaches, straight and gradual inclination (Figure 24, left-right). Based on several trials, it was found that cob can sustain up to 40 degrees of straight inclination with 1:1.25 slope as shown in Figure 24-left. This was possible to achieve without using inner patterns but with slow printing speed of 30 mm/sec. Based on several trials, it was observed that high inclinations (more than 40 degrees) are less stable and require denser design for inner patterns. On the other hand, using gradual inclination required the addition of inner patterns to the geometry, but it showed a possibility to achieve nearly 90 degrees of inclination as shown in Figure 24- left. However, the increase of the inner pattern, in addition to the serpentine path line, caused a dramatic consumption of material per unit volume.

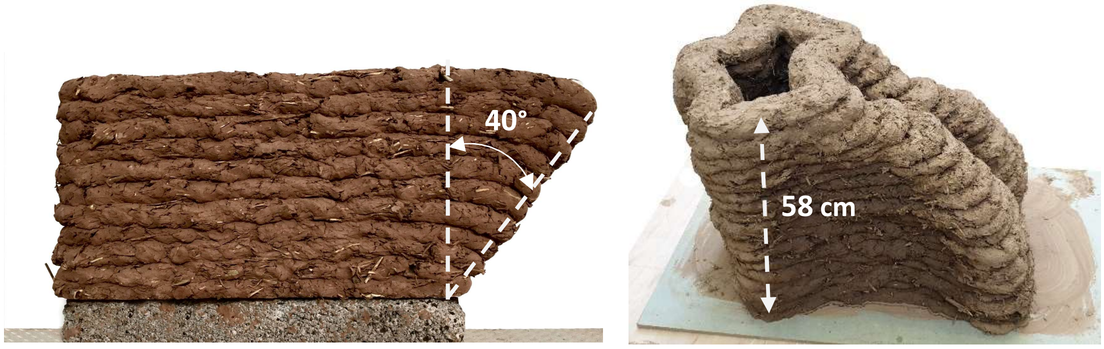


Figure 24. Examining the inclined 3-axis 3D printing; straight inclination (left) and gradual inclination (right)

3.3.3. Inclined 6-axis 3D printing (radial corbelling)

The third exploration aimed to exercise a more complex style of movement that involved all the six axes of the robotic arm. Such added complexity can be leveraged to construct arch-based shapes, like catenary vaults and arches Figure 22-C. The test was able to achieve 45 degrees of radial inclination in a one continuous print (Figure 25). It was possible to continue achieving higher degree of inclination, however, the geometry started to show instability due to its relatively small footprint (40 x 40 cm). It is worth mentioning that 75 degrees of inclination were successfully achieved in a previous study under this project using the small scale nozzle and less water content (Veliz Reyes et al. 2018). During the printing process of the arch prototype, the study observed that the 3D printed cob can gain structural strength from the ramming process, which is created by the extrusion forces and robotic arm compression. Also, similar to the previous two tests, it was necessary to add an inner pattern to geometry to increase the structural rigidity and the printing time per layer.

Figure 25. Testing complex movement through 3D printing arch-based geometry.

3.3.4. Remarks on geometry testing

Generally, the previous prototypes generated a record that has become useful to the planning of the future work on 3DP cob. Table 4 shows the different characteristics for each 3DP geometry. In addition, the testing process have revealed other factors which influence the geometry formation and its achieved quality. These factors are as follow:

- The overall footprint of the printed geometry: As longer foot prints, such as the external walls of a small house for instance, means more time is spent in each layer, which consequently enables the fresh 3D printed layers of cob to gain further strength as they dry. The footprint of the geometries (e.g. Walls), can be also increased by designing denser inner patterns inside the walls, which increase the stability of the printed structure, and also improve the thermal performance (Gomaa et al. 2019).
- Layer height to path line ratio: As discussed earlier in section 3.2, lower layer height creates wider path line. The increased footprint of path line offers greater stability to the geometry. However, reducing the layer height means additional material is consumed due to the increased number of required layers to reach the desired total height of the geometry. This also will increase the overall printing time.
- The relation between printing velocity and hardening time: where this study did not test systematically the competition between printing velocity and material hardening, the study observed that shorter printing paths per layer jeopardise the ability of each printed layer to harden sufficiently in order to sustain the loads of the successive layers. For instance, in geometry 2, the small squared footprint created shorter printing path per layer, which consequently required slower printing velocity, while in geometry 1, the larger rectangular footprint enabled higher printing velocity. However, this issue can be compensated by reducing the printing velocity or design the printing process to follow longer paths. This explains why the extrusion rates as per Table 4 were all maintained at 6.7 kg/ min while testing the current geometries despite the ability of system to reach a flow rate of up to 11 kg/min. Worth mentioning that replacing the empty cartridge manually takes nearly 30 seconds, which is less than the time needed to extrude the other full cartridge This means that the extrusion does not stop at any moment during the total printing process.

Table 4. The different characteristics for each 3DP geometry in the three tests.

	Test 1	Test 2	Test 3	Unit
Printing speed	50	50	50	mm/sec
Volume of printed cob	0.11	0.1	0.08	m^3
Weight of printed cob	198	182	132	kg
Number of used cartridges	16	15	11	
Total printing time	30	27	20	min
Extrusion rate	6.7	6.7	6.7	Kg/min

4. Conclusion

This paper presents a systematic study leveraging a traditional material and its associated embodied knowledge as a driver for digital innovation, specifically to develop a low-cost and sustainable alternative robotic 3D printing process and hardware (an extrusion system). The construction industry has done substantial strides in the 3DP area since the development of large-scale digital fabrication technologies (e.g. contour crafting). Several case studies and prototypes greatly illustrate the potentials of these technologies beyond standard procurement and standard building delivery models by integrating new knowledge into the building delivery from areas such as manufacturing and robotics. In that context, this article advocates that historical, traditional or vernacular material systems are a rich source of knowledge for further research and innovation in the built environment sector, and provides a groundwork of material resourcing, building knowledge and local skills with the potential for more sustainable construction data-driven processes. The impact of this study can be outlined in three key areas:

1) The development of an innovative extrusion system for earth-based materials.
2) The development of a robotic 3DP system that provides the opportunity to prototype new models of earth materials in the context of industrial frameworks of practice;
3) The leverage of vernacular material knowledge and skills to develop new technology in the digital sector.

The system presented here involves material studies and printing characterisation parameters as well as its associated hardware (an extrusion mechanism), and its implementation on small scale tests. The development of this system involved building a series of prototypes through a standard innovation delivery process, from basic ideation and research, up to proof of concept and prototyping stages. Building upon standard liquid deposition modelling 3DP 3-axis strategies, this system allows for more complex geometric configurations with more than 3 axis, and in contrast to traditional cob building processes, it allows for cob building elements to be produced on the basis of a filament (forming a hollow geometry) instead of bulk mass-based components, leading to higher geometrical flexibility, reduced material use and better thermal efficiency as a result of air cavities.

This paper also contributes to architectural design research, as it acknowledges the material cultural context as a springboard for digital and technological innovation delivery. This multi-disciplinary approach reflects on the applicability of this technology in professional practice. This project poses the concept of “material negotiation” to enable more flexible, open ended and multi-disciplinary relationships between design and fabrication by using a recyclable and reusable material prone to on-site modifications and adaptation. For instance, the dual extrusion system allows for a decentralised production model by pre-packaging and procuring cob cartridges from local suppliers and materials, reducing even further the construction’s carbon footprint and involving knowledgeable local suppliers in the delivery plan.

The research suggests, however, further work to develop this system into an industrial demo (and, even further, into a commercially viable system). Broadly, the research sets out a more ambitious agenda addressing the need to acknowledge and further investigate the potential of vernacular knowledge and buildings to facilitate material and digital manufacturing studies. For instance, further work can explore the applicability of machine learning, material feedback and computer vision approach for the robotic fabrication of building elements, as well as the observation of craft and making practices as a way to develop more intelligent and responsive manufacturing systems. Specifically to this study, the extrusion system would benefit from a higher degree of automation by developing a feeding system where cartridges are loaded and unloaded into the extrusion mechanism, ready to deliver material for 3D printing and where empty tubes can be collected and re-filled. A simple computation of printing speed, volume, and daily schedule can inform the size of buffer needed for pre-filled tubes and the required rate of exchange and delivery, which will greatly improve the degree of automation of the system enabling larger continuous prints. Also, in terms of local markets and the need to refurbish and repair existing cob structures, we envisage this technology as a useful alternative for cob building maintenance (e.g. crack filling, construction of pre-dried cob blocks), in alignment with recent strides on the use of robotic technology and intelligent computer vision for building maintenance applications, such as autonomous crack detection.

5. Acknowledgements

We would like to acknowledge Jack Francis and Dr Peter Theobald for their valuable collaboration and support (Cardiff University). We also extend our gratitude to Aikaterini Chatzivasileiadi and Anas Lila (Cardiff University) for their invaluable help. Special thanks also must be made to EMAR Engineering Services in Egypt for their technical support.

6. Funding sources

This work was supported financially by the Engineering and Physical Sciences Research Council (EPSRC) and The University of Nottingham under the Network Plus: Industrial Systems in the Digital Age, Grant number: EP/P001246/1.

This work is also partially supported financially by the University of Adelaide through the Research Abroad Scholarship scheme.

7. References

3D-WASP. 2020. "3D Printers | WASP | Leading Company in the 3d Printing Industry." 2020. https://www.3dwasp.com/en/. [accessed 31-08-2020]

3D WASP. 2016. "The Clay and Straw Wall by The 3 M| Stampanti 3D | WASP." 2016. https://www.3dwasp.com/en/il-muro-di-terra-e-paglia-alle-soglie-dei-3-metri/. [accessed 31-08-2020]

Agustí-Juan, Isolda, Florian Müller, Norman Hack, Timothy Wangler, and Guillaume Habert. 2017. "Potential Benefits of Digital Fabrication for Complex Structures: Environmental Assessment of a Robotically Fabricated Concrete Wall." *Journal of Cleaner Production* 154: pp 330–340. https://doi.org/10.1016/j.jclepro.2017.04.002.

Alhumayani, Hashem, Mohamed Gomaa, Veronica Soebarto, and Wassim Jabi. 2020. "Environmental Assessment of Large-Scale 3D Printing in Construction: A Comparative Study between Cob and Concrete." *Journal of Cleaner Production* 270 (June): pp 122463-122488. https://doi.org/10.1016/j.jclepro.2020.122463.

Benardos, A., I. Athanasiadis, and N. Katsoulakos. 2014. "Modern Earth Sheltered Constructions: A Paradigm of Green Engineering." *Tunnelling and Underground Space Technology* 41 (1): pp 46–52. https://doi.org/10.1016/j.tust.2013.11.008.

Bruno, Agostino Walter, Domenico Gallipoli, Céline Perlot, and Joao Mendes. 2017. "Mechanical Behaviour of Hypercompacted Earth for Building Construction." *Materials and Structures/Materiaux et Constructions* 50 (2): pp 160-175. https://doi.org/10.1617/s11527-017-1027-5.

Choi, Myoung Sung, Young Jin Kim, and Jin Keun Kim. 2014. "Prediction of Concrete Pumping Using Various Rheological Models." *International Journal of Concrete Structures and Materials* 8 (4): pp 269–278. https://doi.org/10.1007/s40069-014-0084-1.

ContourCrafting. 2020. "Building Construction - CC-Corp." 2020. https://contourcrafting.com/building-construction/. [accessed 08-02-2020]

Emmitt, Stephen, and Christopher A. Gorse. 2005. *Barry's Introduction to Construction of Buildings*. Cornwall: Blackwell Publishing Ltd. ISBN 1-4051-1055-4.

Garrett, Banning. 2014. “3D Printing: New Economic Paradigms and Strategic Shifts.” *Global Policy* 5 (1): pp 70–75. https://doi.org/10.1111/1758-5899.12119.
Geneidy, Omar, Walaa S.E. Ismaeel, and Ayman Abbas. 2019. “A Critical Review for Applying Three-Dimensional Concrete Wall Printing Technology in Egypt.” *Architectural Science Review* 0 (0): pp 1–15. https://doi.org/10.1080/00038628.2019.1596066.
Gomaa, Mohamed, Jim Carfrae, Steve Goodhew, Wassim Jabi, and Alejandro Veliz Reyez. 2019. “Thermal Performance Exploration of 3D Printed Cob.” *Architectural Science Review*, April, pp 1–8. https://doi.org/10.1080/00038628.2019.1606776.
Goodhew, Steve, P.C. Grindley, and S.D. Probeif. 1995. “Composition, Effective Thermal Conductivity And Specific Heat Of Cob Earth-Walling.” *WIT Transactions on The Built Environment* 15 (1): pp 205-217. https://doi.org/10.2495/STR950231.
Goodhew, Steven, and Richard Griffiths. 2005. “Sustainable Earth Walls to Meet the Building Regulations.” *Energy and Buildings* 37 (2005)*:* pp 451-459. Elsevier. https://doi.org/10.1016/j.enbuild.2004.08.005.
Hamard, Erwan, Bogdan Cazacliu, Andry Razakamanantsoa, and Jean Claude Morel. 2016. “Cob, a Vernacular Earth Construction Process in the Context of Modern Sustainable Building.” *Building and Environment* 106 (1): pp 103–119. https://doi.org/10.1016/j.buildenv.2016.06.009.
Kennedy, Joseph F., Michael G. Smith, and Catherine Wanek. 2015. *The Art of Natural Building*. Edited by C Wanek, M Smith, and JF Kennedy. Vancouver, Canada: New Society Publishers. ISBN: 0865714339
Khan Academy. 2015. “What Is Volume Flow Rate? (Article) | Fluids | Khan Academy.” 2015. https://www.khanacademy.org/science/physics/fluids/fluid-dynamics/a/what-is-volume-flow-rate. [accessed 01-09-2020]
Khelifi, H., A. Perrot, T. Lecompte, and G. Ausias. 2013. “Design of Clay/Cement Mixtures for Extruded Building Products.” *Materials and Structures/Materiaux et Constructions* 46 (6): pp 999–1010. https://doi.org/10.1617/s11527-012-9949-4.
Kothman, Ivo, and Niels Faber. 2016. “How 3D Printing Technology Changes the Rules of the Game Insights from the Construction Sector.” *Journal of Manufacturing Technology Management* 27 (7): pp 932–943. https://doi.org/10.1108/JMTM-01-2016-0010.
Le, H. D., E. H. Kadri, S. Aggoun, J. Vierendeels, P. Troch, and G. De Schutter. 2015. “Effect of Lubrication Layer on Velocity Profile of Concrete in a Pumping Pipe.” *Materials and Structures/Materiaux et Constructions* 48 (12): pp 3991–4003. https://doi.org/10.1617/s11527-014-0458-5.
Le, T. T., S. A. Austin, S. Lim, R. A. Buswell, R. Law, A. G.F. Gibb, and T. Thorpe. 2012. “Hardened Properties of High-Performance Printing Concrete.” *Cement and Concrete Research* 42 (3): pp 558–666. https://doi.org/10.1016/j.cemconres.2011.12.003.
Leu, Ming C., Lie Tang, Brad Deuser, Robert G. Landers, Gregory E. Hilmas, Shi Zhang, and Jeremy Watts. 2011. “Freeze-Form Extrusion Fabrication of Composite Structures.” *22nd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, (2011: Aug. 8-10, Austin, TX)* pp 111–124. University of Texas at Austin. https://www.researchgate.net/publication/266522915
Lipscomb, G. G., and M. M. Denn. 1984. “Flow of Bingham Fluids in Complex Geometries.” *Journal of Non-Newtonian Fluid Mechanics* 14 (C): pp 337–346. https://doi.org/10.1016/0377-0257(84)80052-X.
Niroumand, Hamed, Juan Antonio Barceló Álvarez, and Maryam Saaly. 2016. “Investigation of Earth Building and Earth Architecture According to Interest and Involvement Levels in Various Countries.” *Renewable and Sustainable Energy Reviews* 57: pp 1390–1397. https://doi.org/10.1016/j.rser.2015.12.183.
Panda, Biranchi, and Ming Jen Tan. 2018. “Experimental Study on Mix Proportion and Fresh

Properties of Fly Ash Based Geopolymer for 3D Concrete Printing." *Ceramics International* 44 (9): pp 10258–10265. https://doi.org/10.1016/j.ceramint.2018.03.031.

Panda, Biranchi, Cise Unluer, and Ming Jen Tan. 2018. "Investigation of the Rheology and Strength of Geopolymer Mixtures for Extrusion-Based 3D Printing." *Cement and Concrete Composites* 94 (November 2017): pp 307–314. https://doi.org/10.1016/j.cemconcomp.2018.10.002.

Perrot, A., D. Rangeard, and E. Courteille. 2018. "3D Printing of Earth-Based Materials: Processing Aspects." *Construction and Building Materials* 172: pp 670–676. https://doi.org/10.1016/j.conbuildmat.2018.04.017.

Perrot, A., D. Rangeard, and T. Lecompte. 2018. "Field-Oriented Tests to Evaluate the Workability of Cob and Adobe." *Materials and Structures/Materiaux et Constructions* 51 (2): pp 1–10. https://doi.org/10.1617/s11527-018-1181-4.

Perrot, A, D Rangeard, and A Pierre. 2016. "Structural Built-up of Cement-Based Materials Used for 3D- Printing Extrusion Techniques." *Materials and Structures/Materiaux et Constructions* 49: pp 1213–1220. https://doi.org/10.1617/s11527-015-0571-0.

Shakor, Pshtiwan, Shami Nejadi, Gavin Paul, and Sardar Malek. 2019. "Review of Emerging Additive Manufacturing Technologies in 3d Printing of Cementitious Materials in the Construction Industry." *Frontiers in Built Environment* 4: 85 pp 1-17. https://doi.org/10.3389/fbuil.2018.00085.

Snell, Clarke., and Tim Callahan. 2005. *Building Green : A Complete How-to Guide to Alternative Building Methods : Earth Plaster, Straw Bale, Cordwood, Cob, Living Roofs*. Lark Books. ISBN: 9781579905323

Tay, Yi Wei Daniel, Biranchi Panda, Suvash Chandra Paul, Nisar Ahamed Noor Mohamed, Ming Jen Tan, and Kah Fai Leong. 2017. "3D Printing Trends in Building and Construction Industry: A Review." *Virtual and Physical Prototyping* 12 (3): pp 261–276. https://doi.org/10.1080/17452759.2017.1326724.

Veliz Reyes, Alejandro, Mohamed Gomaa, Aikaterini Chatzivasileiadi, and Wassim Jabi. 2018. "Computing Craft: Early Stage Development Ofa Robotically-Supported 3D Printing System for Cob Structures." *Proceedings of the 34th Conference of Education in Computer Aided Architectural Design in Europe* (*eCAADe)- Computing for Better Tomorrow*, 1: pp 791–800. Lodz: cuminCad. https://pearl.plymouth.ac.uk/handle/10026.1/12769

Veliz Reyes, Alejandro, Wassim Jabi, Mohamed Gomaa, Aikaterini Chatzivasileiadi, Lina Ahmad, and Nicholas Mario Wardhana. 2019. "Negotiated Matter: A Robotic Exploration of Craft-Driven Innovation." *Architectural Science Review* 0 (0): pp 1–11. https://doi.org/10.1080/00038628.2019.1651688.

Weismann, Adam, and Katy Bryce. 2006. *Building with Cob: A Step-by-Step Guide*. Devon: Green Books ltd. ISBN: 1903998727

Wu, Peng, Jun Wang, and Xiangyu Wang. 2016. "A Critical Review of the Use of 3-D Printing in the Construction Industry." *Automation in Construction* 68: pp 21–31. https://doi.org/10.1016/j.autcon.2016.04.005.

Zareiyan, Babak, and Behrokh Khoshnevis. 2017. "Interlayer Adhesion and Strength of Structures in Contour Crafting - Effects of Aggregate Size, Extrusion Rate, and Layer Thickness." *Automation in Construction* 81 (June): pp 112–121. https://doi.org/10.1016/j.autcon.2017.06.013.

Zhang, Xu, Mingyang Li, Jian Hui Lim, Yiwei Weng, Yi Wei Daniel Tay, Hung Pham, and Quang Cuong Pham. 2018. "Large-Scale 3D Printing by a Team of Mobile Robots." *Automation in Construction* 95 (August): pp 98–106. https://doi.org/10.1016/j.autcon.2018.08.004