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Computing craft: Early development of a robotically-supported cob 3D printing system

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Computing Craft

Early stage development of a robotically-supported 3D printing system for cob structures

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This paper focuses on an ongoing investigation exploring fabrication procedures and methodologies for robotically supported 3D printing utilising cob and other clay-based sustainable building materials, and is part of an ongoing collaboration between Cardiff University and the University of Plymouth. The methodology is that of a prototype development process within the framework of a feasibility studies call supported by the ``Connected Everything: Industrial Systems in the Digital Age'' EPSRC (Engineering and Physical Sciences Research Council) network. This project expects to not only reveal technological and design opportunities for 3D printed cob structures, but more broadly to engage with vernacular practice through digital means. As a result, this paper expects to contribute to the discipline by providing a framework engaging with digital practice as a way to bridge the knowledge gap between digitally-driven and vernacular modes of knowledge production, dissemination and representation.

Keywords: *cob construction, robotics, 3D printing, vernacular architecture*

INTRODUCTION

Cob is a category of unbaked earthen construction consisting of a mix of subsoil containing clay, water, fibrous organic material (e.g. straw), and (sometimes) lime or manure. It is typically utilised to build small and medium-sized buildings (Figure 1) in successive layers. Ancient cob constructions are documented around the world (e.g. North and South America, New Zealand and Middle East, among others), and recent examples can be found in England and France, among other contexts. A variety of cob constructive expressions and techniques is present across diverse locations because of its material properties (e.g. mix ratios) varying throughout different geological, climate and local workforce conditions. Cob construction, then, despite a seemingly simple recipe, operates under established and localised frameworks of practice based on hand-making, hand-assembling and material intelligence.

Figure 1
Cob building in Totnes, United Kingdom.

In this project, we attempt to source operational knowledge from this vernacular practice in order to develop a feasibility study exploring fabrication procedures and methodologies for robotically supported 3D printing utilising cob and other clay-based sustainable building materials. Typically, operational knowledge ("*know-how*") for cob construction has been developed outside the boundaries of academic, technological and professional disciplinary frameworks, and here this study identifies a research need and an opportunity. While the automation of building processes has successfully engaged with the production of building elements and components, it is currently facing development and application challenges for on-site, context-aware construction due to shortages in digital/technological skills and the logistic implications of testing context- and craft-aware technologies in buildings.

This paper outlines an approach to digital modelling and manufacturing as not only methodological and technological pathways towards development of industrial solutions, but also as vehicles to bridge the gap between local, craft-based knowledge and technological principles and applications in both the Manufacturing and the Architecture, Engineering and Construction (AEC) industries. With a focus on early stages of this feasibility study, this paper outlines material properties as well as a series of initial methodological steps including systems integration for the development of extrusion mechanisms for cob. Material studies and mix ratios have been explored through a series of workshops with Architecture students in the context of two "Digital COBstruction" vertical studios at the Welsh School of Architecture in Cardiff University.

THE VERNACULAR AS A FRAMEWORK FOR DIGITAL PRACTICE

Vernacular material systems are often seen as primitive, historical or unsophisticated. Research suggests as a possible cause the fact that vernacular constructions and methods have arisen as a result of emergent, localised and rural traditions developed outside the boundaries of established academic and professional bodies (Brown and Maudlin, 2012). The "vernacular", then, is framed within situated modes of knowledge representation (if any), production and dissemination which do not follow standard disciplinary conventions and often finds distinctive manifestations in the built environment. While cob and earthen architecture examples can be found in developed countries, the use of soil for construction is often associated to contexts at the periphery of mainstream architectural discourses: ethnic groups' domestic spaces, reconstruction efforts in disadvantaged locations, or community driven projects built to access basic needs such as living quarters or schools. Despite centuries of *know-how* development, however, the appropriation of the "traditional" or the "vernacular" is documented and theorised more broadly during the XX century - particularly by architectural historians concerned with matters of function and aesthetics (Pevsner, 1943). Later on, catchphrases such as "architecture without architects" have been associated to buildings, as well as their social, cultural and inhabitation characteristics, produced outside the boundaries of the profession, a "non-pedigreed" (Rudofsky, 1964) mode of production of the built environment that highly contrasts with the contemporary, technologically informed and research-driven nature of digital design and fabrication fields of inquiry.

Such temporal quality (i.e. the vernacular as "the traditional") can be found in literature related to digital design and fabrication referencing some form of historical construction method. For example, the digitally fabricated lamella structure reported by Tamke et al. (2010) is produced by utilising traditional timber joinery techniques - the lamella itself is a structural system dating back to 1908. The more recent work by Gonzalez et al. (2017) parametrizes and prototypes an inventory of timber joinery systems currently at risk of disappearing in the UNESCO-protected city of Valparaiso due to natural disasters and shortage of skilled workforce. Examples of massing construction systems are less frequent; the stone construction language developed by the Inca culture in South America is the foundation for the robotic production of stone masonry walls reported by Clifford and McGee (2015).

In contrast with these cases, this project does not consider cob construction as a practice eminently "traditional" associated to an historical context. Brown and Maudlin (2012) describe the extensions of vernacular architecture to include the "everyday", a range of contemporary buildings outside the "self-authorized discourse and practice of the architectural mainstream" (p. 342). In that sense, this study considers cob as a contemporary material, a trajectory of embodied knowledge and material intelligence worthy of technological interrogation, digital innovation and source of emergent/hybrid modes of architectural design and construction. This approach to the "vernacular", then, does not expect to override existing methods of cob construction (a view often championed by the "jobs automation" narrative), but instead to facilitate socio-technological innovation upon existing knowledge and its associated modes of production, representation and dissemination - this clarification is worth noting in the context of current industrial strides towards technologically informed material systems and potential impacts on design and construction workforce. By interrogating the vernacular through digital means, the approach developed in this project expects to develop a framework for digital architectural research and development stemming from a critically informed view of the vernacular, acknowledging its material intelligence, socio-cultural dimensions and embodied knowledge.

3D PRINTING OF COB STRUCTURES

The aim of this study, as previously stated, is to investigate fabrication procedures and methodologies for robotically supported 3D printing utilising cob and other clay-based sustainable building materials. To achieve this goal, the objectives for this work are planned as an incremental systems development methodology expected to result in not only written material but additionally a series of outputs such as artefacts, devices, products, and digital/visual media. These objectives are:

1. To outline a current state of the art (technological framework), particularly that of specialist and situated operational knowledge (craft) associated with cob construction and its availability for innovation through digital practice.
2. To conduct initial feasibility tests through scale modelling with a robotic arm and prototype clay extrusion systems.
3. To determine challenges and technology development requirements (e.g. extrusion and material feeding systems) as well as associated operational knowledge (e.g. cob con-

struction practice, building elements and consumables, and material availability) for a real-scale feasibility test.
4. To conduct a full-scale feasibility test for the robotic manufacturing of a cob building element (wall) and test associated building systems (e.g. fenestrations and foundation requirements) and material properties (e.g. building performance, material mix ratios and architectural design opportunities).

Notably, this feasibility study is the only design-led project in the "Industrial Systems in the Digital Age" line of funding from EPSRC. As a response to such cross-disciplinary nature, an advisory board will provide feedback and suggestions in relation to specific lines of inquiry and disciplines including Construction and Project Management, Material Science, Industrial Design, Craft, Mechanical Engineering and Building Performance. Additionally, this line of funding supports specific stages of technology development [7] and targets lower technology readiness levels (TRL, on a scale 1-9 ranging from basic & applied research up to technology commercialisation):

1. **TRL 1:** Preliminary idea with a well characterised theoretical case.
2. **TRL 2:** Principles are demonstrated through experimentation.
3. **TRL 3:** Early proof of concept demonstrated in the lab.

As a result this study is still on early stages yet is highly exploratory and speculative, with the intention to gain further insights into the fundamental principles of cob and its material qualities.

The following sections particularly address the first 2 objectives of this study and more notably focus on the process of determining material properties and mix ratios, testing and initial iterations of robotically supported cob 3D printing.

Methodology
Two early stage experiments have been conducted in order to determine extrusion limitations and opportunities, utilising two different extrusion mechanisms. Some key factors being considered include the density, viscosity and mix ratios of the cob mixture, as well as its capacity to respond to varied physical and mechanical conditions during the printing process (e.g. printing speed, drying speed, corners and specific geometric features, among others). A series of tests and samples have been conducted with the collaboration of BA Architecture students as part of the "Digital Cobstruction" vertical studio at the Welsh School of Architecture, Cardiff University. During an intensive 2 week calendar, students have been able to experiment and test a series of different printing configurations and geometries, enabling the determination of key operational knowledge associated to cob construction. A sample of students work can be seen in the video link provided in [5]. Relevantly and acknowledging the complex nature of the material mix (including lumps and other non-uniform features), hand-construction, correction of the 3D printed models, or synchronic human-robot collaboration is often required to achieve adequate printing results.

The series of small-scale prototypes of 3D printed cob have been printed as components of potentially larger assemblies (blocks) considering different design and performance (thermal and structural) properties. The main technique of 3D printing is based on the notion of contour crafting, which was originally developed at the University of Southern California [7]. The prototyping and printing process is divided into two stages according to the applied material extrusion mechanism. The first test utilised an air pressure assisted extrusion, and the second utilised a linear actuator ram extruder developed by Deltabots.

Material characterisation
The proportions of the mix are rarely specified in the literature. According to Lewandowska (2017), a typical cob mix composition consists of 28-32% aggregates, 35-40% straw, 20-30% water and 7-8% clay (by volume). However, as cob is typically mixed in a nearly dry state, those proportions do not fit the

purpose of 3D printing as a more fluid mix is required. An increase of water content can, however, affect negatively other material properties including shrinkage, drying time and mechanical/structural stability during the 3D printing process, limiting the layering height and overall quality of a printed prototype. Based on number of earlier tests, new proportions of cob mix have been determined for 3D printing purposes. Due to the unsuitability of the locally sourced subsoil, the new mixture had to supplemented by fine silica sand, china clay and TWVA (AK) ball clay. The new cob mix proportions are 30% subsoil and 15% silica sand, 15% straw, 18% water, 22% clay (with 1:1 ratio of china and ball clay).

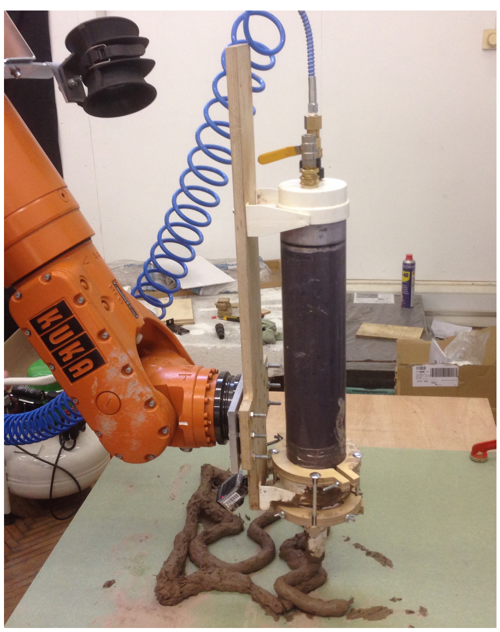

Figure 2
Air pressure assisted tool for cob 3D printing.

This suggested mix is likely to evolve in response to varying material and architectural properties, such as thermal performance or mechanical integrity of larger material blocks. A fundamental difference between cob construction and its 3D printed counterpart is the shift between a massing system and a filament system. While the former enables a substantial thermal inertia and structural stability as a result of its weight, the latter enables the opportunity to consider gaps and cavities (to be measured in consideration to the resulting thermal properties) and a lightweight material system. This emergent digitally-enabled material language is expected to have an impact on the tectonic/architectural expressiveness of 3D printed cob.

Robotic equipment

1. **Robot:** The Architectural Robotics Lab at the Welsh School of Architecture includes a 6-axes KUKA KR60 HA robotic arm (60 kg payload, 2033 mm reach, KRC2 controller). The end effector is a bespoke system for clay extrusion as detailed below.
2. **Software:** The geometries of prototypes have been modelled in Rhinoceros [4] via Grasshopper [3] (KUKA prc [2]) or 3dsMax [1]. Each model has been designed on the basis of unidirectional tool paths.
3. **Air pressure assisted extrusion:** First set of prototypes has been 3D printed using a clay tube connected to an air compressor, in which the pressure was manually controlled. The tube containing the material has a diameter of 110 mm and was capped with a 3D printed removable PLA nozzle with an extrusion diameter of 30 mm. The printing process initially utilised a flat capped nozzle which accumulated straw at the moment of extrusion. That led to the design of a conical shaped nozzle with a cylindrical tip (Figure 2), which gave smoother extrusion and better control of the cob deposition. However, the use of air pressure has revealed a series of challenges in terms of controlling the speed, quality and consistency of extrusion. The increasing air gaps in the cob result in severe stability issues, not allowing the creation of multi-layered models. Real-time human assistance is constantly required in order to adjust the

speed and the deposition, while supporting the printed path in upper layers.

4. **Linear actuator ram extruder:** The second set of prototypes utilised a stand alone linear actuator ram with a 4000 ml tube (Figure 3) procured from Deltabots. The new system, while does not allow yet a continuous stream of cob mixture (and initially intended for clay extrusion, a much more uniform material), considers a stepper motor with a regulator driver providing real-time control over the extrusion speed and consistency when compared to an air pressure system. The steady torque of the stepper motor allowed the use of smaller nozzle with diameters down to 20mm with no significant breakdowns in the process.

Figure 3
Standalone linear actuator ram.

Prototypes and path design

The prototyping process included experimentation of the two extrusion systems, including clay and cob mixtures. Changing extrusion system from air pressure to mechanical extrusion has immediately shown an outstanding difference in quality, accuracy and consistency of printing process and outcome (Figure 4). Some of the geometric constraints for toolpath design have been outlined as:

- The layer heights have been set to 15 mm.
- The diameter of the nozzle in all experiments was varying from 20 to 30 mm, yet, due to the fluid nature of the material, it was expected that a 35-40 mm thick cob path would be created.
- Initially all toolpaths have been created following a standard 3-axis contour crafting approach (X, Y, Z). Using a mechanical extrusion system, however, has resulted in a higher level of confidence in creating more complex tool paths. Further exploration towards increasing the freedom of movement level have been tested. A new prototype was designed to create a path along the outer surface of a braced barrel vault (Figure 5). A polystyrene model of the vault was crafted as formwork for the cob model. The polystyrene model was removed after three days and the cob geometry was able to self-support its own weight.

- Printing speeds has been set at 5 mm/sec for cob, and 15 mm/sec for clay.

PRELIMINARY OBSERVATIONS

The early experiments of cob 3D printing have demonstrated that the robotically assisted printing of cob structures is feasible, yet the complex nature of the material requires an intensive stage of testing, trial and error and systematic approaches to the determination of key factors such as mix ratios. Challenges so far can be categorised as follows:

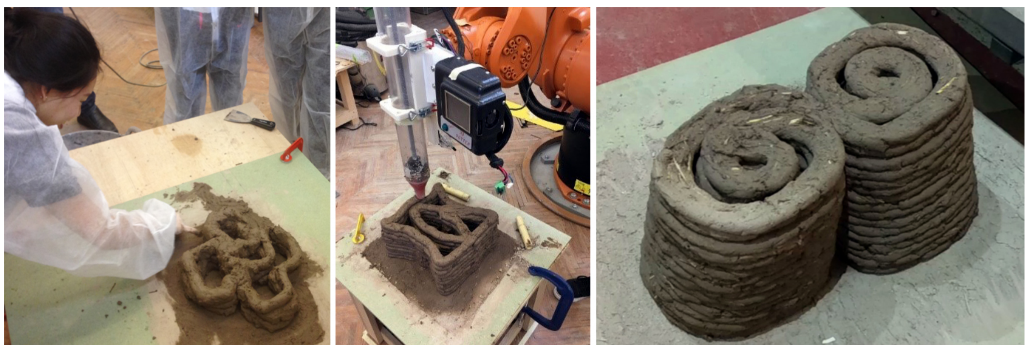

Figure 4
Prototype cob models with different mix ratios and extrusion settings, from initial tests with air compression assisted extrusion (left) and linear actuator ram extrusion (right)

- **Material extrusion system:** One of the most challenging aspects in these experiments is the material feeding and extrusion system. Despite the satisfactory performance of the current extrusion mechanism in terms of printing quality, it is still has a lengthy process that would be problematic on a larger scale of construction, and does not include yet a continuous material feeding system. This is due to the size of the clay container, nozzle diameter and the maximum torque of the stepper motor. The currently used size is a 4000 ml clay container, which roughly accommodates 4.5 kg of cob, with a nozzle extrusion diameter of 25mm. This combination of sizes only allows a cob unit of 200×200×60 mm to be printed at once without reloading the tube. On the other hand, the process of mixing the cob and reloading the tube is rather slow, even for small scale prototypes. Therefore, the project team has been working on upscaling the extrusion system to achieve better performance for larger scale cob structures, potentially utilising a pugmill-like mechanism for material feeding. Further improvement to the extrusion process is also being considered, such as implementing an automated nozzle shutter or testing alternative fibrous materials.
- **Material mix:** The current material composite has shown satisfactory performance in terms of consistency and continuity of extrusion. Furthermore, it has shown structural strength in creating a relatively tall models and complex tool paths. However, the current material composite is considered dense for 3D printing, which challenges the extrusion system and the overall flow and speed of the printing process. An upcoming area of experimentation is then to test different mix ratios attempting to find a balance between a higher viscosity and yet, appropriate mechanical and structural material properties.
- **Geometry and formal studies:** There has been a significant improvement in the complexity and accuracy of potential geometry production when comparing the early experiment using the air compression extrusion to the current system of mechanical extrusion. Yet, further improvements need to be achieved when creating a tool path that goes beyond the conventional printing within three axes of freedom of movement, specially without using a form work to support the cob structures during the printing process. Moreover, formal opportunities have arisen as a result of treating cob as a filament-based system instead of a mass-based structural system. This is likely to result in a series of tectonic explorations aiming at determining new formal and architectural expressions for 3D

printed cob. For this purpose, a smaller KUKA KR5 sixx R850 robotic arm and a modified WASP clay extrusion system have been procured as part of this project in order to conduct scale tests and prototypes at MAKELab in the University of Plymouth.

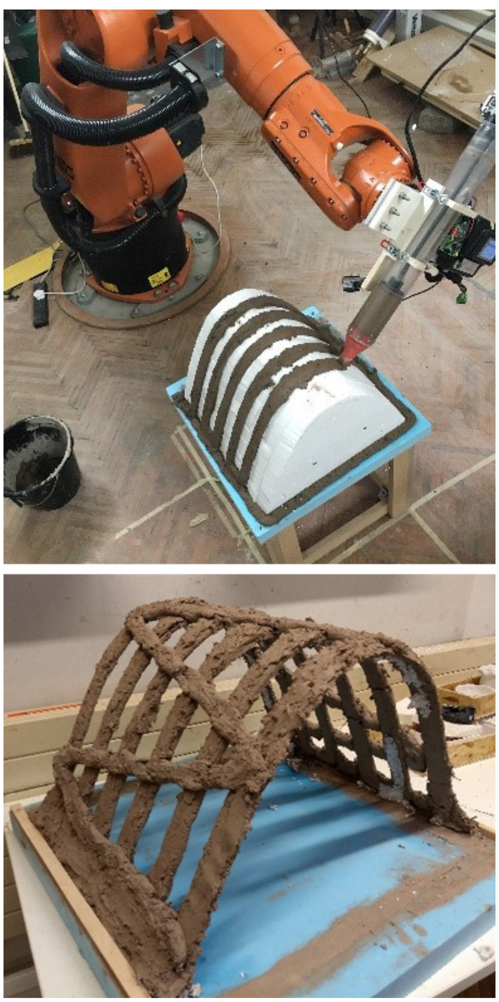

Figure 5
Cob printing test using a supporting formwork.

DISCUSSION

The project "Computing craft" spans across 18 months of development and this paper constitutes an early milestone, with material produced within the first 4 months of preliminary studies. At the moment of this publication, the research team is working in collaboration with Mechanical Engineering in order to optimise extrusion mechanisms and test the overall feasibility of cob as 3D printed matter. Overall, this paper introduces some key methodological (e.g. prototype development), technological (e.g. extrusion systems) and operational (e.g. material mix ratios) aspects of the study, and outlines the complexities and challenges associated to printing with a complex material such as cob. Despite a largely technology-mediated study, an emergent line of inquiry is the investigation of the messiness and cross-disciplinary nature of the process as instigators of rigorous creative practice and serendipity.

It is expected that the knowledge acquired through this project will be applicable to the 3D printing of other non-uniform clay-based materials. This is a key expectation given the localised and specific material properties for cob construction in different contexts and sites, yet the applicability of the project results is still to be outlined once more precision is achieved in terms of material properties and constructive challenges. Further experimentation through scale modelling will help to determine limitations and technology development requirements, such as extrusion and material feeding systems, as well as the required operational knowledge for a real-scale feasibility test.The full-scale feasibility test would encompass the testing of associated building systems (e.g. fenestrations and foundation requirements do not necessarily comprising cob) and material properties (e.g. building performance, material mix ratios and architectural design opportunities). The above will be of relevance to the production of earthen built environments at the periphery of the architectural mainstream (e.g. remote locations, post-disaster recovery).

While the applicability of this project is yet to be outlined, the following benefits are expected as a result of this study:

- **Benefits for the digital manufacturing sector:** This project will contribute to a better operational knowledge associated with the 3D printing of non-uniform, clay-based materials. While this study does not expect to fully resolve this complex challenge, a broader understanding of soil-based material extrusion will benefit ongoing industrial strides towards the automation of massing material systems, without the sustainability challenges currently associated to concrete 3D printing. On a secondary benefit, this study will contribute towards the digital manufacturing of low-cost, locally sourced constructive systems.
- **Benefits for the Architecture, Engineering and Construction (AEC) sector:** The value chain of digitally-augmented craft has been tested in small scale applications such as product and industrial design, yet its impactful benefits to the design and construction industry is a less explored area of development. Previous research demonstrates that robotic technology is able to bridge gaps within the design-to-construction process by directly associating the design process with material and manufacturing constraints. As such, it is claimed that in addition to a modernisation of the industry, this project supports ongoing research framing digital manufacturing as a resource to address novel modes of architectural production through integrating computational logics and construction vernacular practice.
- **Benefits for the partner institutions:** This project follows a common line of collaboration between the University of Plymouth and Cardiff University. The Architectural Robotics Lab at the Welsh School of Architecture has previously researched and tested the applicability of robotic manufacturing throughout diverse areas of construction such as material systems (e.g. high-rise construction, concrete sheets, early tests on cob construction), and design tools and methods (e.g. non-manifold topologies, generative design strategies, parametric design strategies). This project is expected to build upon these lines of work and particularly accelerate the impact of related research in the field of construction robotics. In addition, Plymouth University is situated in an area with the highest amount of cob construction and knowledge in England, and has previously hosted a Centre for Earthen Architecture and the first MA Conservation in the United Kingdom. Locally, it is expected that this project will provide a foundation for a broader impact outside the boundaries of academic practice, towards professional, research and voluntary groups currently focused on cob construction (e.g. Devon Earth Building Association, among others).

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