Computing craft: Manufacturing cob structures using robotically controlled 3D printing

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The aim of this study was to investigate fabrication procedures and methodologies for robotically supported 3D printing utilising cob and similar clay-based sustainable building materials. To achieve this goal, the objectives for this work are planned as an incremental systems development methodology. Cob provides an alternative solution to various economic, social and environmental challenges associated with the modern building industry. Construction techniques, and particularly those using low cost materials such as cob, comprise rather established operational frameworks of practice (know-how), often based on notions of hand-making, hand-assembling and material intelligence. However, while automation of building processes has successfully engaged with the production of building elements and components, it is currently facing adoption challenges for on-site real-scale construction due to shortage of digital/technological skills and the logistic impossibilities of testing full-scale, context- and craft-aware technologies. This project alleviated these adoption challenges, translating the craft-based process into a digital and automated manufacturing process, by adopting a cross-disciplinary approach, which constitutes its core novelty. Through this feasibility study, the team investigated the current state of the art regarding specialist and situated operational knowledge of cob construction, conducted small- and full-scale tests for robotic manufacturing of cob models using bespoke extrusion systems, and determined challenges, technology development requirements and associated operational knowledge based on this experimentation. As a result, a methodological framework was developed, opportunities and challenges were revealed and robotic fabrication was situated within a theoretical view of tectonics and craft practice. By following a mixed methods approach addressing a range of disciplines, the study has demonstrated that in order to enable craft-driven innovation in robotic fabrication, aspects of craft practice should be considered as an integral part of the design and fabrication process, rather than a historical or figurative precedent. Moreover, robotic fabrication allows an open-ended negotiation between matter and designers which aligns with definitions of craft that pre-date contemporary technology-driven frameworks of practice. Finally, this study has suggested specific lines of inquiry, particularly in the areas of knowledge representation and communication, robotic material culture, and human-robot collaboration.
1. Research challenge

The project aimed at developing a robotically-supported 3D printing system for cob structures, through enacting craft-driven innovation in architecture. To achieve this, the objectives of the study were as follows:

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 construction 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).

2. Context

In cob construction, water, sand, clay and organic fibres are mixed to produce a malleable raw-earth construction material. When building a wall, the cob mix is typically layered upon a plinth, while the builder masters the balance between the fluidity of the material and its drying speed, ensuring the stability of the layers as the construction proceeds. In the process of drying cob gains compressive strength, while tensional strength is acquired through organic fibers maintaining the mechanical integrity of the material. Diverse geological conditions comprise different sand and clay qualities, resulting in different mix ratios and constructive configurations. While in some contexts a cob mix is layered to form building elements such as walls (e.g. Southwest England), various material systems have been developed in response to specific modes of earthen architectural production such as adobe (a cob-like mix dried in the form of bricks e.g. McHenry 1989) or “quincha” (an earth mix applied onto a prefabricated layer of interwoven fibrous materials e.g. Carbajal, Ruiz and Schexnayder 2005). Instead of applying a material onto predefined design conditions, the builder regulates mix ratios and building parameters (such as drying speed) to develop “an unknown yet anticipated outcome” (Stein 2011). Accessing that knowledge requires an understanding of material qualities and its inherent construction dynamics. Despite being often described as a “DIY” mode of construction (e.g. Weismann and Bryce 2006), cob requires a high degree of specialisation and localised knowledge in order to negotiate a successful balance between material properties and the resulting configuration and characteristics of the built element.

Recent projects and reports on robotic fabrication in architecture have extensively referenced craft as a mode of production embodying different forms of material engagement. Moreover, it is possible to find references to craft at institutional level, with laboratories, studio courses and research groups approaching robotic fabrication in architecture and design from a craft perspective (e.g. Boza 2006). References to craft are often associated to specific design conditions such as the uniqueness of the produced objects, novel capacities to manipulate and configure materials, the complexity of the resulting design solutions, or the innovative processes involved on the result’s design, production or assembly (e.g. Balik and Allmer 2017). Alternatively, references to craft are not associated with the qualities of the resulting artefact but instead with historical, vernacular or unsophisticated practices (Stein 2011) relegating craft to a notion of “trade” or “skillset”, uprooting the notion of craft from its material-driven sophistication and serendipity.

Contrasting the definition of craft as an open-ended production, robotic fabrication is highly controlled and outcome expectations are anticipated, simulated, visualised and corrected before commencing a production process. Throughout the design process, robot movement paths can be predefined and adjusted, collisions can be avoided and overall, there is a control over the process of production that is intended (and, arguably, designed) to minimise risk and optimise the production of an intended outcome to a high degree of certainty. The avoidance of risk is a procedural aspect of robotic fabrication that challenges the balance between “certainty” and “risk” embedded in the core precepts of craft practice (Pye 1968); while craft practices
emerge from streams of socially and culturally-mediated material engagement, robotic fabrication responds to an understanding of innovation deeply rooted in professional and institutionalised research discourses.

As mentioned, some approaches to craft have comprised a vision of ancient, historical or “vernacular” design – the sort of design practices not performed by professional designers. Notions 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 research. The project “Computing Craft” challenged the view of vernacular material systems as historical or unsophisticated. While cob and earthen constructions can be found in developed countries, earthen architecture 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. Brown and Maudlin (2012), however, describe the extensions of vernacular architecture to include the “everyday”, a range of contemporary buildings outside the “self-authorised discourse and practice of the architectural mainstream” (p. 342). In response to this approach, this study considers cob as a contemporary 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, but instead to facilitate socio-technological innovation upon an existing material system and its associated craft nature. As a result, this study expects to meaningfully bridge local, craft-based knowledge and technological principles and applications in both the Manufacturing and the Architecture, Engineering and Construction (AEC) industries.

3. Approach

The study was the first to adopt a cross-disciplinary approach to translating the craft-based process of cob construction into a digital and automated process. This study introduced a novel approach to craft-driven robotic innovation in architectural research. Here, craft is not portrayed as a source of ornamental or historical inspiration, but instead, as an open-ended process involving material properties, diverging modes of knowledge production and representation, emergent tectonic configurations and embodied interaction with technology. To do so, this project developed a methodological framework outlining a comprehensive definition of craft in the context of robotic architectural production.

Robotic fabrication stands out as a particularly disruptive technology. The capacity to inextricably link design and production within a single cyber-physical environment not only displaces and modifies established frameworks of practice, but also enables a more continuous process of iteration and discovery across digital design and physical production. The affordability, immediacy and accessibility to robotic programming and fabrication resources (Brell-Cokcan and Braumann 2013) allow more creative, playful and open-ended discovery of tectonic results, re-aligning the notion of craft with that of architectural production in the context of digital practice. Gramazio and Kohler (2008) explain that fabrication and digital production allow architects to engage directly with notions of traditional tectonics through the means of digital. As a result, robotic fabrication aligns with pervasive and key definitions of craft, despite being developed within institutionalised professional and research frameworks of practice. The following sections illustrate how the project has acknowledged and followed this approach to craft studies.

4. Implementation

The study followed a mixed methods approach. The reason for a multi-faceted methodology is that craft comprises complex disciplinary and material manifestations that require constant iteration, negotiation and discovery. The determination of a robotically-supported cob 3D printing system includes the development of extrusion systems, material studies and experimentation including site visits, quantitative analyses of different material characteristics as well as literature reviews and
theoretical grounding of findings.

**Prototype development: a bespoke extrusion system**

The Architectural Robotics Lab at the Welsh School of Architecture includes a 6-axes KUKA KR60HA robotic arm (60 kg payload, 2033 mm reach, KRC2 controller) utilised for cob 3D printing in this feasibility study. A key challenge throughout this study was the material negotiation necessary to develop, test and prototype an effective material extrusion mechanism that would optimise the 3D printing process without compromising the material qualities (e.g. viscosity) of the cob mix. For this, a series of extrusion tests were iteratively conducted. The geometries of prototypes have been modelled in Rhinoceros® via Grasshopper’s KUKA|prc plug-in or Autodesk 3DSMax®. Each model has been designed on the basis of unidirectional tool paths.

A first set of prototypes were 3D printed using a clay tube connected to an air compressor, in which the pressure has been manually controlled. The tube containing the material had a diameter of 110 mm and was capped with a 3D printed removable PLA nozzle with an extrusion diameter of 30 mm. The nozzle was subsequently re-designed with a cylindrical tip, enabling a smoother extrusion and better control of the cob deposition. However, the use of air pressure revealed a series of challenges in terms of controlling the speed, quality and consistency of extrusion. The increasing air gaps in the cob resulted in severe stability issues, not allowing the creation of multilayered models. Real-time human assistance was constantly required to adjust the speed and the deposition, while supporting the printed path in upper layers.

A second set of prototypes utilised a stand-alone linear actuator ram with a 4000 ml tube procured from 3DPotter®, originally developed for clay 3D printing. This system considered 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. This setup was effective, but relatively inefficient considering the low capacity and manual changing of the tubes.

A third set of prototypes used a bespoke extrusion system, which included among others a single 9150 ml tube laid out horizontally coupled with a linear actuator and a variable frequency drive (VFD) to control the speed of the extrusion in real-time. The tube was attached to a hose that was mounted on the robotic arm and would move according to the path to be printed. Compared to the previous setups, this one was by far the most effective and efficient and allowed the team to increase the scale of the 3D printed artefacts (reaching approximately 500mm (L) x 500mm (W) 500mm (H)), the speed of the extrusion and the consistency of the printed cob mix.

**Open-ended material studies**

In order to create 3D printing paths, the KUKA|prc plug-in for Grasshopper (McNeel Rhinoceros®) was utilised to design and program robotic movement paths. In this section of the study, there was a focus on experimentation, testing and a more open-ended engagement with the material. The expectation for this method was not to provide quantitative data, but instead a qualitative operational knowledge about the capacities, dimensional and formal parameters and achievable 3D printing configurations. For this, two vertical studio courses were developed at the Welsh School of Architecture with a series of students of the BSc Architecture programme. The expectation for these 2-week courses was not only to induct students to the use of robotic technology and cob 3D printing, but also to test the boundaries of applicability and design opportunities offered by 3D printed cob, as well as enabling a hands-on engagement with the material and the extrusion process.

**Material characterisation**

A series of tests and 3D printing attempts (both successful and unsuccessful) allowed the definition of a cob mix for 3D printing which can be characterised following standard material studies such as thermal performance studies, tensile and compressive strength simulation, among others. The proportions of the cob 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, since 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 prototypes. Based on a number of tests, new proportions of cob mix have been determined for 3D printing purposes. Due to the unsuitability of the locally sourced subsoil, the mixture was supplemented with fine silica sand, china clay and TWVA (AK) ball clay. The cob mix
proportion initially utilised in this study were: 30% subsoil and 15% silica sand, 15% straw, 18% water, 22% clay (with 1:1 ratio of china and ball clay). This suggested mix evolved throughout the study in response to varying material and architectural properties, so eventually the cob mix consisted of 78% subsoil, 2% straw and 20% water.

Several 3D printing tests were conducted 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. Extrusion speed was tested on a range from 0.01 to 0.1 m/sec, while layer height was tested as 30%, 60% and 90% of the nozzle size. In all cases, field tests of the subsoil properties are required prior to determining the appropriate cob mix.

Digital modelling
For 3D modelling purposes, a cob material was created in a Building Information Modelling environment (Autodesk Revit®) and a simulation environment (Autodesk Fusion360®), including a series of physical and mechanical properties for cob typically found in the literature (Table 01). While 3D printed cob enables a different consistency and likely different physical and mechanical properties, the digital material allows early testing and experimentation of different design configurations, ranging from applications in speculative architectural designs up to detailed simulation analysis enabled by Autodesk Fusion360® such as shape optimisation and structural stress.

5. Summary of Results
The result of the described aspects of this feasibility study is a methodological framework that acknowledges the complexity and nuanced nature of craft as a driver for innovative robotic fabrication. It is claimed that through a multi-faceted material negotiation, a rich and open design process embodies key principles of craft such as risk v certainty, and innovation v tradition. It is possible to argue that this methodological framework is composed by a series of interrelated aspects of craft and robotic fabrication innovation. This was developed as a response to the lack of established frameworks that critically address the emergent tectonics of robotic production as a result of engagement with craft disciplines. The following subsections describe the resulting areas of development emerging from this process.

Material properties
Both qualitative and quantitative material properties of cob were outlined. Distinctively, a digital representation of cob was created with the aim of supporting modelling and simulation tasks in a building information modelling environment. More relevantly for robotic fabrication applications, a specific “recipe” for cob mix was determined for 3D printing extrusion, and a series of models and robotic toolpaths were created in order to determine the design space and applicability boundaries of this new tectonic proposal. After initial tests were conducted following a contour crafting approach, the study also experimented with three-dimensional material deposition strategies enabled by robotic 3D printing, achieving more complex tectonic opportunities. The determination of material properties, then, followed an incremental approach and was highly mediated by prototyping at the boundaries of applicability of the material in different constructive and design configurations.

Knowledge production and representation
Recalling the initial arguments of this investigation, cob has been largely described as a material located at the periphery of mainstream architectural discourses, or a DIY alternative for low-cost natural construction. When framing cob in the context of architectural tectonics, however, it is suggested that a possible cause for the peripheral perception of cob in the industry is its origin as a vernacular material system, developed outside the boundaries of professional and academic frameworks. This comprises not only a different mode or architectural production, but additionally diverging modes of representation and communication: while architectural communication is largely based on drawings indicating the location and configuration of material in a construction, craft embodies a principle of uncertainty and tectonic qualities resulting from material negotiations rather than from pre-defined configurations.

Emergent tectonics
A fundamental difference between cob construction and its 3D printed counterpart is the shift between a massing system and a filament-based system. While the former enables a substantial thermal inertia and structural stability as a result of its own weight and gravity, the latter enables the opportunity to consider gaps and cavities, a filament width of near 30 mm, and a resulting lighter material system with the potential for new design flexibility and constructive configurations. Such opportunities (from a building performance approach) were confirmed through material performance studies and more specifically...
through thermal performance exploration that were conducted as part of this feasibility study. The results revealed that 3D printed cob is comparable with hand-made counterparts. While the 3D printed samples did not outperform the hand-made samples significantly, the results suggested that 3D printing can be utilised for cob construction without compromising the building performance of the construction, thus revealing further opportunities for research by exploring additional benefits of robotic fabrication.

As previously suggested, a critical study of 3D printed cob is necessary in order to outline the potential for emergent architectural languages and tectonic qualities. Based on literature surveys, this study found examples and different material configurations for earthen architecture in more than 40 countries (in every continent except Antarctica). As the most utilised building material in the world, cob has demonstrated a remarkable constructive richness and variety, yet a more structured design study is required to frame those opportunities in the context of robotically 3D printed cob.

Embodied interaction
One of the fundamental aspects of craft is the interaction between craftsman and material. This interaction, embodied in a choreographed and open-ended material negotiation, is evidence of the mastery of skills and operational knowledge required to engage with craft disciplines. While robotic fabrication would suggest otherwise, a craft approach to robotic fabrication requires an acknowledgement of emerging embodied interactions with matter. Direct interaction with the material is now mediated by the use of robotic technologies, enabling a potential new area of inquiry for robotic material culture and human-robot collaboration in the context of craft disciplines. This study has produced video documentation of human-robot interaction in cob 3D printing, yet a more focused study with a focus on human-robot interaction is required in order to determine and map diverse modes of communication, human-robot collaborative practices, as well as the broader implications in the construction sector with craftsmen applying their skills in a digitally-mediated working environment.

Other outputs
Other outputs include publications, exhibitions and video documentation that were achieved as part of this feasibility study. Our publications are listed below:

Architectural Science Review (Special Issue “Means, Methods, Machines and Making in Architecture”).


Two exhibitions on cob 3D printing were held at the Welsh School of Architecture (May 2018 and April 2019). These exhibitions were linked to the two vertical studio courses developed at the School with a series of students of the BSc Architecture programme. The video documentation of these can be found at the links below:

- Digital COBstruction II: https://www.youtube.com/watch?v=7lb7VRe-3Vs&t=254s
- Digital COBstruction III: https://www.youtube.com/watch?v=3dg0DeE KwDQ&t=2s

6. Wider applications

The knowledge acquired through this project is applicable to the 3D printing of other non-uniform clay-based materials. This is of relevance to constructive processes used in developing countries and remote locations and is, therefore, expected to optimise building methods under challenging conditions such as post-disaster recovery.

7. Future Plans

The mixed methods nature of this study revealed a number of paths for further work comprising both quantitative and qualitative approaches to robotic fabrication in architecture. Future plans include further explorations on:

- Applying the technology in developing countries.
- New and hybrid material configurations.
- Hybrid manufacturing processes.
- Innovative design and geometric opportunities.
- Conducting further performance testing (e.g. structural etc. on 1:1 scale).
- Standardising the mix consistency through the implementation of an ultrasonic sensor system.

In practical terms, the team has set their sights on applying for funding to further explore the points above through the following options:

1. British Council’s Newton-Mosharafa fund
2. EPSRC ‘Manufacturing the Future’ call
3. EPSRC’s GCRF fund titled ‘Tackling global development challenges through physical sciences research’

The above calls and associated themes align perfectly with the proposed research context in order to pursue broader industrial impact. The team has specifically identified the British Council’s Newton-Mosharafa fund as a key funding option, as it supports proposals addressing the problems faced by developing countries (e.g. Egypt). This aligns with the nature of cob, making it applicable in remote locations and allowing for fast recovery after natural disasters to which developing countries are more vulnerable. Therefore, future research will explore the associated technical parameters of cob construction, as well as the economic and social impacts on the local communities, in developing contexts.

8. Conclusions

This feasibility study has enabled the team to investigate fabrication procedures and methodologies for robotically supported 3D printing utilising cob and similar clay-based sustainable building materials. As a result, a methodological framework was developed, opportunities and challenges associated to the multi-faceted nature of this topic were revealed and robotic fabrication was situated within a theoretical view of tectonics and craft practice. By following a mixed methods approach addressing a range of disciplines, the study has demonstrated that in order to enable craft-driven innovation in robotic fabrication, aspects of craft practice should be considered as an integral part of the design and fabrication process, rather than a historical or figurative precedent. Those aspects are material properties, knowledge production and representation, emergent tectonics and embodied interaction. Moreover, considerations such as accessibility and affordability suggest that robotic fabrication allows an open-ended negotiation between matter and designers which aligns with definitions of craft that pre-date contemporary technology-driven frameworks of practice. Finally, this study has suggested specific lines of inquiry stemming from the team’s publications, particularly in the areas of knowledge representation and communication, robotic material culture, and human-robot collaboration.

a https://www.britishcouncil.org.eg/en/programmes/education/newton-mosharafa-fund
b https://epsrc.ukri.org/funding/calls/manufacturing-the-future-standard-research-proposals/
c https://epsrc.ukri.org/funding/calls/globaldevchallengesphysicalsciences/
9. References


10. Feasibility study team members

The study was conducted by a team of researchers from Cardiff University, the University of Plymouth and the University of Adelaide:

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