Citation for final published version:

Veliz Reyes, Alejandro, Jabi, Wassim, Gomaa, Mohamed, Chatzivasileiadi, Aikaterini, Ahmad, Lina and Wardhana, Nicholas 2019. Negotiated matter: a robotic exploration of craft-driven innovation. Architectural Science Review 62 (5) , pp. 398-408. 10.1080/00038628.2019.1651688 file

Publishers page: http://dx.doi.org/10.1080/00038628.2019.1651688 <http://dx.doi.org/10.1080/00038628.2019.1651688>

Negotiated matter: a robotic exploration of craft-driven innovation

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Wordcount incl. abstract and references: 5958 words

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In architectural design, crafts are often portrayed as a source of ornamental, figurative or historical inspiration. In this paper, instead, craft is framed as an open-ended process of making and material negotiations, involving material properties, diverging modes of knowledge production and representation, emergent tectonic configurations and embodied interaction with technology. By developing this framework, the paper aims to situate the exploratory nature of craft in the context of robotic architectural production. To achieve this, the paper develops a theoretical approach comprising notions of craft (Pye 1968), architectural tectonics (Frampton, 2001) and digital tectonics (Leach, Turnbull and Williams, 2004) in the context of robotic architectural production. Utilising a mixed methods approach, the ongoing project "Computing Craft" is presented as a case study illustrating the proposed framework in the context of cob construction. Finally, the project "Computing Craft" instantiates the proposed framework and helps determine its applicability, impact and limitations.

Keywords: robotic fabrication, craft, architectural innovation, cob, robotic 3D printing, tectonics, material eco-system

Introduction

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 (Figure 01) 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 fibres 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 a sophisticated 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.

The condition of craft in cob construction, then, follows the key tenets of workmanship defined by craft theorists such as Pye (1968). Pye defines “certainty” and “risk” as two poles in a spectrum of emergent possibilities of material engagement, where risk is managed by the dexterity and abilities of the craftsman in anticipation of an unexpected result. While architectural production often refers to craft, this relationship is usually framed as a condition of artisanship or skills associated to designing and making. Stein (2011) notes, however, the more nuanced definition of craft as a process of discovery and negotiation with the material (“open-ended production”) instead of the linearity and rigidity of professional frameworks for architectural practice. Arguably, the delivery- and financially-driven professional framework of architectural practice hardly reflects the open-ended and exploratory negotiation between craftsman and material as part of a design process.

Recent projects and reports on robotic fabrication in architecture follow this trend and have extensively referenced craft as a mode of production embodying different forms of material engagement (e.g. Beorkrem 2017, Bard et al 2016, Kolarevic and Klinger

2013). Moreover, it is possible to find references to craft at institutional level, with laboratories, studio courses, projects and research groups approaching robotic fabrication in architecture and design from a craft perspective (e.g. Boza 2006, Feringa 2014). 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 resulting design solutions, or the innovative processes involved in the resultant design, production or assembly (e.g. Balık 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 process of discovery and negotiation, 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 parametrically predefined and adjusted (Braumann and Brell-Cokcan 2012), 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 very 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 fluid and open-ended material engagement, robotic fabrication responds to an understanding of innovation deeply rooted in professional and institutionalised research discourses.

In order to address this gap, this paper outlines a descriptive framework that acknowledges a more comprehensive understanding of craft as an open-ended material negotiation, potentially enabling new avenues for innovative approaches to robotic fabrication in architecture. The study is grounded on the ongoing project “Computing Craft” aiming at developing a robotically-supported 3D printing system for cob structures. The specificity of this framework to architectural research is provided by analysing theories of architectural tectonics, from both a material (Frampton 2001) and digital (Leach, Turnbull, and Campbell 2004) perspectives. Then, a series of mixed methods are outlined in order to develop this framework, ranging from hands-on material studies to prototype development. Key considerations including material properties, diverging modes of knowledge production and representation, emergent tectonic configurations, and embodied interaction with technology, emerge as the key components of the proposed framework. The Results section illustrates those components in the context of the “Computing Craft” project. Lastly, the paper concludes by discussing the applicability and limitations of the proposed framework, outlines opportunities for further work and potential impacts, and summarises the key contributions of the study.

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

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.

While cob and earthen constructions can be found in developed countries, earthen architecture is often associated the peripheries of mainstream architectural discourses: ethnic groups' domestic spaces (e.g. Joshi 2011), reconstruction efforts in disadvantaged locations (e.g. Sheweka 2011), 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-authorized discourse and practice of the architectural mainstream" (p 342).

In response to these multiple approaches, the project "Computing Craft" considers cob construction 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. Additionally, while related research in cement and clay-based materials requires the development of similar technological propositions (e.g. Fischer and Herr 2016, Marijnissen and van der Zee 2017, Battaglia, Miller and Zivkovic 2018), the heterogeneous composition of cob (including organic fibres and coarse sand) and an eminently hand-made construction method require a unique and innovative response. 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.

This comprehensive engagement with craft has required an expansive and collaborative project governance, including knowledge derived from the fields of Design, Architecture, Material Sciences, Mechanical Engineering, IT in Construction, and Sustainable Systems. More specifically, the project “Computing Craft” enacts craft-driven innovation in architecture by aiming at developing a robotic 3D printing system for cob structures. To achieve this, the objectives of the study 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 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).

These objectives are met incrementally as the feasibility of different 3D printing configurations and cob extrusion systems follow emergent material properties.

A tectonic approach to robotic fabrication

The concept of tectonics carries an array of meanings and interpretations in architecture. While typically the term tectonics is used in reference to material or structural systems, architecture theorists have incrementally expanded its definition to account for the scales and levels of detail of material systems (e.g. Bötticher 1844), the socio-technical systems involved, as well as their resulting inhabitation characteristics. Reinforcing the ideas of Bötticher, Gottfried Semper (2010) distinguished four primary elements of construction; hearth, roof, earthworks and enclosure, each influenced by a range of socio-cultural considerations. For instance, the earthworks not only provide a "stable foundation for the building" but also act as a "cultural connection to the place through the marking of the territory" (Schwartz 2016). Semper paired each of the four elements with a process of material negotiation as the key driver for the execution process, suggesting a synchrony between the architectural design and its construction; the inherent properties of the locally sourced material reflected the characteristics of the architecture of those spaces. This narrative has continued following the work of theorists such as Kenneth Frampton (2006), as he noted the relevance of social engagement and cultural contexts on the interpretation and definition of the tectonic qualities of a building (Hamilton 2018).

Case studies on robotic fabrication provide evidence of an acknowledgement (or lack) of the socio-cultural conditions from which craft-driven innovation emerges. The project "Roboticus Tignarius" (Gonzalez Bohme, Quitral, and Maino 2018) addresses a series of timber joinery mechanisms emerging from local timber construction techniques found in the UNESCO protected city of Valparaiso. At risk of disappearing due to lack of adequate protection policy and skills shortages, local timber craft has been surveyed, prototyped and adapted to a robotic milling system that, while enabling the reproduction of local timber joinery designs, additionally allows the emergence of new design opportunities and diverse material configurations. A joinery system is, as well, aligned with elemental concepts of tectonics put forward by previously introduced theorists: Semper describes the joint as an “essential yet smallest part of the construction” (2010), while Frascari (1984) considers the joint as a detail revealing the narrative about the architecture’s construction (Hamilton 2018). This approach, as a result, contrasts with experimental projects where notions of craft are explored from a formal, figurative or ornamental perspective (Balık and Allmer 2017). Some notable case studies include replicas of historical stylistic conventions, or the delivery of small-scale prototype buildings following specific formal typologies (e.g. Series of 10 houses in Suzhou, by Winsun). It can be argued that, while still in a nascent market penetration stage, techniques such as 3D printing construction are slowly making their way into the industry without critical study of their potential to reveal emergent architectural languages and tectonic configurations.

The disruption of digital technologies, however, goes beyond the material and formal configurations of robotically fabricated material systems. Frampton questioned the notion of tectonics under the light of accessible and ubiquitous digital technologies mediating between architects and their design outcomes (Frampton 2001). This definition approaches the principles of “risk” and “certainly” of craft practice, where the craftsman engages with a material (in this case, a digital one) in an open-ended negotiation resulting in anticipated, yet unexpected results. This emergent notion of “digital materiality” was theorised in depth by Leach, Turnbull, and Campbell (2004), and there is an overarching disciplinary agreement of the consideration of digital technologies and their impact on new modes of digital craft production as a fundamental component of new tectonic languages in architecture (Coyne 1995; McCollough 1996; Mitchell 1998; Jabi 2004). Digital materiality is described by Leach, Turnbull, and Campbell (2004) as a tensioned relationship between digital production and representation. Mitchel (2009) illustrates this point by identifying the computer as a portrayor of tectonic qualities – a representational resource able to accurately acknowledge design complexities and enable new formal configurations resulting from discrete and controlled digital modelling process.

This approach to digital tectonics relying on the representational potential of CAD resources has been key to the development of novel tectonic solutions such as those of Frank Gehry (Hamilton 2018). Such an approach, however fundamental to the understanding of digital tectonics in contemporary architecture, still perpetuates a model of building delivery where digital and physical matter do not evolve in synchrony: a model is a representation of a built object produced or manufactured at a different stage of a delivery process.

Here, 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) support Frampton's approach by explaining that fabrication and digital production allow architects to engage directly with notions of traditional tectonics through digital means. 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 "Computing Craft" has acknowledged and followed this approach to craft studies.

Methods and materials

This study follows a mixed methods approach. The reason for a multi-faceted methodology is that, as stated previously, 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 (Veliz et al 2018), material studies and experimentation including site visits, quantitative analyses of different material characteristics as well as literature reviews and theoretical grounding of findings. The expectation for this study is to test the feasibility of a real-scale 3D printed cob wall. In detail, this research process has been structured around the following methods:

Material characterization

A series of tests and 3D printing attempts (both successful and failed) have allowed the definition of a cob mix for 3D printing which can be characterised following standard material studies such as thermal performance analyses (Gomaa et al 2019), and tensile and compressive strength simulation, among others.

The subsoil for the cob mix has been sourced from farmland near Cardiff, UK. Three subsoil specimens from three locations within the same field were tested by examining the ratio of aggregate: clay in the subsoil (Goodhew, Grindley and Probeif 1995, Weissmann and Bryce 2006). These tests utilised simple deposition tests in order to acknowledge typically utilised on-site tests as well as to eventually simplify the material characterisation process should this method be used in different contexts with little or no access to material testing facilities (Figures 02 and 03).

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, negatively affect other material properties including shrinkage, drying time and mechanical/structural stability during the 3D printing process, limiting the layering height and overall quality of printed prototypes (Figures 04 and 05). 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 has been supplemented with fine silica sand, china clay and TWVA (AK) ball clay.

Prototype development: a bespoke extrusion system

The Architectural Robotics Lab at the Welsh School of Architecture (Cardiff University) includes a 6-axes KUKA KR60HA robotic arm (60 kg payload, 2033 mm reach, KRC2 controller) utilized for cob 3D printing in this study (Figure 06). A key challenge throughout this study is the material negotiation necessary to develop, test and prototype an effective material extrusion mechanism that optimizes the 3D printing process without compromising the material qualities (e.g. viscosity) of the cob mix. For this, a series of extrusion tests have been 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 based on unidirectional tool paths.

A first set of prototypes were 3D printed using a clay tube connected to an air compressor, in which pressure was manually controlled (Figure 07). 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 nozzle was subsequently re-designed with a cylindrical tip, enabling a smoother extrusion and better control of the cob deposition. Another iteration detailed in (Veliz et al 2018) included the use of a step motor to better control the extrusion flow (Figure 08).

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 (Figures 09, 10).

Open-ended material studies

In order to create 3D printing paths, the KUKA|prc plug-in for Grasshopper (McNeel Rhinoceros®) has been utilized to design and program robotic movement paths. In this section of the study, there is a focus on experimentation, testing and a more open-ended engagement with the material. The expectation for this method is 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, 2 vertical studio courses have been developed at the Welsh School of Architecture with a series of students of the BA Architecture programme (Figure 11). The expectation for these 2-week courses is to not only 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.

Digital modelling

For 3D modelling purposes, a cob material has been 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 optimization and structural stress.

Table 01: Summary of mechanical and physical properties utilized for material digital modelling.

Physical/Thermal properties	Value	Source
Young's Modulus	120.0 MPa	(Martins and Varum 2006)
Poisson Ratio	0.25	(Modena et al 2016)
Shear Modulus	40.0 MPa	(Varum et al 2014)
Density	1,450 kg/m3	(Goodhew and Griffiths 2005)
Thermal conductivity	0.45 W/(m*K)	
Specific Heat	0.8 J/(g*°C)	

Results

The result of this mix of methods is a descriptive 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 framework is composed by a series of interrelated aspects of craft and robotic fabrication innovation. It is expected that this framework evolves as further work is conducted, and these key principles are expected to expand, evolve and accommodate further results and tests. More notably, the mixed methods nature of this study has revealed a number of paths for further work comprising both quantitative and qualitative approaches to robotic fabrication in architecture, as well as a series of good practices to be consolidated upon the conclusion and real-scale prototyping stage of this project. This, 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 and practices.

The following subsections describe the resulting areas of development emerging from this process:

Material properties

Both qualitative and quantitative material properties of cob have been outlined. In terms of its physical constitution, the resulting cob mix for 3D printing is: 30% sub-soil and 15% silica sand, 15% straw, 18% water, 22% clay (with 1:1 ratio of china and ball clay). This suggested mix is likely to evolve throughout the study in response to varying material and architectural properties, such as thermal performance or mechanical integrity of larger material blocks. Subsoil tests have revealed that the ingredients of the subsoil match the general recommendations for cob mixture without applying any additional aggregates or clay. The subsoil samples from Cardiff were found to have an average aggregate to clay ratio as 79.5 to 21.5 % respectively.

Additionally, a digital representation of cob has been 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 has been determined for 3D printing extrusion, and a series of models and robotic toolpaths have been created in order to determine the design space and applicability boundaries of this new tectonic proposal. After initial tests have been conducted following a contour crafting approach, the study is currently experimenting with three-dimensional material deposition strategies enabled by robotic 3D printing, potentially achieving more complex tectonic opportunities. The determination of material properties, then, follows an incremental approach and is 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 paper, 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 established professional and academic frameworks. This comprises not only a different mode of 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 (Figure 12). Ongoing studies on material performance are being conducted in order to determine these opportunities from a building performance approach (Gomaa et al 2019), but it is acknowledged that given the shift on structural and formal configurations, robotic 3D printing will result in new tectonic and design opportunities for cob structures.

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 has found examples and different material configurations for earthen architecture in more than 40 countries (in every continent except Antarctica). As a result, cob has demonstrated a remarkable constructive richness and variety, yet a more structured and expansive 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, this study has required an acknowledgement of emerging embodied interactions with matter. Some examples of this include the material properties affecting the development of a bespoke extrusion system – during early stages, the use of air pressure revealed a series of challenges to control the speed, quality and consistency of extrusion. Air gaps in the cob mix resulted in stability issues, limiting the creation of multilayered models. Real-time human assistance has been constantly required to adjust the speed and the deposition, while supporting the printing filament. Likewise, human input is required to control the mix ratio in relation to the printing nozzle, with the wrong mix resulting in pressures (and sometimes, destruction) of nozzle components.

While robotic printing does not replace the human intelligence and embodied knowledge require to construct 3D printed cob elements, such embodiment shifts towards a distributed robot-material-human production environment. 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.

Conclusion

The two primary outcomes of this study (developing a descriptive framework and situating robotic fabrication within a theoretical view of tectonics and craft practice) represent the key contributions this paper makes to the field of robotic fabrication in architecture.

Firstly, this article has introduced a descriptive framework that acknowledges the nuanced nature of craft as a driver for robotic fabrication in architecture, extending the definition of craft to incorporate key tenets of craftsmanship theorised by Pye (1968) and Stein (2011) such as “risk” and “certainty” as drivers for a negotiation with the material. Furthermore, this framework is instantiated in the project “Computing Craft” which focuses on the development of robotically 3D printed cob structures. By following a mixed methods approach and a knowledge derived from 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 architectural design and production process, rather than a historical or figurative precedent. Those aspects are material properties, knowledge production and representation, emergent tectonics and embodied interaction.

Secondly, the notion of tectonics has been critically addressed, and robotic fabrication has been framed within the continuous development and re-definition of key concepts of architectural tectonics such as the relevance of socio-cultural contexts of practice and the disruptive nature of robotic fabrication in architectural practice. 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.

It is expected that the impacts of those contributions are twofold. While craft practices are often referenced throughout a range of material expressions in contemporary architecture, this framework provides a pathway to acknowledge a more nuanced and complex acknowledgement of craft for robotic fabrication. Moreover, it provides an alternative framework to bridge the gap between the delivery-focussed nature of professional frameworks, and the exploratory and negotiated process of craft. This is expected to benefit architects, designers and researchers currently looking into craft as a source of material and design sophistication and knowledge. Additionally, the proposed approach to craft-driven innovation has required contributions from a range of specialists including from material science, design, architecture, robotics, and mechanical engineering disciplines, with innovative solutions emerging at the crossroads of multi-disciplinary collaboration and research.

Finally, this study has suggested specific lines of inquiry stemming from this article, particularly in the areas of knowledge representation and communication, robotic material culture, and human-robot collaboration.

Acknowledgements

This research is supported by the projects “Augmented Vernacular” (University of Plymouth) funded by The Chartered Institute of Building, and “Computing Craft” (Cardiff University and University of Plymouth) funded by the “Connected Everything: Industrial Systems in the Digital Age” network, Engineering and Physical Sciences Research Council UK.

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Figure Captions

Figure 01: Exposed cob construction in Totnes, United Kingdom.

Figure 02: Laboratory setup for the determination and testing of the cob mix.

Figure 03: Samples of cob utilised to measure aggregate:clay ratios and shrinkage.

Figure 04, 05: Initial extrusion tests with different mix ratios and printing path configurations.

Figure 06: 6-axes KUKA KR60HA robotic arm at the Architecture Robotics Lab, Welsh School of Architecture.

Figure 07: Air compressor extrusion system.

Figure 08: Step motor extrusion system.

Figure 09, 10: Development of a bespoke extrusion system: destruction of the cob loading mechanism due to pressures caused by the cob mix.

Figure 11: Digital COBstruction Workshop at the Welsh School of Architecture.

Figure 12: A lack of coordination between drying and extrusion speeds results in unexpected filament-based configurations.

Figure 01

Figure 02

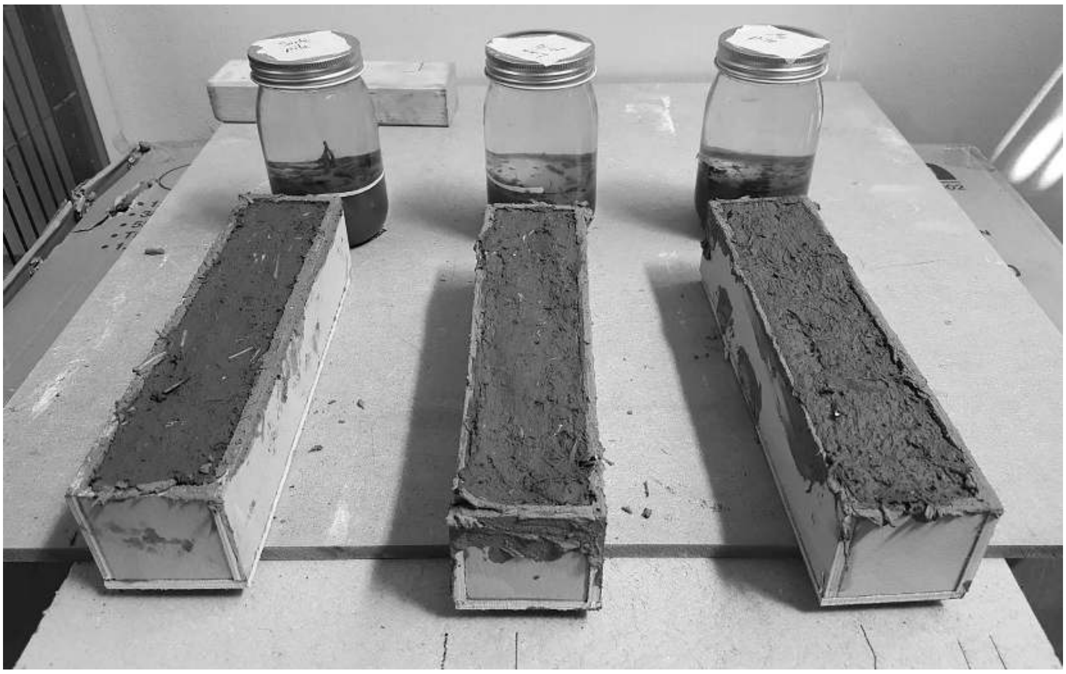

Figure 03

Figure 04

Figure 05

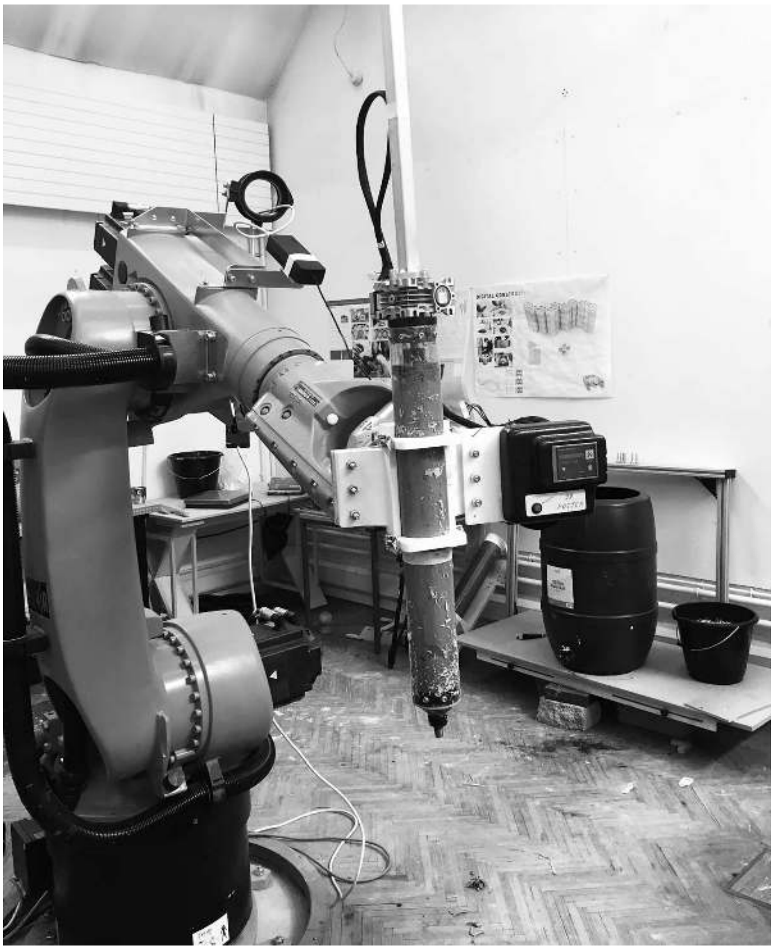

Figure 06

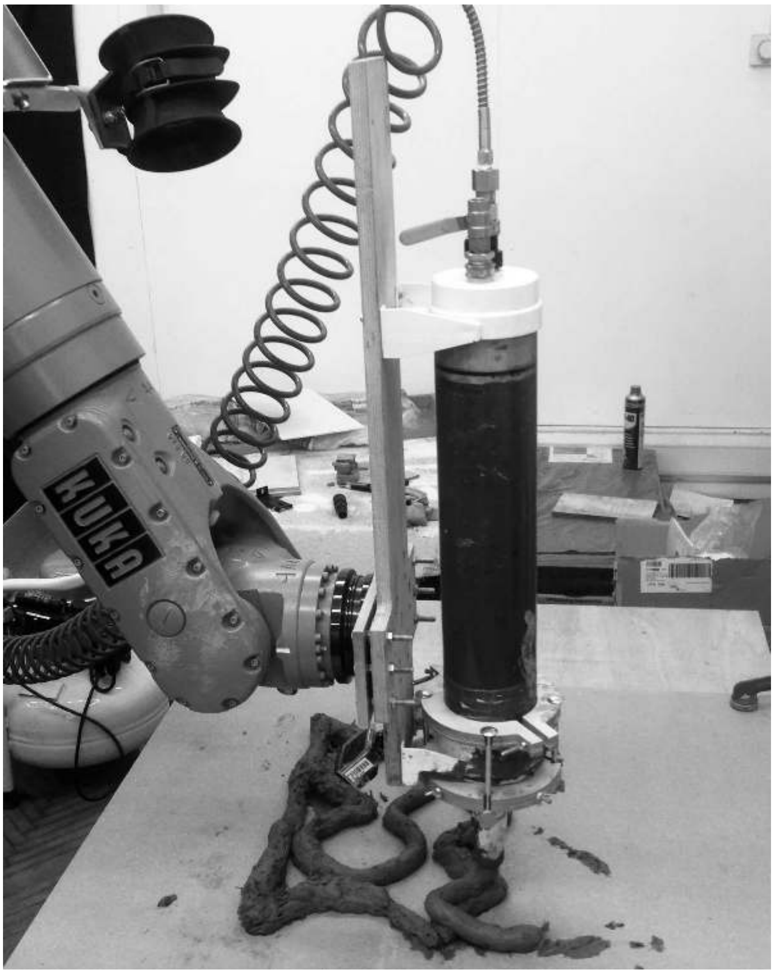

Figure 07

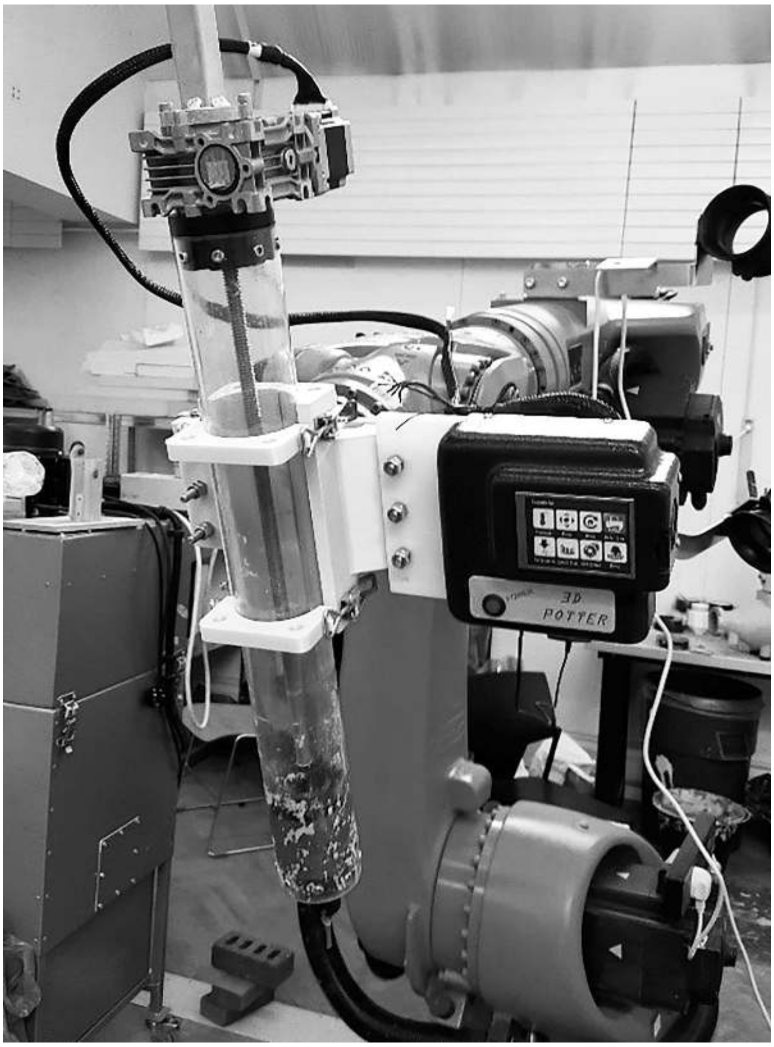

Figure 08

Figure 09

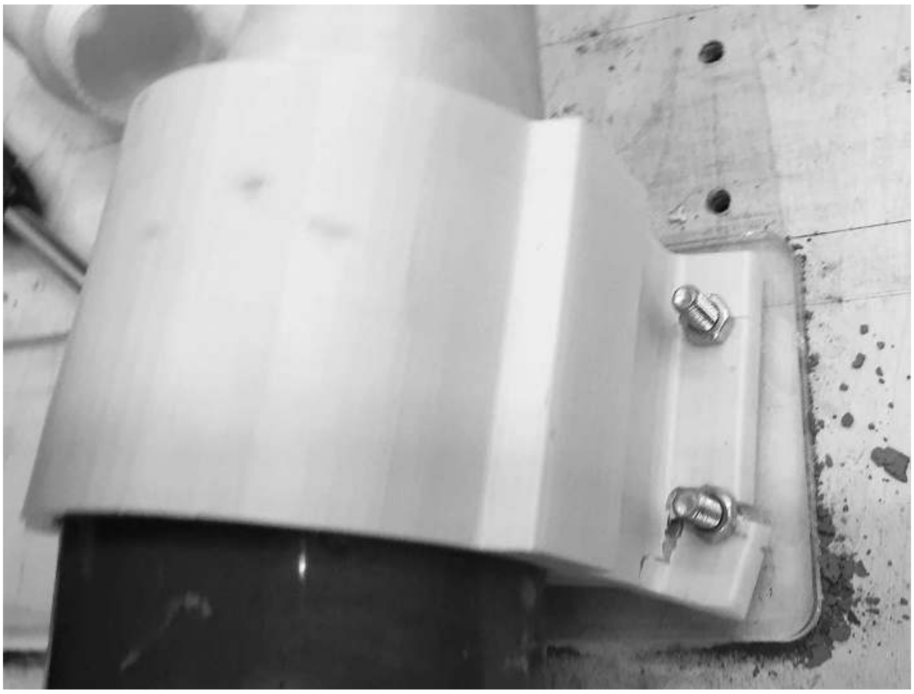

Figure 10

Figure 11

Figure 12