MEETING IN THE MIDDLE

Hybrid Clay 3D fabrication processes for the creation of bio-reef structures

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Abstract. Clay 3D printing remains an underutilised digital fabrication technique in the production of architectural artefacts. Many current digital fabrication workflows being researched in clay 3D printing aim to overcome these challenges by streamlining and automating the manufacturing process, however, a better understanding of the participatory and collaborative roles designers play in fabrication processes could prove valuable in the future development of complex clay 3D prints. This research looks to reconsider how humans and machines can fabricate together, focusing on integrating the human ability to intuitively handle clay and adapt and the machines ability to work efficiently with precision. An action research approach, is used to iteratively test, analyse and gradually refine collaborative strategies, while experimenting on a computationally designed structure bio-reef structure. These collaborative strategies and interventions were used to inform a framework for hybrid fabrication between human and machine that can be used in the printing of complex geometries in clay with improved print quality outcomes. This offers an alternative approach to traditional digital fabrication methods, which distance the designer from the fabrication process, that can be used to overcome the limitations that can exist when using natural materials in 3D printing, and in doing so allows for outcomes that could not be achieved if machines or designers fabricated in isolation.

Keywords. Clay 3D printing; digital fabrication; hybrid fabrication; digital craft; human/machine interaction

1. Introduction

Clay 3D printing remains an underutilised digital fabrication technique in the production of architectural artefacts in part owing to the unpredictable nature of clay as a feed material as well as the attendant need for specialized equipment. A range of research exploring digital fabrication in clay has aimed to overcome these constraints by streamlining and automating workflows (Anton and Abdelmahgoub 2018; Rael and San Fratello 2017; Rosenwasser et al. 2018), yet often in ways that further distance the designer from the material and fabrication processes. This reflects a typical assumption that the role of new technologies is to displace bodily skill (Bard et al. 2016). By contrast, this research argues that better understanding of the participatory and collaborative roles designers might play in clay 3D printing processes — towards the pursuit of digital craft — could prove valuable in extending its viability as a fabrication medium. Digital craft (Scheurer 2012; Senske 2014; Oxman 2007) much like traditional craft, is rooted in understanding not only the tool (software/fabrication technique) but also how to best use it via a process of learning and thinking through making and experimentation. Accordingly, this research explores the activity and levels of involvement of humans and machines fabricating together and focuses on ways to more productively integrate the human ability to intuitively and adaptively handle clay with the machine's ability to work efficiently and with precision. This research also seeks to understand the impacts that human/machine collaboration, and varying the degrees of human/machine agency, can have on print outcomes. To explore these issues, this research adopts an action research methodology to iteratively test, analyse, and reflect on various collaborative modes of 3D clay printing a parametrically designed complex artefact intended for an artificial bio-reef project that requires a material solution suitable for ocean environments. The outcomes of this iterative and exploratory process intend to inform a new framework and workflow for the hybrid human/machine fabrication of complex geometries in clay towards improving print quality results. The digital craft-based approach adopted here, that engages an integration of material consciousness with praxis, intends to challenge the perception that digital tools create a distinction between design intent, generation, and fabrication, and distances the designer from the physical fabrication process (Oxman 2007). In so doing, this further contributes ways to overcome the supposed limitations of adopting natural materials such as clay in 3D printing and to open a range of new possibilities.

2. Research Aims

This research aims to explore ways that computationally driven fabrication processes and human skill can be combined in collaborative contexts (Bard et al 2016) towards enhancing the fidelity, and by extension, accessibility and utility, of 3D printed clay artefacts. More specifically, this research focuses on the case example project of 3D clay printing a computationally generated bio-reef structure using a readily available Delta Potterbot XLS-2 ceramic printer. The bio-reef structure is a significant case example as clay is envisioned as a more viable material for ocean environments over typical polylactic acid (PLA) used for 3D printing. By exploring various iterations of hybrid human/machine fabrication processes through this case example, the project further aims to understand ways to improve the fidelity of print outcomes.

3. Research Questions

Given the issues outlined above, and within the broader research inquiry around the ways computationally driven fabrication processes and human skill can be combined in collaborative contexts, the questions this research project seeks to address are:

In what ways do hybrid processes of human/machine fabrication impact the outcomes of digitally designed 3D printed clay artefacts?

How can the documentation and knowledge of hybrid human/machine fabrication processes improve printing outcomes as well as feedback into complex geometry generation?

4. Methodology

This research project adopts an overarching methodology aligned to the action research paradigm. While originating in the social science disciplines, action research has been more recently adopted in relation to interdisciplinary inquiries that connect activities of design with digital technologies and software development (Foth 2006). Action research is categorized by its distinctive cycle of iteration, where an initial understanding of a problem is developed, and an intervention strategy is planned and executed. After specific interventions are undertaken, reflection on the consequences are used to inform future actions until the desired outcome is achieved (O'Brien 1998). The "Learning by Doing" approach described by action research is also situated within the realm of craft and digital craft, where the thoughtful act of engaging in a process is often as important as the outcome. The goal of producing an artefact through the solution of practical problems in the 3D printing process while addressing the theory of human computer interfaces and digital craft also helps to situate this research in the realm of action research (Cole et al. 2008)

5. Background Research

In the process of design, increasingly digital fabrication processes such as 3D printers, computerized numerical control (CNC) milling, and laser cutting have been adopted for both rapid prototyping and manufacture. Assumptions that these technologies operate autonomously to produce artefacts, and that humans are thereby distanced from material engagement/ and/or shaping of the material, has reinforced the distinction between design generation and the digital tools used in fabrication (Oxman 2007). This has resulted in a separation of the design intent and the fabrication, or as Bernstein laments, gone are the days of the "Master Builder", where the design and built artefact were controlled by a single authority (Bernstein 2012).

Numerous scholars have challenged this perspective and describe the notion of digital craft. Digital craft much like traditional craft is rooted in understanding not only the tool (software/fabrication technique) but how best to use it, and that simple use and experience doesn't equate with more thoughtful use. "Adapt[ing] to the constraints and opportunities of the medium, rather than slavishly follow[ing] procedures, leads to improvisation and innovation" and true crafts(manship) (Senske 2014, pg. 4). Richard Sennet in the *Craftsman* notes that the craftsperson is distinguished from the layperson by their ability to use the tools at their disposal with minimum effort and a maximum result (2008).

Digital craft can be understood as the process of learning or thinking through making, to master the material and the tool, one must be willing to adapt, edit and repeat through experimentation. In pursuit of digital craft, Doyle warns against the separation of human and machine. "If fabrication and digital craft is seen as the completion of an idea that is then constructed by the machine, then indeed the most valuable aspect of craft is lost to over-determination" (2014, pg. 5).

Clay is intrinsically connected to traditional notions of craft, with some of the oldest known crafted items dating back to the Paleolithic era (Rael & San Fratello 2017), and with the term craftsperson conjuring images of potters methodically working their art in clay. Given its rich tradition as a building and construction material, due in part to its unique characteristics, sustainability and cost (Anton and Abdelmahgoub 2018, pg. 71) it is no surprise clay has seen an increase in popularity in 3D printing.

Assumptions around 3D printing are that it can produce fast, high quality prints with little skill and increasingly 3D printers are becoming more accessible. Clay 3D printing challenges these assumptions. Unlike traditional 3D printing materials such plastic filaments, clay is heavy, making it harder to achieve complex geometries that would require formwork. The result is that often clay 3D printing produces artefacts of typologies already typically native to clay like tiles and vessels. The plasticity of clay makes it a desirable material to work with one's hands but makes it hard to be controlled by machines. This plasticity makes the clay unpredictable reducing print quality and sometimes resulting in print damage as shown in *Clay Non-Wovens* (Rosenwasser, Mantell, and Sabin 2018, pg. 509). By applying the notions of digital craft to processes in clay 3D printing, challenges like the above look to be overcome.

Recent projects such *G-code Clay* and *Seed Stitch Wall* exploit the benefits of 3D printing – designing in a digital space and assigning fabrication responsibilities to 3D printers – in the creation of traditional clay artefacts such as tiles and vases (Rael & San Fratello 2107) but in doing so remove the human from the fabrication process in attempts for greater automation.

Clay Non-Wovens (Rosenwasser, Mantell, and Sabin,2018) applies the principles of traditional craft to clay deposited by a six-axis robot arm. The research is focused on understanding the extruded bead and how clay can be used to print rectangular screens with patterns of varying permeability. Through the rigours of experimentation, an understanding of digital craft is developed.

Digital craft is also explored in *Ceramic Components* (Anton and Abdelmahgoub 2018). A clay 3D printer and a robotic arm are used to create an architectural artefact on a rotating cylindrical surface. Much like *Clay Non-Wovens*, new knowledge is generated through informed experimentation. The approach looks to develop a greater understanding of the capabilities of robots in digital craft particularly in overcoming the material constraints of clay. The iterative process of trial and error and its importance in the development of clay 3D printing digital craft is further reinforced in *Informed Design to Robotic Production Systems* (Mostafavi, Bier, and Anton 2015). In these projects, the development of digital craft is evident, particularly in the thoughtful use of fabrication tools and software, however, human intervention is reserved solely for the digital realm, never the clay. While innovative, the outcomes seem to be at mercy of the clay and the difficulties its materiality brings to the fabrication process. Rather than strive for full robotic automation, a more hybrid fabrication approach might be more suitable.

Arc, a CNC engraving tool for ceramics developed at the University of Washington by a team of scholar-makers and two Seattle based ceramic artists (Saegusa, Tran, and Rosner 2016), looks to understand more fully the role of the human in the context of digital craft. Using an iPad, *Arc* can translate sounds and gestures into CNC tooling paths that shape clay during the making process. The artists found that while gesturing could open new frames of design for ceramics, particularly in performing precise tasks, *Arc* wasn't able to capture the subtleties of the human hand which ultimately led to frustration and abandonment of the tool.

Another project that looks directly at the re-involvement of the human in the fabrication process is the aptly named project *Being the Machine*, (Davendorf and Ryokai,2015). In *Being the Machine*, the role of the robot and human are reversed, and the human follows the G-code instructions (usually reserved for instructing 3D printers). The G-code is translated and displayed as instructions for the human to follow. *Being the Machine* examines the relationship between the human and machine and the emerging field of hybrid fabrication, which looks to create "new roles for digital fabricators in the physical making practices." The study directly responds to the idea that a symbiotic relationship can be created when the machine does things it is good at - like visualizing and analysing models - and humans do what they are good at - like adapting to changing circumstances, reacting to the unexpected and working with materials.

By understanding how *Arc* and *Being the Machine* approached the use of the human in the design process this research looks to understand the impact of various participatory roles the designer can have in fabrication process. Using processes rooted in the tenents of craft such as learning by doing, this research explores the relationship of the human and the machine and the ways they can collaborate to open new design spaces.

6. Case Study

The case study examined looks to understand how clay 3D printing outcomes – of a single computationally generated model – are impacted through the application and adaptation of various human/machine fabrication processes and strategies. In this research human/machine fabrication strategies are reflected upon and the impacts on print fidelity are used to inform a workflow based on experimentation, that can be referenced in the development of complex 3D printed clay models. As it closely aligned with the practice-based way that craft skills are learned through repetition and iterative improvement (Holmes 2015), the research focused on the improvement of a single form in the case example. The use of a single model allowed for the impacts and outcomes of individual strategies to be evaluated while providing an opportunity for past learnings to be applied in future iterations. The learnings from each strategy would be used on subsequent iterations to reflect the pursuit of continuous improvement.

The complex form used in this case study was taken from a larger bio-reef model that had been designed and printed in plastic PLA by Yannis Zavoleas in conjunction with the University of New South Wales (2016). Zavloeas' 3D printed model is shown in figure 1, both during and after the 3D printing process. Figure 1 highlights the amount of supports required to achieve a successful print outcome for the bio-reef model. A smaller section of the overall model was selected (as circled in figure 1) as it allowed for the isolation of the key features of interest to the print improvement process (see figure 2).

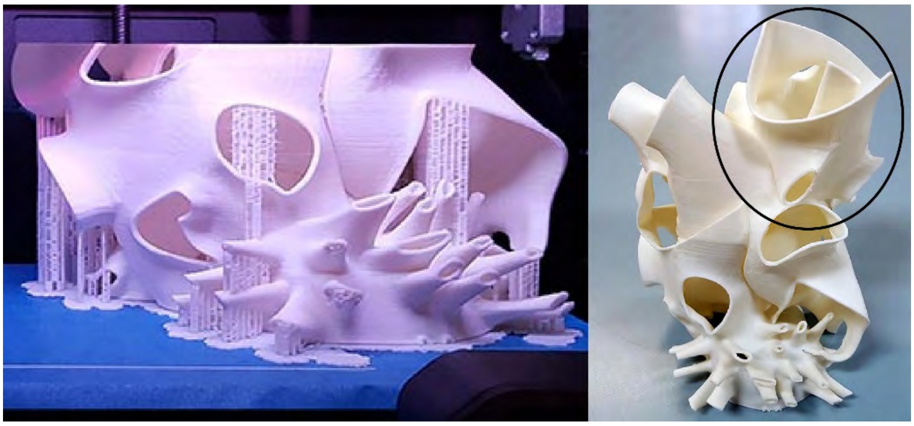

Figure 1. (left) Test print of bio-reef structure in PLA, showing the considerable amount of formwork and support required; (right) 3D printed model of the bio-reef structure, with the portion of the model used in this project circled (images, Zavoleas 2016).

This project made use of a Potterbot XLS-2, a large-scale ceramic 3D printing arm with a 6 mm diameter print nozzle. The printer is equipped with an external control panel that enables the user to make manual adjustments to printing speed and extraction rate during the printing process. A digital version of the bio-reef was translated into G-code using Simplify3D and the G-code was visualized and is shown alongside the digital bio-reef model in figure 2. The visualization of the G-code was used to develop a familiarity with the tool path and acted as an initial method to become familiarized with the printing process and the expected areas of key interest such as the overhang [label 1] and the spans to be bridged [label 2,3] shown in figure 2.

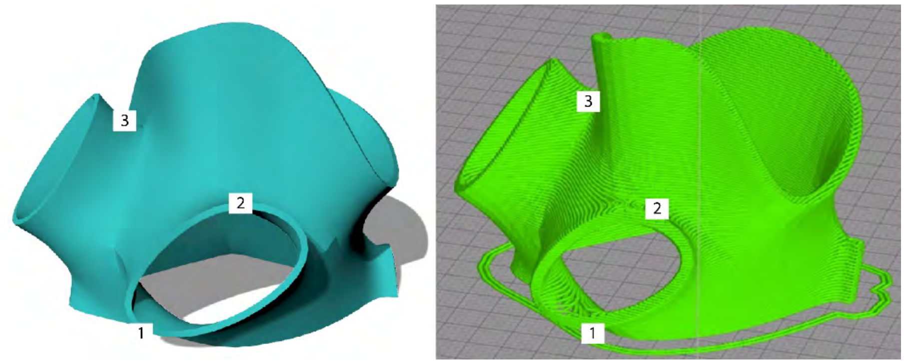

Figure 2. (left) Digitally rendered 3D model of the bio-reef structure (right) Visualization of printing G-code

To understand the Potterbots' ability to print the selected model with no human/machine fabrication strategies a benchmark print was executed. This benchmark, as shown in figure 3, indicates the starting place in which each subsequent model could be evaluated against. In order to determine the initial human/machine strategies to be undertaken in first print iterations, the outcomes of the benchmark were evaluated. As the print result had several inconsistencies – the result of compounding print issues – observation of the printing process rather than the inspection of final print led to the identification of key areas for focus in the initial hybrid fabrication strategies.

Figure 3. Photographs documenting the outcome of the benchmark print

6.1. INTUITIVE STRATEGIES (ITERATIONS 1 THROUGH 3)

During the initial print stages, it was observed clay would not adhere correctly to the build platform, or itself, which resulted in clay accumulating on the build plate and print nozzle. This clay buildup impacted the ability of the Potterbot to correctly extrude layers on top of one another causing print issues to compound. Additionally, excess clay on the nozzle could bump into and displaced existing printed layers, causing further print errors. These problems can be seen in figure 4, and represented critical issues to address in the human/machine fabrication processes.

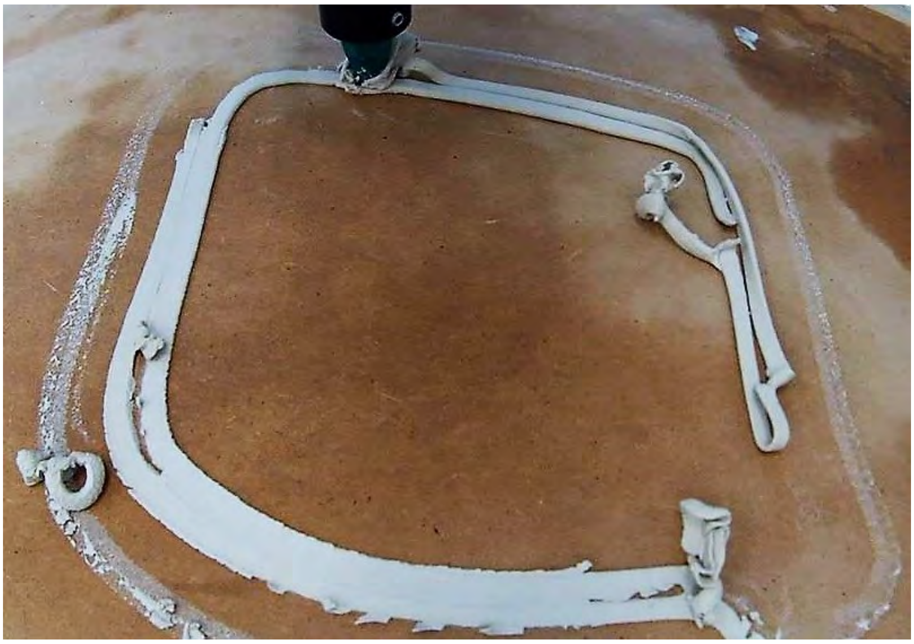

Figure 4. In the initial stages of printing with no intervention is was common to get clay accumulating on the platform and nozzle, which would result in ongoing print problems if not resolved

During the printing process there was an instinctive response of the fabricator to attempt to clear the nozzle and tap clay layers to the build plate or onto the layer beneath it. Intuition and experience with previous 3D fabrication processes indicated that these simple actions performed by the fabricator could prevent the accumulation of errors. Based on these observations and the outcomes of the benchmark print, the following strategies were developed and iterated through in test prints 1 through 3:

1. Clearing the print nozzle to be free of accumulated clay, with either fingers or a small piece of dowel.
2. Tapping the clay into place directly after extrusion; to ensure adhesion to the build platform or layer below it.
3. Positioning or placing clay in the correct place if it had been moved by either the machine or the fabricator.

These strategies based on simple intuitive strategies – that could be easily performed – closely reflected the types of interventions the fabricator instinctively desired to make during the printing process – in clear efforts to create a successful print. These approaches represented the adaptive ways the fabricator could utilise simple human/machine interactions to alter outcomes. Figure 5 shows how these strategies of instinctive interventions facilitated the printed clay into flat consistent layers, which reduced layer separation and collapse, resulting in better print fidelity.

Figure 5. Improvements between two test print iterations realized through the application of the simple human/machine intervention strategies

6.2. EXTRUSION WIDTH (ITERATION 4)

The next human/machine fabrication strategy that was explored looked to address issues caused by unintended gaps between the inner and outer walls of the model. By increasing the extrusion width of the clay, so that the inner and outer walls connected it was tested if greater print stability would be achieved. To increase extrusion width, the diameter of the print nozzle was increased from 6.0 mm to 7.1 mm allowing for a greater volume of clay to be extruded. In order to accommodate the larger nozzle, the extrusion rate of the clay was increased. This was done by manually increasing the extraction speed on the external control panel of the Potterbot, and a series of tests were undertaken to evaluate the impact of extrusion rate on extrusion width. Through observation of the outcomes of the manual extrusion rate adjustments an optimal rate of 2.00x speed was determined for the print model. The outcomes of the extrusion tests are shown in figure 6.

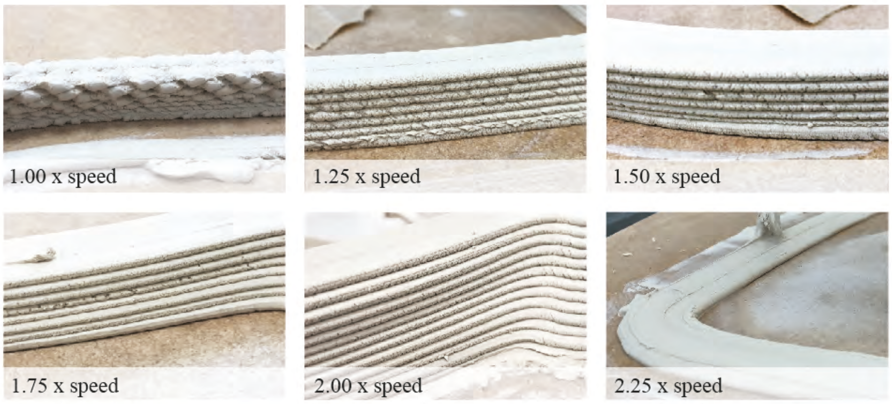

Figure 6. Photographs showing the impact on clay extrusion width and consistency with increasing extrusion speed with a 7.1mm nozzle.

Manually adjustment of the extrusion rate resulted in the inner and outer wall of the model widening and connecting. The connection of the clay prevented the inner and outer walls from separating and collapsing during the print process and contributed to the overall stability of the model. Additionally and perhaps more importantly, the additional extrusion width increased the area available for each layer to be extruded on, which decreased the errors that occurred when a layer deviated from the layer beneath it (both as intended and when the printed clay had been accidentally shifted). Figure 7 shows the impact of the increased extrusion width on the connection of the inner and outer walls of the model.

Figure 7. The impact of increasing extrusion width on the separation of the inner and outer walls of the printed model (left) 6mm nozzle and 1.00 x extraction speed; (right) 7.1mm nozzle and 2.00 x extraction speed.

6.3. FORMWORK AND SUPPORTS (ITERATIONS 5 AND 6)

Features of the bio-reef model had considerable overhangs, and for these to be printed successfully the model required adequate layer build up or formwork to ensure layers were supported. The overhang in the bio-reef model (label 1, figure 2) required a layer deviation that could not be accommodated by the print layer height and extrusion width of the clay printer which resulted in layers being extruded with no support as can be seen in the top left image of figure 8. These unsupported layers created print issues where as the next layer would also print without support, led to compounding instability and print fidelity quickly deteriorated. To address this problem and provide a surface for the clay to be printed on, supports were designed and deployed. The initial supports were cut from 3mm cardboard allowing a single card-board layer to be used in conjunction with each print layer. Cardboard was also chosen because it could be cut to fit the required geometry during the printing process and could easily be adjusted and amended. The use of supports on the lower overhang is shown in figure 8 and shows how the use of cardboard supports greatly improved the printing of the lower half of the model. The supports provided a surface so that the overhanging layers could be printed on, meaning they could in turn support the layers extruded on top of them.

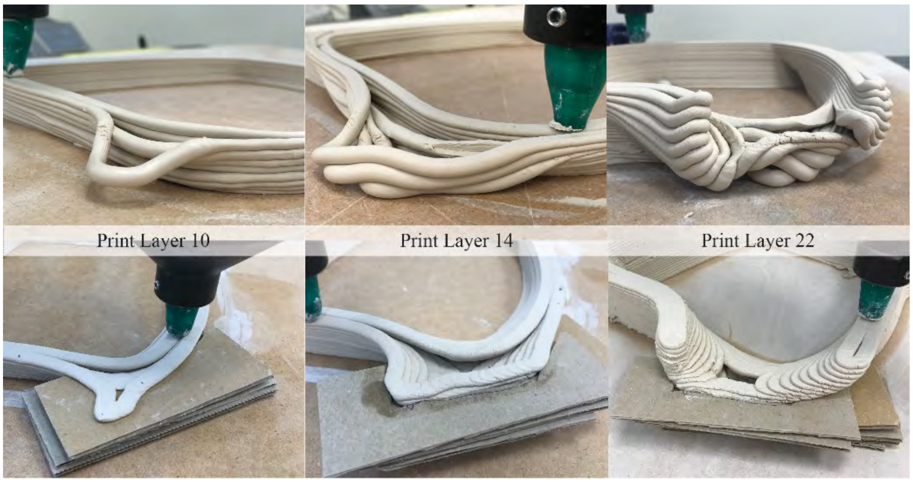

Figure 8. The benefit of human places supports on print outcomes at three separate stages in the printing process, layer 10, layer 14 and layer 22.

Through observation of the print process, support layers could be deployed alongside the printed clay and the shape of the supports was improved on in print iteration. Initially the supports were cut to fit the shape of the print (see figure 9), but this required considerable involvement by the fabricator, however, as experience was gained, a set of universal support shapes were developed. The refined support shapes as shown in figure 9, could be pre-cut and assembled on the overhangs as required, which reduced the effort required by the fabricator (no longer needed to customize each support layer).

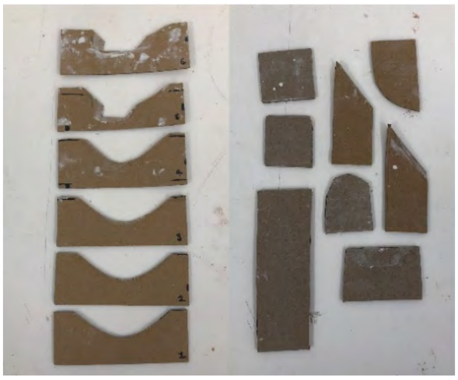

Figure 9. (left) Initial support shapes used, cut from 3mm cardboard to fit the exact shape of the print model; (right) Standardized support shapes cut from 3mm cardboard.

A secondary support was developed for the upper bridging of the model, as initial attempts to bridge the span without any support were unsuccessful. The upper support was developed out of cardboard, used again for its flexibility and the ease of deployment by the fabricator as cardboard could be folded to the required height during the process. Strips of cardboard, precut to a width of 2.5 cm coupled with a secondary smaller cardboard layer, were used to assist in the extrusion of clay over the span (see figure 10).

Figure 10. (left) Print outcome with no upper support structure; (middle and right) Photographs showing the use of the upper support structure and the result on print outcomes.

The fabricator's experience, and skill with the supports improved the ease in which the supports could be deployed, which contributed to the success of their deployment and maximized the benefits of their use. As more thoughtful support shapes were found that required less effort to use, the fabricator was able to devote more attention to other print improvement outcomes. It was largely the development and successful use of the support structures by the fabricator, combined with the learnings and intuitive strategies previously explored that resulted in a fully realized bio-reef model being printed (figure 7)

6.4. CLAY HANDLING (ITERATIONS 7 THROUGH 10)

Iteration 7 reflected the outcomes of previously established strategies such as supports and intuitive interventions, when used in conjunction, on the fabrication of a fully realized 3D printed model. To understand how the next series of fabrication strategies would impact outcomes, iteration 7 was situated as a new benchmark print which represented the continuous improvement process of the hybrid fabrication strategies developed in iterations 1 through 6. Rather than the continuous improvement experienced earlier, each strategy detailed here looked to understand how the tested strategies impacted on print outcomes of the fully realized model. Having shown that human/machine fabrication strategies could result in a fully realized printed model, the final stage of research looked to understand the impacts of strategies that involved a greater level of human embedment in the fabrication process.

Figure 11. Outcomes of print iteration 7, using supports and intuitive interaction strategies

The three strategies tested were influenced by traditional ceramics techniques, scoring, pinching/merging and slipping. Iteration 8 was used to evaluate scoring – which involved spreading and lightly scoring the clay with a toothbrush during the entire fabrication process. Scoring involved creating a crosshatch pattern on the extruded clay layer and is used in traditional clay craft to help join clay pieces. The outcomes of iteration 8 are shown in figure 12. While functionally successful, visual inspection and comparison to iteration 7 indicate a less successful print due to considerable layer separation. These errors were the unintentional outcomes of the more involved role of the fabricator in the process, particularly the pressure required to adequately score the clay resulting in the existing layers being shifted and destabilized which led to layers pulling apart and collapsing.

Figure 12. Outcomes of print iteration 8 that involved scoring of the clay. Layer separation particularly evident in the middle image.

The strategy used on iteration 9 involved lightly pinching or merging clay layers together by hand during the printing process. Figure 13 shows the outcome of this print strategy, which doesn't show the same layer separation as iteration 8. The pinching/merging of the layers also tended to result in unintentional deviations in layer placement, but as the fabricator had greater agency of the clay, they could better adjust and correct these errors, and therefore less layer separation is evident. Impacts of this strategy are particularly evident in the upper fin of the model. Rather than a smooth gradient (see iteration 7 – figure 11), there is considerable distortion in the layers which were unintentionally displaced as they were pinched.

Figure 13. Outcomes of print iteration 9 that involved the pinching and merging of clay layers, the impact of the fabricator evident on the appearance of the clay.

The last strategy undertaken involved painting a layer of slip onto the clay behind the printing nozzle. Slip is a mixture of water and clay, roughly the consistency of cream, and is used in traditional clay craft as a glue when adhering clay pieces. As the slip could be applied with little force and with a paint brush, this method of intervention introduced the least fabricator error, however layer separation/offsets because of fabricator intervention were still evident.

Figure 14. Outcomes of print iteration 10 that involved the application of clay slip between the print layers with a paint brush

While each iteration provided valuable experience into the process all three approaches introduced unintentional errors not evident in iteration 7. When adjustment was only made as required (as in iteration 7), the print fidelity appeared to be closer to the original intended digital model. These strategies offer insight into potential techniques that could be attempted in the printing of other clay 3D models and offer a way to investigate and interrogate the printing process in the aims of finding solutions to print problems.

7. Discussion

Through experimenting and iterations of human/machine fabrication strategies varying levels of print improvement outcomes were achieved. Comparison of the final printed forms (that used the learnings from the strategies tested in iterations 1 through 6) to the benchmark print, reflect the benefits that human/machine strategies can have on the reliability in which a bio-reef structure can be printed in clay. The strategies developed in iterations 1 through 3 first reflected the human response to the process, what small thing can I do to make this more successful, and often the results were as expected, and it was from these initial engagements with the clay that future strategies were developed.

A major contribution to print success in the case example was the development and deployment of support structure. Supports deployed by the fabricator increased printing stability and provided the required formwork for the overhang and spans to be printed without significant error. Iteration and experimentation with support strategies reduced the effort required while maximizing results, reinforcing the notion that the "development of craft leads to the most efficient solutions which minimize effort while maximizing outcomes" (Senske 2014, pp. 832).

Collaborative strategies such as those engaged in iterations 8 to 10, provided a more detailed insight in to the way human skill can improve but also introduce error into the printing process. These fabrication processes such as the merging of print layers by hand throughout the entire print process produced functionally successful outcomes, but sustained human interaction tended to result in unintentional movement of the printed clay and a reduction of print fidelity. Reflection on strategies undertaken at the beginning of the research seems to suggest that simpler engagement which emphasized the human's adaptability and flexibility rather than the machines precision, were not only easier to execute, but yielded the most consistent results. This reinforces the notions of craft being the thoughtful considered engagement with the material and the process (Sennett, 2014) – just because you can doesn't mean you should. The improvements documented in the case example reinforce the importance and types of participatory roles designers can have in fabrication processes and how productive and experimental collaboration between humans and machines can be used to challenge norms in 3D fabrication processes.

Reflection on the process undertaken emphasizes not only the importance of strategies used, but also the experience and skill gained from engagement and experimentation in the printing process. Much like craft, experience with the tools, the material, and process, facilitated in the development of improved and innovative strategies which could be used to more effectively collaborate with the machine and improve print outcome. It was through physical manipulation of the clay that an understanding of how much and what pressure would result in the desired outcomes, and how those manipulations would impact print results. Through in-depth engagement in the fabrication process on a participatory level the fabricator was able to collaborate productively with the machine, anticipating the machine's actions and deploying support structure and clay adjustment, in what could be considered choreographed dance between the human and the machine.

The methods of experimentation proposed in this project focused on blurring the line between the designer/fabricator to overcome the limitations of the print material and tools in the production of a complex clay 3D model. By understanding human/machine fabrication processes and a deeper knowledge of the fabrication process learned through engagement on a craft level, one can better understand the problems that may be faced in fabrication, and ways in which to approach solutions. This provides a foundation for future praxis in hybrid fabrication that can be used to solve emerging challenges in digital fabrication and suggests fabrication processes benefit from an understanding and experimentation in hybrid fabrication processes.

8. Conclusion

This paper documents the ways human/machine fabrication processes can be used to impact the outcomes of a clay 3D printed computationally generated bio-reef structure. While the constraints of natural materials such as clay can introduce barriers on clay 3D printing fabrication processes, craft and human/machine interactions have been explored to understand the participatory role of the fabricator in overcoming fabrication challenges. In the case example of the bio-reef structure clay 3D print results were shown to be improved through iterative testing of human/machine fabrication processes. Human skill – honed through experience in the fabrication process – when coupled with human/machine interaction strategies that focus on collaborating the human ability to intuitively and adaptively handle clay with the machine's ability to work with precision, yielded the greatest improvements to print fidelity. While not applicable to all printing scenarios, the key contribution this research project makes concerns rethinking how we engage with the fabrication process and print materials. In so doing, this research project has pointed towards productive new ways to, not only overcome the challenges of printing in clay, but also enhance print outcomes.

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