Guiding Instability

A craft-based approach for modular 3D clay printed masonry screen units

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As the field of 3D printing technologies expand, complex materials that require a deeper engagement, due to their more unstable properties, are of increasing interest. Cementitious composites, clays and other ceramic materials are of particular relevance: their potential for fast large-scale fabrication and local availability position these technologies at the forefront of expansion for 3D printing. Despite the extensive benefits inherent to clays, their irregularities and the largely unpredictable deviations that occur when printing from a digital model, currently limit design and architectural-scale applications. However, these deformations could conversely be harnessed as design generators, opening up avenues for both aesthetic and functional exploration. The paper presents an investigation into the inherent material instabilities of the clay 3D printing process for the development of an architectural masonry facade system. Through an iterative process based in craft, a new capacity for material expression and authenticity beyond previous manufacturing capabilities can become actualized.

Keywords: 3D printing, digital craft, clay, material computation, uncertainty, hybrid fabrication

INTRODUCTION

The 4th industrial revolution promises the distribution of manufacturing and the re-conceptualization of the means of production. 3D printing processes are part of this shift. These technologies are utilized with the intent for accurate and precise reproductions of complex geometries and as such, most research has focused on achieving predictable and “stable 3D deposition shapes” (Gibson, Rosen, and Stucker 2015). For this purpose, materials with relative low cost and predictable behaviour, like photopolymer resins or dimensionally stable thermoplastics have been ideal (Dizon et al. 2018). However, as the spectrum of 3D printing technologies continues to expand, new applications and materials are being explored that more directly engage these complex properties and question the paradigm of control and imposition of form in the applications of 3D printing technologies. Furthermore, despite this paradigm for precision, inherent to many 3D printing processes - notably fused filament fabrication (FFF) processes that rely on material build up through directional layering - are material anisotropies resulting from the printing process which introduce unde-
sired deviations in the final print (Dizon et al. 2018). While extensive literature exists to understand and mitigate some of these irregularities to produce reliable and repeatable parts within narrow tolerance margins, these material instabilities can conversely be engaged to open up new and unique design territories. For instance, stress concentrations as well as micro and macroscopic anisotropies have been explored as drivers of 4D behaviour (Correa Zuluaga 2015; Tibbits 2017; Momeni et al. 2017) while toolpath orientation in FFF has been used for the development of functionally differentiated (Oxman 2011) or structural optimized components (Chapiro 2016; Malek 2017; Compton and Lewis 2014). Key within them, is the engagement of materials that may have been previously overlooked for 3D printing processes due to their inherent material irregularities, instabilities or non-linear behaviour. Clay - due to its low cost, local material availability, and rich craft tradition – is one of these materials of interest for FFF processes.

Clay is widely used in both vernacular construction as well as high tech applications: traditional ceramic crafts have developed specialized methods that harnesses and celebrates the variability of each piece, while industrial ceramic manufacturing have developed precise processes and recipes (e.g. dies and moulds) in order to mass-produce standardized, repetitive pieces of high dimensional precision. Yet, despite its ubiquity, clay is seldom found in 3D printing processes for architectural applications due to its inherent material irregularities, instabilities and non-linear behaviour while wet.

3D printing clay via FFF presents a multitude of internal and external challenges, including but not limited to, clay viscosity, slumping, ambient environmental conditions, and movement of the print-head, each of them contributing to unpredictable deformations and deviations in the resulting print (Gursoy 2018). Consequently, it is difficult to predict and simulate all the variables and their interactions within a digital model (Gursoy 2018; Rosenwasser, Mantell, and Sabin 2017). Realtime adjustment to error is also difficult as multiple parameters, such as uneven drying or sagging due to self weight can cause internal stresses that will still affect the final outcome post-print. Several architectural scale projects have been developed using clay FFF processes (Peters 2014; BAT 2017), which operate under a “clear mandate of tight construction tolerances” (Seibold et al. 2017). In other words, these projects have optimized workflows to minimize potential deviations and consider the irregularities of clay as obstacles for geometry fidelity.

However, recently this error-prone predisposition of clay FFF processes has been investigated by designers with the explicit aim to express emergent aesthetics through its composition variability, and to reveal emergent effects created by the printing process (Gursoy 2018; van Herpt and van Broekhoven 2015; Rael and Fratello 2018). These experiments explore new material aesthetics and re-interpret artisanal methods from handmade ceramics where a deep understanding and learned knowledge of material and technique inform the final outcome (Kolarekic 2008). However, literature is limited in providing methods to achieve these results or examples that identify the architectural potential of these instabilities at the larger scale needed for design and building construction. Furthermore, existing research for architectural scale projects that readily engage the expressive potential of instability in clay FFF processes are currently limited to panel type screen assemblies (Friedman, Kim, and Mesa 2010; Rosenwasser, Mantell, and Sabin 2017).

In this context, the presented paper demonstrates a clay FFF method that harnesses the material computation capacity of clay and the unpredictable deviations between digital input and final artefact as design drivers for an architectural masonry façade system. Through a reciprocal, digital to analogue, experimentative and iterative design process based in craft, it is demonstrated that the instrumentalization of material instabilities can be used to achieve desired functional performance and material expression.
METHODOLOGY

Using paste extrusion deposition, an interlocking screen system was developed that parametrically modulates light while testing the plastic deformation properties of clay for formal expression and ornamentation through the addition of loop forms. The printed test wall consists of 32 unique interlocking masonry units, stacked four rows high, measuring 1000mm x 300mm x 175mm (Figure 1).

The prototype was developed using the Potterbot Scara XLS-2, with a 3600 ml extruder. A commercially available earthenware clay product, containing a 50:50 talc to ball clay ratio, was used for its high plasticity and drying performance. The clay was prepared, prior to printing, by increasing the moisture content of bagged clay (10 oz per 25lb of clay). The pieces were printed onto melamine boards to minimize moisture absorption and adhesion to the printing bed. A geometric strategy of manipulating single layer shells was adopted for the masonry unit design in order to accommodate a continuous spiral toolpath, and an integrated digital parametric model was developed using Rhinoceros and Grasshopper, which allowed for precise manipulation of geometric variables (Figure 2). The digital model was then translated into G-code toolpaths using Simplify3D, while on-the-fly adjustments of extrusion speed and flow rate, using the printer interface, accounted for slight
discrepancies in material consistency.

To better understand the material behaviour of the clay filament, an iterative design approach to the development of the masonry unit was implemented. Each iteration tested deviations (e.g., slumping, sagging, and collapsing) between a prescribed digital model and the resulting form. The results were evaluated based on their potential to enrich the printed masonry unit as a design feature. Certain variables were kept constant such as temperature, clay “wetness” (moisture content), extrusion speed, and extrusion layer height, while other variables were further modified such as nozzle diameter, orientation of print, slope, height, size and geometry of the masonry unit.

Documentation of the masonry units became integral to the development of the design and were used as references to understand the deviations found between the printed clay masonry unit and digital model. Photographs of the bone-dry masonry units were used to compare the varying printing parameters. The masonry units, while leather-hard, were sliced to understand how the changing parameters affected the interlocking fit. Digitally scanning key prints provided additional insight to the modes of deviation between digital model to printed masonry unit (Figure 3).

The material computation capacity of clay and its effect on the final form - notably the overall shape deformation due to self-weight (also referred to as slump) and the “loops” that emerged from unsupported clay bead overhangs - became the primary focus for the design team. Once these key design drivers were determined, the digital model's parameters were calibrated to investigate the interdependence of, and potential design space, that these material properties could facilitate in the physical form.

RESULTS

The final digital model and corresponding toolpaths were informed by specific parameter values after extensive testing and calibration as there was no way to predict the natural tendencies and reactions of clay a-priori. An iterative method of experimentation between analog parameters (nozzle diameter, slump deformation), and digital parameters (tool path, extrusion rate and movement speed) allowed for the final objects to emerge.

Slump

The malleability of the clay was an important factor in understanding several properties of the masonry unit. In addition to maintaining a consistent extrusion rate, keeping the viscosity of the clay consistent allowed for the controlled testing of global deformation due to self weight, i.e., slumping or warping. Due to the plasticity of the clay and the slanted angles of the exterior surfaces of the masonry unit, each brick had a tendency to globally deform and slump. A paradigm of zero tolerances and perfect fitting systems would not have been suitable here. This deformation could have been catastrophic if each unit was to perfectly match the digital model’s assembly parameters (Figure 4). However, printing the matching interlocking masonry unit upside-down, keeping clay viscosity and environmental conditions consistent, computed a matching fit. Flipping alternating masonry units also affected the sag direction of the loops, creating distinct texture characteristics for each side of the wall (Figure 5).
Figure 5
Slumping match when print orientation is inverted.

Figure 6
Nozzle diameter size testing for overall form, surface pattern quality and consistency.
Figure 7
Tests of nozzle diameter in relation to loop pattern creation

Digital Tool Path

Throughout the iterative testing of physical parameters, a continuous and parallel calibration of the digital tool path was necessary to adjust to the natural reactions of clay. As the loops were designed as unsupported cantilevers, the nozzle diameter and viscosity of the clay ultimately determined the length and shape of the loop's final digital tool path. Different nozzle diameters affected the flexibility and weight of the extruded clay bead, consequently the same digital tool path resulted in noticeably different loop appearances and geometries. Therefore, a careful calibration of the digital model was required. For instance, the configuration of the loop pattern required various test prints in order to achieve the desired surface quality (Figure 8). The final loop configuration consisted of loops separated by three extrusion layers in a staggered pattern to prevent draping of loops on top of each other. Additionally, the chosen configuration seemed to provide additional interlayer adhesion by allowing the loops to form additional contact points to the layers below.

Nozzle Diameter

The layer height and nozzle diameter used for the extrusion of the clay filament affected the surface quality, wall thickness, inter-layer bonding and general structural stability of the overall print, therefore multiple diameters needed to be tested in order to determine a suitable size. If the nozzle diameter was too narrow, the lower structural capacity of the thin walls combined with the self weight of the masonry unit, caused the piece to excessively slump and buckle until failure. While if it was too wide, geometric definition was reduced, compromising subtle features of the masonry system (Figure 6). Additionally, the nozzle diameter altered the effectiveness of the loops in terms of size and strength. For example, loops created with wider nozzle diameters sagged less and were stiffer, causing loops to tear in the curvature points. Alternatively, loops extruded from narrower nozzles sagged more and thus increased in size, but the greater overall slumping of the masonry unit resulted in poor adhesion between layers (Figure 7).

Due to the malleable nature of the clay while printing, the movement and speed of the print head had unexpected effects on the clay wall. The tool path action to print loops, combined with the self-weight of the clay bead, incrementally pulled the clay wall inward and eventually resulted in print failure due to the misalignment of layers. To correct this deviation, a small counter-loop action (a small cantilever in the opposite side of the wall) was added into the toolpath after each loop to pull the wall back in alignment (Figure 9). Various testing of counter-loop depths were taken place to evaluate the appropriate size. (Figure 10) If the counter-loop was too small, the movement was not sufficient to correct the initial pull and caused layers to misalign. Conversely, if the
Figure 9
Counter-loop mechanism: A) toolpath aligned with wall. 2A) loop action causes printhead to pull wall. 3A) wall is no longer aligned with toolpath. 2B) small counter-loop action pulls wall back. 3B) wall is re-aligned with toolpath

counter-loop was too deep, the resulting excess clay build-up on the surface and corner of the masonry unit compromised the fit of the interlocking system.

DISCUSSION
Working with clay in a multi-component assembly offered a complex set of design challenges. The FFF process is highly susceptible to irregularities that were easily compounded in a multi-component assembly. The development of the presented masonry units required a direct engagement and an openness to experimentation with both the material qualities and the fabrication process. This open-ended process, supported by consistent documentation and controlled through an integrated parametric model, created a framework that allowed for both the systematic calibration of parameters and the emergence of unexpected findings.

Flipping the print orientation provided a direct method of resolving the geometric compatibility within the interlocking system; however, it also offered a different manifestation of the loops depending on print orientation that contributed an additional layer of complexity to the material aesthetics of the masonry assembly. While this technique enables interlocking designs to meet fit tolerances, it also suggests there is more investigation needed in exploring other applications and design potentials of the material computation capacity of wet clay. Similarly, the loop’s capacity to increase interlayer adhesion provides opportunities for further investigation into the aesthetic, formal, and structural potentials of different loop configurations. By strategically layering loops, different wall thicknesses, sectional variations, and textures could be achieved, and could also present an alternative method to creating thick walls. More testing is needed to fully understand the impact of these layered loop structures on durability and overall slumping.

Imagined at a larger scale, a customizable architectural masonry screen assembly with parametrically controlled apertures may be able to respond to a number of design criteria such as solar control, airflow, visibility gradients, etc. The printed test section of the masonry screen, presented here, demonstrated the feasibility of the system, both in terms of multi-unit assembly as well as its architectural potential, to modulate light and provide visual complexity (Figure 11). However, building a larger section of the wall assembly would be necessary to fully understand the requirements for implementation in practice under various environmental conditions.

Figure 10
Counter-loop depth tests showing effect on layer slippage and surface quality

CONCLUSION
Redefining what is made and how it is made sits at the forefront of the 4th industrial revolution and is a core question within the architectural practice. With
the embrace of heterogeneity, there are opportunities for unexplored material properties to emerge as design generators of new functional characteristics rather than obstacles preventing reproductions of imposed platonic forms. Instead it offers opportunities to enrich the process and outcome. For architectural design, this opens up new avenues for local adaptation, contemporary ornamentation and shared authorship - where incorporating a mediated variation adds another layer of aesthetic complexity in the final form. While in practice, the potential given by guiding instabilities of clay FFF processes expands the applications of large scale construction and rapid prototyping, due to its low cost, local material sourcing (clay, adobe, biocomposites, etc), workability of material and ease of post processing.

Through an iterative process based on craft, a new capacity for material expression and authenticity beyond previous manufacturing capabilities can become actualized. The precision of new manufacturing methods like 3D printing combined with an inquisitive engagement of material processes can result in hybrid processes of design and making. Perhaps the 4th industrial revolution is a challenge of fusing territories as it is a challenge of mediation, the unique and the ordinary, the mass produced and the vernacular, the designed and the emergent.

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