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The study of correlation between material properties and textural formation engendered by experimentation with G-code of 3D printer

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This paper presents intermediate results of an experimental research directed towards development of a method to use additive manufacturing technology as a generative agent in architectural design process. The primary technique is to variate speed of material deposition of a 3D printer in order to produce undetermined textural effects. These effects demonstrate local variation of material distribution, which is treated as a consequence of interaction between machining parameters and material properties. Current stage of inquiry is concerned with studying material agency by using two different materials as variables in the same experimental setup. The results suggest potential benefits for mass-customized fabrication and deeper understanding of how different materials can be employed in the same manufacturing system to achieve a range of effective behaviors.

Keywords: digital fabrication, digital craft

INTRODUCTION

The paper presents series of experiments that are part of ongoing research directed towards devising methodology on using 3D printer as a generative component of design process. The overarching thesis is that manipulation of fabrication parameters leads to various architectural elements being informed. The objective is to understand interdependencies between geometry, materials and machining parameters so that they can be employed to produce diverse performative effects as tangible artifacts of the translation from pixel to matter.

In this stage of research, we are focusing on the role of material properties and behaviors in making of undesignable textural patterning. Several series of geometrically identical models were printed in two different materials: plastic and porcelain. We applied the same manipulation of speed of deposition in G-code to fabrication of both material sets. Speed of deposition controls how much material is extruded at any given point of a toolpath. The faster printer moves the less matter it deposits. This simple princi-
ple allows to achieve surface heterogeneity by shedding and accumulating mass in various patterns. Resultant texturization is undesgnable due to proliferation of minute deviation; it also embodies traces of digital making. Ceramic and plastic groups of models with matching digital geometry and same manufacturing instructions diverge not only in local geometry of ensuing patterns, but in the nature of overall effects that they demonstrate. Understanding of underlying structure of these differences may suggest novel ways of incorporating material agency in CAM, concurrently, it advances the discourse on digital manufacturing as a contingent and dynamic process.

THEORETICAL BACKGROUND AND PRACTICAL PRECEDENTS
Inquiry’s conceptual base draws primarily from the discourse on digital craft. Overall framework of the research is formed by such principles as continuity between design and production through translation of algorithmic logic from stage to stage, integral involvement of maker/designer in all aspects of actualization and an element of risk, for the ability to modify production parameters converts space of making into space of discovery (Kolarevic 2008). Outcome is not pre-determined yet falls within pre-specified range based on certain criteria (Pye 1968). Value of indeterminacy, error, glitch and deviation resides in questioning the use of CAM as a linear process meant to engender continuous variation, a process that merely extends industrial mass production (Perez 2017). Other promising aspects of error include an opportunity to study the non-linear response of an object to manipulation of the system of relationships that defines it (Kolarevic 2008) and shift from ideal, intended state to constrained and limited reality, a chasm that distinguishes making of architecture from manufacturing commodities (Frampton 2010).

Digital craft sees fabrication machine as a filter translating data into matter; the role of material is to process informational input and produce a tangible output informed by innate properties and behaviours of the material itself. Through this double translation the specificity of initial abstracted parametric setup increases. Digital craftsman's project is to design the process of interaction between digital and material logics (Gramazio and Kohler 2008) by building a system that directs how material is going to be shaped in a specific fabrication environment and allowing material to affect the outcome (Satterfield Schwackhamer 2017).

Experiments, presented here are designed in alignment with principles of digital craft. Continuous involvement of designer is needed during fabrication, intermittent necessity to adjust certain parameters is due to variable behavior of material, which cannot be precalculated. Designer has to learn the behaviour of each material, understand its constraints and affordances in relation to geometry being printed so that they can respond appropriately in-situ. In this way, even though the control is indirect, the research closely relates to traditional craft. More advanced approach to continuity of the making hand is found in the work of (Brugnaro and Hanna 2017). They tackle the problem of introducing material feedback in CAM. By utilizing machine learning in robotic carving to process force feedback, they were able to teach the robot to adjust the pressure and direction of the cut according to specific material behaviour. Robot acts as instrumentalization of carpenter’s expertise constantly adapting to respond to concrete constraints.

Fundamental part of the work is to encourage the emergence of such 3D-printing effects, commonly perceived as erroneous, as stringing and looping. The system is designed to produce a deviation from the homogeneous norm. Undesignable intersection between machine configuration and material agency performs as effect generator. In terms of exact surface articulation, the most direct precedent of this research is Andrew Atwood's work on negotiating heterogeneous architectural system and homogenous skin through design of continuous process of structuring (Atwood 2012). Striving to main-
tain continuity of logic throughout CAD and CAM revealed a range of surface irregularities, by-products of the system. For Atwood, the effects were a part of discovery, for this research they are part of the method. An example of intentional insertion of error into the automatic machining process is the work of Yota Adilenidou on introducing deviation into matter distribution by using cellular automata systems (Adilenidou 2015). Her work presents an insight into inducing differentiated repetition; it presents another method to modulate production concurrently and positions error within the space of digital fabrication as source of variation.

Another case of embracing imperfection that arises during translation from ideal digital geometry to a specific material-workflow and tooling procedure is Robofab pavilion by Santiago R. Perez. Pavilion’s shape was intended to be a continuous spiral patterning of sticks, however, robotic fabrication caused rotational shear effects and therefore subverted original geometric logic. Perez argues: “The subtle shift from the ideal diagram to a space of projection, on the one hand, and the tactile space of material process and manual skill, on the other, introduces unforeseen properties and affects, that may otherwise lay dormant and unrealized within the latent spaces of digital simulation” (Perez 2017). Act of imperfect translation enriches the object. He sees the source of imperfection to be linked with the necessary “re-skilling” of a designer, so they can be fluent in creating and managing a feedback loop from data to matter and from matter to data.

Throughout the experiments we designed and manipulated only the G-code in order to construct a system of relationships, not a form. In previous work, speed of deposition was a single variable, keeping system simple allowed to understand and predict effects; in this stage, a second material is added to study material agency. Organizing forces of materiality and surface heterogeneity as trace of formation feature as a secondary to form-finding theme in a succession of work, dedicated to technique of flexible formwork. Flexible formwork for concrete panels is legacy of Miguel Fisac, who felt that the true nature of concrete as a fluid, pliable material was subverted by use of wooden formwork. Inspired by it, MATSYS’s series of P projects, P Wall and P Folds are a link between multi-scalar formation, materiality and physical forces. P-Wall is irregular on surface scale, there are bulges, creases, wrinkling, only the larger pattern is predetermined. Imperfection is allowed within the limits of surface range of effectiveness (Kudless 2012). Partially drawing from these precedents, VarVac wall by HouMinn Practice uses flexible wire formwork to shape polystyrene sheets achieving variation throughout the surface which could not be accurately predicted. Variables, whose interaction causes it are very simple (Satterfield and Schwackhammer 2017).

Presented precedents explore various facets of digital craft: material agency causing unpredictable variation, imperfection produced by the machine as an extension of a making hand, significance of designing the process from digital geometry to fabrication setup to material behavior as one continuous feedback loop. The research strives to draw from these examples and explore their themes in its own specific context.

**METHOD**

Methodology of research is experimental; series of experiments were carried out aiming to produce controlled yet undetermined surface texturization in plastic and ceramic by manipulating the G-code of a generic FFM printer and a self-made universal paste extruder. Experimental framework consists of three main agents: geometry, fabrication setup and material. Each of the agents in the system has a set of parameters, variables and constants that inform behavior of each agent and their relationships.

Geometry is a constant, it is a simple cylinder in all experiments. G-code has a set of variables: retraction (on/off and edited pressure parameter), toolpath geometry and direction, speed of deposition. Main generative variable is speed of deposition, printer is instructed to move faster or slower at certain points
Figure 1
12 ribs with 60° rotation, extrusion
5mm Vrib: 400mm/min, Vcyl: 800 mm/min

Figure 2
18 ribs with 60° rotation, extrusion
5mm Vrib: 400mm/min, Vcyl: 800 mm/min

Figure 3
18 ribs with 120° rotation, extrusion
5mm Vrib: 400mm/min, Vcyl: 800 mm/min

Figure 4
18 ribs with 180° rotation, extrusion
5mm Vrib: 400mm/min, Vcyl: 800 mm/min
along the printing path, thus accumulating or shedding mass and achieving surface texturization. In many of experiments retraction is disabled or manipulated, so that stringing and looping, normally erroneous effects, could happen. It was observed that these effects are systematic and therefore controllable. Research uses these undesirable formations to generate variation at the local surface scale. Focusing design intervention in the space of G-code allows to construct the process of fabrication through continuous iteration as well as ensure at least partial repeatability of the experiments. Fabrication has to be monitored carefully in order to respond promptly if texturization is undermining the structural integrity of an object or if it exceeds the local scale. Certain parameters can be adjusted during the process by a designer who sees potential problems of a print before they are realized.

Accumulating mass through ribbing (ribs, extruded ribs, intersecting extruded ribs), shedding mass through ribbing, shedding and accumulating mass through tessellation were three main techniques used on both plastic and ceramic, which resulted in formation of mainly webbing and stringing effects on plastic models and weaving and knotting effects on ceramic models. After each model had been printed, it was examined and evaluated to determine whether it satisfied following criteria of controlled variation (replicability of type and variation of instance).

1. Can the overall textural pattern be reproduced?
2. Is there variation within the pattern from instance to instance?
3. Does variation fall within the effective range of texture?

Then, correlating models in both materials were compared and studied to understand the difference and its possible causes. In a system with two materials and two types of printers, complexity increases exponentially, such fabrication parameters as retraction and layer height become essential in addition to initial 1-material system’s defining parameters of speed of deposition and tool path. Material properties of ductility, solidification rate, viscosity and weight differ for plastic and ceramic. Distinct property makeup of each material instigates qualitative difference of behavior under the influence of deliberately designed apparatus of formation and independent structuring forces.

EXPERIMENTS
The basis of method consists of programming speed of deposition in G-code in a range of patterns. In G-code lower and upper cylinder bases are subdivided into segments, end points of corresponding segments are connected and then the top base is rotated around z-axis (Mohite, Kochneva and Kotnik 2017). That produces ribbed pattern if speed is set to be slower at end points of segments (Figure 1). When speed is higher at those points than at the rest of cylinder, tessellation pattern is observable (Figure 5). If printer is set to move outwards at the end points and then return, while retraction is off for plastic printer and in self-made ceramic extruder retraction parameter is not available as modifiable setting and therefore it is always off, extruded ribs with webbing or looping in-between appear (Figure 2, 3, 4). Finally, if the speed of surface printing is much higher than that of ribs, so there is an abrupt change, in plastic a prorous arrangement emerges whereas in ceramic it produces a simulation of retraction, resulting in a complex knitting motif (Figure 6, 7).

We attribute the difference in surface articulations, produced by two materials, to layer height, which is much larger in ceramic, so all ceramic textures attain weaving and knitting appearance and higher viscosity of plastic, which is responsible for webbing and stringing, effective traces of the machine path. Slower solidification rate of ceramic also contributes to weaving effects; together with greater weight of ceramic it also causes an overall pattern of densification of the deformation towards the base of all models. In ceramic models, where mass is shed through ribbing (Figure 6, 7), radical change of speed...
Figure 5
6 indent with 30 rotation, Vindent: 1600 mm/min, Vcyl: 800 mm/min
Layer height 0.2 mm
Start retraction = 0.6
End retraction = -0.6
Offset = 0.6 mm

Figure 6
12 ribs with 60° rotation Vrib: 400 mm/min, Vcyl: 1600 mm/min

Figure 7
18 ribs with 120° rotation Vrib: 400 mm/min, Vcyl: 1600 mm/min
Radical change of speed creates retraction, a gap into which next layer falls

Figure 8
12 ribs with 90° rotation extrusion 10 mm
Vrib: 400 mm/min, Vcyl: 800 mm/min
12 ribs with -60° rotation, extrusion 5 mm,
Vrib: 400 mm/min, Vcyl: 800 mm/min
Tool path adjustment.
causes the same gap as in plastic version, however, slow solidification rate and weight under compression cause each consecutive layer to fall down and fill the gap, so in areas that correspond to openings in plastic, in ceramic a continuous threading occurs. Tessellation models differ, because tensile stress is created due to significant change of speed; under tension, high ductility of plastic filament causes hair-like formation, lower ductility of ceramic creates a pattern of breaks (Figure 5).

During experimentation it became evident that certain formations are possible with one material and not the other. For example, extreme looping effect in ceramic, where printer offsets 10 mm, can not be recreated in plastic because of plastic’s ductility and light weight (Figure 8). On the other hand, plastic is capable of producing crisscross pattern of intersecting ribs, while in ceramic, mainly due to layer height the same setup results in structural collapse (Figure 8).

The aim of the research is to understand and methodize affordances and constraints of a dynamic, open system defined by internal qualities and external forces. Through persistent experimentation with patterns of semi-controlled material distribution, we hope to enrich the technique of 3D printing with the instrumentality to craft surface ornamentation as trace of making informed by a specific material.

RESULTS
Presented experiments contribute to the work on treating material agency as an integral part of digital fabrication. Research is accumulating data on the interdependencies between specific material parameters, their manipulation and resulting textural deformations. Translated to the scale of architecture, described techniques could be used in production of mass-customized panels in a range of materials. They could serve as a support system for green wall structures. Modifiable directionality, density and depth of effect could be used to facilitate drainage, assist in ventilation and insulation. This method could also integrate into currently developing process of 3D printing concrete walls. Making surfaces characterized by controlled overall distribution of textural formation and local, undetermined diversity ensures cheap and easy to make variation, so that no two surfaces are identical.

At this stage, research is concerned with surface scale and variation emerging at that level without critically affecting structure or form. Focusing on one level of resolution as a space of discovery allows to limit the number of active variables and therefore control the process more effectively. A reinforcement of this seemingly reductive strategy is a firm stance of David Pye, a fervent proponent of the value of exercising disciplined command over unpredictable aspects of craft, on that creation and manipulation of texture is “chief reason for continuing the workmanship of risk as a productive undertaking” (Pye 1968). He saw texture as a manifestation of diversity, a system of progressive reveal of the object to observer on approach. Making texture has not been an important objective for architecture, often an afterthought, it used to lie on the margins of design process. However, it can be argued that short-range formal expressions are located in the space of convergence of material and digital logics, which makes texture into a suitable problem for digital craft. Nevertheless, it is not the strategy of this research to indefinitely engage with texture in isolation. Difference in overall distribution and arrangement of patterns begins to reveal ways in which texture acts structurally, indicating a path to broach the form/structure/material aggregate as a continuous whole.

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