Transforming unpredictable material effects into aesthetic expressions via sensor-informed fabrication grammars

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Abstract— **A growing practice of robotic architecture considers materiality as an active generator of design ideas. They argue that certain material behaviors, including eventual imprecisions or flaws, can lead to unique material expressions that cannot be digitally modeled a priori. However, most of their technological advancements still require an iterative process of manual experimentation that is then replicated via a custom robotic implementations, limiting the design opportunities to material-specific application domains that simulate rather than capture material agency via feedback loops. We thus present a grammar framework that formalizes the relations between discrete fabrication operations and their material outcomes in a more generalizable and controllable manner. Inspired by the rule-based concept of making grammars, we deconstruct the orchestration of fabrication operations on three levels: a) a basic vocabulary of operational transformations; b) the sensed material conditions under which these transformations should take place; and c) the composition of these transformation and sensing rules to generatively create a semi-controlled physical outcome. We demonstrate how this grammatical approach allows the fabrication of unmodellable material expressions in the context of subtractive corrugated cardboard cutting and formative clay molding, and discuss its still largely untapped potential towards sharing or combining semantically meaningful fabrication operations instead of their geometrical outcomes, which also opens the opportunity to produce fully unique material-sensitive customized products.**

I. INTRODUCTION

Common digital fabrication practice considers materiality as a passive receptor of a predefined geometry that has to be digitally modelled beforehand. In contrast, a growing research practice in robotic architecture, now considers materiality as an active generator of design ideas [1]. Among many conceptual and technological advancements, their experiments demonstrate that many material processes that seem inefficient to digitally model can still be purposefully used for fabrication purposes, such as to create organically-looking acoustic panels from expandable foaming of polyurethane [2], uniquely expressive concrete formwork from the gradual aggregation of sand [3]; or unconventional column structures from the successive dripping of wet concrete [4]. Other researchers even argued that the unpredictability of material behavior during the fabrication process can form a powerful resource of novel design ideas. Their experiments similarly demonstrated how particular 'undesired' fabrication flaws can be purposefully controlled by explicitly merging their unpredictable material outcomes back in the original digital model [5] or by experimenting and then taking considerate decisions when deciding upon the sequence of the fabrication process [6]. Research on imprecision-based fabrication has already produced compelling ripples and bulges in concrete wall panels [7], as well as webbing and stringing effects on plastic models and the weaving and knotting effects on ceramic models [8][9], among many others. In contrast, current research is also directed towards overcoming the unpredictability of particular material behaviors via advanced cyberphysical approaches that autonomously adapt the robot trajectory during fabrication based on closed sensor feedback loops, such as by scanning the resulting surface shape while spraying cementitious plaster [10], or by identifying veins or cracks when carving stonework [11].

We yet observe that most of the conceptual material design advancements initially require a process of manual experimentation to discover the agency of the chosen material, which limits the fabrication operations and tools to what can be manually executed instead of what can be robotically created. In addition, most technological advancements seem to be based on custom software and hardware implementations that only target narrowly defined application domains, making the chosen fabrication solutions challenging to share or apply to alternative materials, machine setups or material outcomes.

Therefore, this paper presents how we augmented our previous research endeavours on controlling unpredictable material expressions that cannot be digitally pre-modelled, [12] via 'fabrication grammars' [13] with the ability to take into account materiality as an active factor during the form-finding process. On a technical level, this means our grammar implementation is now capable to take into account real-time sensor feedback that captures how the material behaves during the execution of the fabrication process.

Our fabrication grammar approach is inspired by the concept of 'making grammars' [14], a rule-based generative theory that formalises the embodied performance of 'making' by explicitly relating discrete physical operations with their corresponding material outcomes [15]. We applied and then extended the original making grammar concept into a generative, rule-based fabrication framework that encodes three relations between a sequence of fabrication operations: a) the transformations that determine the physical execution of a specific operation; b) the feedback conditions that correspond to a material state that is derived by the operations; and c) the purposeful composition of transformations and con-

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ditions that determines the sequence, duration and location of operations to reach a certain end state. Despite lacking a geometrical model, we demonstrate that the purposeful combination of these three rules allows the creative design of a wide range of inefficiently modellable material expressions in two contexts: subtractive robotic corrugated cardboard cutting and formative clay molding. Finally, we will discuss the qualities and shortcomings of this approach.

II. Fabrication grammars

A fabrication grammar consists of three distinct rules, each of which can have multiple instantiations. A 'transformation rule' determines one or more sequential fabrication operations that together result in a physical change to make material state X become X'. Multiple transformation rules can thus define different 'families' of material states X', X", etc. A 'sensing rule' results in the sensing of material state X until it becomes X'. Multiple sensing rules can thus identify the successive intermediate states X', X", etc. that a material must undergo to end up in a specific outcome Y. It is the 'composition rule' that defines how specific transformation and sensing rules should invoke each other in a purposeful way to result into Y. Due to the generative character of these rule sets and the relative unpredictability of the sensing rule, multiple composition rules can lead to different variants Y', Y", etc. within the same family Y.

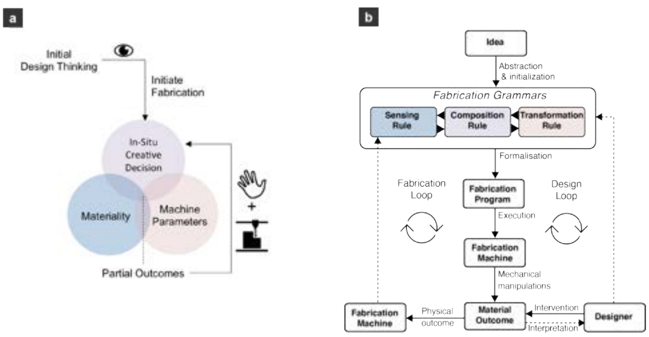

Fig. 1. The fabrication grammar concept: a) adopts the 'Human-FabMachine' [16] workflow that describes how the creative thinking process is based on interpreting the partial outcomes of human action and machine computation; which are b) formalized as two feedback loops: the sensor feedback (left) that measures the material states and calls different fabrication grammar rules, and the designer feedback (right) that interprets the fabrication outcomes and then fine-tunes these rules instantiations.

III. Experimentation

The fabrication grammar framework controlled the basic physical movements (i.e. start and end position, rotation and speed) of a collaborative UR5 robot arm that was equipped with a blunt knife as its end effector. The sensing rule was informed by a Robotiq FT 300-S Force Torque sensor, installed on top of the end effector. The fabrication grammar framework was implemented in Grasshopper [17], a visual programming system within Rhinoceros [18], a popular computer-aided design (CAD) application software. The Robots [19] plug-in enabled the communication of the generated toolpath by the rule algorithm. All the rule instantiations and the real-time communication between the force torque sensor, the rules and the robot, were custom developed as Python scripts that ran within Grasshopper. The fabrication design process relied on two parallel feedback loops. The designer feedback loop (right side of Figure 1b) consisted of a designer who subjectively interpreted the physical outcomes of a grammar, and then fine-tuned its definition accordingly. The robot feedback loop (left side) consisted of a relatively basic process of monitoring the continuous torque sensor stream for different threshold values, which then triggered the appropriate sensing rule.

A. *Use Case 1: Corrugated cardboard cutting*

The initial transformation rule consisted of a straight cut in the cardboard, whereas the sensing rule made sure that the cut ended at a predefined distance and torque measurement. As this purposeful combination was able to freely vary the height of the extruded carton board, the composition rule could be more creatively applied, such as to execute a sequence of modulating cuts. The encompassing 'extrusion' grammar was thus able to 'control' what seemed to be an unpredictable material effect into a gradually modulating landscape of extruded carton material, as shown in Figure 2 (top). Moreover, the same grammar could also be extended by a different composition rule, in order to align the transformation rule circularly to a prior 'extrusion'. The resulting material expression resembled a convoluted 'polka-dot' of frizzled-out cardboard material (Figure 2, bottom).

Fig. 2. Use case 1: Corrugated cardboard cutting. A series of cardboard panels were cutted (top image) by re-composing the transformation rules of the curvilinear extrusion (upper rows of the cardboard) with the polka-dot (lower rows) expression. As a result, the expression gradually morphed from one family to another by way of new, unpredictable patterns.

Being grammatically defined, each ruleset could also be subjected to a higher-level grammatical description. Figure 2 shows how the ‘extrusion’ grammar was gradually ‘morphed’ into the ‘polka-dot’ grammar by successively replacing each rule from one grammar with the other, opening up a new collection of unpredictable material expressions that conveyed physical features from both families.

B. Use Case 2: Robotic clay molding

The initial transformation rule consisted of a straight cut by the same blunt cutting knife in a moist clay surface that was accompanied by a simultaneous rotation around its axis. The sensing rule determined the relatively ’weight’ of the expression that was generated by this combined operation by measuring the torque force that was extorted by the accumulated material. Due to the generative nature of the sensing rule, material accumulations of earlier expressions inadvertedly influenced the generation of following expressions. Because the sensing rule picked up the agency of the material, even this simple grammar lead to several unpredictable material effects, such as an effect that resembled a ’bulge’ (see Figure 3b) and a swirl (see Figure 3c). Although both effects appeared ’imprecise’ at first sight, they also open up a novel design space. By capturing the underlying rule executions together with their sensor feedback, the relevant parts of the underlying grammar could be identified. By then understanding the relations between the three rules, the ’imprecise’ material effects were fine-tuned into stable and ’precise’ aesthetic expressions in their own right (Figure 3).

Fig. 3. Use case 2: Robotic clay molding. A clay tablet that was generatively formed by a basic cutting grammar, was inspected for promising ’imprecise’ material effects. After the designer identified a ’bulge’ (b) and a ’swirl’ (c), these effects were isolated and fine-tuned into ’precise’ expressions. By applying grammatical instantiations that determine their size and height, the bulges resulted into decorative cladding tiles, while the swirls lead to sculptural earrings.

IV. Discussion and conclusion

By focusing the creative design on fabrication operations, the resulting physical outcomes are driven by what the robot is able to produce instead of what can be digitally modelled. This yet means these outcomes might look imprecise at first. For instance, each of the presented expressions looked rough and unfinished, as they resulted from physical interactions *inbetween* discrete material effects instead of being directly affected by the end effector itself. As these initial expressions thus depend on the serendipity of successive material effects, we believe that our fabrication grammar design process resembles that of artisan making, i.e. allowing the agency of a material to manifest itself in an undetermined and even unanticipated way that emerges, instead of being imposed by the fabrication process.

By encoding a material behavior instead of a geometrical outcome, a grammar definition can be semantically labelled in a meaningful way, such as to ’extrude’ or ’swirl’ a material. Because a grammar is solely defined by the relations between operations, it thus has the potential to be reproducible among different fabrication machines and materials. We thus believe that similar grammars can be applied among different fabrication machines with comparable end effectors and materials to achieve quasi-identical results, allowing operational knowledge to be efficiently shared among practioners.

As a type of language, multiple semantically-labeled grammars can also be combined with each other to reach higher-level goals. We thus applied the ‘heightened’ or ‘circularly align’ composition rule on the ‘extrusion’ grammar to create alternative expressions of the same family. While some might lead to undesired effects, successful combinations can be semantically loaded into independent grammars. This combinatory approach thus invites for a much more systematic exploration of material agency, which even can potentially lead to an interpretable dataset for alternative form-finding methodologies like machine learning. It also suggest potential research in combinatory grammars, i.e. rulesets that describe which and how lower-level rules can be combined.

We realize that our current fabrication grammar implementation is relatively basic, being based on a single feedback loop that captures discrete material states by threshold values instead of capturing more intricate transformations. At the same time, we find that the physical outcomes are sufficiently rich and promising to propose the grammatical approach towards more complex materially-informed [20] fabrication and construction applications. We also note that our grammar definition is open for different extensions, such as to ensure that grammatical combinations will lead to predictable results for different material contexts. Therefore, other types of crucial information that underlie a fabrication process could also be encoded, including the fabrication context (e.g. material properties, environmental conditions, machine specifications) or additional sensor streams that capture the behavior of the material or the robotic operator.

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