Figure 1: Designing 'with' fabrication operations: an example of reproducing variations of an emergent material effect on corrugated cardboard via cutting operations.

Material Sketching: Towards the Digital Fabrication of Emergent Material Effects

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ABSTRACT

Designing for digital or robotic fabrication typically involves a virtual model in order to determine and coordinate the required operations of its construction. As a result, its creative design space becomes constrained to material expressions that can be predicted through digital modeling. This paper describes our preliminary thinking and first empirical results when this digital modeling phase is skipped, and the designing occurs interactively 'with' the fabrication operations themselves. By analyzing the material responses of corrugated cardboard to simple linear cutting operations that are executed by a robotic arm, we demonstrate how emergent material effects can be discovered improvisationally. Such material effects cannot be virtually modeled, however, they can be recreated

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Figure 2: A few examples of our exploratory experiments on the digital fabrication of emergent material effects on different building materials. Top: bricks that were purposefully broken along curved surfaces, revealing more natural stone surface textures. Bottom: robotically folded and squished fibre cement panels after drying, revealing handmade-like topographies.

and controlled by the robotic manipulations. We believe this form of 'material sketching' broadens the advances in 'human-fabrication interaction' towards novel and unforeseeable expressions of physical form that require a much more direct, yet still digital, relationship with materiality.

KEYWORDS

human-fabrication interaction; digital fabrication; robotic fabrication; material design; craftsmanship

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1. INTRODUCTION

Digital and robotic fabrication are promoting innovative opportunities for material-driven exploration in design. Recent advancements in making robotic fabrication technology accessible have empowered designers to make creative decisions related to the choice of materials, their transformation into buildable elements, and their assembly into physical artifacts [3]. The rich variety of the resulting design space is perhaps most significant in the field of *Architectural Robotics*, which exploits the unique operative characteristics of industrial robotic machinery to create novel forms of architectural expression on a wide range of materials. Early experiments in this realm commenced with algorithmically varying, aggregating and combining operations like stacking or cutting traditional materials such as bricks, timber, marble or concrete; and evolved to more elaborate operations like deforming, folding or weaving discrete, granular or malleable materials such as carbon-fibre wires, sand, or clay [2]. The rich variety of examples brought forward by this field highlights how the conceptual role of materials can be re-thought once they are manipulated and assembled through computational means. In other words, materiality is no longer considered as a fixed and passive receptor of premodeled form, but has become an active generator of creative design thinking [2].

The close integration of digital fabrication in design evokes a form of *digital craft*, which aims to bring typical crafting sensibilities back to the design practice, such as the direct manipulation of materials and the tactile relation between design conception and the action of *making* [6]. The recently proposed concept of "Human-FabMachine Interaction" [1] describes how particular crafting qualities could become reinstated by allowing designers to tangibly interact with physical artifacts during all phases of the fabrication workflow, such as by grounding incremental design decisions on intermediate physical outcomes. D-Coil [5] aimed to make an expressive digital model by allowing designers to reflect while manually manipulating an extruding tool that fabricates a physical wax prototype. ReForm [7] demonstrated the concept of *Bidirectional Fabrication*, by allowing designers to asynchronously

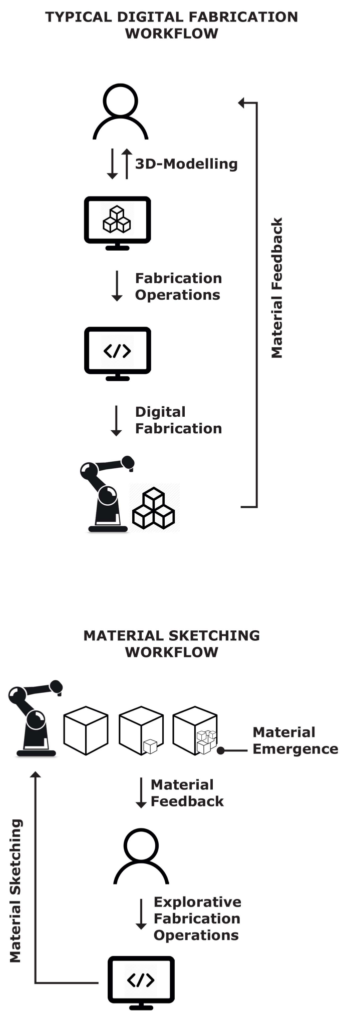

Figure 3: Comparing the typical digital fabrication workflow to the material sketching workflow: the direct manipulation of materials via digital fabrication enables designers to discover emergent material effects that the fabrication infrastructure is able to produce.

switch their attention between the digital 3D model and the automatically corresponding physical object. RoMa [4] explored how designers can integrate real-world constraints during the fabrication process by allowing a partially finished artifact to function as a physical canvas on which can be further prototyped.

Despite these groundbreaking examples, there still exists a misfit in capturing the performative value of craftsmanship in computational design. For example, physical matter is not always responding as expected to the fabrication operations and unpredictable material effects can emerge during the process. Such emergent effects can introduce a particular mode of *material exploration* or *digital materiality* when they are assigned a form of *material agency* and become the trigger of creative design decisions (Figure 2). Yet as emergent material effects depend on a wide variety of causal factors, they tend to be relatively uncontrollable, unmodelable and thus are, at least theoretically, essentially 'undesignable'. Accordingly, the typical digital fabrication workflow (Figure 3) misses out on achieving intrinsic material expressions that the available fabrication infrastructure is actually physically able to produce. Therefore, our research investigates how to design with, and for, such emergent material effects to occur by deepening the idea of *material design*, which highlights the design potential of exploiting and leveraging material qualities [3]. We thus believe our research will provide valuable insights towards the digital augmentation of more natural and improvisational forms of material-driven digital design.

2. MATERIAL SKETCHING WORKFLOW MODEL

We propose a preliminary *material sketching* workflow model that enables a designer to manipulate materials directly via digital fabrication operations, without the use of a digital model that predicts the physical outcome. Accordingly, the design thinking occurs mainly in physical reality, while the designer explores how materials behave in relation to particular fabrication operations. When the designer discovers an emergent material effect with future design potential, she further explores its causal factors in order to reproduce, control or vary the effect. By controlling, yet not necessarily fully understanding, the material effects, they can be predicted, modeled and become incorporated in future design intents. As shown in Figure 3, the designer is in constant dialogue with the material and the fabrication operations. In the current state of our research, the designer is still required to iteratively program the fabrication operations, yet in the future the workflow might solely occur in physical reality.

3. EXPLORATORY STUDY OF MATERIAL EMERGENCE

A small industrial robotic arm (i.e. UR5) was programmed to execute a relatively simple linear cutting operation with a relatively blunt cutting tool into a thin slab of commonly available corrugated cardboard (H:7mm x L:600mm x W:200mm) (Figure 4). First, we started with freely changing and

Figure 4: An emergent material effect was discovered: the cardboard material ripped and accumulated in parallel to the cutting operation. The extruded material is eventually pulled out of the cardboard surface by the lift of the end-effector.

combining operational parameters like the fabrication operation speed, the cutting depth (how far the end-effector goes inside the material) and the length of the cutting trajectory, meanwhile capturing and comparing the effects of the different cutting operations. We discovered various emergent material effects (see Figure 5) and became particularly interested in a type of material extrusion that resulted from how the cardboard material ripped and then gradually accumulated through out the cutting trajectory (Figure 4). We claim this particular material effect could not have been pre-modeled digitally, and thus requires a process of material sketching through the actual fabrication procedures (Figure 3). We were able to make following observations:.

Fabrication end-effector. The use of a relatively blunt object as the end-effector allowed more material to become torn and ripped off. In contrast, cuts by a sharp knife led to more predictable results, as the resulting rips were clean and gradually extended without disturbance.

Fabrication operation. The cutting depth had a significant effect, as more material became ripped off, accumulated and eventually pulled out of the cardboard surface by the lift-up movement of the end-effector. However, this effect did not always materialize in the same manner. For instance, we discovered that too short cutting operations resulted into insufficient material accumulations, while too long cuts (i.e. longer than 5 cm) made the emergent effect more unpredictable as the large amount of accumulated material happened to obstruct the gradual accumulation in more discrete, sudden and abrupt ways.

Fabrication material. As corrugated cardboard is not a homogeneous material, we discovered that the underlying corrugation pattern of the cardboard affected the material effects. For instance, when a single linear cutting operation happened on a mountain of the corrugation pattern, the inside material became peeled off and accumulated. On the other hand, when the cutting operation happened on a corrugation pattern valley, only the upper material ripped off.

Fabrication tool. While the robotic arm is able to physically execute an identical operation in a precise and indistinguishable way, we discovered that the relative position of the operation to the robot itself played a crucial role. For instance, we observed that the material effects were more exaggerated on the edges of the cardboard. Several factors could play a causal role, such as a slightly differing surface tension in the material, minuscule height differences in the supporting table surface, or small static unbalances in the robot limbs when the robot undergoes the physical stress of the squished end-effector in a more stretched-out posture.

4. DISCUSSION

Material sketching. The close feedback loop between the designer and the material via fabrication operations can be considered as a type of sketching, as it is similar to how designers produce visual, physical or digital models to iteratively explore and develop their design ideas. Here, the physical remnants form the tangible remnants of the sketching process. Yet, physical sketches are hard to

Figure 5: Material sketching for exploring material behaviour to particular robotic actions.

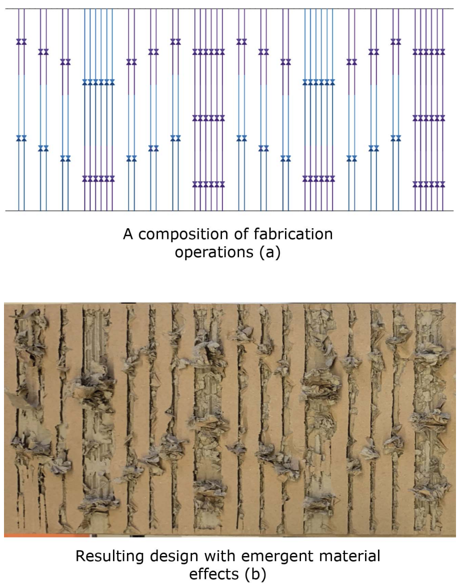

Figure 6: Different linear cutting operations are represented in different colors (a) were operated on the cardboard to incorporate emergent material effects into design (b).

adapt or correct iteratively. In our current setup, material sketching thus tends to commence from a new slate, which also allows the designer to control for all potential influences and experiment with a single potential causal effect (Figure 5). Material sketching resembles a scientific process in methodological terms, combining experimentation and the need to fully document the process for potential future reproduction and alteration.

Reproducibility. Although we show that our emergent material effect is dependent on a small range of factors, many other influences might exist that we have not identified. A whole range of emergent material effects occurred during the first exploratory phase, however, we deliberately chose not to investigate further many of them, often because their causal factors were deemed too complex or too sophisticated. Moreover, we cannot fully assure that an identical digital fabrication infrastructure will be able to create identical material effects. Different factors might influence the results, ranging from obvious environmental aspects like ambient air humidity that would make the cardboard softer, to technical factors like the forward kinematics algorithms that determine how the robot joint movements are coordinated. These issues bring forward the need to be able to accurately and completely capture the fabrication process beyond textually or visually describing the exact sequence of operations. Instead, we propose that material sketching should probably be captured by an open-ended model that encapsulates the whole fabrication infrastructure and its parameters, the material properties as well as other situational factors.

Modeling the unmodelable. By trying to understand the causes of material effect, our workflow broadened into the parameterization of the fabrication process. Consequently, the unmodelable or undesignable material effect actually became modelable and therefore designable (Figure 6). Ideally, this parameterization should not be based on iteratively-discovered and then hardcoded parameters, but incorporate dynamic measurements that determine the actual state of the material in relation to the fabrication. Such data could be captured by a range of sensors that recognize the real-time state of the tool, the end-effector as well as intermediate material effects. In theory, real-time material feedback could significantly overcome many reproducibility concerns. Once such a dynamic fabrication model exists for a single emergent material effect, one could even imagine obvious application domains, such as those that target the use of alternative materials, different scales, or slightly differing end-effectors. Moreover, different material sketching models could potentially be combined or merged towards even higher levels of material expression.

Augmenting material sketching. Material sketching enables the designer to 'measure' the emergent material effect, recognize and then 'sense' its causal influences, consider the repercussions and reprogram the fabrication operations towards particular design intents. However, one can imagine a technological future in which these different steps could become digitally augmented or even partly automated towards more embodied and direct forms of material fabrication sketching. Such exploratory "Human-FabMachine Interaction" [1] could be accomplished via manipulating a virtual tool (e.g. RoMA [4]), the physical artifact itself (e.g. ReForm [7]), or the fabrication tool itself (e.g. D-Coil [5]. We believe more research is required in creating fabrication 'interfaces' that facilitate a level of digital/physical craftsmanship, in terms of allowing various degrees of fabrication intuition, material agency and material feedback.

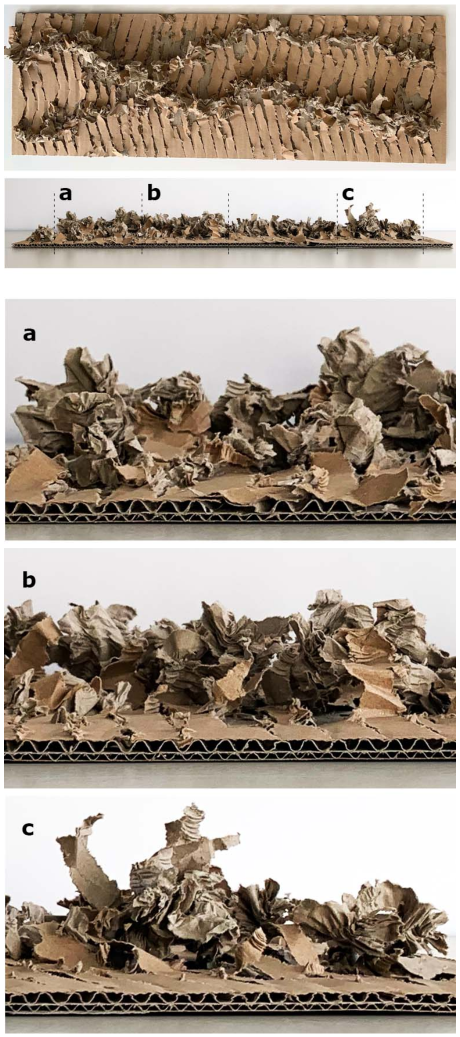

Figure 7: Reproducing and controlling the emergent material effect via iterative fabrication operations towards rich and variant material expressions (a, b, c).

5. CONCLUSION

Based on our preliminary empirical results of an emergent material effect that was created by a relatively simple cutting operation on a corrugated cardboard, this paper proposed a preliminary model of material sketching for digital fabrication. We demonstrate the potential of shifting the modeling phase in the fabrication workflow from the digital realm to the physical reality. Insofar that the material manipulations are accomplished by digital means, their effect on materials can be recognized, captured, recreated and then controlled for real purposes. We recognized several issues that underlie the reproducibility of material emergence, and draw a future in which technological advances are able to augment a more natural interaction between the designer, the material and the fabrication process. Moreover, we argue that interactive fabrication should be more holistically captured and the whole feedback loop should be sensed in real-time, so that intended material effects can be accurately reproduced in other design contexts.

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