A Declarative Human-Robot Interaction Workflow: Integrating Improvisation and Materiality in Robotic Fabrication and Design

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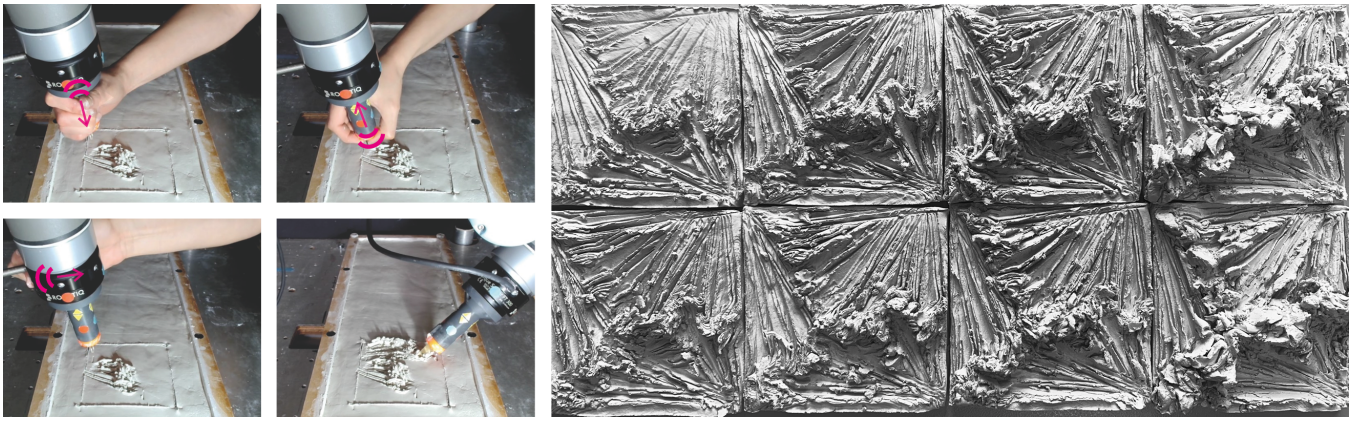

Figure 1: The user's applied forces dynamically influence the robot's actions based on declarative HRI rules (left), while the unexpected and intricate material expressions–such as layered and piled textures–emerge. Since the declarative rules continuously record fabrication data, the emergent expressions are captured, reproduced, and customized for their incorporation in design, like the decorative wall tiles (right).

Abstract

Collaborative robots, with their computational power and versatile manipulation capabilities, hold significant potential in design and fabrication. However, their reliance on predefined CAD models and algorithms limits their effectiveness in creative, dynamic and unstructured contexts. In contrast, humans easily adapt to dynamic conditions during craft, improvise novel making strategies and embrace emergent material properties as part of form-finding. This paper investigates how human-robot interaction (HRI) can augment human adaptability through the computational power of robotics while embracing materials as a medium for creativity. The main contribution of this study is a declarative HRI workflow and its software implementation that relates real-time sensor feedback to robot's action selection. The results showed how this workflow enabled the improvisation, reproduction and modification of material expressions through dynamic tool path planning in robotic sand casting and clay forming. Consequently, this paper expands ongoing discussions on innovative ways to combine robotic technology with craft sensibilities.

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CCS Concepts

• **Human-centered computing** → **HCI theory, concepts and models**; **Haptic devices**; *User centered design*; **Collaborative interaction**; • **Computer systems organization** → **Robotics**.

Keywords

Human-robot interaction, Computational fabrication, Interactive fabrication, Material design, Reflective design, Hybrid craft

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1 INTRODUCTION

Robotic fabrication has introduced new opportunities by allowing designers to investigate materials through versatile mechanical manipulations at various scales [29]. Working with collaborative robots in creative sectors, such as architecture and design, has initially been enabled by parametric control of robots within computer-aided design (CAD) platforms [16, 17]. The parametric control depends on a linear workflow, beginning with the digital modelling of a predefined design form and then programming the

robotic motion trajectories to fabricate this form. This linear workflow aligns with CAD's geometry-based form-finding processes, which are inherent in other common digital fabrication workflows. For example, digital 3D printing relies on the translation of a CAD model into an executable G-code. The G-code or robotic motion trajectories generated based on a CAD model specify explicit, sequential commands that directly instruct the fabrication machine on how to perform tasks, thus following an imperative programming approach. As a result, the role of material is reduced from an active *form-giving parameter* to a mere embodiment of the physical replica of a CAD model [53]. Accordingly, material affordances which can generate intricate and aesthetic forms are excluded from the fabrication design space which becomes limited to "unified and perfect" machine-made forms [8].

Unlike the linear workflow of robotic fabrication, artisans embrace materiality as a creative medium as they spontaneously uncover novel formal transformations by engaging with material affordances and constraints [49]. They iteratively refine the design idea while they observe emergent expressions and forms, that are neither predefined nor anticipated until they materialize in the process [34]. Improvisationally adapting their making actions and guiding material response, artisans learn how to appropriate these emergent expressions and incorporate them into design artefacts. Accordingly, each artisan builds up their unique design language that is hardly found in digitally produced artefacts [104]. Skilfully appropriated emergent expressions and forms in craft are particularly appreciated as the reminiscences of an authentic relationship between the artisan, tools, and materials [74]. Transferring such an iterative and dynamic making process into robotic fabrication does not align with the widely used imperative programming approaches. Instead, a declarative approach should be adopted in robotic fabrication to integrate human adaptability and material behaviours, emphasizing design intent based on constraints and conditions rather than explicit procedural instructions.

This research paper explores the shift in robotic fabrication from a linear to an iterative, craft-inspired design and fabrication workflow by investigating the following research questions:

(1) How can Human-Robot Interaction (HRI) combine human adaptability and the computational powers of robots for an iterative design and fabrication process?
(2) How can improvisation be incorporated into robotic fabrication to transform it into a medium for creativity?
(3) How does the integration of materiality into robotic fabrication influence the design ideation?

Ingold uses the term *morphogenetic design* to describe how design intent evolves through the relationship between the designer and the materials, tools, and machines within craft workflows. Thus, the generation of a design form is not a "lateral" process, as a transposition from an image to an object, but a "longitudinal" process involving a confluence of forces and materials [39]. Tokac et al. demonstrated how a craft-inspired robotic fabrication workflow has enabled human users to iterate their design ideas as they discover and adapt robotic actions to dynamic material changes [87]. Deepening the research on craft-inspired fabrication workflows, this paper introduces a declarative approach to human-robot interaction. This approach depends on formalising the interactive fabrication process by declarative rules that integrate sensor feedback into robotic fabrication to adapt robotic actions. Accordingly, these rules facilitate dynamic path planning through real-time human interaction. Broadening the research on integrating rule formalism to material-in-the-loop fabrication workflows [86], this research paper demonstrates the applicability of rule formalism to establish creative human-in-the-loop fabrication workflows and capture the fabrication data.

A declarative HRI workflow aims to enable a kind of *correspondence* [39] between the hands of users and the material affordances through embodied interaction, which is traditionally associated with craft. Its potential is demonstrated through robotic sand casting and clay forming because both sand and clay are capable of producing a wide range of emergent material expressions due to their malleable characteristics. This paper details how the declarative HRI workflow is implemented as a custom-developed software add-on that works in Grasshopper [35], a visual programming interface which is widely used in design and architecture. The custom-developed add-on enables users to define declarative rules that describe how robotic action sequences should be updated according to the sensor conditions. Two novice users explored the software add-on by defining HRI rules and then interactively engaged in the design and robotic fabrication of tiles, guided by these rules. Each tile design showcases a unique tectonic quality reflecting the inherent properties of the materials used.

This paper contributes a declarative approach to HRI by integrating material affordances into design ideation without the need for synchronisation with a 3D digital model, thus extending HRI to the material-driven design and digital fabrication research [22, 37, 100]. This approach opens up a new design and fabrication space with intricate and complex forms beyond the "unified and perfect" machine-made forms based on CAD models, as seen in Figure 1. The introduced rule formalism integrates the machine's computational power with human creative adaptability to dynamic conditions, enabling fabrication processes that embody a unique combination of craftsmanship and machine precision, referred to as *crafts-machine-ship* [4]. The declarative rules facilitate bridging the gap between how humans and machines interpret and process information, thus proving a foundation for shared-mental models [20]. Furthermore, the rule-based approach facilitates more transparent data collection on contextual and material intricacies, as well as machine constraints. This can offer valuable insights for designers, artists, architects, and HCI researchers interested in developing intelligent, co-creative systems that support human-material interaction and adaptive fabrication processes.

2 RELATED WORKS

This study is grounded in and contributes to, three key research areas: human-robot interaction, interactive fabrication and material-driven design.

2.1 Human-Robot Interaction (HRI) and Human-Autonomy Teamwork (HAT)

Human-Robot Interaction (HRI) is a growing field that investigates interaction interfaces and modalities for facilitating collaboration between humans and autonomous agents. An intuitive and efficient collaboration requires a common ground for the communication

of intent between human and autonomous parties [19], leading to human-autonomy teamwork [52]. It has been advocated that Augmented Reality (AR) interfaces could provide this type of communication within human-autonomy (or human-robot) teams by overlaying computer graphics on the real world view [36, 84]. However, recent studies have shown that embodied interaction modalities, without graphical feedback or overlays, encourage users to engage with autonomous agents in intuitive and heuristic ways [77].

Moreover, the AR interfaces of HRI mostly rely on superimposed CAD models and user input, for example, to guide fabrication operations [62] or to visualise trajectories [55]. Although these modalities successfully provide a common frame of reference and spatial referencing between the real world in which the fabrication takes place and the virtual world in which the robot computes its actions, they are limited to CAD capabilities that do not cover all the events that may occur in unstructured environments [99]. To mitigate such limitations, interactive systems should focus on real-time data collection [46] and interpretation of the changes in their states and the environment [94], to subsequently select the next step [78].

Looping back to the communication of intent, such interactive systems need to establish a flexible common ground among human and non-human agents, so that they communicate through shared mental models [75]. Mental models refer to the knowledge structures that humans use to describe, explain, and predict in engineered environments [40, 41, 76, 90]. The theory of mental models was later extended to describe collaboration and interaction dynamics through the concept of shared mental models [20]. The rule formalism and its implemented HRI workflow may lay the foundation for developing shared mental models between human and robot agents. By establishing a common understanding of actions and intentions, this approach could enable more intuitive and effective collaboration, where robots can anticipate human actions and adapt accordingly. Over time, this shared cognitive structure could significantly enhance the fluidity and efficiency of human-robot interaction in creative and technical tasks.

2.2 Interactive Fabrication

Interactive digital fabrication establishes a human-in-the-loop relationship with the physical fabrication process [97]. Within this scope, custom interfaces have been developed to facilitate human input, enabling even novice designers or makers to utilize digital fabrication technologies [30, 31, 96]. For instance, Free-D [103], a hand-held milling device, allows milling operations to continuously sculpt a block of polyethylene foam under partial guidance based on a 3D-model. D-Coil [64], a computer-guided wax-extrusion tool, allows novice users to design physical forms reflectively, which are then converted into digital models for 3D printing. Subsequently, ReForm [95] enabled designers to work synchronously with both the digital model and its physical outcome, where modifying one would automatically alter the other. Integrated AR setups efficiently capture human intuitive physical inputs, such as drawing in air [5] or on physical objects [92], automatically transforming them into digital models.

Although the AR system allows designers to determine trajectories, the physical fabrication process only commences once the final forms or movements are optimised. Optimised toolpaths from a 3D model can guide users engaging directly with materials through iterative scans, projecting feedback onto the artefact-in-progress to indicate where to add or remove material and to highlight surface features such as ridges and valleys [68]. Exploring the relations between imprecision and creativity, Devendorf et al. proposed a hybrid fabrication approach, *Being the Machine*, wherein humans directly engage with materials to fabricate artefacts by following machine-generated instructions. This shift in agency between human and machine prioritised the potential for unexpected and emergent forms over strict precision and control. [26]

Other research advancements have focused on applying the principles of *direct manipulation*[80] to the modification of physical outcomes. For instance, FormFab[58] enables designers to continuously shape a material outcome by commanding mechanical manipulations of the fabrication setup through hand gestures. Similarly, Adroid [85] demonstrates how direct physical input from the designer can move a robotic arm continuously, facilitating hands-on, open-ended tasks with machine precision. However, these systems do not specifically focus on the design space that is generated by material emergence. This paper contributes to broadening the research in interactive fabrication by integrating material affordances into robotic fabrication and design.

2.3 Material-Driven Design

In the realm of design, material-driven approaches view materials as enablers of design, emphasizing their integral role in creative processes [25, 54, 61]. Karana et al. framed *material-driven design method* that accepts material affordances as part of the product design and user experience [43]. Extending this concept, material-driven digital fabrication [82] further integrates computing systems into material-driven design practices, treating these systems as a creative medium. This leads to not only considering but actively exploring materials as a part of their design ideation. Rather than beginning with a predetermined final form, the material-driven approach to digital fabrication starts by establishing the parameters of a machine, such as delay and speed, or a 3D model. Accordingly, designers explore various material expressions through the alteration of these parameter values [24, 83]. The subsequent imperfections [56] or imprecisions [101] of a fabrication outcome that occurred due to a parameter change can be interpreted as aesthetic qualities that suggest yet unexplored design spaces. What may initially be considered imprecision can actually reveal how materials behave. Understanding these behaviours allows designers to shape form through the material's transformation, such as fabrication-induced bending [6] or shrinkage during the firing process [10].

Furthermore, recent research advancements have shown that the addition of human input to the fabrication process–either before [88] or after generating the toolpath [15]–offers opportunities for in-situ collaboration for material expressiveness. The unique aspects of material agency were explored via versatile movement capacities of fabrication machines, such as by weaving clay [32], throwing cement [27], spraying polyurethane [29], printing raw-earth construction materials [91] or robotic depositing, piling and pressing reinforced concrete [23]. Moreover, computational control of toolpaths optimized for the fabrication material led to enhanced structural strength and an expanded design space for production

methods [33]. Even though this research advances the incorporation of material behaviour into digital fabrication, programming such processes is exclusive to experts who are skilled in computing, tooling, materials, and fabrication through hands-on experience [44]. The declarative approach to HRI presented in this study simplifies the implementation of robotic fabrication, eliminating the need for extensive programming. This approach has the potential to enhance material-driven digital fabrication, making it more intuitive and accessible to novice users.

3 TRADITIONAL PRODUCTION WITH MALLEABLE MATERIALS AND ROBOTIC FABRICATION SETUP

This section, first, gives an overview of traditional sand casting and clay carving. To explore how these traditional methods could be digitised, two separate robotic fabrication setups were used: one with a 7-axis KUKA iiwa and the other with a 6-axis UR5 robotic arms.

3.1 Traditional Production with Malleable Materials

In design, architecture and construction, malleable materials, such as clay and sand, provide a flexible medium that can be shaped and moulded to create unique and bespoke forms, whether ornamental or structural.

3.1.1 Sand casting. Sand casting, also known as sand moulded casting, is a fabrication process characterised by using sand forms as the mould. It traditionally requires a replica of the object to be cast. This replica is first modelled and fabricated, then placed in forming sand containing water and chemical binders. Once the sand is compacted, the replica object is removed, leaving a cavity in the shape of the object to be cast. Subsequently, a substance, typically molten metal, is poured into the cavity. After the substance has solidified, the cast product is taken out of the forming sand.[21] Sand casting is a process that is predominantly employed for the fabrication of metal objects. However, other substances, such as plaster, can also be cast using this method.

While sand casting is a versatile method for producing artefacts in a wide range of shapes, it has inherent limitations when it comes to producing intricate forms [14, 89]. Specifically, creating a replica object with organic and finer shapes prior to casting adds extra complexity to the process. Instead of using a replica object, this study leverages emergent sand expressions that result from the iterative sand compaction as an integral part of formwork design. For example, the complex dispersal of sand particles and the intricate shapes created through sand compaction contribute to novel formwork designs. In this study, sand casting plaster is chosen because it is widely used in architectural and industrial design for many use cases. Casting plaster also allows most of the sand to be reused, except for the small portion that remains stuck to the plaster surface. Moreover, it is a safe material, as it does not emit harmful chemicals or volatile compounds. [51].

3.1.2 Clay forming. Traditional clay forming is an ancient art form and technique in which artists sculpt and shape raw clay into bespoke designs. Although this method is closely associated with pottery, it extends beyond the scope of pottery with its applications in architecture and construction [66]. The design of ceramic elements plays an important role in defining the unique character of a building with detailing and ornamentation [11]. In architecture, these ceramic elements not only provide an aesthetic appeal but also offer functionality like improved ventilation, shading, or structural interlocking [9]. Moreover, clay is considered one of the most sustainable materials in construction due to its low energy in production, local availability and transportation[81].

Despite these advantages, working with clay is labour-intensive, which leads to higher costs for production. It involves using various hand tools to shape clay through several techniques [65], such as incising, pressing, and relief carving [60]. Consequently, it requires specialized skills and accumulated knowledge gained through hands-on experience and observation [42]. However, such specialised knowledge is rarely prevalent, especially in architectural contexts [13]. Therefore, this paper aims to facilitate an interactive fabrication system where the artisans or skilled workers can intuitively perform and record their crafting process. The captured fabrication data can subsequently be leveraged to reproduce and modify intricate artefacts, thereby empowering a limited workforce to manage a higher volume of projects.

3.2 Robotic Fabrication Setup

The rule-based approach is implemented in two separate robotic fabrication setups to test interactive robotic sand casting and clay carving. By utilizing two robotic platforms and different materials, this study aims to demonstrate the versatility and applicability of the approach across various fabrication machines and material types.

3.2.1 Robotic sand casting setup. Figure 2-a shows a sand casting setup with a 7-DOF collaborative robotic arm, KUKA iiwa. The robotic arm was equipped with a custom-made end effector which allows stamping into forming sand. This end effector consisted of a wooden plate with a diagonally cut edge (sized 13.5x5x2 mm) that was bolted into a 3D-printed holder. Due to its diagonally cut edge, it offered a variety of impressions when pressed into forming sand. The forming sand was held in a container (61.5x81.5 cm or 50 x 50 cm), which was fixed to a workstation located in front of the KUKA robot. Inside the container, a smaller working area measuring 39.5 × 23.5 cm was defined by a steel frame, serving as the boundary for creating the sand patterns. The KUKA iiwa robotic arm is equipped with an internal force-torque sensor that measures force and torque values in real-time at a frequency of 50 Hz. This sensor provides continuous force data during the interactive fabrication processes. Furthermore, the tool center point (TCP) positions of the robotic end effector were tracked in real-time by directly receiving data from the robot.

3.2.2 Robotic clay forming setup. A 6-DOF collaborative robotic arm (UR5) and a 7-DOF collaborative robotic arm (KUKA iiwa) were used in the robotic clay forming processes. Both of the robotic arms allowed transitional and rotational carving movements along three axes. Brass sheets with a thickness of 2 mm were cut in sizes L: 80 mm x W: 5 mm and L: 80 mm x W: 15 mm, then were inserted into a 3D-printed holder as seen in Figure 2-b and e. These end effectors were designed as clay manipulators for KUKA iiwa and UR5 robots.

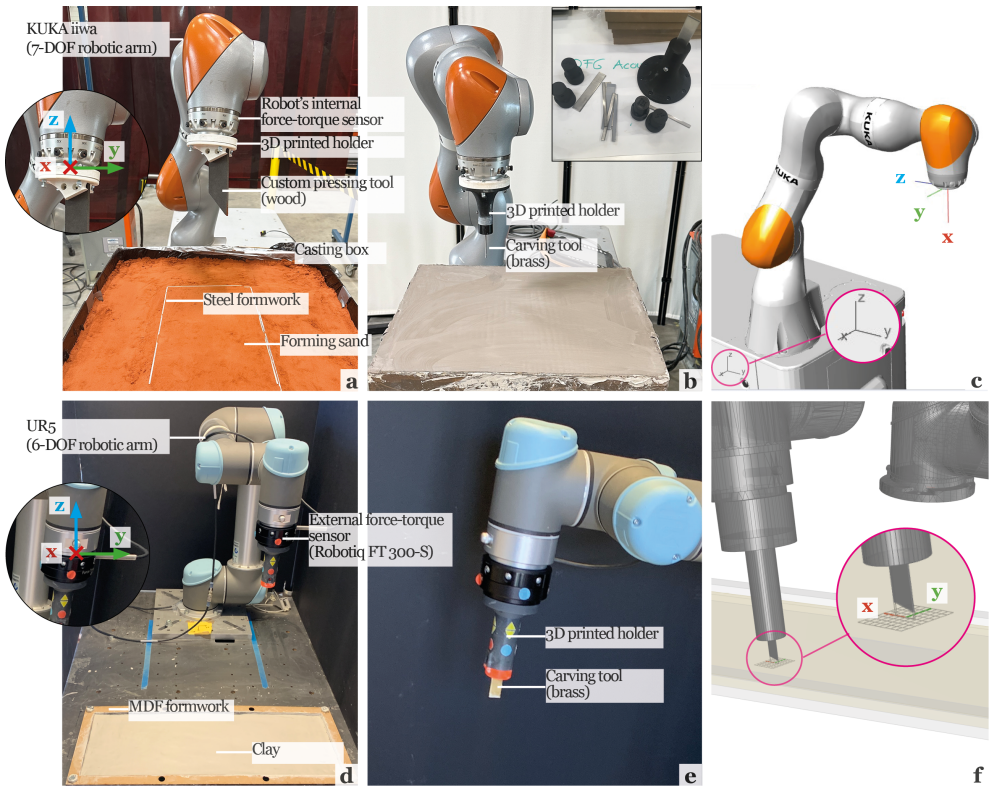

Figure 2: (a) Robotic fabrication setup for sand casting and (b) clay carving with a 7-DOF robotic arm (KUKA iiwa). (d, e) Robotic clay carving setup with a 6-DOF robotic arm (UR5). In the close-up views of (a) and (d), the flange coordinate systems for both robotic arms are visualized. (c, f) The last figures in both rows show the coordinate systems to describe robotic motions within Grasshopper interface, which may differ than the flange coordinate system.

Unlike the KUKA iiwa, the UR5 was equipped with an external force-torque sensor (Robotiq FT 300-S), as seen in Figure 2-d and e. This sensor measured real-time forces (100 Hz) along three axes (X, Y, Z) of UR5. On the other hand, similar to the KUKA iiwa, the tool center point (TCP) positions of the robotic end effector were also tracked in real-time by directly receiving data from the robot.

4 A DECLARATIVE APPROACH TO HUMAN-ROBOT INTERACTION

This section introduces a novel rule-based approach to human-robot interaction, which allows users to describe action sequences, sensor thresholds, and their relationships as declarative rules. It begins with an explanation of the rule formalism based on an algebraic notation structure, details the technical implementation of this rule formalism, and then explains how this implementation facilitates an iterative, craft-inspired robotic fabrication workflow.

4.1 Algebraic Rule Notations

A set of algebraic symbols, shown in Figure 3, acts as operators for describing spatial, temporal and conditional relationships between the action and sensing parameters. The action and sensing parameters are identified based on the robotic fabrication setups. For example, the parameters fx, fy, and fz describe the force applied along the X, Y, and Z axes. The force feedback corresponds to the robot flange's coordinate system, as seen in the close-up views of Figure 2-a and d. Users should keep this information in mind when defining the force thresholds. These thresholds describe the conditions for adapting the robot's actions based on the magnitude (N) and direction. In the beginning, users explore how their physical interventions affect sensor measurements. Based on the results, they set thresholds to steer the robot's actions by physically applying force on the robot's end effector. For instance, a gentle push or pull on the robot's end effector can be identified by approximately a 10 N change along the three axes. Thus, a simple push is encoded like $fx : 10$, $fy : -10$, or $fz : -10$.

Both the KUKA iiwa and UR5 robotic arms perform linear translations along the X, Y, and Z axes, and the parameters tx, ty, and tz represent these movements, respectively. Additionally, both robots can rotate about the X, Y, and Z axes, where the parameters rx, ry, and rz denote the corresponding rotational movements. For example, $tx : 50$ declares a 50 mm long linear movement along the X-axis. Combining this movement with $fy : -10$, which denotes a gentle push forward, in the form of $tx : 50 \leftrightarrow fy : -10$, results in each forward push moving the end effector ahead, e.g., from point A to point B as seen in Figure 4. Similarly, pulling the end effector caused the force sensor to measure approximately 10 N; therefore, the force threshold is represented as $fz : -10$ to detect this pulling action.

Operator symbols		Action parameters		Sensing parameters	
:	Assigns a value to increment	tx	Translation along X-axis	fx	Force exerted along X-axis
( )	Includes transformation method to apply on a rule	ty	Translation along Y-axis		
•	Denotes recursive rule application	tz	Translation along Z-axis	fy	Force exerted along Y-axis
∘	Denotes simultaneous rule application	rx	Rotation about X-axis		
⇒	Denotes a measurable change of sensor state	ry	Rotation about Y-axis	fz	Force exerted along Z-axis
↔	Denotes biconditional relation between rules	rz	Rotation about Z-axis		

Figure 3: The rule-based implementation depends on algebraic symbols for defining specific relationships between action and sensing parameters.

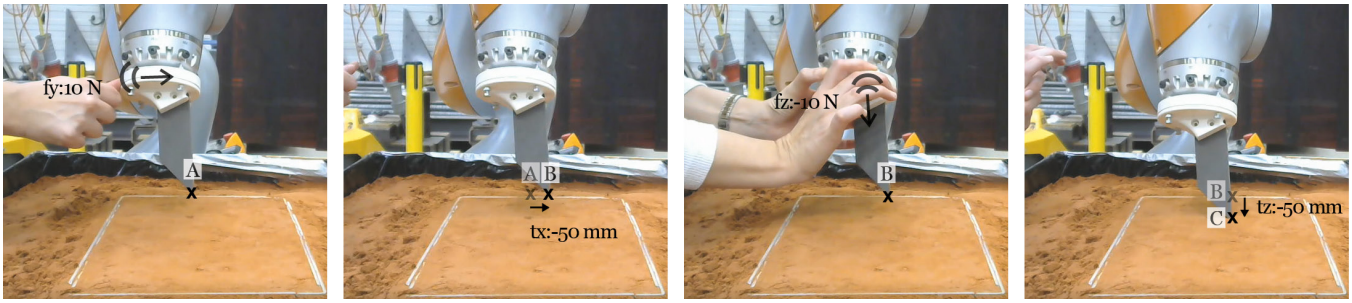

Figure 4: The rules define how a user's physical actions influence fabrication processes, depending on sensor readings and the robot's current position. For example, the composition rule $tx : 50 \leftrightarrow fy : 10$ governs the horizontal robotic action from point A to B, while the rule $tz : -25 \leftrightarrow fz : -10$ computes the vertical motion from B to C.

This force threshold is combined with a linear action along the Z axis, which is represented as $tz : -50 \leftrightarrow fz : -10$. This combination governs linear movement along the negative Z-direction—for example, from point B to point C.

It is important to note that while defining the robot's actions, users should follow the coordinate system of the program interface (i.e., Rhinoceros) and the robot programming libraries (i.e., KUKA|prc for iiwa [7] and Robots for UR5 [69]) as seen in Figure 2-c and f. For example, KUKA|prc uses a flipped coordinate system where the Z axis is replaced with the X axis (Figure 2-c). Therefore, while working with KUKA iiwa, the parameter *rx* denotes the rotation about the Z axis in this study. The rules describing the fabrication action sequences are termed 'action rules', while those that define thresholds or changes in sensor measurements are called 'sensing rules'. The combination of an action and a sensing rule, i.e., 'composition rule', declares how a fabrication action sequence should be updated according to real-time sensor feedback. Consequently, these rules orchestrate a dynamic, responsive robotic fabrication process in which the robot adapts its movements in real-time based on user or material feedback.

4.2 Custom-Developed Software Add-On and Middleware

The technical implementation of the rule-based human-robot interaction includes a custom-developed software add-on which works in Grasshopper[35] and a middleware program that manages a real-time sensor feedback loop. The software add-on consists of custom-developed components that convert the algebraic notations of rules to fabrication programs. As seen in Figure 5 (1), users write a list of action and sensing rules into simple panels, which are standard Grasshopper components used to hold textual data. These panels are then plugged into a custom-developed component *composition encoder*. This component combines action and sensing rules with matching indices and activates one of these combinations (i.e., composition rule) based on sensor feedback, i.e., the sensor state. The activated rule is then encoded into waypoints (i.e., action planes) and the sensor thresholds by the custom-developed components, *action encoder* (Figure 5-2a) and *sensing encoder* (Figure 5-2b), respectively. Figure 6 illustrates the technical implementation of the interactive robotic fabrication workflow enabled by the custom-developed Grasshopper add-on and middleware.

4.3 Iterative and Craft-Inspired Robotic Fabrication Workflow Driven by Rule-Based Interactions

This section demonstrates the capabilities of the declarative HRI workflow via robotic clay carving. First, it shows how a simple technique of incising clay is described by using rule notations. Later, it explains how these rules govern dynamic toolpath generation, resulting in patterns created by continuous incising. Finally, it exemplifies the design space by the (quasi)reproduction and modification of the dynamically generated toolpaths.

4.3.1 Rule notations and their transferability across different robot platforms. By using the algebraic notations, a simple incising rule

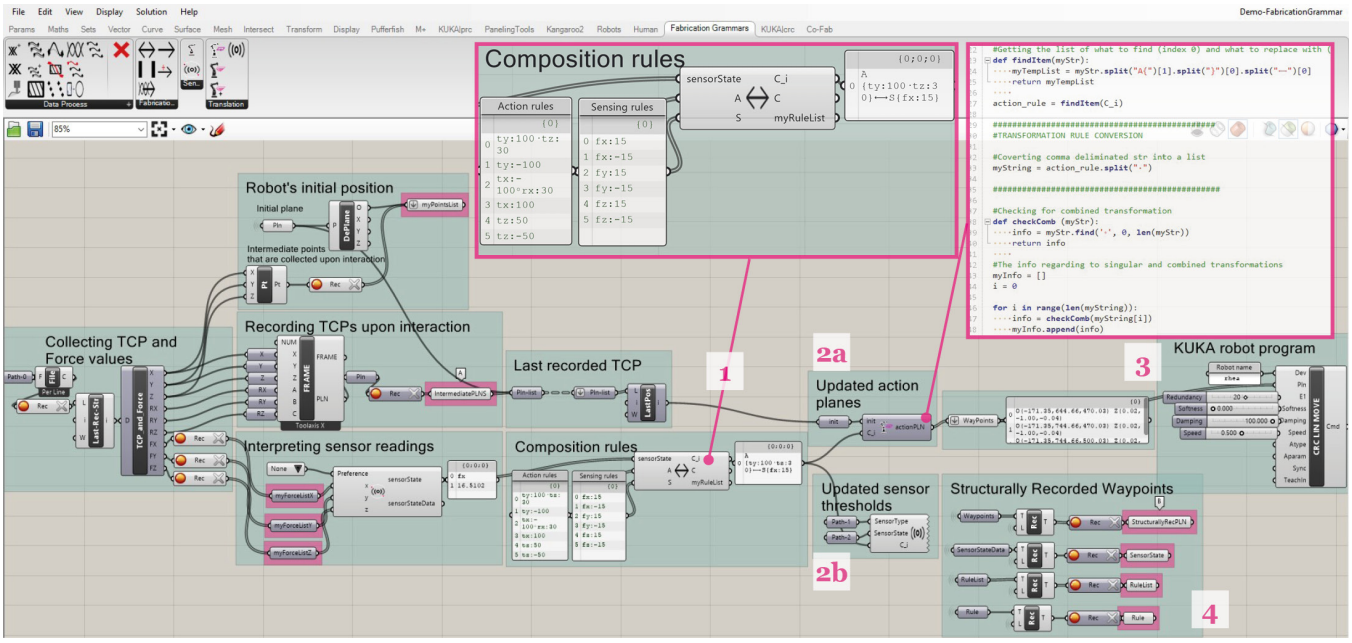

Figure 5: A novel software add-on, Fabrication Grammars, has been developed to (1) enable users to encode rules as algebraic notations. (2a and b) Fabrication Grammars add-on provides custom-developed components which translate these rules into sensor-responsive robotic fabrication programs. (3) Depending on the type of robot, these programs are then converted into the machine's specific language. (4) Accordingly, with each user interaction, the rule-based system records the robot's real-time position, corresponding sensor state, and the updated action planes for the subsequent step.

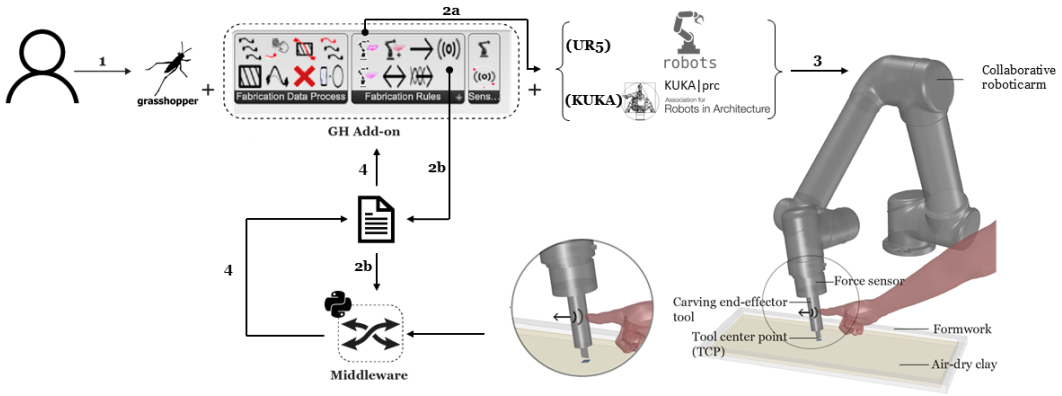

Figure 6: (1) The human user defines the rules to dynamically generate (2a) the robotic action planes based on (2b) the sensor thresholds. (3) The external plug-ins, namely KUKA|prc [7] and Robots [69] convert the action planes into the native robot languages. Based on the rules, (4) a middleware manages real-time sensor data to detect human and material feedback and sends the robot's position at the point of interaction back to the custom add-on.

(i.e., action rule) was defined as $tx : 150 \circ rz : 30 \circ tz : -1$. This rule moves the end effector 150 mm along the X-axis while simultaneously rotating 30 degrees about the Z-axis and penetrating 1 mm more into the clay, thus creating a widening groove on the clay surface as seen in the last column of Figure 7. To allow the continuous incising of clay to be controlled by the user's physical interactions, force thresholds were established as sensing rules. A set of other user interactions, including pulling ($fz : -10$) and pushing up ($fz : 10$), right ($fy : 10$), left ($fy : -10$), forward ($fx : -10$) and backwards ($fx : 10$), was described using the rule notations to orchestrate incising actions.

For example, combining a gentle pull, represented as $fz : -10$ (Section 4.1), with the incising rule, $tz : d \cdot tx : 150 \circ rz : 30 \circ tz : -1 \leftrightarrow fz : -10$ applies incising on the spot after moving down the end effector. This included the translation along the Z-axis (tz), the

distance between the end effector tip and the material surface is represented by the variable d. As these notations describe the robotic process independently of specific CAD and robot platforms, they can be transferred across different design and fabrication platforms. For example, the incising rules were used to control a different collaborative robotic arm, KUKA iiwa. Consequently, the interactive fabrication modality for incising, based on this specific rule set, can be performed with different robot platforms.

4.3.2 Dynamic toolpath generation and process. The rule-based approach enables a structured process of recording the dynamically generated toolpaths. The robot's position is recorded at each point of interaction and stored in a list. For example, upon the user's pulling action, position A was stored in a list in which all interaction positions are collected. Simultaneously, the action rule, $tz : d \cdot tx : 150 \circ rz : 30 \circ tz : -1$, computed a toolpath that started from the interaction position A and continued through B and ended at position C. These consecutive positions describe the simple incising trajectory and are stored in a separate list for rule-induced action positions. The full capacity of this trajectory is demonstrated in Figure 7. However, when the user intervened during an ongoing incising, the robot gently paused before completing the full expression, and began an updated incising action. As seen in Figure 8, while the robot's end effector was moving along this incising trajectory, the user's push ($fy : 10$) at D (which was in between A and B) momentarily paused and updated the robot's actions. The user's push was recognised by the sensing rule $fy : 10$, which simultaneously triggered its action rule counterpart $tz : d \cdot ty : -2.5 \cdot tz : -d \cdot tx : 150 \circ rz : 30 \circ tz : -1 \leftrightarrow fy : 10$. This action rule updated the action trajectory, starting from D and aiming to arrive at H. Accordingly, position D was stored after position A, in the interaction position list. On the other hand, the updated action sequence including positions D, E, F, G, and H were stored in the rule-induced list. Based on these two lists, the dynamically created toolpath was automatically calculated. Since the linear action from B to C was interrupted at position D, C was replaced by D, which was also the initial position of the subsequent action.

Based on the dynamic toolpath generation which was explained above, the rule-based interactive fabrication process enables users to improvise and explore material expressions. Figure 9 showed a material sketch composed of varied lengths of incising expressions created by dynamically generated toolpaths. Since these toolpaths are recorded, they can be replayed at will. Subsequently, users can define a set of rules that log the robot's positions when force is applied to the end effector, without altering the robot's actions. Based on these positions, the recorded toolpath was automatically segmented thanks to the custom-developed add-on components. As a result, specific material expressions are isolated from their corresponding material sketches.

4.3.3 Toolpath modification: dynamic mapping and customization of material expressions. Once a promising expression was isolated, the rules were reconfigured to start composing intricate textures with the isolated expression (Figure 9). Subsequently, Figure 10 showed how two sets of rules were combined to dynamically map the toolpath of an isolated expression between two points that the user interactively defined. Consequently, the isolated expression was reproduced between these points with various sizes, allowing for a relatively controlled creation of design compositions with it. Figure 11-a and c exhibit tile designs that were composed by the isolated expressions shown above. Moreover, each user intervention triggered its corresponding action rule that computed new action planes to update the movement of the end effector. Since these action planes were captured in a list, altering some or all of them would change the toolpath, thereby customizing its respective texture. For example, Figure 11 (top) demonstrated that increasing the axial rotation about the Z-axis of the action planes widened the distance between clay threads, making them more pronounced (a-b). On the other hand, applying the same alteration to the 'layered' expression caused the tearing and piling in its composition (c-d). The resulting piling also increased the expression's height. Altering the respective action planes within the overall collections of the two tile compositions led to more convoluted designs, as seen in Figure 11-b-d. As a result, once emerging material expressions have been captured, fine-tuned and incorporated into tile designs that reflect a unique tectonic through intricate and organic qualities (Figure 1).

5 EXPLORING THE DESIGN SPACE OF INTERACTIVE ROBOTIC SAND CASTING AND CLAY FORMING

This section presents the design and fabrication processes of interactive robotic clay forming and sand casting enabled by the declarative human-robot interaction workflow. It specifically focuses on how novice users applied the implementation of rule-based HRI workflow and engaged with improvisational design processes in the context of producing bespoke cladding elements.

5.1 Users

Two novice users participated in exploring the rule-based interactive robotic fabrication. It should be noted that these were preliminary tests rather than structured and comprehensive user studies. The aim was to collect insights for organising a comprehensive user study with different groups in future. The novice participants will be referred to P1 and P2. Both P1 and P2 have no prior experience in robot programming or working with industrial robots. They are complete novices to the Grasshopper interface to test whether it is possible to define HRI processes only via algebraic rule notations, or not. P1 has a bachelor's degree in civil engineering and extensive work experience in construction. On the other hand, P2 has a bachelor's degree in architecture and work experience in architectural design and construction. Although these participants are novices to robotic fabrication, they are potential users due to the increasing demand for digitalisation in construction and human-robot teams in design tasks [47, 50].

First, the participants had an introductory lecture on the robot platform (KUKA iiwa) regarding the robot's joints, reach, singularities, and movement capabilities as well as safety precautions. Then, the declarative HRI workflow and its rule-based implementation were introduced to them. This introduction consisted of explaining the structure of algebraic notation and how to define and combine action and sensing rules through hands-on experiments. The novices were provided with a grasshopper definition in which they only needed to fill in the rules (1, Figure 5). By using this, they

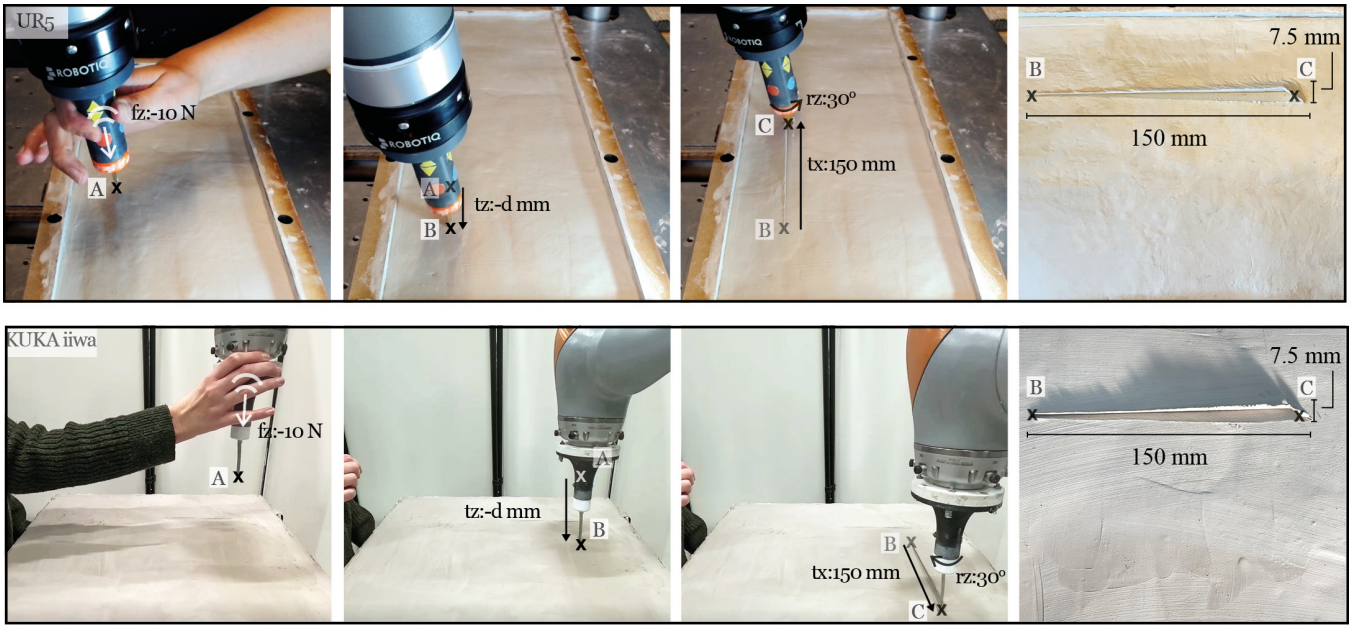

Figure 7: The top row (from left to right) shows the human-robot interaction guided by the rule $tz : d \cdot tx : 150 \circ rz : 30 \circ tz : -1 \leftrightarrow fz : -10$. The user's pulling the end effector caused force measurement to exceed $-10N$. This sensor state, first, triggered the linear translation from A to B ($tz : d$), where d is calculated based on the distance between the real-time TCP and clay surface. Subsequently (·), the robotic action that combines linear translation and axial rotation ($tx : 150 \circ rz : 30$) has begun from point B aiming to arrive at C. The final image in this row (right) illustrates the full outcome. The bottom row shows the human-robot interaction process governed by the same set of rules with a different robot platform, allowing the reproduction of a similar expression.

readily started to explore material manipulations with various sets of rules.

5.2 Exploring Materials via Rules

P1 explored the rule-based system through robotic sand casting studies. First, she focused on stamping by using the digital setup with a KUKA iiwa collaborative robotic arm (Figure 12-a-d). Later, she adapted the rule set for drawing geometrical patterns on sand (Figure 12-e and f).

5.2.1 Human and material feedback. By using the custom GH add-on components, P1 defined a set of stamping rules that control pressing the robot's custom end effector into the forming sand based on the applied force. Accordingly, by pushing left, right, forward, and backward, she defined the stamping positions through user feedback. Once the position was set, pulling down the end effector caused it to press into the sand. During pressing, the compacted sand exerted force onto the end effector, i.e., material feedback. When the exerted force exceeded the threshold value in the sensing rules, the end effector lifted, leaving its impression in sand. Figure 13-a illustrates the stamped patterns that P1 interactively created. Subsequently, she gradually reduced the travel distance of the end effector along the X and Y axes in the rules. In the first stamping experiment, the travel distances were defined as 50 mm along the X and Y axes, then reduced to 25 mm, and finally 25 mm for the second and the third experiments, as seen in Figure 13-a, b, c, respectively. Figure 13-d, e, f show their reproductions following the same order. As the material uncertainty increased due to multiple manipulations, reproducing the same pattern exactly became harder. For example, a comparison of the results shown in Figure 13-c and Figure 13-d shows that although replay allowed the same mechanical manipulations to be reproduced and a similar overall expression to be maintained, details such as the fragmentation of the sand varied significantly.

Reducing the travel distance caused the successive stamping actions to become closer to each other. Consequently, the material embodiment of previously made cavities interacted with the end effector and caused deflections during the trajectory update. This is visible in the outcomes that are transitioned from simple repetitive patterns to complex textures (Figure 13). These textures were characterized by material uncertainty due to displacement and fragmentation of sand. As a result, consecutive cavities overlapped, forming the complex sand textures, which were not anticipated by P1 or defined in the action rules. P1 found the complex outcomes surprising as they were achieved by very simple rules, only appropriating material expressiveness and uncertainty. Later, P1 hypothesized that reducing the stamping depth would maintain the irregular alignment of sand patterns while minimizing displacement and fragmentation, thereby reducing material uncertainty. Accordingly, she created three variations of the most complex sand texture (Figure 13-c,f) by incrementally decreasing the stamping depth. Figure 14-a-d demonstrates that how the sand texture became

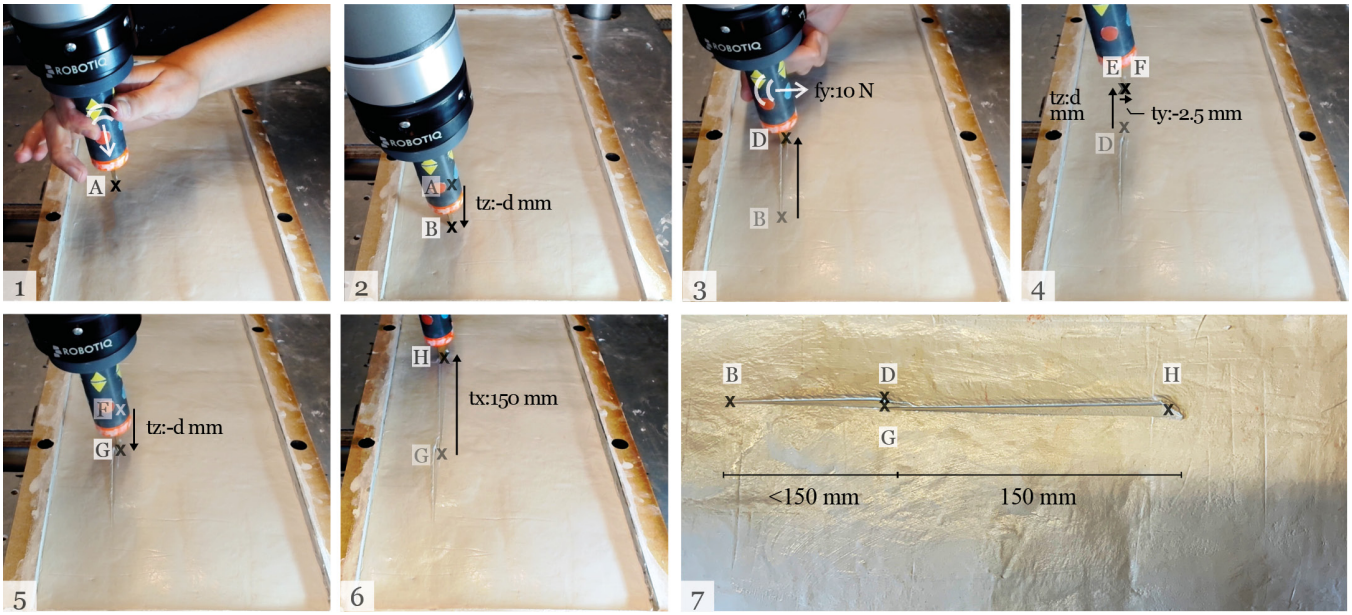

Figure 8: (1) The user pulls down the end effector and causes the force sensor state to exceed -10 N. (2)Consequently, the robot moves from A to B ($tz : -d$), and subsequently ($\cdot$), continues moving from B to arrive C while rotating around the end effector's local Z-axis the robotic action ($tx : 150 \circ rz : 30$). (3) Before the end effector reaches C, the user pushes the robotic end effector causing the force state to exceed 10 N at D ($fy : 10$). (4-5) Due to this user intervention, the robot momentarily paused and updated its actions to reproduce the incising outcome slightly below ($ty : -2.5$ mm) the previous incision. (7) The outcome consists of two incisions that vary in length and position.

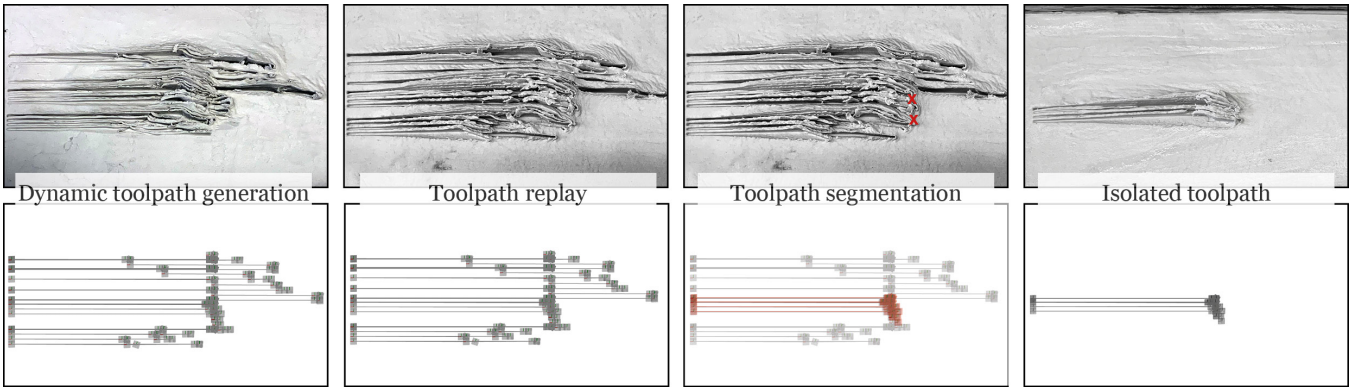

Figure 9: Dynamically generated toolpaths are structurally recorded based on declarative HRI rules. The material expressions become quasi-reproducible, as their recorded underlying toolpaths can be replayed. During the replay of a recorded toolpath, the user can mark positions by applying force to the robot's end effector. These marked positions are then used to segment the toolpath, isolating a specific section that captures a distinct group of material expressions.

more geometrically defined. Specifically, the reduction of stamping depth minimized the sand fragmentation and displacement, so that the cavities preserved their reverse pyramid-like shape in the same irregular pattern. In order to produce prototypical bespoke cladding elements, P1 used these sand patterns as casting formworks and poured plaster into them. As a result, she created a set of tile designs that went from an expressive and organic aesthetic characterized by material uncertainty to a more subtle linear texture characterised by robot's precise control of actions (Figure 1).

5.2.2 Restricting material feedback. At any time during the fabrication, the user could define along which axis or axes they prefer to interpret force. Accordingly, P1 defined a set of rules for drawing geometric patterns on sand by restricting force readings along Z axis. These rules enabled P1 to draw lines by pushing the robotic end effector in any direction without deflection caused by the exerted force along the Z-axis. Once the robot started moving, the

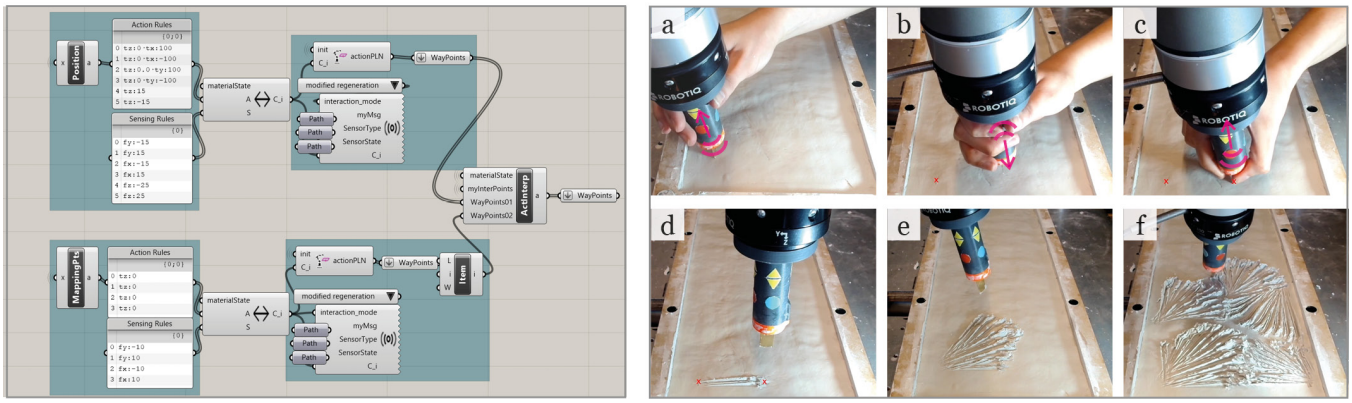

Figure 10: The rule-based approach allowed for the combination of two interaction modes: one that enabled positioning of the end effector tool, and the other that enabled defining two points between which a selected toolpath would be mapped (a-c). Consequently, the toolpath of a 'layered' expression became mapped between user-defined points, eventually composing into an intricate texture (d-f).

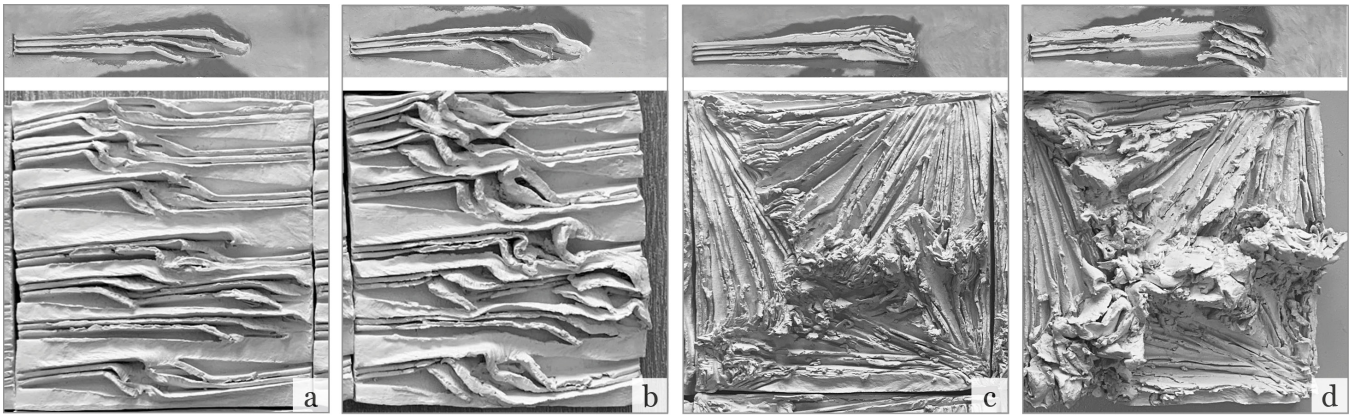

Figure 11: Each user interaction triggered a list of action plans. These action plans were recorded in a data tree that captures material outcomes. The user customised the outcomes by modifying the toolpath based on the recorded action plans. As a result, both isolated expressions (top, a and c) and their compositions (bottom, a and c) were customised while retaining their original size (b and d).

subsequent pushes continuously adapted the movement direction, resulting in overlapping lines as seen in Figure 15-a. However, the outcome still reflects the material uncertainty because the relocated sand particles dispersed on the texture. Upon replaying the recorded action planes, she discovered that the linear pattern could be reproduced whereas the dispersed sand particles appeared in different positions each time, thus the pattern looked different. Later, she modified the depth of the recorded action planes to create articulated lines. Due to the increased depth, the volume of relocated sand also increased, leading to greater material uncertainty, as seen in Figure 15-b and c.

5.3 Controlling Material Expressions and Their Reproduction via Rule-Based Modification

P2 explored the declarative HRI workflow and its rule-based implementation by using the KUKA iiwa collaborative robotic arm and tested the custom-developed software add-on via robotic clay forming and sand casting studies. He wanted to design and fabricate custom skyline panels. A skyline panel is standardized cladding element that consists of protruding cubic blocks arranged at varying lengths to create a complex texture for sound diffusion. Such panels are commonly used to control room acoustics. He investigated how this geometric design could be adapted to take advantage of the inherent characteristics of different materials.

5.3.1 Emergent material behaviour. P2 designed a wooden rectangular end effector to press into clay to create cavities for fabricating a "negative skyline pattern". He defined a rule set similar to stamping in sand. However, instead of a fixed depth, he introduced a 5 mm to 50 mm range that the pressing depth randomly assigned upon user interaction to achieve varying depths. During HRI process, he discovered that each pressing action resulted in an emergent

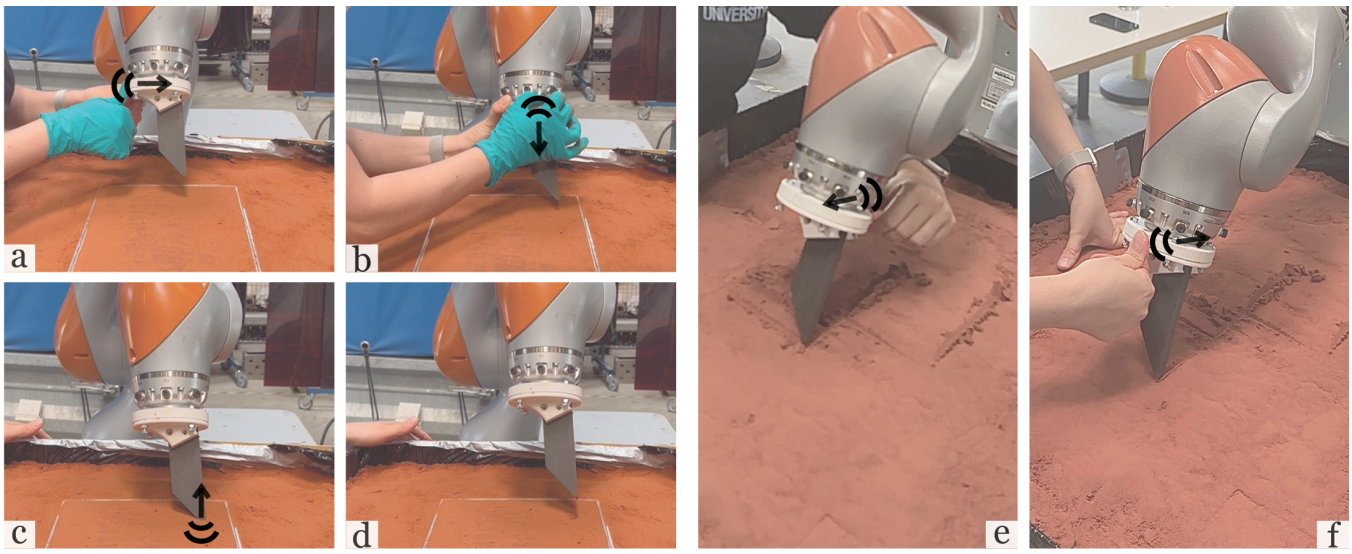

Figure 12: The user, P1, created a rule-based human-robot interaction for stamping and drawing on sand. (a) Pushing and (b) pulling the robot's end effector guide the robotic stamping actions based on human feedback. (c) When the robot's end effector presses into sand, (d) the compacted sand exerts force on the end effector that further affects the robot's movements. (e,f) Material feedback can also be restricted for precise control, such as in the case of robotic drawing on sand.

rounded expression around the end effector tool as seen in Figure 16-a. These expressions embodied a soft and organic aesthetic, highlighting the malleable qualities of clay. This contrasts with the rigid, geometric appearance of the existing skyline patterns. Based on the recorded rules, he clarified that these rounded expressions appear in relation to the consecutive pressing actions. By segmenting these actions, P2 isolated the cavities with the rounded walls around them. Later, he controlled and designed a series of patterns by using and modifying the segmented actions (Figure 16).

Figure 16-b shows a repetitive pattern with articulated rounded walls. This articulation was achieved by increasing the distance between the isolated pressing action planes. On the other hand, reducing the distance between pressing actions resulted in clearing the rounded walls (Figure 16-c) and he created a texture without the rounded walls by preserving the soft appearance as seen in Figure 16-d. Each dynamically generated toolpath was recorded during the HRI processes of clay forming. Subsequently, P2 modified the action planes that tilted the robotic end effector. As a result, the recorded toolpaths replayed with a tilted end effector tool pose, which was demonstrated in Figure 16e. The tilted tool had a diagonal ridge that was imprinted into the clay when pressed, resulting in a diamond-shaped grid with concave impressions. Since the tilted pose reduced the interaction area between between end effector tool and material, the emerging bulging became minimized. Accordingly, the consecutive robotic pressings created patterns with a more structured aesthetic compared to the earlier patterns that are softer and organic-looking. However, the curves and natural irregularities of the clay still reflect a sense of smoothness to the overall appearance.

5.3.2 Gradual modification of material expressions. P2 also explored the rule-based interactive fabrication through a robotic sand casting study as seen in Figure 17. Keeping the rules for clay forming, he explored sand compaction for creating textures with material qualities. Although both clay and sand have malleable qualities, their behaviour under pressure varies. For example, clay kept its embodiment while sand became fragmented, cracked and dispersed under pressure. Additionally, as opposed to clay which always adds softness and curvature as a response to pressure, it is possible to compact the sand into geometric shapes with sharp edges (Figure 18-a and b). P2 replayed the pressing actions after modifying the depths to explore "materially enhanced skyline patterns". As a result of this, he fabricated patterns consisting of sharp-edged cavities. Through modification of recorded action planes (i.e., increasing and decreasing the distance between pressing actions), the sizes of these cavities were controlled.

While adhering to the rules for clay forming, P2 investigated sand compaction to create textures that highlight the material qualities of forming sand. Although both clay and sand exhibit malleable properties, their behaviour under pressure differs significantly. For example, clay retained its form, whereas sand fragmented, cracked, and dispersed under pressure, as shown in Figure 18. P2 replayed the clay pressing actions with modified depths and overlapping distances to explore the material qualities of forming sand. Unlike clay, which responds to pressure by producing expressions with softness and curvature, sand can be compacted into geometric shapes with sharp edges (Figure 18-a and b) as well as intricate and organic-looking expressions (Figure 18-c and d).

By adjusting the recorded toolpaths (i.e., increasing or decreasing the distance between pressing action planes), he was able to control the size of the sharp-edged cavities, as demonstrated in Figure 18-a and b. Moreover, incremental modification, i.e., the distance between individual compaction, allowed fabricating expressions that

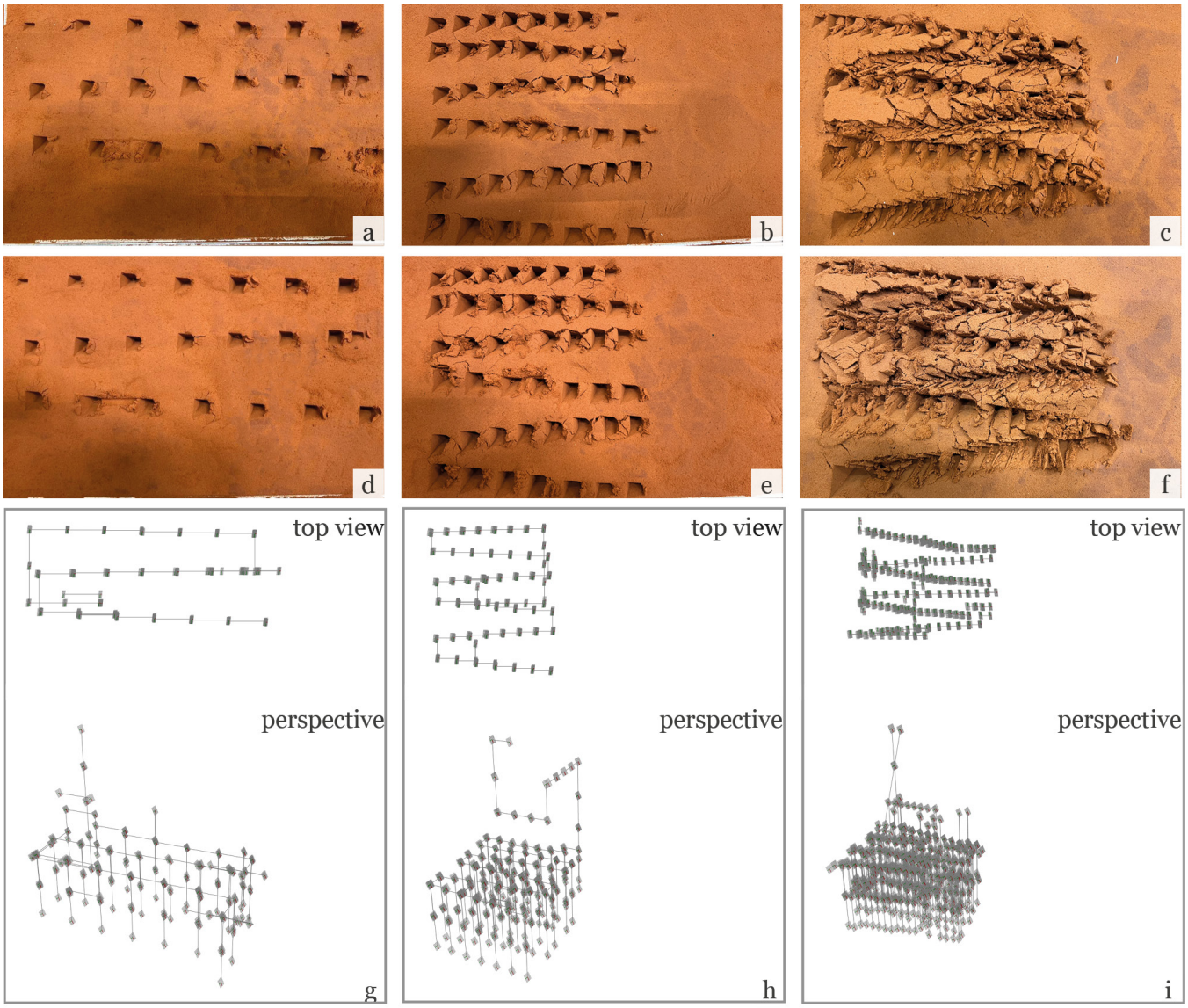

Figure 13: While keeping the sensing rules the same, the user progressively reduced the action rules. These rules direct the robot's end effector to move distances of (a) 50 mm, (b) 25 mm, and (c) 12.5 mm along the X and Y axes. (a, b, c) The images at the top display the patterns created through human-robot interaction (HRI), (d, e, f) while the images at the bottom illustrate the reproduction of these patterns based on replaying their dynamically generated toolpaths through HRI. (g, h, i) The rule-based implementation enables recording and visualizing the dynamically generated toolpaths through HRI in the Rhinoceros interface. The alignment of the action planes becomes noticeably more irregular as each stamping action occurs at closer proximity to the previous ones.

gradually changed from finer ridges to wave-like textures shown in Figure 18-c and d. On the other hand, the incremental depth increase caused fragmentation and displacement of sand at depths greater than 50 mm when the distance between consecutive robotic actions was 5 mm or less. Due to the manipulations occurring within a very narrow range multiple times, the previously compacted sand was disturbed and displaced by subsequent actions, leading to material uncertainty as seen in Figure 18-c. Keeping the depth below 50 mm allowed for successful control of the intricate textures, such as fine ridges and waves, as shown in Figure 18-d. Finally, P2 cast plaster by using these robotically manipulated sand patterns as formworks. The plaster filled in the intricate cavities in the sand, and it was left to dry there for a day. The dried plaster embodied the cavities, as a negative form of sand. Figure 18-e-h demonstrates patterns of plaster tiles.

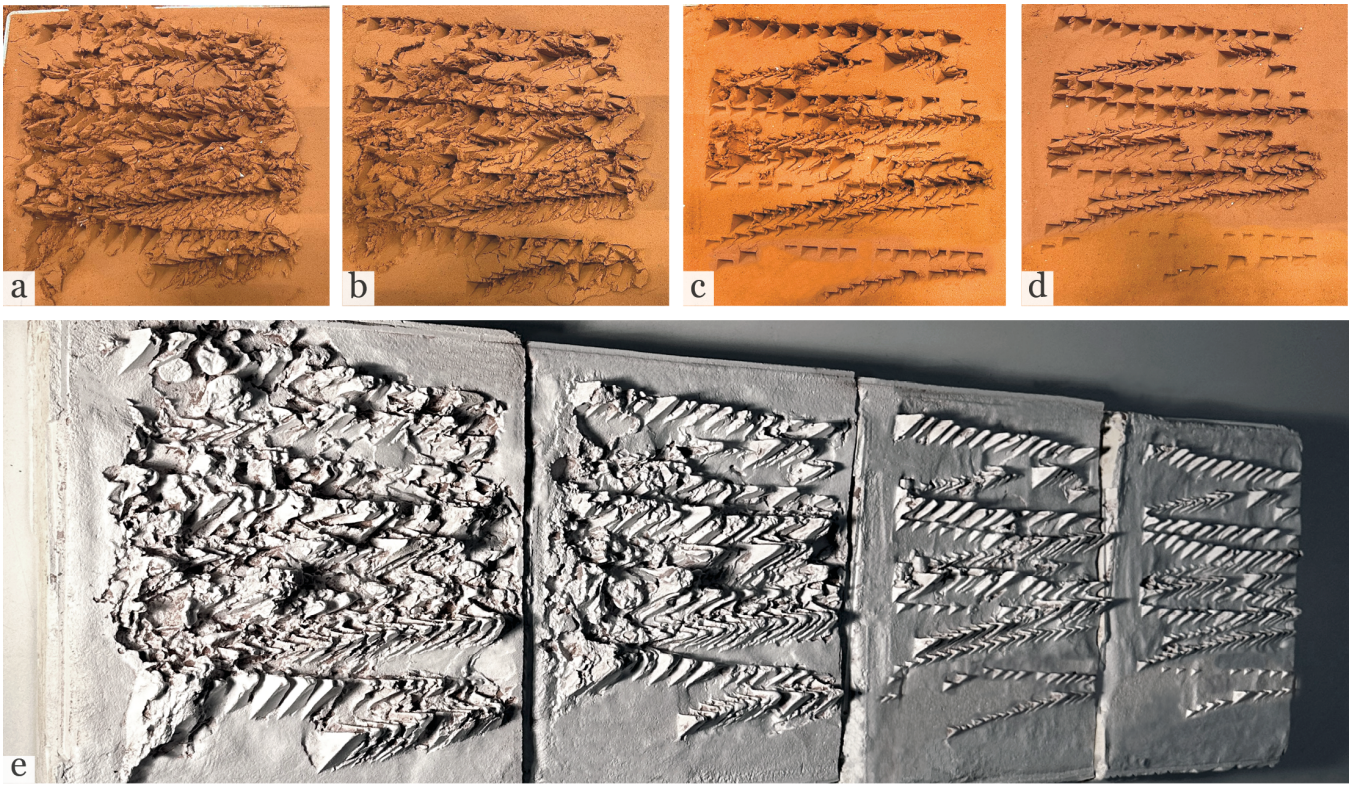

Figure 14: (a) Complex sand texture comprises displacement and fragmentation of sand due to the robot's stamping actions. Replay of the stamping action planes (b) 10 mm, (c) 20 mm, and (d) 30 mm upwards along the Z axis. (e) Materially expressive tiles were produced by casting plaster on sand patterns.

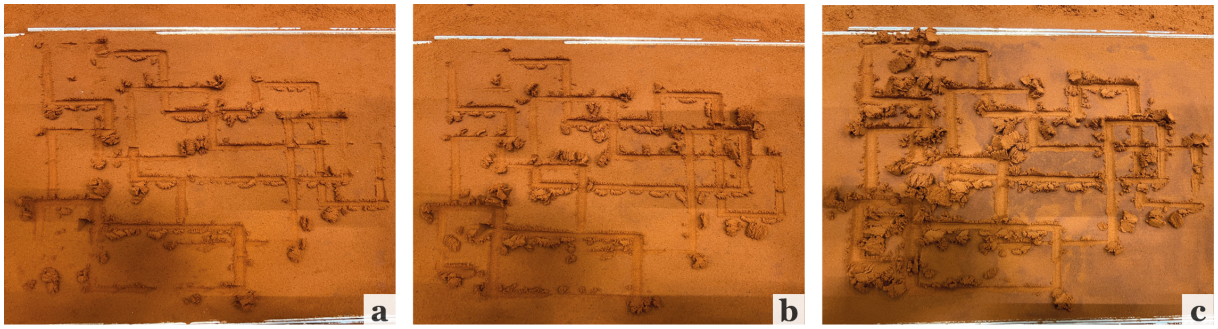

Figure 15: By selecting to interpret forces along only the X and Y axes, (a) linear patterns were carved without deflection caused by force exerted along the Z-axis. Since each dynamically created toolpath was recorded, (b) it was replayed at will to reproduce the linear pattern with material uncertainty, and (c) modified by increasing the depth of the recorded action planes in the sand.

6 Discussion

This section discusses how the declarative HRI workflow and its rule-based implementation could first enrich the design space of robotic fabrication, then broaden the responsiveness of robotic fabrication systems, and finally facilitate a level of accessibility to robotic fabrication technologies.

6.1 Enriching Creative Design Space of Robotic Fabrication

The rule-based approach enriches the design space of robotic fabrication with material expressions that are difficult to predetermine or predict in CAD mediums. As illustrated in Section 5, the users spontaneously discovered material expressions conveying an organic and intricate aesthetic through embodied interaction. This embodied process resembles the "dialogue between the maker and the material" that frames the creative act of making [39]. As a result,

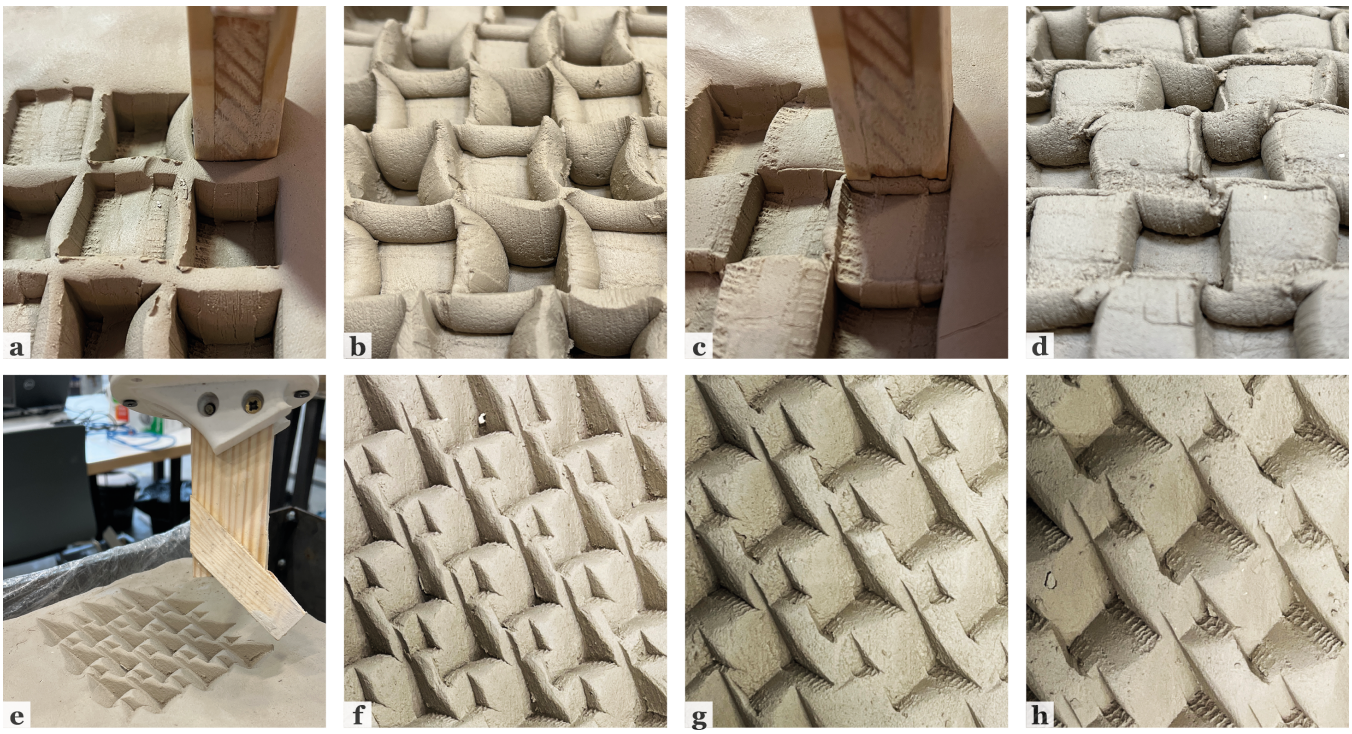

Figure 16: After discovering (a) a rounded and soft expression emerged through pressing in clay, (b) this expression was isolated and reproduced to create patterns with emphasised softness. (c) Slightly overlapping consecutive pressing actions modified the thickness, and by carefully combining these actions, (d) a texture with minimal bulging was achieved, while still preserving the softness. (e) Replaying the recorded toolpaths with a modified tool pose resulted in more structured patterns, as the interaction area between the tool and material was reduced. (f, g, h) A series of pattern variations was achieved by controlling the overlap between consecutive pressings.

the users delved into material exploration through physical robotic manipulations, designing with material affordances [8] moving beyond mere geometrical operations of parametric form-finding of established robotic fabrication procedure [28, 45, 67, 93, 98]. This creative process closely resembles crafting in terms of developing a unique design language specific to each material [74, 105].

Bridging traditional craft methods and computational technologies has been a longstanding focus in HCI research [70, 73, 102], revealing how tools and production processes uniquely shape, inform, and sometimes constrain creative thinking through material engagement [71]. This paper contributes to this ongoing discussion by exploring how material engagement through a rule-based approach can facilitate the (quasi)reproduction, isolation, and modification of emergent material expressions. As demonstrated in the Figures in Section 4, the rule-based approach enabled users to reconfigure and combine rules, defining various interaction modes. This approach led users to establish a creative process characterised by the improvisational fabrication of outcomes, isolation of promising emergent expressions from these outcomes, and composition of the isolated expressions into more complex designs. Accordingly, this study extends the recent advancements of HCI research in material exploration from craft machines with integrated 3D-printers [15, 57, 83] or looms [2] to robotic fabrication. Furthermore, the variances and imprecision inherent in material states can be efficiently employed for bespoke designs through rule-based computation, deepening the free-form exploration with robotic fabrication [22, 27].

6.2 Materials as Active Participants in Interaction

Rule-based interpretation of sensor feedback facilitates material-robot interaction, thereby empowering materials to actively influence robotic actions. As shown in Figures 13, the material embodiment of cavities deflected the robotic motion trajectory, composing emergent curvilinear expressions. The action sequences for creating such expressions were not directly present in the action rules; rather, they emerged from combining these rules with the sensing rules. Accordingly, our study reinterprets interactive fabrication as a creative design medium, viewing it through the lens of material agency. Until now, rather than focusing on material feedback, the interaction has mainly been associated with incorporating human input, through bidirectional [63, 96], augmented [55, 62] and continuous [58, 85] fabrication workflows.

In these workflows, captured human input is translated into geometries that are compatible with CAD/CAM. Based on these geometries, the mechanical fabrication operations are calculated. Naturally, these mechanical operations are restrained to the ones in the CAD environment, such as cutting, scaling, or extruding. In

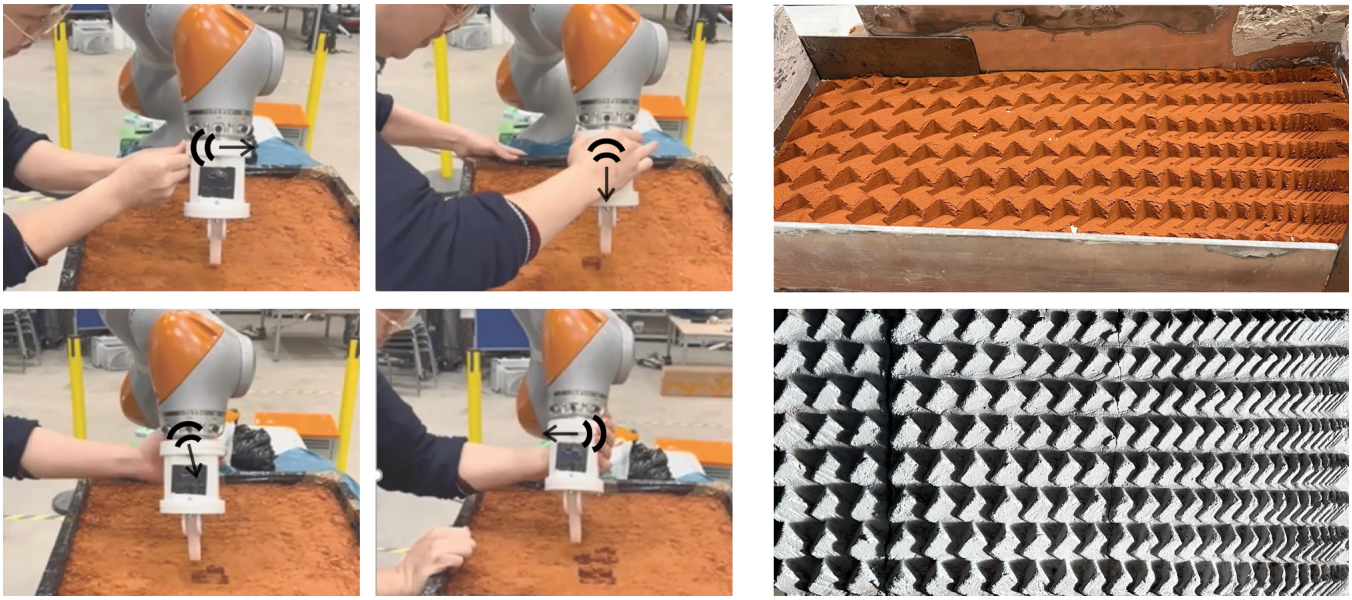

Figure 17: The user, P2, discovered the sand compaction via a rule-based HRI process. The compacted sand expressions are fine-tuned and controlled to create sand formworks and cast plaster.

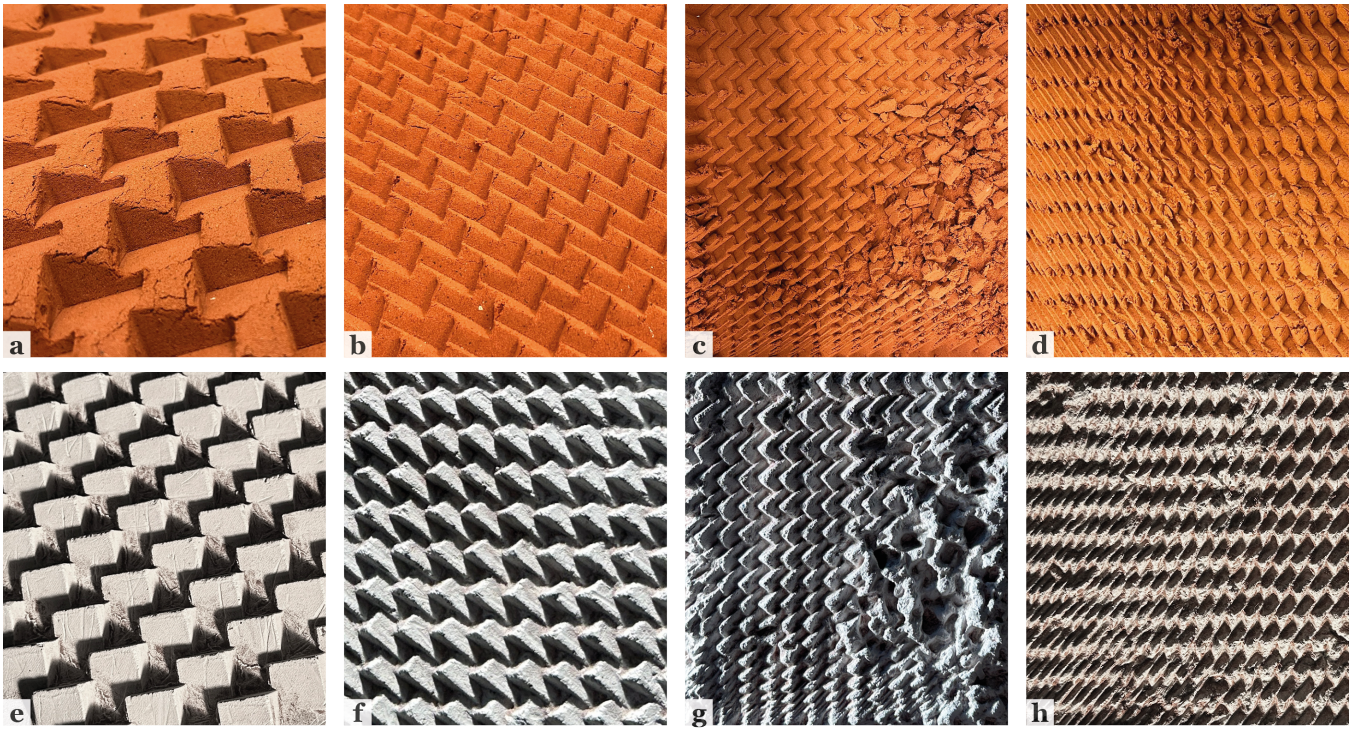

Figure 18: Robotically stamped sand patterns and cast plaster tiles by the modification of the recorded toolpaths.

contrast, interfaces that allow material feedback should consider operations within the material affordances and constraints. Because the sequence of fabrication actions was computed iteratively based on physical input from the material, these actions embody mechanical operations that are specific to the material agency, such as dispersing (Figure 13) or tearing and piling (Figure 11). However, the big challenge is to transfer such physical operations into the computational realm where the robot agency belongs.

The rule-based approach might leverage the development of data structures that improve the efficiency of material-specific operations by the structured process of recording interactions. Creating interfaces for material-robot interaction is a crucial step towards establishing a sensory environment for machines, ultimately transitioning them into autonomous agents [52]. An environment like this would not only help with learning but also with reasoning. Currently, reasoning is seen as a skill only humans possess in mixed human-non-human teams [48, 52]. If autonomous agents start showing even basic reasoning abilities, they could become collaborators or teammates instead of just tools.

6.3 Rule-Based Force Sensor versus Hand-Guiding Methods

While both rule-based force sensor and hand-guiding methods can generate repeatable and manipulable toolpaths, they differ significantly in terms of user interaction, precision, and applicability. The hand-guiding approach—where the user physically moves or manipulates a robot or a machine in space—offers highly intuitive control and real-time haptic feedback [1]. Its low technical threshold and directness have made it a popular approach in contexts such as human-robot collaboration and robotic learning by demonstration [12]. However, hand-guiding can suffer from variability introduced by human motor noise [79] and lacks the precision needed in applications requiring high repeatability of robotic motions. For example, Figures 16-a, b and d show clay expressions achieved by multiple robotic actions repeated at highly controlled positions, which might be challenging for hand-guiding applications to achieve.

By contrast, the rule-based force sensor method with sensing-to-toolpath translation decouples force sensing from motion execution, allowing the data to be processed, filtered, or mapped through algorithmic strategies. This abstraction layer supports greater repeatability and post-processing, essential for scenarios that require quantifiable, analysable force interaction [38]. Accordingly, this rule-based sensing-to-toolpath translation allows for fine-tuning and modification of toolpaths derived from force data. For example, the data collected from interactive sand compaction includes structured toolpath segments and associated rule information describing the robotic motion parameters. This allowed for controlled modification of complex sand compaction patterns, as shown in Figures 17 and 18.

Additionally, such HRI setups can incorporate advanced control strategies (e.g., impedance control, force filtering, or adaptive feedback loops), which can enhance stability and consistency in material engagement [3]. Although this research focuses on the advantages of rule-based sensing-to-toolpath translation in design and fabrication, the approach can extend beyond these fields to any area requiring haptic research, particularly where dynamic interaction with complex surfaces or sensitive materials is involved, such as in surgical robotics [59]. To sum up, hand-guiding excels at intuitive HRI, while rule-based systems might provide a structured framework for precision, analysis, and modification. A hybrid or task-specific choice between the two may offer the best compromise, and future work could explore how to integrate the strengths of both paradigms.

6.4 Facilitating Accessibility to Interactive Robotic Fabrication and Limitations

The proposed declarative HRI workflow is designed to support a broad and interdisciplinary audience, particularly those with limited experience in robotics. As demonstrated in Section 5, novice users from civil engineering and architecture backgrounds were able to engage with both simple interaction modalities, such as sand casting, and more complex ones like clay forming. By abstracting low-level robotic control into high-level, rule-based logic, the workflow lowers the technical entry barrier and enables users to focus on design intent and material behaviour. This makes the system accessible not only to architects, engineers and designers—who can use it for prototyping material-driven processes [18, 27, 43, 91]—but also to artists and makers exploring expressive and responsive digital fabrication methods [15, 56, 101]. Furthermore, HCI researchers may benefit from the rule-based approach to facilitate co-creative human-machine interaction studies. The successful implementation of the workflow on two different robotic platforms (UR5 and KUKA iiwa) across varied fabrication setups demonstrates its flexibility and generalizability, reinforcing its potential impact across a wide spectrum of creative and technical communities.

Participants with no prior experience in robotic fabrication or the Grasshopper interface found the rule-based application intuitive. They were able to use custom components without writing code or building complex Grasshopper definitions, relying instead on simple algebraic notations. However, participants pointed out several limitations, as well. P2 noted, “Writing complex actions was time-consuming because you always need to copy-paste the symbol (i.e., algebraic notation)," highlighting a limitation regarding user experience. Future studies may explore more natural forms of symbol generation, such as speech recognition. Both P1 and P2 appreciated being able to bypass the “complicated" Grasshopper interface. P1 emphasized the accessibility of algebraic notations for creating simple actions by combining translations, rotations, and sensor thresholds. However, she found the system inefficient for complex, consecutive actions involving multiple rotations and translations, which led her to work with simpler rules. Despite this, she was surprised by the emergence of complex expressions due to material uncertainty, describing how she “physically coded the complex textures," pointing to the embodied nature of interactive fabrication. The study suggests that the essence of fabrication complexity lies in the “performance of making"—a process in which humans continuously shape materials and guide robotic manipulations.

6.5 Versatility of Robotic Fabrication: Tools, Materiality and Future Opportunities

The users designed their own end effectors, which significantly shaped their creative process [71, 72]. The choice of end-effector tools in the presented robotic fabrication system is driven by the desired surface texture and the specific interactions with materials like sand or clay. For instance, the wooden stamping tools shown in Figures 4, 16, and 17 were specifically designed to produce precise, geometric imprints suitable for structured textures and subsequent casting. In contrast, Figures 7, 8, and 10 demonstrate the brass carving tool, optimized for creating dynamic grooves that are composed into expressive patterns responding to real-time human interaction

and applied forces. Both tools are designed for interchangeability, allowing users to quickly swap them depending on the intended outcome–whether generating geometric forms or more organic, free-form textures. This modular approach enables a broad range of surface effects within a single robotic setup, significantly enhancing versatility and creative experimentation in robotic fabrication.

Since manual material engagement has led to the discovery of unique forms [26, 103], exploring the integration of direct material manipulation alongside robotic processes presents a promising future direction for enhancing our system. Currently, this capability is not included; however, incorporating it could significantly enrich the craft-inspired workflow. Allowing users to interact directly and tactically with materials while engaging in rule-based robotic actions would foster a dynamic interplay between human intuition and machine precision. This hybrid approach enables users to respond immediately to material properties, thereby deepening the creative process through tactile exploration and adaptation. Future developments could focus on creating interfaces or tools that facilitate transitions between manual and automated manipulations, offering novel opportunities for innovation in material-driven design and interactive fabrication.

7 Conclusion

This paper presents a declarative human-robot interaction workflow that integrates real-time sensor feedback for the dynamic control of robotic actions. This workflow enables a correspondence between the hands of users and the material affordances through embodied interaction, which was traditionally associated with craft. During the interactive design and fabrication processes, participants closely engaged with material manipulations, drawing inspiration from and incorporating material agency into their design ideation. Combining the computational powers of robots and traditional craft methods, this work focused on capturing creative making actions (i.e., robotic manipulations) via structurally recorded fabrication data. As the implementation of this declarative HRI workflow, a custom Grasshopper add-on was developed and tested by two novice users. The results showed that this software add-on enabled users to define rules for action sequences and real-time sensor measurements, as well as their respective combinations. The design explorations demonstrated an iterative design and fabrication workflow, shifting robotic fabrication from a CAD-dominant, linear process to an intuitive making performance. The contributions were discussed in terms of enriching creative opportunities, empowering material feedback, the potential of rule-based force sensor method and facilitating accessibility in robotic fabrication. Ultimately, this work represents a significant step towards combining the computational power of machines with the material affordances in the improvisational performance of the human user. We believe this study lays the groundwork for human-robot interaction that embodies the authenticity of craftsmanship, opening new possibilities in design and architecture.

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