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A Method for Integrating Complex Material Variation in Human-Robot Co-Creation Design Processes

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To advance the understanding and application of complex material variation within the built environment, this study investigates the development of an interactive fabrication setup that supports co-creation workflows between craftsman, robot, computational system, and non-homogenous materials. By establishing a framework for human-robot co-creation, the study seeks to explore a fabrication workflow where design-specific information (analogue and digital) affords both human and robotic decision-making. In so doing, the study examines a critical method for integrating technological, cognitive, and architectural challenges by adopting nondeterministic co-creation workflows with increased implementation of biogenic and reused materials.

Keywords: *Human-Robot Co-Creation, Robotic Fabrication, Material Studies, Design Creativity.*

INTRODUCTION

With the present material crisis, the built environment is required to reconsider the complexity and uncertainty of chosen building materials, giving rise to a re-introduction of both biogenic and reused materials, leading to increasing material variation. To advance the understanding and application of complex material variation within the built environment, this study investigates the development of an interactive fabrication setup that supports co-creation workflows between craftsman, robot, computational system, and non-homogenous materials.

In recent years, research in computational design and robotic fabrication has gradually shifted towards more adaptable and non-deterministic manufacturing strategies, seeking to embrace unpredictable processes (of various origins) and the dynamic work environments in which they occur. Research in this field spans from studies focused on adaptation towards dynamic material properties to the integration of human agents, with varying levels of interaction and collaboration.

Notable studies associated with material variation include investigations of adaptative strategies for robotic rod bending by (Vasey, Maxwell and Pigram, 2014), explorations of robotic weaving by (Brugnaro *et al.*, 2016), and explorations of adaptive robotic molding of plastic sheets by (Schumann and Johns, 2019). Common features for these research endeavors are the establishment of a sensor-based input, that allows the robotic system to sense and interpret selected aspects of its surrounding context, on which to base or re-adjust its material interactions. Another shared focus is the adaptive strategies employed, largely aiming to impose corrective measures in the pursuit of a predetermined material organization, thereby disregarding any unforeseen potentials that might occur during robotic fabrication.

In seeking to engage with the often closed and error-correction-driven process of robot-based material adaptation, the integration of human collaborators has been the main driver in specific research projects. Among these studies are the user-informed subtractive procedures of robotic wax melting (Johns, 2014), in which a negotiation between adjustable structural loads and physical input of user preferences, informs the melting/removal of wax, iteratively reinforming and reshaping the material object. Through research into the fabrication and assembly of filament-wound structures (Vasey *et al.*, 2016) Vasey et al. extend the influence of the human collaborator by utilizing the fine motor control of human hands. Humans and robot thereby engage in an interactive fabrication process, where a clear distribution of tasks allows for a sequential deployment of robotic precision and human dexterity. A similar approach to human-robot task delegation can be seen in the recent work by (Mitterberger *et al.*, 2022), here applied in a cooperative workflow, defined by the authors as *machine-assisted human fabrication*, focused on the assembly of wooden structures with rope joints. However, this project extends the flexibility of the human-robot fabrication system and allows for spontaneous design decisions – a flexibility that is made possible by the "ability to continually feed human-induced changes into a digital model" (ibid., p. 290).

Based on these research trajectories in human-robot fabrication, there is substantial potential for further studies that investigate the interconnection of machine intelligence and human creativity/knowledge, in a pursuit to encompass the variations and uncertainties in applying reused biogenic building materials. Following such potential, it is essential to examine the affordance of human-robot co-creation and to which degree such collaborative fabrication processes allow for material systems and construction scenarios that might otherwise not have been feasible.

By establishing a framework for human-robot co-creation, the study seeks to explore a fabrication workflow where design-specific information (analogue and digital) affords both human and robotic decision-making. In so doing, the study examines a critical method for integrating technological, cognitive, and architectural challenges by adopting nondeterministic co-creation workflows with increased implementation of biogenic and reused materials.

The paper presents the computational methods needed to construct the human-robot co-creation workflow, enabling a coupled human-system analysis and decision-making process with complex materials, followed by a qualitative analysis of the implemented design and fabrication process. In closing, the paper discusses the need for shared design intentions and the potential of nondeterministic design methods for successfully integrating material variations.

METHODS

The research is based on the construction of, and subsequent experimentation with, a digital-physical framework that facilitates human-robot co-creation design processes. To illustrate how the study integrates complex materials and how these are analyzed through both quantitative and qualitative methods, the following sections present the robotic co-creation framework that enables the execution of human-robot co-creation design processes, followed by a presentation of the shingle façade used as a test case, the applied analysis methods, and the semi-deterministic design investigations afforded by the proposed method.

The human-robot co-creation framework

The proposed human-robot co-creation framework consists of a shared digital-physical workspace. The physical workspace (see figure 1) consists of a collaborative robot arm (KUKA LBR iiwa 14 R820) equipped with a vacuum gripper (piCOBOT) and a depth camera (Intel RealSense D435). The robot arm is mounted in a fixed position on a steel table and is directly connected to a computer via ethernet and TCP/IP communication, enabling bidirectional data

Figure 1
The physical workspace of the co-creation framework.

transfer between the CAD environment and the robot. This setup allows for robotic execution of simple pick-and-place tasks and for camera-based visual recognition of selected aspects in the near context.

On the digital side of the co-creation framework, all elements, including the parametric design model, robotic control, image recognition, and behavior model, are implemented in the Rhino and Grasshopper environment. The parametric design model, elaborated upon in the Case Study section, contains the logic of the design system and specifies the desired cartesian position for all elements in the final physical assembly.

The robotic fabrication process is based on a basic pick-and-place routine. Kinematic simulation and code generation for controlling the robotic arm is implemented through KUKA|prc. With the support of SunriseOS (the operating system for KUKA LBR iiwa) this Grasshopper add-on allows for streaming data to and from the robot via UDP connection. This connection allows the co-creation framework to trigger specific behaviors based on the current position of the robot or through user activation of the 'Application button' located at the flange of the robotic arm.

To extend the range of robot-based sensory input, and thereby exceed the basic reading of position data and Boolean true/false values, the co-creation framework incorporates bespoke Grasshopper components that communicate directly (via USB connection) to the robot-mounted RealSense camera. By utilizing functions from the RealSense SDK (through the python wrapper 'pyrealsense') and OpenCV (Open Source Computer Vision library) the framework incorporates pre-established visual recognition methods for both edge- and color detection. In combination with the RealSense camera, these additions allow the co-creative framework to identify physical objects based on their physical appearance (either color-based or geometric), thereby giving the robotic system the ability to sense and react to the context in which it is situated.

To design and coordinate the collaborative interaction between human and robot, the framework is deploying a behavior model based on the concept of the finite-state machine (FSM). A state machine is a mathematical model of computation in which the behavior is prescribed by a predetermined series of actions triggered by specific events or inputs. Each set of actions is associated with a specific state and the FSM can be in exactly one state at any given time. The implementation of an FSM within the Grasshopper environment builds upon existing work by (Jensen and Das, 2020; Jensen, Foged and Andersen, 2020) and allows the user of the co-creative framework to control not only the data flow, which the visual flow-based programming environment is built for, but also the process flow. The importance of controlling process flow for interactive robotic fabrication has also been studied by Braumann, Gollob and Singline, arguing that "…controlling the process flow is essential for interacting with robotic fabrication processes, so that they can react to input such as user interaction or sensor data." (Braumann, Gollob and Singline, 2022).

Test case: Wood Shingle Façade

As an experimental design and fabrication case, the study constructs a façade system (540 x 230 cm.)

comprised of approx. 1200 wood shingles (with varying geometric properties) arranged in a dynamic pattern (see figure 2). Poplar, in a state of decay, was chosen as construction material due to its highly fluctuating surface composition.

The physical façade system was subdivided into 12 modules, each comprised of a wooden frame onto which the poplar shingles could be placed by the robotic arm and manually fastened with a nail gun (see figure 3 and 4). During the fabrication process, the varying material expressions of the poplar shingles (see figure 5) are seen as a design opportunity and catalyst for human creativity and aesthetic-driven decision-making. While the specific length of each poplar shingle was defined by the computational design model, the robotic fabrication setup was deliberately constrained from cutting the shingles into shape, and instead focused on camera-based measurements of each wood shingle, subsequent selection of best candidates, and positional adjustment of the selected shingle, as a strategy for achieving the desired facade configuration. To enable the robot-based visual recognition and shingle measurement routine, the physical workspace was, in addition to the RealSense camera, equipped with a storage system consisting of eight cassettes, each holding five poplar shingles. The design of the storage system deliberately limits the co-creation process to base its selection routine on the eight shingles currently stacked at the top of each layer. Also, the physical arrangement of the storage system was configured so that both human and robot have visual and physical access to the stacked shingles, allowing both participants to physically engage on "equal" terms.

The fixed mounting position of the robotic arm, in combination with its limited reach, does not afford robotic placement of shingles along a 180 cm. wooden frame. Instead of solving this limitation by extending the physical framework with a linear track or an autonomous mobile robot (AMR), the study sought to utilize the potential of human-robot task delegation. Thus, the solution is addressed through the construction of a simple mobile aluminum scaffold that allows mounting of the wooden frames in a fixed position. When fabricating, the mobile scaffold is guided by a linear rail that restricts its movement to a single direction/axis - ensuring precise sideways movement and positioning by the human co-worker. Information on when the scaffold needs repositioning, allowing the robotic arm to reach the next subset of shingles, resides within the computational system and thereby requires communication from the digital workspace to the human co-worker. To strengthen the co-creation

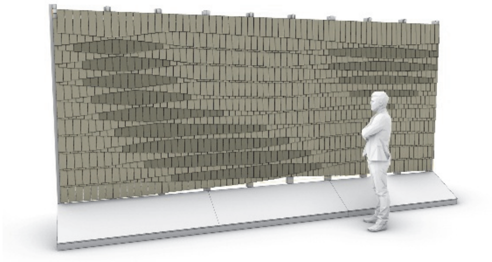

Figure 2
Digital version of the Wood Shingle Façade, comprised of 1200 poplar shingles of varying lengths.

Figure 3
A fabricated module consisting of 120 poplar shingles mounted on a wooden frame.

Figure 4
The poplar shingles are placed by the robotic arm and manually fastened with a nail gun.

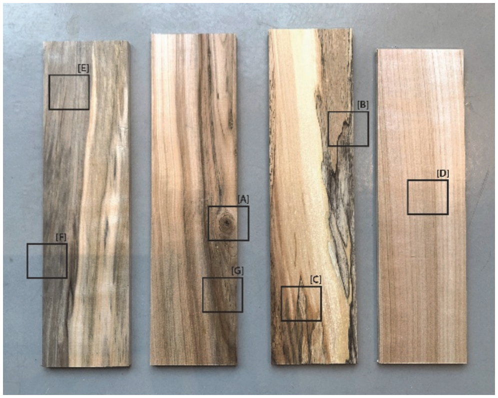

Figure 5
Material samples of the poplar shingles, with labeled zones displaying: A) Knots, B) Black grains, C) Brown artifacts, D) Light brown longitudinal grains, E) Grey patches, F) Blue patches, G) Dark brown patches.

Figure 6
With the robot-mounted RealSense camera, the robotic system can recognize the position of a colored glove, worn by the human co-worker, thereby allowing communication through simple human gestures.

experience and promote human-robot interaction, the robotic arm is assigned as a mediator of digital information with robot-to-human communication achieved with the triggering of simple light signals and implementation of anthropomorphic robotic gestures.

The implementation of anthropomorphic robotic gestures can be seen in the work of (Gannon, 2018; Hinwood *et al.*, 2018), both studying how robotic arms, through their inherent capacity to perform human-like movements, can communicate intentions and, to a certain degree, express intelligent behavior. Besides communicating the need for 'scaffold movement', achieved through a sideways pointing gesture, the study also deploys robotic gestures to communicate, again through a pointing gesture, which shingle elements that are available for human selection. The following process of communicating the shingle selection, or in other words human intentions, back to the robotic system, is achieved by running a color-detection procedure. Using the RealSense camera, the robotic system can recognize the position of a colored glove, worn by the human co-worker, thereby allowing communication through simple human gestures (see figure 6).

A hybrid (mixed) analysis approach

To enable the human-robot co-creation process, the study implements a hybrid analysis approach in which both human and robot contribute to an iterative evaluation of material properties. As previously mentioned, the robotic arm is equipped with a RealSense camera, allowing the robotic system to perform a quantitative analysis based on visual edge detection of depth and color maps (see figure 7). While this quantitative method allows for precise (+/- 2 mm.) measurement of shingle lengths, it does not capture variations related to the material composition of individual elements. Instead of pursuing a solution for this missing feature through the advancement of the technological setup, it is crucial for this study to construct a suitable balance within the distributed human-robot skillset, while simultaneously being aware of the inherent abilities of both parties, which is why this evaluation process is assigned to the human co-worker. The strength of this hybrid analysis approach lies not in a fully automated setup, but in a distributed analytical procedure, where all active agents contribute with unique skillsets and share captured data/knowledge within the human-machine team (see figure 8). Adapting this approach aligns with Murphy's definition of *joint cognitive systems*, focusing on how humans and robots "cooperate and coordinate with each other to accomplish the team goals" (Murphy, 2019, p. 21).

Semi-deterministic design investigations

As color maps are already captured by the robot-mounted camera, machine intelligence could have been implemented to achieve automated image recognition of specific material features. While this approach, as mentioned above, would work against the distribution of skills within the human-robot team, an equally important consequence is the loss of open-ended design exploration. The automated image recognition sequence would only be capable of identifying and responding to the features for which it has been trained, making it incapable of embracing novel material features and adapting its response patterns. Instead, in giving a human agent the opportunity and authority to analyze, evaluate and make decisions, the study seeks to promote semi-deterministic design investigations – allowing the human-robot team to work as a joint cognitive system, capable of adaptive co-creation. As such, it is the embedment of human interaction that makes the co-creation system adaptive.

Figure 7
Edge-detection routine. Bottom image: captured image from the RealSense camera with colored edge detections. Top image: screenshot of edge detection data translated to the expected length of the eight wood shingles.

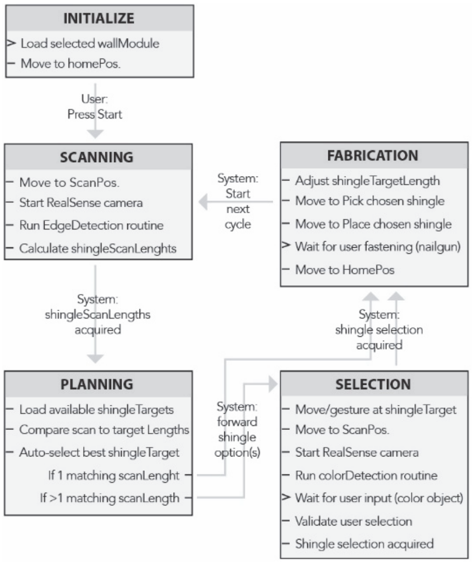

Figure 8
State-graph conceptually representing the human-robot co-creation process.

RESULTS

Through the presentation of the fabricated shingle façade and the underlying design and fabrication framework, this study showcases how material variation can be treated as a core parameter and primary generator during a human-robot co-creation design process. In addition to the established digital/physical co-creation framework and the built full-scale demonstrator, the result of the study includes findings based on observations and empirical data acquired during the human-robot co-creation process.

Human build versus human-robot co-creation

To identify possible implications of adopting a human-robot co-creation design process a direct comparison was facilitated by assembling six out of the twelve shingle-based modules through a human-only fabrication process. During this process, design and fabrication information was communicated through a CAD interface (rhino and grasshopper), while physical measurements, selection of desired shingles, making adjustments based on length deviations and accurate placement/fastening of shingles were human-driven. The repeated analogue measurements of wood shingles and the mental arithmetic needed to adjust these measurements to the intended lengths and placements of each individual element, led to several human errors.

Based on observational data, including all occurrences of human errors (incl miscalculations, forgotten values, and incorrect shingle placements) the human-only fabrication process revealed an undesired cognitive load that could only be managed when in an uninterrupted flow. In comparison, during the human-robot co-creation process, all the needed fabrication data is gathered, managed, and calculated by the robotic system. The human agent, now relieved of a cognitive load highly based on numeric data, could instead delegate cognitive capacity to activities requiring higher levels of pattern recognition and emotional response.

Robot-based design intentions

By entrusting the robotic system with the task of making decisions and presenting suggestions based on quantitative analysis, the resulting co-creation process succeeds in integrating both human-, robotic- and material-based design input. As the study implements a shingle-based design and fabrication framework that allows for adaptation to detected material variation, the co-creation design method promotes an open and parallel creation (i.e. design+fabrication) process.

In allowing the robotic system to compute how best to fabricate the shingle assembly with the, at any given time, available shingle elements, the study was faced with the challenge of how to communicate three different scenarios: 1) there are no available shingle elements that fit the size criteria, 2) there is one shingle element that fits the size criteria, 3) there are two or more shingle elements that fit the size criteria. To communicate these scenarios without the use of a display monitor, the study investigated methods for communicating intentions through robotic gestures. By taking advantage of the anthropomorphic abilities of the robot arm, pointing movements and small "wiggly" rotations of the robot's wrist (7^{th} axis on the iiwa robot) was successfully implemented to inform the human co-worker of both intended placements and which shingle elements that were available to choose from during each pick-place sequence. As a result of this simple communication strategy, no additional screen was needed during most of the co-creation process. However, when the process did not proceed as planned, the communication strategy was found to be inadequate. This was often due to errors in the computer vision routine (inaccurate measurements or failure to detect the colored glove), or in lack of human attention during robotic gesturing (failing to intercept the message).

The final discovery made during the study was related to those periods of the co-creation process where the robotic system was engaged in computation of visual input data and their implications for the design system and the following fabrication process. In these periods (4-5 sec. on average, but longer when errors occurred during the computer vision routine) a lack of visual feedback was observed to cause frustration and impatience in the human co-worker. Not knowing what one's teammate is thinking can be seen in normal human-human teamwork, but not knowing if one's teammate is thinking, is not common. During the study this was addressed through the implementation of externalized "mental activity", more specifically by communicating the occurrence of computational activity through the existing LED lights integrated around the wrist of the robotic arm – when lights are on the robot is thinking.

DISCUSSION

Human-robot co-creation processes, as argued in this research, have the potential of incorporating material variations, thereby supporting increased use of both biogenic and reused materials within the built environment. To advance the understanding and application of material variation, the study investigates the development of an interactive fabrication setup that supports co-creation workflows between craftsman, robot, computational design system, and non-homogenous materials.

Distributed design intentions

Through exploration of novel methods for human-robot co-creation, the study seeks to change the way robots are treated within the field of architecture and the built environment. As described in the Introduction, research in computational design and robotic fabrication has, in recent years, shifted towards more adaptable and non-deterministic manufacturing strategies. This development entails the integration and appreciation of robots as more than mere tools, but rather as agents with the ability to sense and adapt to new situations. However, when adopting an agent-based view of robots it is essential to point out that their adaptive abilities only apply to pre-anticipated situations (Murphy, 2019). In other words, and relating to this study, robotic agent can only react and adapt to events that are anticipated and built into the robotic system in advance. In this case the recognition of, and adaptation to, varying material dimensions.

As previously described, in creating a design method for human-robot co-creation the study seeks to distribute both skills and design intentions within the human-robot team. In the study, the intentions assigned to the robotic agent are based on a skillset featuring computer vision, computation and data management, and the precise gripping and positioning of physical objects. This entails that the decision-making capabilities of the robotic agent are hard-coded into the digital design model, thereby predefining all possible robotic actions. While the study argues that the distribution of design intentions and decision-making capabilities affords a reduction in the cognitive load imposed on the human agent, it remains that the creative potential of the human-robot co-creation process solely relies on human intelligence – the robot fails to act as an intelligent co-creator.

So how can we advance the human-robot design framework to truly incorporate shared co-creation processes? The solution might be found in the definition of what design is. As argued by Research Professor John Gero:

> "Any notion of design that does not include learning is bound to be deemed unintelligent. In design, unlike in fields which rely on deductive processes, getting the same solution twice for the same problem is considered a failure." (Gero, 1991, p. 2)

This argument strongly implies that achieving a collaborative and creative design process entails that all agents (humans and robots) should possess learning capabilities. The solution to this challenge is the implementation of artificial intelligence. AI, especially the sub-field related to machine learning, has already infiltrated the AEC sector (*Spacemaker AI*, 2021; *Finch*, 2021; *Higharc*, 2021) and research in the field of robotic fabrication in architecture has showcased that the integration of machine learning methods can "extend the adaptation of design and fabrication information into the fabrication process", thereby "establishing a continuous feedback loop between making and learning." (Tamke, Nicholas and Zwierzycki, 2018). By integrating artificial intelligence, the co-creation framework can become: "equipped with comparable learning capabilities, allowing a parallel acquisition of design knowledge." (Jensen, 2021, p. 213). If such capacity for learning was integrated into the co-creation framework, the robotic arm would exceed the role of a tool as well as that of an adaptive agent. Instead, it could potentially become a collaborating partner within a joint cognitive system - enabling the human agent to: "share authorship in the act of designing, evaluating and materialising architecture." (Wit et al., 2018, p. 246).

Evolve-on-site

In current architectural practice, detailed computer-aided construction drawings generally act as legal documents, accurately specifying the construction of a given building. In the effort of reducing unforeseen challenges and complying with industrialized norms, material variation is often neutralized. In addition, the high accuracy of CAD and BIM modeling can induce a blinding effect, hiding the variation and quality of applied materials, leading to overdetermination (Sennett, 2008). As a result of reoccurring construction challenges caused by overdetermination, a principle described as solve-on-site (SOS) has advocated for a positive approach to the incomplete (Scheurer, 2017). By utilizing computational design and digital fabrication this approach seeks to embrace unpredictability and allow corrections and adaptations to occur during construction. However, while the principles of solve-on-site support the solving of unexpected problems, it doesn't address the source of the problems, namely the overdetermined digital design models preconceived by the architect.

If architects, through their digital models, could embrace and incorporate indeterministic strategies, focusing not on the specification of individual elements, but instead on defining essential boundary conditions and desired performance requirements, creative agency could be transferred to the building site. Here the robot-assisted craftsman could be given the creative freedom to imbed material sensitivity and embodied knowledge to the fabrication of build architecture. The deliberate exploitation of shared human-robot sensitivity, adaptability, decision-making, and execution could support an increased implementation of reused and biogenic materials - addressing the challenges associated with complex material variation. Instead of trying to solve construction problems on-site, humans and robots could collaborate in a creative strategy to evolve-on-site.

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