Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-site Robotic Plastering

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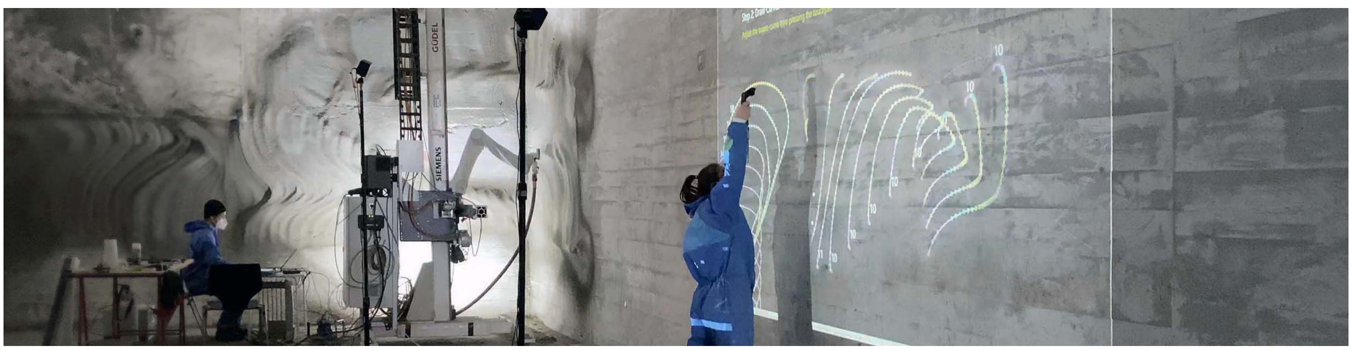

Figure 1: *IRoP* is an interactive robotic plastering system enabling users to fabricate and design unique plasterwork in-situ.

ABSTRACT

This paper presents Interactive Robotic Plastering (*IRoP*), a system enabling designers and skilled workers to engage intuitively with an in-situ robotic plastering process. The research combines three elements: interactive design tools, an augmented reality interface, and a robotic spraying system. Plastering is a complex process relying on tacit knowledge and craftsmanship, making it difficult to simulate and automate. However, our system utilizes a controller-based interaction system to enable diverse users to interactively create articulated plasterwork in-situ. A customizable computational toolset converts human intentions into robotic motions while respecting robotic and material constraints. To accomplish this, we developed both an interactive computational model to translate the data from a motion-tracking system into robotic trajectories using design and editing tools as well as an audio-visual guidance system for in-situ projection. We then conducted two user-studies of designers and skilled workers who used *IRoP* to design and fabricate a full-scale demonstrator.

CCS CONCEPTS

• **Applied computing → Computer-aided design**; • **Human-centered computing → Mixed / augmented reality**; *User interface programming*.

KEYWORDS

interactive fabrication, augmented reality, robot, digital fabrication

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1 INTRODUCTION

In the past decade, robotic fabrication in architecture, engineering, and construction (AEC) has made remarkable advances, leading to significant improvements in customization of construction, production speed, and precision, as well as opening up new design opportunities [14, 18, 27, 46, 72]. However, most robotic construction processes are based on well-defined and linear sequences of actions where the work environment, materials, and processes are unambiguous and predictable.

Construction processes involving complex or soft material systems, such as concrete, plaster, or clay face many challenges that make their automation difficult. An example of such a difficult-to-automate process is robotic plastering. The malleability of plaster is difficult to control, as it changes from a liquid to a solid-state during processing. This change is influenced by several parameters, including ambient temperature, material composition, and spray parameters. Even with the most advanced digital modeling and rendering software, the behavior of such a malleable material is difficult to simulate [44, 52, 69]. Moreover, advanced rendering and visualization environments still fail to convey the same depth, texture, and sense of materiality that can be achieved through manual handling and tacit user interaction [30]. Yet, the application of robotic plastering could help to create more controllable, repeatable, and precise surfaces and would rely less on strenuous physical labor. Therefore, plastering is an excellent example of a construction trade that would greatly benefit from combining craft-specific knowledge, tacit interaction, and robotic fabrication to define novel design potentials and process innovations.

One potential solution to the difficulties posed by materials like plaster, would be a balanced combination of human interaction with robotics and digital technology. Such collaborative systems could leverage the unique strengths of both machine precision and human tacit knowledge. The potential and need for such human-in-the-loop processes are clear, but so far, only few studies [37, 38] have examined how to include humans in larger-scale robotic fabrication. Furthermore, human-in-the-loop processes in AEC are still perceived as a limitation rather than as a source of potential. There are several reasons for the scarcity of research on this topic in AEC. One of them is the lack of understanding of the complexity of bringing full automation into an unstructured environment like the construction site. Another reason is that industrial robots have only limited options for user interface customization [2], which makes it challenging to develop customizable and intuitive craft-specific interfaces for robotic processes in construction. In summary, most research on robot manufacturing in architecture is aimed at full automation, which excludes any aesthetic and technical potential of human-in-the-loop manufacturing.

The aesthetic potential of such processes is strongly linked to the physical participation of the human during the fabrication process. Studies on the importance of physical participation in digital and robotic processes touch on concepts of interactive fabrication [51, 71] and digital embodiment [35], as well as emphasizing the close connection between physical action and cognition in the design process [56, 62]. In particular, direct engagement with the material can serve as a fundamental cognitive resource for designers and skilled workers [63]. An interactive robotic fabrication workflow coupled with a customizable design interface could help designers and skilled workers intuitively learn and manipulate complex design and manufacturing processes. In addition, such tools could minimize the background knowledge needed to program such a robotic process.

This paper presents such a system for plastering, the Interactive Robotic Plastering system (*IRoP*), which enables users to engage intuitively with an in-situ robotic plastering process. The system combines a robotic spraying setup with a controller-based interaction system and an augmented reality interface. The proposed method utilizes the controller's movements to program intricate robotic spray paths (robot trajectories), thus capitalizing on the embodied knowledge of designers and skilled workers. The system developed here allows users to design complex digital models in minutes, rapidly generate multiple design alternatives, and instruct a robot by demonstration.

This research is developed for robotic and computational applications in AEC, which has stakeholders with a broad range of knowledge and skills. The target user-group for this system includes both designers and skilled workers. We use the term skilled worker to refer to a craftsperson who has extensive plastering knowledge but limited robotic programming experience. The term designer includes individuals specialized in computation and the creative use of robotics for architecture fabrication with diverse levels of computational and robotic competence.

Specifically, the contributions of this paper are:

(1) a novel method for on-site robotic plastering that uses programming by demonstration to define complex robotic trajectories (spray paths) and fabrication parameters. This method proposes a projection-based augmented reality interface for taking design decisions and previewing their effects on the fly.
(2) a full-scale demonstrator and user-study conducted with 18 designers validating the hypothesis that enabling design decisions during fabrication can provide new opportunities for future crafting and as presented in this paper can lead to novel forms of creative expression.
(3) a user-study with skilled workers demonstrating that this system can substantially simplify the programming of robotic fabrication and thus make robotic fabrication accessible for users with no or little prior knowledge of robotics. The results of this approach suggest that we can use controller-tracking in combination with projection mapping as an interactive design tool for on-site robot manufacturing.

This paper is structured as follows: We begin by reviewing human-guided machine fabrication, robotic plastering, and projection based augmented reality. The method section then introduces the system architecture, presenting how the system works, the necessary hardware components, and a description of the software features. More specifically, we focus on the customizable computational toolset, the motion-tracking system, the set of design and editing tools that can remap user input to robotic spray paths, and the audio-visual guidance system for on-site projection. In results, we present two experimental studies: one with designers and one with skilled workers. Study 1 shows how designers explored the design pipeline of *IRoP* and interactively designed and fabricated a large-scale architectural implementation. Study 2 evaluated the usability of *IRoP* by conducting a user-study with skilled workers. In conclusion, we discuss our findings, limitations and potential future investigations.

2 BACKGROUND

The following sections describe how our research builds upon existing work in exploring new modes of human-guided machine fabrication, robotic plastering, and projection-based augmented reality.

2.1 Human-guided machine fabrication

Human-guided machine fabrication in digital fabrication describes a system in which a user provides an input to the fabrication system and a machine responds with a physical feedback, allowing for direct manipulation of a physical form during fabrication [9, 71]. The user's physical actions are sensed through an interactive interface and interpreted in real-time. This workflow allows for a semi-autonomous fabrication processes, where the user can either physically handcraft with machine precision or interactively change the design outcome during fabrication.

2.1.1 Handcrafting with machine precision: A way to offer a hands-on fabrication experience is to use devices which correct users' physical movements by providing real-time feedback on design outlines and constraints. Projects such as "FreeD" [79], "Protopiper" [1], "Human-in-the-loop Fabrication of 3D Surfaces with Natural Tree Branches" [39], "Adroid" [65] and the "Shapertool" [60] show how the additional automated actuation and correction mechanisms of a tool can enable safer handcrafting with machine precision. However, these systems focus primarily on reproducing a digital model in physical space and do not support interactive design in 3D from scratch. Another limiting factor of those systems for architecture is that they are designed to manipulate objects on a relatively small scale.

2.1.2 Interactive fabrication: Several systems explore interactive fabrication in which humans can intervene creatively in the digital design and fabrication process. For example, "ReForm" [68] shows how users can manually alter clay forms to influence the digital design process. "Spatial sketch" [70] allows users to sketch in 3D and to transform the digital sketch into real world objects. Other systems also combine robotic fabrication and human interaction to fabricate larger scale artefacts. "The Endless Wall" by Gramazio Kohler Research [29] allows a user to change the design of a robotically assembled brick wall by adjusting a line in-situ. "RoMA" [54]) allows users to interrupt a robotic printing process to adjust the design while fabricating. Finally, in the project "FormFab" [51], users can change the surface curvature of a plastic sheet in real-time using reversed vacuum-forming techniques. These systems enable the human to intervene creatively in the fabrication process, but they do not apply any constraints to the human input or provide information to the user about potential failure or the constraints of the machine, structure, or material. "RobotSculptor" [45] is an interactive robotic fabrication system that allows users to fabricate clay models using a robotic arm, while providing design, and fabrication constraints. This system enables creative expression through user's definition of sculpting area, stroke direction, density, and tool selection. However, the user still interacts with a graphical user interface, not with the workpiece itself, which leaves out the creative potential that a hybrid design and fabrication environment could offer.

2.1.3 Robotic Fabrication with soft materials: Robotic fabrication processes with soft materials often require human interaction and supervision to validate results and to facilitate automation. Projects such as "Meshmould" [28] and Soil 3D-printing [49] combine a robotic process with manual fabrication steps, while "Smart Dynamic Casting" [43], "Shotcrete 3D Printing" [42], and research in 3D concrete printing such as [75] use sensory feedback to inform users about material performance. All these processes require human participation in the robotic process for either material deposition, quality control, or finishing. However, they do not explore human interaction for providing feedback on potential structural or material failures and do not enable direct process intervention.

2.1.4 Creative programming by demonstration: To allow human guided machine fabrication through direct tacit interaction, this research focuses on programming by demonstration (PbD). PbD is an end-user development technique for teaching a computer or a robot new behaviors and tasks [11]. Instead of conventional machine command programming utilizing CAD software, the user directly demonstrates the desired motion trajectory through actions. This demonstration can happen through vision [5, 34, 36], data gloves [66], controllers [8], or kinesthetic teaching (i.e., by manually guiding the robot's arms through the motion) [31]. Such systems shift the programming power from the professional programmer to the end-user but focus mostly on pure guidance for automation processes. Projects such as "Adaptive Robotic Carving" [16] and "Seeing is Doing" [6] show how PbD can allow skilled workers with limited programming skills to transfer their techniques and knowledge to the machine. However, these systems do not allow users to interactively fabricate or design on-the-fly. In contrast, *IRoP* focuses on controller based PbD to instruct a plastering robot based on user interaction, and thus it has the potential to enable designers and skilled workers to interact with computationally difficult technology.

2.2 Robotic plastering

Plaster is typically used for interiors, on ceilings, walls, or on facades. It has diverse roles ranging from protecting the building structure to improving the acoustic performance of spaces by making use of the tree-dimensionality of the material. The latter inherently includes visual and ornamental qualities. When generating ornaments with plaster, traditionally, customized tools or running moulds are used [48]. Early research on automation in the 1990s [25, 58, 61] and several contemporary academic research projects and start-ups have been exploring the robotic application of plaster. Such processes target the reduction of the dependence on manual labor addressing to automate a standardized plastering process [13, 26]. Furthermore, there have been research on robotic plastering, which focuses on exploring material formation, ranging from smooth to articulated surfaces [7]. These systems show the potential of creating novel forms of plasterwork through robotic plastering. However, none of the previous examples have implemented an interactive fabrication system or allowed a plasterer to interact directly with a robot in a shared workspace. Furthermore, they lack real-time feedback during the fabrication process that could alert the user of material and structural failures.

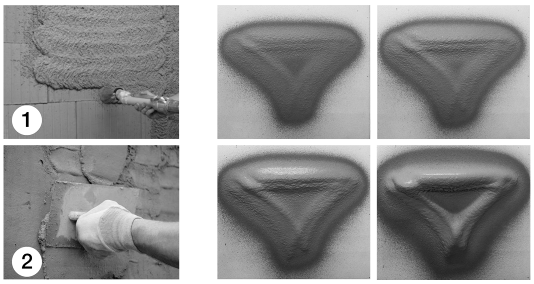

Figure 2: Left: (1) Manual spraying of the material (2) and smoothing, leveling or shaping with additional tools. Right: Robotic Plaster Spraying, an adaptive thin-layer printing technique, building a volumetric formation without any additional formwork or support structures.

In this paper we will use the process of "Robotic Plaster Spraying" (*RPS*), which creates plasterwork through an adaptive thin-layer printing technique. This technique involves spraying multiple, millimeter-thin layers of plaster on existing building elements in order to incrementally build-up volumetric formations (Fig. 2, right [24]). A typical manual plastering process consists of (1) manual spraying of the material (2) and smoothing, leveling or shaping with additional tools (Fig. 2, left [23]). In comparison to the manual spraying of plaster, robotic plaster spraying combines spraying and shaping of the material in one process step, which makes it a repeatable and scalable process. This is achieved by digitally controlling specific fabrication parameters, such as the robotic arm's distance, angle, and speed. Furthermore, *RPS* allows for an adaptive process control by using sensory feedback. Such a robotic plastering process shows the potential of making plastering efficient for standard and non-standard construction by promising up to 50% of material savings. Moreover, the process can create complex volumetric plasterwork without the need of any additional formwork or support structures.

Our goal in the presented work is to combine the process of "Robotic Plaster Spraying" with an interactive fabrication system using a projection based augmented reality system enabling users to intuitively program a robot by demonstration using real-time feedback.

2.3 Projection-based augmented reality:

Recent advances in immersive and augmented technologies allow users to receive fabrication related information on-site, introducing novel forms of interaction between the physical and the digital realm for fabrication and construction. The overlay of the actual, physical environment with computer-generated images is known as augmented reality (AR). AR systems usually accomplish this combination of the real and virtual world via optical or video technologies, which carry both advantages and disadvantages [4]. Video technologies usually overlay a live video onto the physical world, most commonly on a display, or a mobile device such as a tablet or smartphone [3, 19, 50]. The overlayed graphics are updated continuously to appear to be inserted into the real-world. This approach has the disadvantage that it might divert attention away from the site condition as the user focuses on watching the screen or mobile phone display. Optical systems such as head-mounted displays (HMD), address this shortcoming but require very expensive and sensitive equipment that is not ideal for unstructured environments, rough handling, dirt, and dust of a construction site [12, 32]. An alternative approach to achieve direct viewing of digital content on the physical world is to use projection-based augmented reality. Research exploring projection mapping ranges from small-scale projection [74] to room size projection mapping [76]. Several examples show how large-scale projections can cover entire surfaces and rooms [10, 33, 73].

Some researchers have explored using a motorized platform to reorient a single projector and camera to view arbitrary locations throughout a room and to avoid being limited by the field of view of a single projector [15, 17, 21, 57]. Pevzner et. al. [55] focus on wall plastering, discussing how projection and scanning technology could provide workers with real-time information and feedback on the quality and accuracy of wall plastering. *IRoP* takes this approach of room size projection mapping for human instruction of complex materials further and links it with an interactive design system for large-scale robotic fabrication.

3 INTERACTIVE ROBOTIC PLASTERING

The research presented in section 2 highlights how programming by demonstration can be used to explore interactive design and engage users creatively in the fabrication process. However, state of the art human-guided machine fabrication systems described in 2.1 either reproduce a digital model in physical space or implement open-ended systems with minimal constraints. *IRoP* aims to combine such an interactive design system with robotic plastering to translate human intentions into robotic motions via programming by demonstration. While most systems rely on predefined 3D models, *IRoP* uses data from users combined with robotic and material constraints to design 3D models from scratch. As such, this system capitalizes on the intuition of the human user while still leveraging the power of machine precision and computational iteration. The method of this research can be largely defined as Research through Design [78] involving two user groups: designers and skilled workers. The research findings emerged through physical experimentation.

Walkthrough: *IRoP* is designed around three different key modes that assist a user in interactively designing a plastered surface and output the necessary robotic spray paths, starting with *1. Stylistic filter selection*, *2. Interactive design mode* and *3. Robotic plaster spraying* (Fig. 3). After selecting a stylistic filter, users can use the computational model in the interactive design mode which includes three steps: *Localize, Design* and *Adjust.* During the interactive mode the user is instructed by an audio-visual guidance system. Figure 4 shows the hardware components of *IRoP* starting with the computational setup, the user interaction-tracking system with projection mapping, and the robotic fabrication setup. Furthermore,

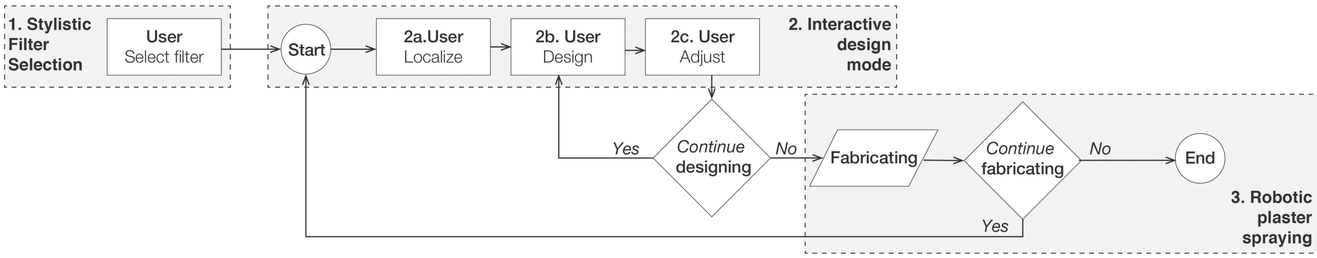

Figure 3: The design and fabrication workflow designed around three key modes.

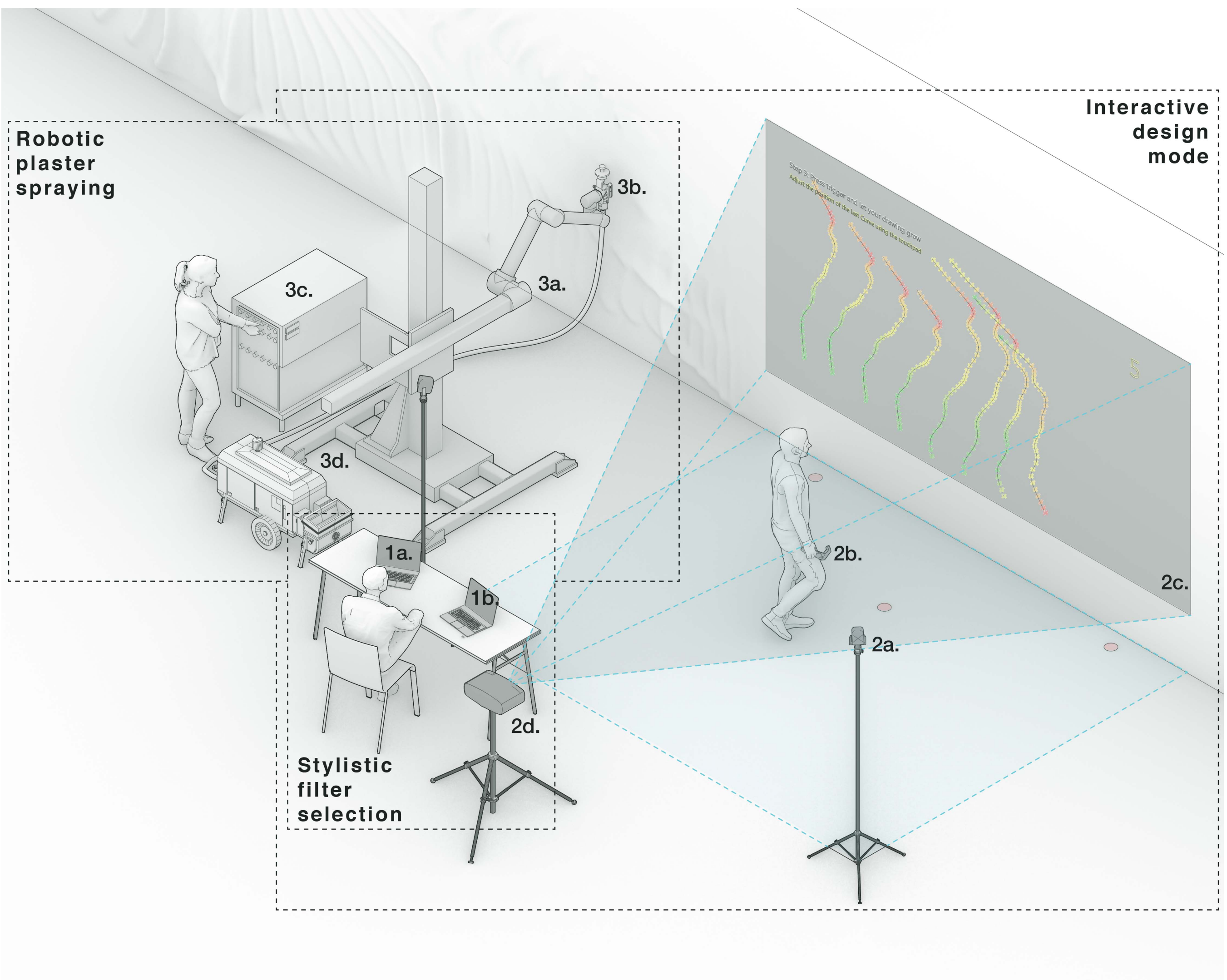

Figure 4: System architecture: computational setup (1a, b), the user interaction-tracking system with projection mapping (2a-d), robotic fabrication setup (3a-d)

the graphic shows that the user and the robotic arm are situated next to each other, where the 3D design is first interactively designed and then fabricated. To illustrate a typical interaction using the *IRoP* system, we consider the case of a designer fabricating a custom interior plaster element from scratch as shown in Figure 5. The user follows a routine of alternating between interactive design and fabrication sessions.

Figure 5: (A) Selection of filter (B) localization (C) designing, adjusting the design (D) robotic spraying.

Selection of a stylistic filter (Fig. 5: A): Before the start of an interactive design session the user can choose different stylistic mapping methods, which we refer to as stylistic filters. The term filter is chosen in reference to image-filters [47] used in digital image processing and graphical software such as Photoshop[1]. These filters describe a technique to alter the characteristics of 2D or 3D images by changing the colors of the pixels as well as adding a variety of special effects. In *IRoP* a similar logic is applied to translate and remap analogue human input into robotic output such that it complies with material and machine constraints. These constraints include parameters such as maximum joint accelerations, robotic reachability, and other locally manipulated process parameters. The underlaying computational model of the filters is based on the idea of a synthesizer, where the analogue input of the user, such as controller position and orientation, can be adjusted and transformed according to a set of different aesthetics and styles. Different filters result in different plaster surfaces, allowing users to choose how their input is stylized. Furthermore, users can extend the skeleton of the interactive computational model by creating custom filters to adjust for different requirements. The resulting robotic spray paths and additional important fabrication data are visualized as line drawings on the wall in real-time via an audio-visual guidance system (see Fig. 6).

[1]Adobe Photoshop is a raster graphics editor developed and published by Adobe Inc.

Localize (Fig. 5: B): After selecting a filter, the user first localizes the motion tracking system by registering the controller position at pre-measured area points in the physical space.

Design (Fig. 5: C): In the *Design* step the user can record the position of the hand-held device by pressing the trigger on the controller. Depending on the filter system chosen, these positions can then be used to create geometry (points, curves), manipulate a surface, or generate a pattern. In the example shown in Figure 5 C, the positions of the handheld device were used to create points and interpolated curves to design the plaster surface. As the user selected the "tween" filter, the system offsets the hand-drawn guide curves in real-time by making the distance between the curves smaller or bigger. Using the same interaction steps, the user adds more lines to fill the wall segment.

Adjust (Fig. 5: C): Since the user is drawing in 1:1 scale, the user can transform the design in the "adjustment step" by scaling, moving, and extending it. This feature allows the user to reach areas that otherwise could not be reached, such as ceilings and high wall areas.

Robotic Plaster Spraying (Fig. 5: D): In the last step, the user approves the design outcome and exports the spray paths (robot trajectories) to start the robotic spraying process. The robot trajectories are simulated before they are executed, thus allowing the user to preview a safe and feasible robot motion within the work envelope. Next, the user mixes the plaster and when the wet material is ready to be sprayed, it is fed into the pumping and spraying system. The user starts the spraying process by sending the robot trajectories to the robot controller for execution, which drives the material flow (spraying) and pumping. After finishing a sprayed segment, the user either continues fabricating or ends the process. If the user decides to continue fabricating, the system advances to the scanning step, which adapts the robot trajectories. To acquire the geometry of the current state of a target surface, an *Intel RealSense Depth Camera D455*, mounted on the pneumatic spray gun is used. The robot trajectories are adapted after each spraying iteration by projecting them onto the current state of the target surface. This results in an adjustment of the desired spraying distance and angle.

The next sections describe the hardware and software components of the system in more detail.

3.1 System Setup:

The system architecture, as displayed in Figure 4, consists of three main parts: (1) computational setup (2) the user interaction-tracking system with projection mapping, and (3) the robotic fabrication setup.

3.1.1 User Interaction-Tracking system: For the user interaction tracking system, we used an *HTC VIVE* with two base stations (lighthouses)(Fig. 6: 2a), one controller (Fig. 6: 2b), and two computers. Computer A (Fig. 6: 1a) is used to render the visualization and run the customizable interactive computational model. Computer B (Fig. 6: 1b) is used to send and receive the sensor data. We chose the *HTC VIVE* tracking setup, as the precision for indoor tracking is under 5mm and the system costs less than custom built setups.

3.1.2 Projection mapping: An angled adjustable projector (Fig. 6: 2d) was used as an augmented interactive interface. We used a standard projector with 2000 lumen, which was fixed on a tripod and projected frontally onto the wall (Fig. 4: 2c). The position of the projector was registered in the digital model and was used as a camera position for projection.

3.1.3 Robotic plaster spraying setup: The overall robotic fabrication setup includes a 6-DoF, collaborative robotic arm (*UR10*) (Fig. 6: 3a), a pneumatic (plastering) spray gun (Fig. 6: 3b), an *Intel RealSense Depth Camera D455*, a *Collomatic Collomix XM2* mixer, a modified *PFT Swing L* pump (Fig. 6: 3d), and a *Kaeser SXC* series compressed air system. The material used is a base coat, lime-cement plaster that is fed into the pneumatic spray gun by the pumping system, which is driven by the *UR10* robot controller. The robot is mounted on two external axis (Fig. 6: 3c) that extend the working space of the *UR10*. For the global localization of the external axis tower in a room, we use a total station.

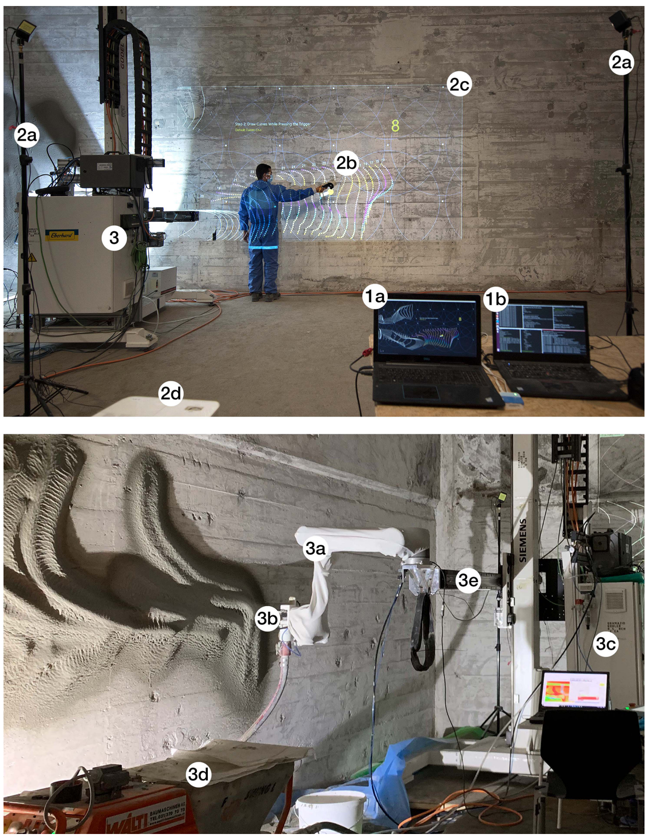

Figure 6: User interaction-tracking system including visualization computer (1a), *ROS* master (1b), *VIVE* tracking system (2a), controller (2b), projection mapping (2c), projector (2d); Right: Robotic fabrication setup including *UR10* robotic arm (3a), spray gun (3b), controller box (3c), pump (3d), external axis (3e).

3.2 Interactive computational model:

At the core of the interactive computational model is the (1) tracking of user input (2) remapping of the analogue human input to robotic output and (3) generating of trajectories for the robotic arm. The computational framework is set up in *Python* and *Grasshopper*[2], and the visualization happens in the 3D modelling software *Rhinoceros*[3]

3.2.1 Tracking of user input: A necessary component for the user interaction-tracking system described in 3.1 is a scalable, near real-time communication system for connecting multiple devices and back-end computational processes, which in this case was achieved utilizing a *ROS* publish-and-subscribe architecture and the rosbridge package [59]. The interactive computational model receives as an input the *HTC VIVE* controller 6DoF location and orientation as well as the button and trackpad information of the controller. To access the *HTC VIVE* localization on *ROS* we used the *OpenVR SDK* and a *ROS* package for publishing device locations using *robosavy*. The *ROS* node interfaces with the *OpenVR SDK* to obtain the position of each device.

The user starts recording the tracking by pressing the trigger on the controller, which stores the position and rotation of the controller as frames defined by an origin point and two orthonormal base vectors. Depending on the chosen filter system, these frames can then be used in different ways.

3.2.2 Remapping of human input to robotic trajectories: At the beginning of the process, the user could choose different filter systems to translate the human input into different robot outputs. In the computational model, the unaltered recorded controller poses (position and orientation) are stored as a list of frames (origin point, x-axis, y-axis) in a `filter_base` class. The `filter_base` class first transforms and scales these recorded frames from the VIVE coordinate system to the model coordinate system. Second, it trims the beginning and end of each frame list to filter out noise. Custom filters are methods in the `filters` class that remap spatial human inputs to machine outputs (Fig. 7). Different filters allow the user to either specify a more direct robotic action or create more generative designs driven by user input.

The hand's position in space (P), hand distance to a target surface (D), and gesture velocity (V_h) are translated respectively to robot target planes (T), end-effector distance to a target surface (E_d), and velocity of the trajectory (V) (see Table 1). The distance and velocity values are remapped between tested key parameters that were defined using empirical testing. The hand distance D is remapped between 200mm and 500mm end-effector distance E_d. Therefore, the closer the user's hand is to the target surface, the smaller the distance of the end-effector to the target surface. This results in a unique rippling pattern for smaller distances as the air pressure from the nozzle of the pneumatic spray gun displaces the wet plaster resulting in a carving effect (see Fig. 8). Therefore, D also influences the height of plaster deposited for each layer.

Furthermore D influences also L_n, the number of layers that need to be sprayed to achieve a specific geometry or pattern. A parameter that influences the amount of material deposited is the

[2]Grasshopper is a visual programming language and environment that runs within the software *Rhinoceros*
[3]Rhinoceros is a 3D computer graphics and computer-aided design (CAD) software developed by McNeel and Associates

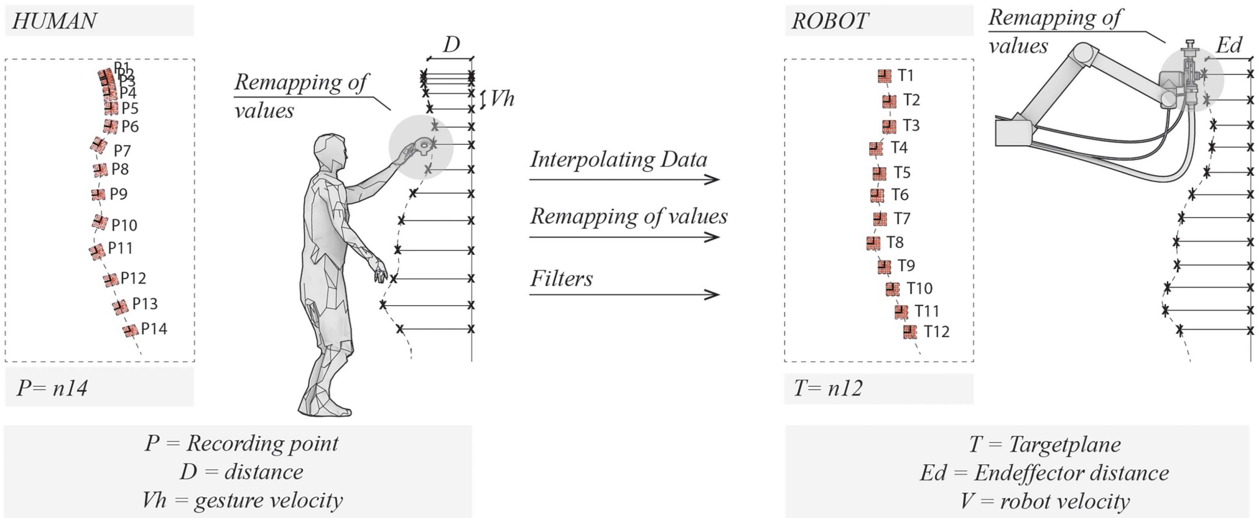

Figure 7: Translation of human input to robotic trajectories via interpolation and remapping of gesture input data to fabrication output data: $P \rightarrow T$; $D \rightarrow E_d$; $V_h \rightarrow V$

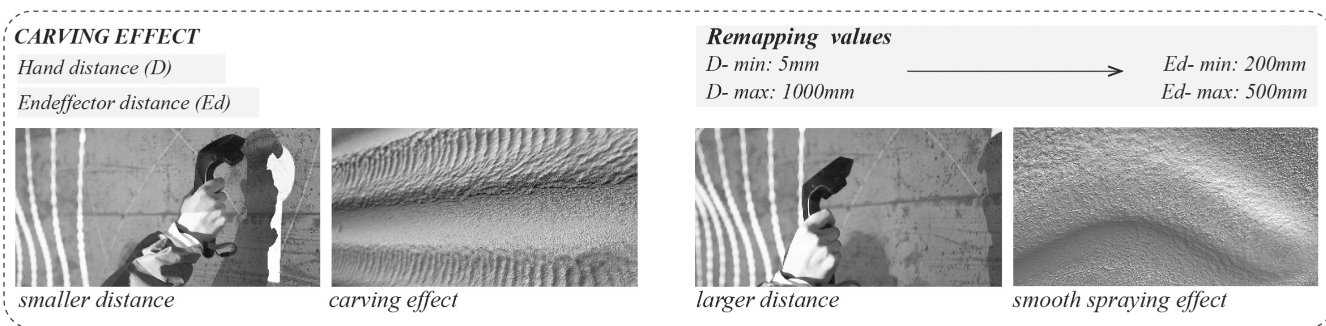

Figure 8: The remapping of the distance value D translates into specific plaster effects as a smaller D results in a smaller E_d leading to a carving effect.

gesture velocity value V_h, which translates to the velocity of the robot's trajectory (V). V_h is remapped between 0.1m/s to 1 m/s of V. High-velocity V_h values result in high V and therefore lead to less material being deposited on the surface. In return, this translates to thinner layers. The end-effector angle is linked to a global variable that is defined at the beginning of each spraying session.

3.2.3 Robot movement: Once the user decides on a design, it is stored in a JSON file format by pressing a button, which is followed by importing it in the fabrication module, to be used by the robot to spray. The fabrication module we are using is built predominately within the open-source framework *COMPAS*[4]. This framework is also used for simulation of the robot trajectories before execution.

3.2.4 Audio-visual Guidance System: IRoP provides an audio-visual guidance system to instruct the user while operating the interactive design mode. As described in the *System Walkthrough*, the interactive design mode has three different substeps with different functionalities: *(1) Localize*, *(2) Design*, and *(3) Adjust*. The audio-visual information changes when the user switches between substeps by pressing a predefined controller button. The user-interface for each

Table 1: Table showing the key remapping parameters

Abbreviation	Explanation	Unit
P	Hand position in space	-
D	Hand distance to target surface	mm
V_h	Gesture velocity	m/s
T	Robot target planes	-
E_d	End-effector distance to target surface	mm
V	Velocity of the trajectory	m/s
L_n	Layer number	-
E_a	End-effector angle	-

[4]https://github.com/compas-dev/compas

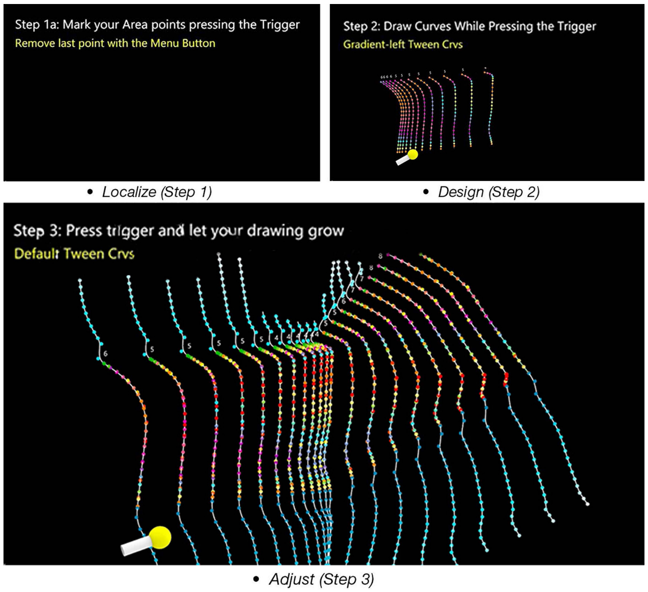

Figure 9: Screen recordings of the different interaction modes: Localize (Step 1); Design (Step 2); Adjust (Step 3).

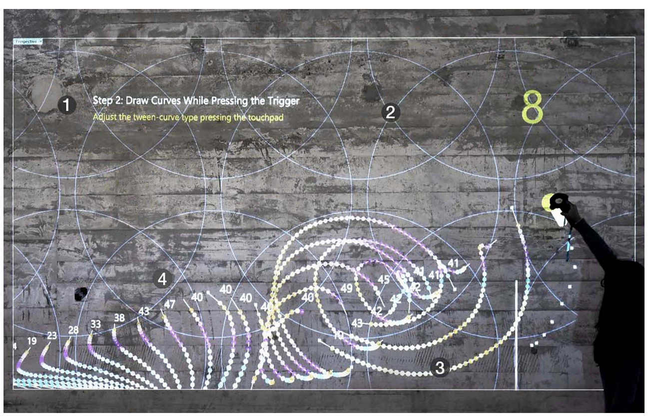

Figure 10: On-site projection mapping of Design step (Step 2): Interface shows fabrication parameters such as information on current (1) interaction mode, (2) robot reach from a stationary position, (3) distance of frames to the wall surface, and (4) number of sprayed layers.

substep has task-relevant information that is projected directly onto the building surface. All three different substeps (Fig. 9) have textual information in the upper left corner of the user-interface instructing the user about the functionalities of the selected step.

IRoP provides the following interactive steps with distinct functionalities:

- Localization step (Step 1) to localize the system
- Design step (Step 2) to design the robot trajectories and sprayed geometry
- Adjustment step (Step 3) to adjust the designed outcome

Localization step: In this step, the user interface does not show any additional visual clues as the system is not yet localized. To instruct the user, we use tones to signal when the user records an area point as described in section 3.

Design step: An abstracted digital controller symbol shows the user the current position of the controller in space, allowing for a real-time experience. Projected fabrication constraints, such as the outlines of the robot reach from a stationary position (Fig. 10: 2), permit a more fabrication informed design. Different gradient-colors visualize the distance of frames to the wall surface, as the input is in 3D (Fig. 10: 3), ranging from purple dots indicating a distance of 5cm to white, which indicates more than 1m. The numbering describes the number of sprayed layers (Fig. 10: 4).

Adjustment step: The adjustment step shows users their extended or moved curves and the resulting updated design.

Audio-guidance: In many process steps, the user needs to direct visual attention to the construction site or the robotic manufacturing process. To overcome the limitations of purely visual cues, along with the visual interface we developed an audio guidance to signal certain events. Figure 11 shows the connection between the different interaction steps and the audio guidance. The audio guidance comes in the form of voice cues and tones. Voice cues alert the user to major events, such as the start of the system *("Welcome to the construction site")*, the localization of the system *("Points are marked, projection is starting")* and the change between the different interaction steps *("You can start drawing", "Use the trackpad to reach higher", "Press trigger to let your drawing grow")*. Tones notify the user of special events within the substeps, for example, indicating that a position has been registered or has been successfully erased.

4 EXPERIMENTS AND RESULTS:

To validate the feasibility of the proposed method and to evaluate and clarify for real application of the interactive fabrication system, we focused on two experiments with different user-groups: designers and skilled workers. The first group, the designers, tested the interactive design model by developing their own filter system and using the set-up to build an articulated base-coat plasterwork. The skilled workers were five plasterers who tested the usability of the setup to evaluate it in a qualitative user-study. In both cases, the experimental setup was used to evaluate the potential and disadvantages of an interactive fabrication system on a larger scale.

4.1 Study 1: Designer

We tested the system and procedure by fabricating a ~110 sqm interior wall design with robotic spraying over a period of 10 working days (Fig. 12). The system setup and procedure was as described in Section 3. Participants were 18 designers (Master students, PhD students and researchers), who are frequent users of digital design and robotic fabrication tools. Four of the 18 participants supervised the usage of the system and were more actively involved in the development of the AR user interface.

4.1.1 Phase 1: Filter development. First, participants developed their own filter system within the synthesizer design framework provided by *IRoP*. The filters were implemented by the participants are shown in Figure 13 and included:

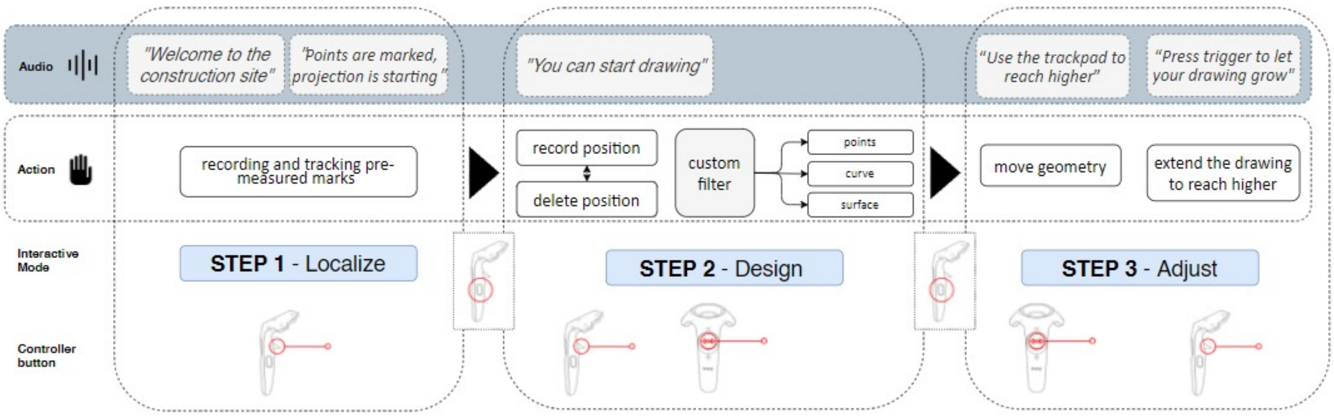

Figure 11: Audio-visual guided fabrication workflow.

Figure 12: Experimental setup showing the design and fabrication routine.

"Hand-drawing" filter: The user can draw in real scale the robotic 3-dimensional trajectories. The distance to a selected surface is translated into the number of sprayed layers for each trajectory.

"Pattern" filter: The user can translate the hand movements into small-scale patterns to populate a target surface. For this different stroke and brush patterns were tested such as circular, curve and hatch patterns.

"Tweening" filter: This filter is defined by user-drawn guide curves which influence a linear pattern infill. The distance between the curves can be adjusted by the user, who chooses between equidistant interpolated, exponentially interpolated, and expressive interpolated curves.

"Sculpting" filter: The sculpting filter allows the user to deform a digital mesh with hand movements. The robotic trajectories are then automatically generated by slicing the deformed mesh. Two types of spray paths were used - one for volume generation and one for texturing. The mesh was sliced vertically, so thicker volume resulted in slower robot movement.

"Agent-based-approach" filter: The user gives directionality and velocity as input to manipulate an agent-based system which fills a target surface. This approach limits user interaction time as the user's control of the design is limited, which at the same time enables efficient design on a large scale.

The participant's filter development proved to us that the system can be used by different designers to develop custom filters. These custom filters allow designers to quickly develop a multitude of geometric articulations. To test the overall workflow of interactive design and fabrication, the same designers were then asked in Phase 2 to use one of the filters to fabricate a custom large scale architectural implementation.

4.1.2 Phase 2: Full-scale Architectural implementation. For the full-scale architectural intervention, the designers chose the "tweening" filter as described in the previous section. Furthermore, participants chose the option to extend the curves using an agent-based approach to reach to the ceiling. As described in section 3, design and fabrication phases alternated on-site. The participants decided to design collectively rather than choosing a single master-drawer.

Localization steps for full-scale implementation: The sensor systems of the interactive design system did not cover the entire room, and the robotic spraying system was not an autonomous mobile system. Therefore both systems had to be manually moved, localized, and calibrated daily to cover the entire room. It was important to enable rapid and precise localization to ensure a smooth and efficient working process.

Localization of the Interactive tracking system: Participants localized the local (*VIVE*) coordinate system (LCS) for each wall element by recording and tracking pre-sprayed, and pre-measured marks on the floor using Step 1 of the software (see Fig. 5:B). Once the input from LCS had been transformed to the global model coordinate system, the drawing procedure was the same as described in section 3. Participants repeated this process after finishing each wall element. Furthermore, we used the projector to validate correct localization by aligning the digital twin of the space onto the physical space as described in section 3.1.

Localization of the robot: The first step in localizing the robot was to setup the total station for defining a world coordinate system (*WCS*) by measuring any two of the ten fixed (pre-recorded) reference points on the walls of the room. After this, a reflector prism

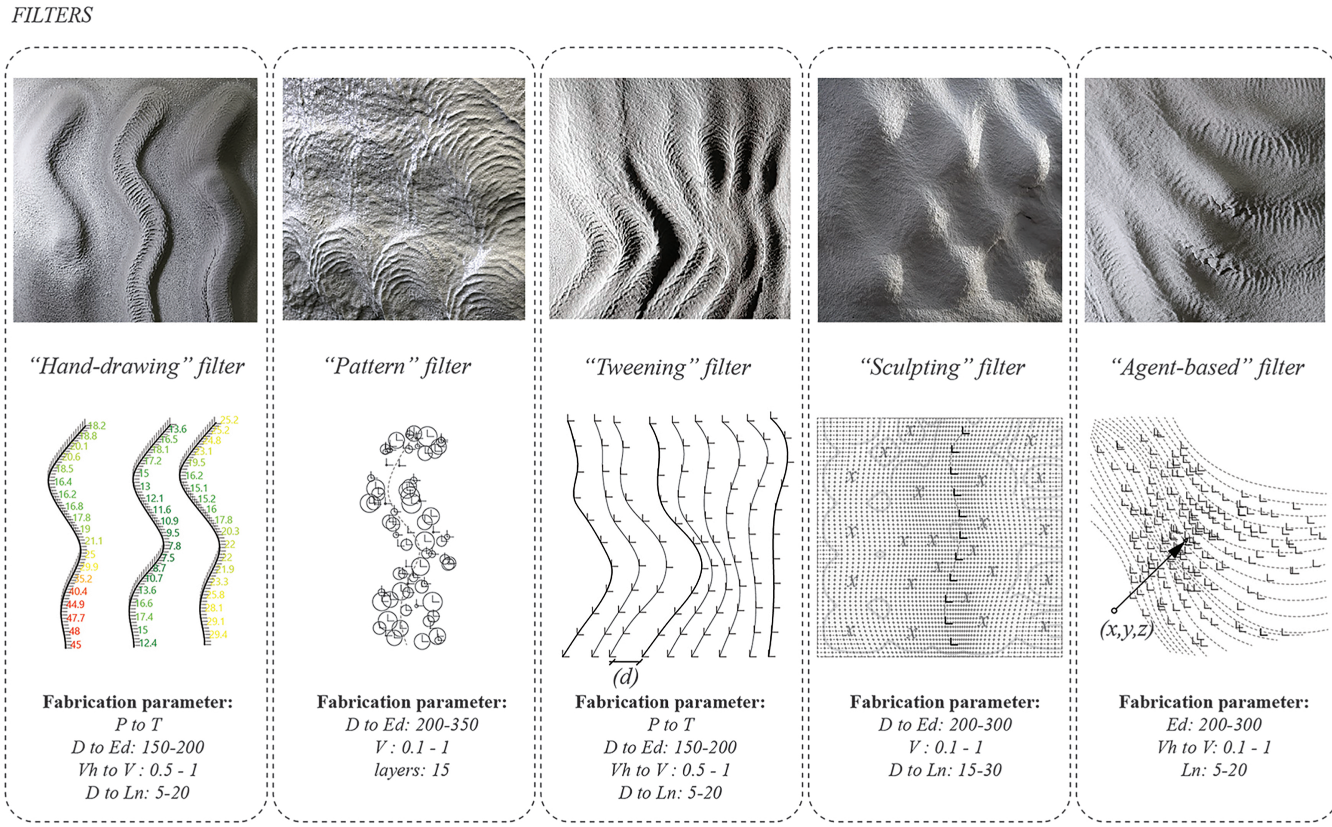

Figure 13: Different filter systems and their distinct translation of human input to machine output.

was mounted on the spray gun (on the robot arm). The position of the reflector prism was measured and recorded for three different points in space, corresponding to three different configurations of the robotic arm. The user chose the first point as the origin of the robot coordinate system *RCS*; the second point as the *X-Axis* of the *RCS*; and the third point as the *Y-Axis* of the *RCS*, defining a 3-point localization method [22]. Then, in the digital building model, the origin of *RCS* stayed unchanged, and the rest of the geometries were transformed, thus transforming the robot trajectories from *WCS* to *RCS*.

The interior space (Fig. 14) was fabricated to facilitate an evaluation of our methods, specifically the instruction of robotic processes via interactive fabrication coupled with an open-ended design system.

4.1.3 User-study: Designer. To assess how designers perceived *IRoP*, we observed behavior and opinions expressed during the fabrication period and developed a questionnaire following the Post-Study System Usability Questionnaire model (PSSUQ) [41] and extended it to include the following questions:

(1) What do you think about the level of abstractness of the visualization?
(2) What do you think about the audio cues of the guidance system?

Additionally the questionnaire offered a comment section for more open-ended notes by the participants.

The PSSUQ (Version 2) consists of 19 items using a 7-point Likert-type Scala. The PSSUQ score starts with 1 (strongly agree) and ends with 7 (strongly disagree). The lower the score, the better the performance and satisfaction. The evaluation of the PSSUQ can further be broken into four categories: Overall score, System Usefulness (SYSUSE), Information Quality (INFOQUAL) and Interface Quality (INTERQUAL). To avoid social desirability bias, the survey was conducted anonymously and in solitude, and before the task, participants were informed about the anonymity of the quiz. Furthermore, participants were instructed that the system and not their performance was under evaluation.

Observations: The most consistent findings involved the change of behavior of the participants during the entire fabrication and design period as well as the importance of audio signals. As the participants decided to not pick a "master-drawer" they used a voting system to define the "winning" design at the end of each section. This voting was first carried out verbally and then shifted to an online platform. We observed that users started to contextualize their design intent by reacting to already existing elements such as wall shapes, cantilevers, and windows. In addition to the abstract interface, we offered participants a visualization software module to predict and preview their design outcomes. However, they soon stopped using the visualization of the volumetric outcome, due to the lack of real-time feedback, as the loading of the mesh was too computationally expensive.

User-study: The most apparent advantage of the system voiced by the participants was the ability to test the design in 1:1 scale directly on the construction site. Participants found the system fun, easy to use and useful for design applications. One participant stated that the wall was treated as a canvas, which helped in the understanding of scale. The most criticized aspects of *IRoP* were the lack of comprehensible error messages and the missing help section.

Abstract augmented reality interface: The general feedback on the abstract visualization was that it is perfect for a knowledgeable user but difficult for a novice. Participants learned to interpret the abstract visualization and intuitively understood its relationship to the potential sprayed outcome. 5/18 participants voiced that they would like to also have a volumetric preview, as the results were in 3D but were visualized only in 2D.

Auditive signals: All participants reacted positive to the auditive signals. The users described the auditive signals as very useful, playful, and informative. One participant proposed using headphones instead of speakers.

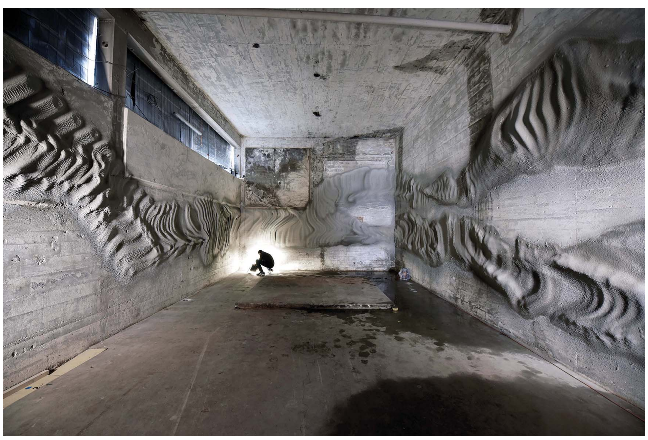

Figure 14: Interior space fabricated solely by using *IRoP*.

4.2 Study 2: Skilled workers

The experimental set-up above tested the implications of *IRoP* for the design and fabrication process, but several questions regarding *IRoP* from the perspective of the skilled worker were left unanswered. Therefore, we tested the usability and the user perception of the system and procedure by conducting a post-session usability study with five skilled workers over a trial period of 15 to 20min for each participant. The setup and procedure was the same as described in section 3, and the skilled workers went through all steps of the interactive mode. Participants were five professional plasterers between the ages of 34 – 54, and none of the skilled workers had any previous knowledge of the system. User performance was studied similar to the user-group designer via observation, as well as a self-reported metrics completed in paper form after the session. Before the task, users were encouraged to think out loud and freely express their opinions and feelings about *IRoP*. This method provides very useful feedback [40], as users might point out flaws that were otherwise completely unknown to the testers and were thus not covered by the questionnaire.

The study aimed at answering the following questions:

(1) Can the system be used by a novice?
(2) Is the system useful for plasterers?
(3) What do plasterers think of the system?
(4) How much did the user's performance improve during the experiment?
(5) How did the interface support an interactive handling of the system?

Additionally the questionnaire offered a comment section for more open-ended notes by the participants.

4.2.1 User-study: Plasterer. After the task completion, users were asked to fill out a paper questionnaire following the PSSUQ model (Fig. 15).

Overall system scored 2.3. Users were excited by the novelty of the system and its game-like features. Frustration level was described as very low, and the gamification elements of the interface were described as fun. Nevertheless, the controller's buttons were described as not sensitive enough for smooth interaction. In addition to the audio and visual interface, users would have liked to have additional tactile signals, such as vibration, to signalize specific aspects of the spraying result. Users proposed that the handle could haptically visualize the 3D movement and strength of spraying via vibration. Furthermore, users found the act of "drawing" to be very intuitive, and easy to learn and use.

System Usefulness scored 2.2, and participants underlined the usefulness of the software as a method to easily attain the desired robotic spraying result.

Information Quality scored 2.8. Users would have liked to have a better explanation with legends and a dedicated help section for novices to understand the system without verbal instructions. Users also wanted error messages to be more explanatory.

Users were very content with the quality and look of the interface, and thus *Information Quality* scored 1.9. Generally, users supported the idea of a pattern catalogue to choose from when designing. In addition to the provided filters, users mentioned that a filter to straighten hand drawn lines and lock specific points of lines would enhance the drawing process. Furthermore, additional functionalities such as a clear regulation of the tween curves and the ability to delete individual curves were requested.

User performance stayed consistent throughout the study, as the skilled workers gained a quick understanding of the system. All participants said that the system can be used by novices.

Although the study only included five plasterers, the feedback was informative enough to strengthen the hypothesis that such a system appeals to plasterers and allows for an easy introduction to robotic fabrication processes on the construction site. Although Spool and Schroeder [64] recommend more than five participants, according to Virzi [67], five users are enough to detect 80 percent of usability problems. Our results, therefore, suggest that such a system is of high interest to skilled workers for implementing robotic processes in their daily tasks. Additional studies should continue to explore different interfaces and user experiences

4.2.2 *Acquiescence bias.* As the additional questions provided in the PSSUQ questionnaire for the skilled workers were formulated in a way that only allowed for a yes or no answer, the results may have been influenced by acquiescence bias. This response bias may have influenced the users to select a more favorable response option. Nevertheless, observing the participants and reading their open-ended comments, we received similar positive cues about system usability and usability for a novice. Therefore, we decided to include these answers in the results. We also found that questions that were more open-ended, such as the comment section, resulted in more insightful and revealing answers in this research stage.

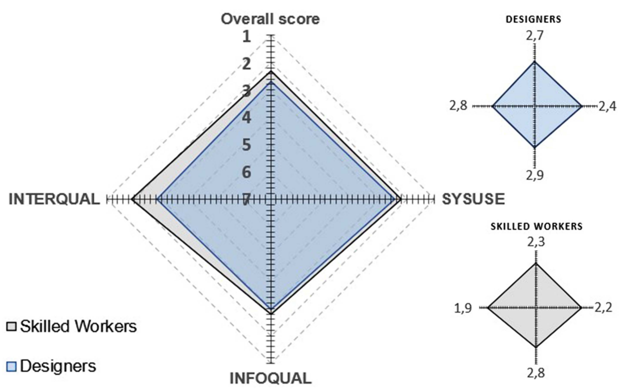

Figure 15: Results of user-study 1: designer and user-study 2: skilled worker.

5 DISCUSSION ON EXPERIMENT RESULTS:

This section discusses the results of all experiments conducted. The field study with designers and the qualitative user research with both designers and skilled workers helped to understand the potential and the qualities of *IRoP*. Our qualitative data helps to understand the motivations, thoughts, and attitudes of the two user-groups. More generally, we have significant evidence that such an interactive fabrication system can be effective in architectural scale fabrication. In the following, we discuss and consider this evidence with respect to three key points: why the system was effective, whether it will be successful in real-world tasks with more functional criteria, and what the potential problems of interactive design during fabrication will be.

Effectiveness of IRoP: The system was well accepted in both studies because the user interaction was real-time, precise, and easy for novices to understand. The frustration level was low in both scenarios and users experienced the interactive design interface as enjoyable. It is important to note that the system can adapt to fit the user's expertise. For example, a designer can customize different filters for the interactive design system and use the robotic spraying setup, and a skilled worker can use the system to program a robotic fabrication process using pre-designed filters. Another advantage is that robotic trajectories can be adjusted for specific special scenarios such as windows, corner situations and special surfaces, enabling users to perform non-standard and personalized fabrication tasks at an architectural scale. The system is intended to facilitate automated robotic processes by allowing a designer or skilled worker to switch between automatic and human-guided mode.

Real-world application: To understand the real-world application of *IRoP*, we need to investigate whether the system can perform required fabrication tasks, utilize low-maintenance technologies, and be expandable to other materials and scenarios.

First, the task performed by the designers and skilled workers in these studies was a creative construction scenario with limited performance and functional requirements. To open the system to real-world applications, we need to extend the developed interactive functionalities of our system to include typical daily tasks of plasterers, e.g. optimized generation of trajectories for the production of flat surfaces for arbitrary and irregularly selected areas. A predictive toolset for the assessment of time and material consumption would be beneficial. Furthermore, the current robotic system can only be manually moved in space and therefore the system has limited spatial freedom and an increased down-time for robot re-positioning. At the same time, re-positioning of the robotic system introduces challenges in maintaining material continuity. A continuous fabrication workflow could be achieved by a mobile robotic setup, which comprises a robotic arm on a mobile platform similar to the "In-Situ Fabricator" [20] or to the setup of the construction robotics startup *CyBe*. Even more continuity and scalability in material deposition could be achieved by synchronizing arm and base movements suggested by [23, 53, 77]. This approach could increase seamless continuity between plaster layers applied on larger surface areas. Furthermore, such a system could enable discrete and continuous fabrication during the continuous movement of the robotic system.

Second, low maintenance technologies are essential for the use of such systems on the construction site. *IRoP* uses a setup (motion tracking system and projector), which supports easy integration, as these technologies are relatively inexpensive and accessible. The *UR* robot is a versatile collaborative industrial robot that allows users to work in proximity and is therefore suitable for human-in-the-loop processes and a wide range of applications.

Third, this paper focuses on plaster spraying, but *IRoP* is suitable for many complex material systems that require manual dexterity and direct observation and thus has a wide range of potential practical use cases.

Benefits of skilled workers using the system: *IRoP* allows users to instruct a robotic process using a handheld device in an interactive design system. With the handheld device, it is possible to capture micro-gestures, resulting in subtle differentiation between the sprayed plaster artifacts. Even though skilled workers are trained to apply plaster by hand, the required knowledge to direct the handheld device differs from their hand-plastering skills. Nevertheless, the system includes multiple steps that would benefit significantly from the plasterers' skills. Plasterers have a broad understanding of the material, the process, know how to monitor it, and have extensive knowledge on how to supervise quality control of finished plaster walls. Furthermore, plastering is a medium of artistic expression, and skilled workers may have a more nuanced understanding of what effects are possible with plaster. Therefore, even though *IRoP* does not fully translate their tactile knowledge into robotic processes, it still helps skilled workers to use their implicit knowledge to inform the robotic process.

The challenges of interactive design during fabrication in architecture: There are, of course, complications in overlapping the design process with the fabrication procedure, including questions regarding integration, authorship, and responsibility. Typically, AEC uses a linear production workflow based on static systems, i.e., plan drawings executed before construction. This type of workflow enables a clear delineation of responsibility between project stakeholders and process stages. *IRoP* does not provide predefined plan drawings, as the result emerges through the interactions of several individuals. In the case of an error, it would be challenging to establish culpability. In addition, construction processes have downstream dependencies. Predefined drawings allow third parties to prepare in advance. For an open-ended design process to be viable, an interactive digital model shared by all parties would be necessary. This networked computational model would need to be updated to the as-built design rather than the desired design. Finally, an interactive fabrication process requires new understandings of shared authorship, as the outcome results from human interaction in combination with developed digital tools and stylistic filters.

6 LIMITATIONS AND FUTURE WORK:

So far, we have tested and introduced five different custom filters. We plan to continue to study and develop those filters and extend them with different variations. Furthermore, different visualization models should be tested, especially volume and mesh visualizations that render and update fast enough for real time interaction.

Although our approach holds some promise, there are several limitations. First, even though skilled workers make design decisions on-site, designers do not usually design on the construction site. By extending the on-site interactive design with a teleoperated design system, we could further extend collaboration possibilities between skilled workers and off-site designers. Second, our robotic system is currently moved manually, and our tracking system has a limited reach of recording. This requires extensive localization and calibration. Therefore, we will focus on including a fully mobile setup for plastering as well as a better motion capturing setup with a broader reach. We are already looking into including motion capture technologies in tracking human gestures. Third, a custom-built handle which includes vibrating information would also support the visual and auditive interface. Finally, our projected augmented reality system is limited by the field of view of the projector. We partially overcame this by introducing multiple static projectors, but this method increased the complexity of our system. To overcome such drawbacks of projected AR systems, we aim to test a mobile projector able to re-orient the projected image according to the new field of view. In this way, we furthermore address the challenge of combining a real-time prediction and visualization tool with a mobile projector system.

7 CONCLUSION

We have developed a system that allows an in-situ robotic plastering process to be used intuitively. This is achieved by combining interactive design tools, an augmented reality interface, and a robotic spraying system. The experimental setup was tested with two different user groups to show that this approach can substantially simplify the programming of robotic processes with complex material systems and capitalize on the intuitive potential of programming by demonstration.

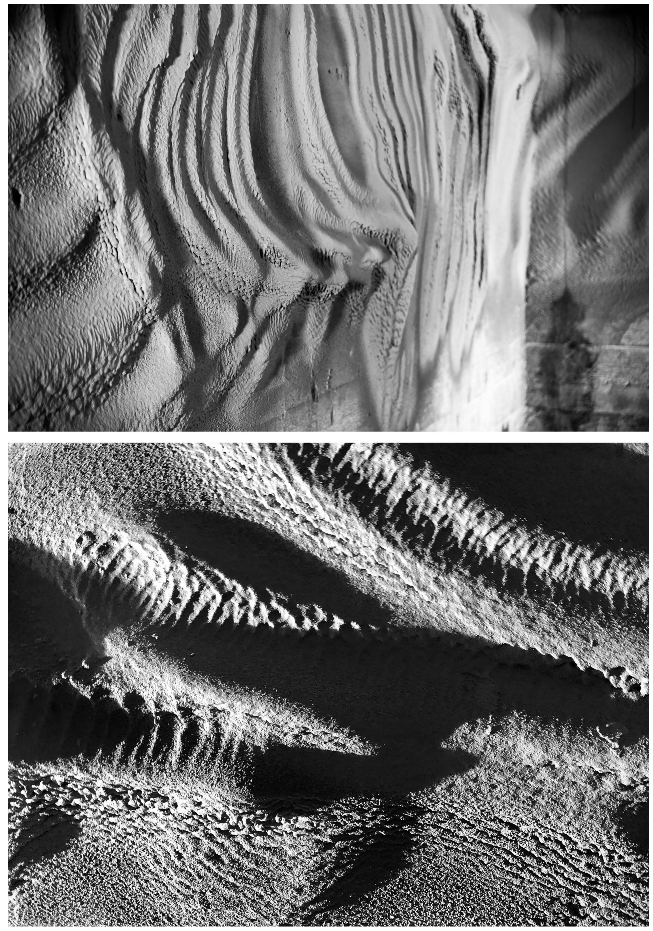

Figure 16: Details of the wall elements showcasing results of micro-gestures.

For these groups, we have arrived at the following conclusions: The plastering process is typically challenging to simulate or preprogram, but *IRoP* enables designers to draft and fabricate articulated plasterwork in-situ with a controller-based interaction system. Our system shows that it is possible to capture micro-gestures that result in custom effects. Furthermore, designers using traditional 3D modeling tools would have most likely not designed such robotic trajectories (see Fig. 16). Thus, such a system contributes to the unique aesthetic qualities of the design outcome, as illustrated in Figure 17. In addition, we demonstrated that fabrication without a master-design but with the selection of specific filters allowed 18 designers to create a space with continuous and consistent aesthetics. In full-scale architectural implementation, we also showed that *IRoP* was suitable for reacting to site conditions on-the-fly. For instance, the designers were able to react to existing elements in the space, such as an uneven surface, a corner, or edge situations. In conclusion, the large-scale prototype shows how such a new interactive design interface can provide new opportunities for future crafting, leading to novel forms of creative expression as designers interact on-site with complex material processes.

For skilled workers, the user-study validates that *IRoP* enables those with limited robotic programming and design experience to manipulate complex design and robotic fabrication processes intuitively, particularly due to the gestural input. Thus, *IRoP* has demonstrated a high potential to lower the barriers for skilled workers to robotic fabrication technology and computational design.

As a general conclusion, *IRoP* demonstrates a great potential to be able to intuitively integrate challenging-to-automate processes in architecture, engineering, and construction and to capitalize on the tacit knowledge of humans. This was mainly thanks to the real-time feedback, which increased user control on-site, shifting the attention back to the human in automated robotic processes. Finally, the project shows that by implementing intelligent and collaborative human-machine workflows, we can support a socially sustainable integration of robotic construction processes and expand our repertoire of potential material systems.

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Figure 17: Wall detail showing the aesthetic qualities of *IRoP*

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