Crafting plaster through continuous mobile robotic fabrication on-site

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Abstract

Industrialization of architectural components and technological advances have had a significant impact on how we design and build. These developments, resulting in mass-produced and panelized architectural components, have rationalized building construction. However, they often do not reveal the true potential of the inherent qualities of malleable materials. This research investigates the bespoke design potentials of combining a cementitious plaster, with a robotic spraying and forming process, and proposes an adaptive thin-layer additive manufacturing method for plasterwork. Research goals address an on-site construction system that is capable of performing continuous robotic plaster spraying on building elements. To support the understanding of the complex-to-simulate material behavior in this process, systematic studies and physical testing are proposed to be conducted to collect empirical knowledge and data. The goal is to explore bespoke surface qualities, with minimal waste, moving away from the modular and standardized form of the material. The paper presents the preliminary results and findings of the method that aims addressing the challenge of an adaptive construction system capable of performing continuous fabrication, for which mobile robots are proposed to be deployed.

Keywords On-site mobile robotic fabrication · Robotic plaster spraying · Adaptive thin-layer printing

1 Introduction

Surfaces inside or outside of building structures are treated with malleable materials such as cement, lime, or gypsum that play both functional and ornamental roles. The primary function is to protect the building structure, increase fire resistance, provide durability, and to improve thermal insulation. Thanks to the malleability of such materials, they can, at the same time, add texture to the building structure, providing unique visual effects. However, such surface treatment being applied in a fluid state then shaped and textured takes skill and craftsmanship. This can increase construction costs, making such applications niche add-ons in a building.

One contemporary example taking advantage of thermal and aesthetic properties of a cementitious malleable material can be found on the façade of the Fondation Laurenz Schaulager building in Münchenstein, Switzerland, by Herzog de Meuron Architects, being a hybrid building with a function that lies between a warehouse and an art center (Fig. 1). The building

façade has been constructed out of earth, gravel, and concrete to provide the stringent climatic environment indoors, required for the conservation of artwork. To give the façade of an expression of durability, the outer layer of the surface was manually removed by the craftsmen to expose the larger aggregate on the façade, providing an aesthetic texture. One of the main challenges in such a process is to describe the “design intent” to the craftsmen on-site, who then have the responsibility of translating such an expression of a durable and thermal finish to the physical surface, with an end result that more or less mirrors the digital blueprints. This separation of the roles of the architect as the “designer” and the craftsmen as the “builder” is a phenomenon of the industrial world (Carpo 2011), where it is not easy to reenact the medieval way of building in which the “design” of such an artisanal and bespoke surface quality would not be separated from the craftsmen “building” it.

We can see similar challenges in a typical plastering process used on interior walls and ceilings, as well as on façades, which consists of several steps and layers,¹ such as

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¹ A typical plastering process consists of (1) spraying of the base coat, i.e., lime and cement mix, (2) smoothing and leveling of the base coat, (3) scratching or scraping of the base coat, (4) spraying of the top coat, i.e., lime and white cement mix, (5) troweling of the top coat, (6) and finally application of the smooth coat, i.e., gypsum and lime hydrate mix.

Fig. 1 Craftsmen working on the façade of the Fondation Laurenz Schaulager building, Herzog de Meuron, 2003

Fig. 2 Left: steps of a typical plastering process; (1), (2), (3) application of the base coat; (4), (5) application of the top coat; (6) application of the smooth coat. Right: plasterboard attached directly onto the building structure in a single step

Fig. 3 Left: humanoid robot HRP-5P manipulating gypsum in its panelized form, 2019 (Kaneko et al. 2019). Middle: Material Gesture—Gypsum, Studio Anne Holtrop, ETHZ, 2018. Right: Mor-

phaux—Probing the Proto-Synthetic Nature of Plaster through Robotic Tooling, 2012 (Bard et al. 2012)]

(1)–(6) exemplified in Fig. 2. Such challenges led to common usage of the so-called “plasterboard”’s (Fig. 2, right), being gypsum in an industrial form that has become prevalent as a time- and labor-saving alternative to typical “wet” plastering, acting as a thermal and an acoustic barrier on walls and ceilings. Such prefabricated elements are cheap, optimized alternatives to a typical plastering process, with the downside being that the malleable qualities of the material have been lost (Fig. 3). As an additional downside, the usage of prefabricated plasterboard generates 10–35% of the ~3 million tons of plasterboard wastage produced annually only in Europe², ~10% of which is recycled, with the remaining ~90% ending up as landfill³. Strikingly, this wastage occurs on-site, only in the construction phase of a building, which is predominantly in the form of plasterboard off cuts produced when providing surface finishing to irregular sized areas and from stripped-out plasterboard.

This research proposes an on-site, adaptive construction system—robotic plaster spraying—using an off-the-shelf, base coat cementitious plaster in a digitally controlled process. For this, a fully mobile robotic platform⁴ is proposed to be deployed. The system addresses the challenge of sensing and control for robust material spraying and forming, aiming at bespoke surface qualities. For this, it proposes a novel additive manufacturing method—adaptive thin-layer printing on building elements, iteratively repeated, where thin layers of plaster build up the physical result. The goal is to eliminate the need for additional formworks or tools used in the conventional plastering to produce textural patterns and volumetric formations. Rather than working with the modular and generic forms of the material that are optimized for manual assembly, such as plaster in its panelized form (Fig. 3), this research explores the material’s unique properties, bringing it together with on-site mobile robotic fabrication.

2 State-of-the-art

In this section, two distinct topics are introduced, which are identified as the leading challenges within this research. These challenges lie in the establishment of appropriate interfaces for the on-site mobile robotic plaster spraying and

forming process, ensuring the data flow between the design space and the mobile construction robot, aiming at:

1. interlinking the building information and the robot map;
2. material manipulation with feedback.

Both streams have been the subject of growing research in the field, and some of the key developments are discussed below.

2.1 Interlinking building information and robot map

Robotic fabrication has traditionally been associated with high-tech assembly lines, where fixed positioning and constant conditions determine the role that the robot may undertake in the fabrication process. Although recent developments indicate an increase in the use of robots on construction sites, their use has been limited to monitoring roles, progress tracking⁵, or registering differences⁶ between the digital blueprints and what has been built. To facilitate a *fabrication* process on a construction site, a mobile construction robot must be able to understand the context within which it is working; and to localize itself via a robot map, both globally in reference to an absolute coordinate system, and locally in reference to the already built elements (i.e., walls) and the task being executed. In addition, it must be able to detect and understand any divergences between “as-planned”, which is the state of the design as it should be (digital blueprints), and “as-built” conditions, which is the state of construction as it is (Tang et al. 2010). Registering differences between the digital blueprints and the as-built data captured on-site is not only a problem of robotic fabrication. Conventionally in construction, builders take dimensions from paper drawings—the blueprints—and measure the current state of building elements in the execution of their tasks (Kolarevic et al. 2011). To achieve this in an on-site robotic fabrication process, a key challenge is to link the building information to the mobile robot’s internal representation of the world (referred to as “robot map”), which is, i.e., a point cloud where the underlying geometric relationships are unknown.

Such a linkage between the building information and the robot map would allow for coping with any divergences and the associated inaccuracies of the building materials, and to apply decision-making strategies while transferring the blueprints to physical results. To facilitate this link, there must be a flow of data between the complex building information and the construction robot. The inherent difficulty in facilitating

² Waste Resources Action Programme, Plasterboard Case Study, 2008.

³ European Commission Life+ Programme, GTOG Project Facts and Figures, 2018.

⁴ Within the scope of this paper, a fully mobile platform refers to a construction robot with synchronized arm and base movements—that is enabled by a whole body motion planning and control system—and which does not need to be stopped and stabilized for executing the building tasks.

⁵ <https://www.doxel.ai/>

⁶ <https://www.scaledrobotics.com/>

Fig. 4 Left: Robotic AeroCrete, MAS DFAB ETHZ, 2018 (Taha et al. 2019). Right: hold up: machine delay in architectural design, investigating the constructive and aesthetic possibilities of combining malleable materials with digitally controlled machines, 2019 (Cohen 2018)

Fig. 5 Diagram showing the first interface, in gray, aiming at interlinking the “as-built” state building information with the robot map, and the second interface, highlighted in black, aiming at adaptive material manipulation, which is described in this paper

this data flow lies in the development of an appropriate software interface that can react to the “as-built” state of the building elements when generating new robot trajectories from the design space. This necessitates the receiving of feedback on the continuously changing conditions, and the dynamic processing and adaptation of the robot trajectory when the task in hand is spraying with a malleable material system. Previous studies in the field have put forward proposals for interfaces that facilitate the adaption of robot trajectories during the execution of the task, where each task generated for manipulation is the result of a feedback loop, though employed in a limited workspace (Lundeen et al. 2019; Lussi et al. 2018; Sutjipto et al. 2018).

The problem of how to manage the flow of data between construction robots and the complex building information is rather an emerging topic. Early automation attempts in the 1990s seeking to replace manual processes with robotic building technologies in the construction sector resulted in early stage mobile construction robots (Andres et al. 1994; Apostolopoulos et al. 1996; Navon 2000; Pritschow et al. 1996). While these studies were able to show the validity of the concept, they did not have the ability to generate robot

tasks based on complex building information, or to develop a feedback-based fabrication process. An early attempt to have a mobile construction robot carrying out integrated sensing capabilities is exemplified in the DimRob research project at ETHZ (Helm et al. 2012), which involved a decoupled robotic arm and a mobile base, aiming at on-site construction in discrete steps, but lacked a strategy for linking the complex building information to a robot map.

The on-site deployment of construction robots is getting closer, with the challenge of appropriate interfaces to the complex building information being addressed to a limited extent (Furrer et al. 2018; Halvorsen et al. 2016; Peters et al. 2012), allowing the definition of robot tasks in reference to the already existing building elements (i.e., walls, columns) on-site (Dorfler et al. 2016). However, they can operate in a quasi-static mode—within a discrete fabrication strategy—and this falls short of the necessary continuous fabrication that is crucial for the on-site plaster spraying and forming processes offered by the whole-body motion planning and control capabilities proposed in this paper. Such systems cannot be adapted to continuous fabrication—in which the operating arm carries out its task, while the mobile platform is in motion. Still, current research in the field has sought to address the issue of continuous fabrication applications for such tasks as concrete 3d printing, getting closer to a fully mobile construction; however, the potentials of an enlarged workspace and uninterrupted continuous trajectories are not fully exploited (Zhang et al. 2018). To the extent of the published work, the mobile platforms are currently only in use in a decoupled manner, where the base is fixed in position and stabilized for the execution of the 3d printing of one segment of the concrete structure.

2.2 Material manipulation with feedback

An early attempt of addressing the challenge of an uninterrupted continuous fabrication process in an enlarged workspace can be exemplified with the construction robotics

Fig. 6 Top: the overall (stationary) fabrication setup. Bottom left: image showing the fabrication setup and the sprayed surface. Bottom right: close-up of the physical result

start-up OKIBO⁷, where a mobile construction robot with integrated sensing capabilities is deployed in generating continuous robot trajectories for an on-site wall plastering process. However, the potential of combining such a malleable material system with a fully mobile platform for addressing bespoke surface qualities is not fully exploited.

Early investigations in the field have yielded approaches addressing novel architectural impacts, such as combining the self-formation of malleable materials with digitally controlled processes to provide beneficial acoustic properties (Bonwetsch et al. 2008). Such early studies sought to understand the complexities associated with the material systems by defining appropriate parameters in a digital fabrication process, however, lacked a robust control due to the absence of feedback. Current research in the field investigates new

⁷ <https://okibo.com/>

Table 1 Control parameters defined for the process

Abbreviation	Explanation	Unit
E_d	End-effector distance to the target surface	mm
E_a	End-effector angle in reference to the target surface	°
V	Velocity of the trajectory	m/s
L_n	Layer number representing each consecutive spraying path	–
N_d	Nozzle diameter of the plastering spray gun	mm
W_t	Waiting time after each consecutive spraying path	s

means of construction by looking into material manipulation with feedback for continuous building processes such as robotic *Slipforming* (Lloret-Fritsch et al. 2017), shotcrete 3D printing (Herrmann et al. 2018; Neudecker et al. 2016), and similar applications such as robotic *AeroCrete* (Taha et al. 2019), as shown in Fig. 4, including plastering (Bard et al. 2018). However, these processes occur within limited workspaces. Additionally, recent research as exemplified in *Machine Delay in Architectural Design* (Cohen 2018) investigates the specific native constructive and aesthetic possibilities of combining malleable materials with the digitally controlled machines, as illustrated in Fig. 4, hinting at a new form of architectural craft, yet without the necessary feedback.

Currently, there are no viable options for the robust and reliable manipulation and control of malleable materials with feedback, informing the design process. Thus, there are currently no means to explore material informed design processes with complex material systems, supported by visualization tools, addressing diverse surface qualities. Nor do any adaptive fabrication systems in previous studies propose a method to explore the potentials of plaster, or other malleable material systems in a continuous, mobile fabrication process, and with interfaces for adaptive fabrication.

This research addresses the challenges that lie in the establishment of appropriate interfaces for an adaptive material manipulation and for interlinking of the updated (“as-built” state) building information with the robot map (Fig. 5) in an on-site plaster spraying and forming process. This paper describes one of the interfaces being developed to address this gap, involving the experiments to test the potentials of a feedback-based material visualization and manipulation through continuous robot trajectories, which has been tested in a temporary stationary setup, as a first step.

3 Fabrication setup

3.1 Hardware setup

The overall (stationary) fabrication setup used in the experiments is illustrated in Fig. 6 where “A” indicates

the 6-DoF manipulator (robotic arm), “B” indicates the plastering spray gun attached to the robotic arm with an integrated *Intel RealSense Depth Camera D435i*, “C” indicates the standard mixing pump *PFT G4*, “D” indicates the flow of the material from the mixing pump to the plastering spray gun, “E” indicates the initial and the adapted robot trajectories (spray paths), and “F” indicates the target surface.

Robot A 6-DoF robotic arm, with a 12 kg payload and a 1250 mm reach, is temporarily used in a stationary setup for the initial experiments. The fully mobile setup employs the same type of arm that would be mounted on a wheeled base, which allows for synchronized arm and base movements enabled by the whole-body motion planning and control system.

Plastering spray gun The plastering spray gun used in the experiments is controlled by a squeeze valve and an air valve. The squeeze valve addresses the problem of time delay in the material throughput when spraying is stopped. It stops the material flow and prevents the material from dripping. Air valve removes the need for the manual control of the mixing pump. Like this, the digital start/stop of the spraying task is enabled.

Pump The pump chosen for the tests is a standard mixing pump, being a *PFT G4*, which has a working pressure of 30 bar, a delivery rate of 85 l/min, and a conveying distance of 50 m. It contains an in-built air compressor to supply air to the spray gun.

3.2 Software setup

Generation of robot trajectory A mock-up CAD model of the hardware setup and the target surface are visualized in the 3D modeling software Rhino. The kinematic model of the robot is built using the COMPAS FAB package of the

Fig. 7 Selected results of the first set of experiments exploring the effect of the geometry—the applied pattern and the velocity of the trajectory—on achieving a more-controlled textural variation

Fig. 8 Selected results of the second set of experiments exploring the effect of the reduced layer thickness and the waiting time on gradual building up of the volumetric formations and the surface quality

COMPAS⁸ framework. To align trajectory planning from the design space with the robot on-site, a software interface between the robot controller and design space is developed. This allows to visualize the current robot state and the robot trajectories (spray paths) in relation to the target surface. The communication between the robot controller running

in a ROS⁹ environment and the design space is established using the ROS Bridge library roslibpy¹⁰.

The velocity of each trajectory is calculated as follows:

$$D_p/T_s = V_t, \quad (1)$$

⁸ <https://github.com/compas-dev/compas>

⁹ <https://www.ros.org/>

¹⁰ <https://github.com/gramaziokohler/roslibpy>

Fig. 9 Top: close-up from the selected result of the second set of experiments, achieved with the feedback-based spraying (in 15 iterative layers). Bottom: target surface states from layers 11 and 15, together with the initial spray path and the adapted spray path

where D_p is the distance between two consecutive poses in a spray path (robot trajectory) and T_s is the chosen controller time step¹¹ value.

Task execution and spray driver This driver enables the opening and the closing of the air valve and the squeeze valve. If the air valve is closed, it is registered by a pressure sensor in the external mixing pump, which switches the system to stand-by mode. If the squeeze valve closed, the material flow is instantly blocked and the throughput stops.

Scanning, feedback-based material visualization, and manipulation This software component is planned as a first step for in-process (task scale) control and for visualizing the actual state of the target surface in the design space prior to the execution of the spraying paths, to inform the design process. The goal is to program adaptive spraying trajectories, depending on the actual state of the target surface. In the tests described below, the robot trajectory is adapted after each spraying iteration, by projecting it on the actual state of the target surface for adjusting it to the desired spraying distance, and velocity (Fig. 6). Additionally, the target surface geometry is scanned and stored together with the relevant fabrication data (Fig. 5)—selected values for the fabrication

parameters—in each iteration of the spraying, prior to the adaptation of each consecutive spray path. Like this, it will also be used as a means to visualize the material behavior through camera feedback.

3.3 Fabrication parameters

The initial experiments aimed to define the relevant control parameters of the process, being the end-effector distance to the target surface, E_d ; the end-effector angle in reference to the target surface, E_a ; the feed rate of the material set by the velocity of the trajectory, V ; the layer number representing each consecutive spraying path, L_n ; the nozzle diameter of the plastering spray gun, N_d ; and the waiting time introduced after each consecutive spraying path, W_t , as shown in Table 1.

4 Preliminary results

The following section describes the results of two sets of experiments, using the stationary setup (Fig. 6). For each experiment, a conventional base coat plaster, a lime and cement mix—*Weber IP 18 Turbo*—was used.

In the first set of experiments, all control parameters (Table 1) were kept constant except for V , being the feed rate of the material set by the velocity of the trajectory, and the design of the trajectory—the pattern—which was altered primarily to explore the possibilities offered by the setup, and so to identify novel means of materializing and manipulating the material (Fig. 7). In these set of experiments, the same pattern was applied, with V either being kept constant at 0.4 m/s or varying between 0.1 m/s and 0.4 m/s. As a result of the selected pattern getting applied in a wider workspace and that had a feed rate varying between 0.1 m/s and 0.4 m/s, it was observed that a more-controlled textural variation, based on the proximity of the gaps between the neighboring trajectories, was achieved as compared to the iteration where V was kept constant at 0.4 m/s. In each iteration of this first set of experiments, single layers of spraying (with ~10mm of thickness) were executed. The values for the velocity of the trajectories were manually adjusted to explore the possibilities in terms of the bespoke patterns resulting from these varying values.

The second set of experiments (Fig. 8) looked into the gradual building up of volumetric formations and the end surface quality with a decreased layer thickness (of ~5mm) and with a decreased N_d , nozzle diameter of the plastering spray gun. In these set of experiments, a manual spray gun was robotically manipulated to achieve the decreased layer thickness. These tests aimed to explore the proposed adaptive thin-layer printing process for plasterwork. For this, each spray path was iteratively repeated, where thin layers of

¹¹ The time increment executed at each iteration of the control loop of the robot controller.

Fig. 10 Top and right: the hardware platform—6-DoF manipulator mounted on a wheeled base, involving synchronized arm and base movements. Left: testing the same continuous trajectory for cementitious base coat plaster spraying, with the temporary stationary setup

plaster built up the physical results. Also, W_t , a waiting time of 30–180 s was introduced, after each consecutive spraying path. In these experiments, the same spraying path was repeated 10–15 times, with V varying between 0.00625 m/s and 0.1 m/s, and with E_d kept at 500 mm or at 400 mm. In every iteration of the experiment, after a certain thickness was accumulated, the trajectory was adapted in reference to the target surface state (Fig. 9, bottom, target surface state from layer 11 indicated with “A” and target surface state from layer 15 indicated with “B”). Instead of interpolating a feed-forward input curve for the robot trajectory, it was generated relative to the actual state of the target surface. This was facilitated by projecting it on the actual state of the target surface and adapting to maintain the values chosen for E_d (Fig. 9, bottom, initial spray path indicated with “C” and adapted spray path indicated with “D”). With this feedback integrated and with a reduced layer thickness applied at each iteration of the experiment, a final material thickness on the target surface, varying between 10 mm and 100 mm, was built up in successive layers, more stably, and with a much smoother end surface quality as compared to the previous set of experiments (Fig. 9). This result was achieved in an integrated step of feedback-based spraying which would normally require multiple steps of spray and smoothing or additional tools and formwork, hinting at the architectural possibilities of building with an adaptive robotic plaster spraying process.

Eventually, the developments will be taken to the mobile setup (Fig. 10) where experiments that utilize whole-body motion planning and control will explore the architectural potentials of material manipulation within a workspace that is not limited to the footprint of the robot base, thus investigating the design possibilities of continuous on-site plaster spraying. These further experiments will be conducted with the mobile robotic setup, which employs the same type of 6-DoF robotic arm, with the same spraying method, mounted on a wheeled base, that is able to execute continuous trajectories (Fig. 10, right). For this, the deployment of a mobile robot with whole-body motion planning and control system will be essential, as the setup enables spraying processes to be conducted over longer distances, removing the need to stop and stabilize the platform for each subsequent spraying task. The focus of the assessment will be on investigating novel architectural effects of surface treatment with continuous mobile fabrication, i.e., corners where multiple building elements come together, showcasing the full potentials of on-site robotic plaster spraying process. In this regard, initial testing has started to be conducted with the temporary stationary setup, as shown in Fig. 10 (left).

5 Outlook and discussion

As a following step, further testing will be carried out, with the intention being to collect the necessary data on material behavior for developing a design, visualization, and fabrication tool that allows for robotic spraying and forming. This tool will have the capability of informing the designer on the combined effect of the fabrication parameters together with physical parameters such as the gravitational force. Therefore, on one hand, it will enable to design bespoke surfaces intuitively, and on the other hand, it will provide the fabrication data such as the number of layers to be sprayed to achieve a specific geometry. Eventually, it will enable to explore the design space of adaptive robotic plaster spraying. For this, the feedback methods will be extended to facilitate the continuous monitoring of the material, using, i.e., laser triangulation in combination with high-speed cameras. Additionally, the goal will be to fuse 3D LiDAR measurements that will be facilitated to localize the mobile robot against target surfaces on-site, providing an initial coarse alignment.

However, to be able to make use of extended sensor data for controlling the on-site plaster spraying and forming process, it will be necessary to identify the key data to be collected. Accordingly, the research also aims to explore the appropriate means to create data sets for such a fabrication process, to support the future research in the field. To this end, the previously mentioned interfaces in Sect. 2 will be important, as they will facilitate the flow of data between

the building information and the mobile construction robot, which will be crucial for dynamic processing of the data possibly within the design space.

The key contribution of this research will be the delivery of a design tool that supports the understanding of material behavior in a mobile fabrication process, and the use of such a tool to produce a broad range of bespoke surface qualities, with minimal waste, moving away from the modular and generic form of the material that is optimized for manual assembly. Extending the direct automation approaches that address only standardized, flat surfaces, the architectural potentials of combining the plasticity of plaster with an agile robotic arm in a digitally controlled fabrication process will be explored, re-introducing the degrees of freedom offered by the craftsmanship of the past. The suggested approach will make a major contribution to the digital fabrication research by the proposed adaptive thin-layer printing method for plasterwork and enable the reinterpretation of the surface qualities inside or outside of building structures by introducing a digital craft with additive manufacturing. Thus, it will permit a fair use of such malleable materials other than panelized formats, and potentially make a major contribution to revisiting the functional layers of the building structure and a craftsmanship that has become a niche trade in building construction.

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References

- Andres J, Bock T, Gebhart F, Steck W (1994) First results of the development of the masonry robot system ROCCO. In: Proceedings of 11th international symposium on automation and robotics in construction (ISARC), pp 87–93
- Apostolopoulos D, Schempf H, West J (1996) Mobile robot for automatic installation of floor tiles. In: Proceedings of IEEE international conference on robotics and automation, Minneapolis, MN, USA, vol 4, pp 3652–3657. <https://doi.org/10.1109/ROBOT.1996.509269>
- Bard J, Mankouche S, Schulte M (2012) Morphfaux: probing the proto-synthetic nature of plaster through robotic tooling. In: Proceedings of the 34th annual conference of the association for computer aided design in architecture (ACADIA), pp 177–186
- Bard J, Bidgoli A, Wei Wei C (2018) Image classification for robotic plastering with convolutional neural network. In: Proceedings of the robotic fabrication in architecture, art and design (ROBARCH), pp 3–15
- Bonwetsch T, Baertschi R, Oesterle S (2008) Adding performance criteria to digital fabrication: room-acoustical information of diffuse respondent panels. In: Proceedings of the 28th annual conference of the association for computer-aided design in architecture (ACADIA), pp 364–369
- Carpo M (2011) The alphabet and the algorithm. MIT Press, Cambridge
- Cohen Z (2018) Hold up: machine delay in architectural design. In: Proceedings of the robotic fabrication in architecture, art and design (ROBARCH), pp 126–138
- Dörfler K, Sandy T (2016) Mobile robotic brickwork. In: Proceedings of the robotic fabrication in architecture, art and design (ROBARCH)
- Furrer JM, Gramazio FM, Kohler M, Ercan S (2018) System for placing objects on a surface and method thereof, Patent WO2018063100A2
- Halvorsen H, Henning TA, Fagertun K (2016) Mobile robotic drilling apparatus and method for drilling ceilings and walls, Patent WO2016066615A2
- Helm V, Ercan S, Gramazio F, Kohler M (2012) Mobile robotic fabrication on construction sites: DimRob. In: Proceedings of the IEEE/RSJ international conference on intelligent robots and systems (IROS), pp 4335–4341
- Herrmann E, Mainka JLC, Lindemann H, Wirth F, Kloft H (2018) Digitally fabricated innovative concrete structures. In: Proceedings of 35th international symposium on automation and robotics in construction (ISARC)
- Kaneko K, Kaminaga H, Sakaguchi T, Kajita S, Morisawa M, Kumagai I, Kanehiro F (2019) Humanoid robot HRP-5P: an electrically actuated humanoid robot with high-power and wide-range joints. *IEEE Robot Autom Lett* 4(2):1431–1438. <https://ieeexplore.ieee.org/document/8630006>
- Kolarevic B (2001) Digital fabrication: manufacturing architecture in the information age. In: Proceedings of the 21st annual conference of the association for computer-aided design in architecture (ACADIA), pp 268–278
- Lloret-Fritsch E, Reiter L, Wangler T, Gramazio F, Kohler M, Flatt RJ (2017) Smart dynamic casting slipforming with flexible formwork—inline measurement and control. In: Proceedings of 11th high performance concrete (HPC) and the 2nd concrete innovation conference (CIC)
- Lundeen KM, Kamata VR, Menassaa CC, McGee W (2019) Autonomous motion planning and task execution in geometrically adaptive robotized construction work. *Autom Constr* 100:24–25
- Lussi M, Sandy T, Kathrin D, Hack N, Gramazio F, Kohler M, Buchli J (2018) Accurate and adaptive in situ fabrication of an undulated wall using an on-board visual sensing system. In: Proceedings of IEEE international conference on robotics and automation (ICRA)
- Navon R (2000) Process and quality control with a video camera, for a floor-tilling robot. *Autom Constr* 10:113–125. [https://doi.org/10.1016/S0926-5805\(99\)00044-8](https://doi.org/10.1016/S0926-5805(99)00044-8)
- Neudecker S, Bruns C, Gerbers R, Heyn J, Dietrich F, Dröder K, Raatz A, Kloft H (2016) A new robotic spray technology for generative manufacturing of complex concrete structures without formwork. *Procedia CIRP* 43:333–338

- Peters SL, Podkaminer N, Rock SJ, Puffer RH, Kleinigge MR, Gullotta JD, Collier TC (2012) Brick laying system. Patent US20120053726A1
- Pritschow G, Dalacker M, Kurz J, Gaenssle M (1996) Technological aspects in the development of a mobile bricklaying robot. *Autom Constr* 5:3–14
- Sutjipto S, Tish D, Paul G, Vidal-Calleja T, Schork T (2018) Towards visual feedback loops for robot-controlled additive manufacturing. In: *Proceedings of robotic fabrication in architecture, art and design (ROBARCH)*, pp 85–97
- Taha N, Walzer AN, Ruangjun J, Bürgin T, Dörfler K, Lloret-Fritschi E, Gramazio F, Kohler M (2019) Robotic AeroCrete—a novel robotic spraying and surface treatment technology for the production of slender reinforced concrete elements. In: *Proceedings of the 37th eCAADe and 23rd SIGraDi conference*, pp 245–254
- Tang P, Huber D, Akinci B, Lipman R, Lytle A (2010) Automatic reconstruction of as-built building information models from laser-scanned point clouds: a review of related techniques. *Autom Constr* 19:829–843
- Zhang X, Li M, Lim JH, Weng Y, Tay YWD, Pham H, Pham QC (2018) Large-scale 3D printing by a team of mobile robots. *Autom Constr* 95:98–106

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