they show how this methodology can be applied successfully to form-adaptive and geometrically complex modular construction. The performative capacities of the fabrication based, bio-informed material system are derived from the integration of biomimetic, fabricational, structural, and architectural principles in one digital design environment. The project illustrates how generation, management, and control of increasingly complex datasets require adequate, efficient, and very often custom data structures that support design exploration. While the evaluation of the built prototype through 3D laser scanning showed that the resultant tolerances and deviations slightly exceeded the prediction, it also showed that the structural system showed almost no deformation over the lifespan of the project and proved to be extraordinarily stable. Further research will be directed to more accurately reflect fabrication and construction tolerances, as well as material behavior within the design environment to be able to make better predictions on the physical result of robotic fabrication processes.

In this sense, the project attempts to computationally synthesize not only the physicality of robotic fabrication and the focused exploration of the design space, but also that of material behavior within the computational domain.

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IN-SITU ROBOTIC CONSTRUCTION:
EXTENDING THE DIGITAL FABRICATION CHAIN IN ARCHITECTURE

ABSTRACT

In this paper, viable applications are explored for mobile robotic units on construction sites. While elucidating potential aims and requirements for in situ fabrication in the construction sector, the aim of this work is to build upon innovative paradigms of human-machine interaction in order to be able to handle the imprecision and large tolerances commonly faced on construction sites. By combining the precision of machines with human cognitive skills, a simple yet effective mobile fabrication system is experimentally developed for the construction of algorithmically designed additive assemblies that would otherwise be impossible to build using conventional manual methods, because of the sheer number of individual building blocks and the scale of the structure. This new approach for the collaboration of humans and machines—aiming at a fuller integration of human abilities and the advantages and capabilities of digitally controlled machines—will result in advances in the construction industry, opening up new fields of application for architects and designers in the design and realization of buildings.

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figure 1

1 INTRODUCTION

The distinguishing feature of the construction industry (when compared to other manufacturing sectors) is the nature of building construction itself: carried out in the most diverse environments, using a wide range of building materials from fine substrates to massive elements (Han 2011). The technical requirements of building processes are becoming ever more complex, and as such increasingly require custom solutions. For building sites involving state-of-the-art processes and components, this requires an unusually large number of precisely arranged elements, together with highly sophisticated detailing, where even familiar building materials can appear in wholly new applications (Gramazio and Kohler 2008). Computer-controlled prefabrication methods represent one solution for the fast and cost-effective manufacture of custom components. Thus far, construction processes have been mainly handled statically. In a novel approach to the future requirements of construction, a generic mobile fabrication unit is proposed to be used directly on a building site to carry out tasks that have previously only been performed by prefabrication using specially developed machines, typically at a fixed, off-site location. The proposed combination of the advantages of digital manufacturing and in situ construction represents a compelling alternative to conventional approaches to the prefabrication of building elements. If the underlying software and the precision and sensitivity of a robot are sufficient to deal with unique and specific situations, as well as the tolerances required, this effectively allows it to handle the physical conditions of any given construction site through the introduction of responsiveness to the process, which ensures the necessary adaptability. If digital fabrication can be done on-site, as envisaged, this removes the need for costly and unsustainable transportation of large structural elements. This would also effectively entail the extension and advancement of the digital fabrication chain of large architectural components.

Unlike a typical prefabrication facility, even a simple construction site is a spatially complex and heterogeneous environment, where a robotic unit would be exposed to continuously changing conditions, unpredictable events, obstacles, and the activities and movements of people working on-site. Consequently, such a fabrication unit must "know" its surroundings and its own position, as well as be able to work with the tolerances generated by inaccuracies in the materials with which it is working. The particular tools used for these purposes in our research project outlined here include scanning systems and object recognition technologies that can be overridden and guided by human instruction. Since every construction site is unique, and such technology is still in comparative infancy, a robot is still slower and less competent than a person, in many respects, in the autonomous sensing of position and form of the environment.

The overall aim of this research is to expand the application of a number of digital manufacturing processes for building construction, identifying future areas of application for mobile robotics in architecture, tested in full-sized experiments. In this, instead of developing new advanced pieces of machinery, an existing model of industrial robot has been employed. For proving the viability of in situ fabrication, this research project has aimed to demonstrate successful (1) handling of tolerances; (2) human-machine interaction; and (3) the mobility of the fabrication unit. This paper is thus structured according to these three objectives.

2 PRELIMINARIES

In contemporary building processes, there are several potential scenarios for human-robot collaboration, in which the advantages of humans, who possess remarkable environmental cognitive skills, are combined with those of robots, which surpass human physical abilities in several respects (Han 2011). Deployed on a construction site, a robotic fabrication unit is able to precisely and uniquely place individual building components without the need for continual optical reference, unlike a manual method. Such reference is usually unavoidable, depending on the characteristics of the building components and the number of them in an assembly (Gramazio and Kohler 2008). Despite the potential advantages, in comparison to other industries the construction sector has been slow to adopt innovative digital fabrication methods; most construction work on-site is still carried out using manual methods (Bonwetsch, Gramazio, and Kohler 2007).

figure 1

An algorithmically generated timber structure, robotically fabricated in situ.

The research on automation and robotics in construction conducted in the 1990s can largely be categorized as relating to perspectives on automation and robotics in construction; design, construction planning, and management; elemental technologies for automation and robotics; or applications (Ueno 1998). Some building processes that emerged as targets for application were masonry construction, assembly and finishing operations, surveying and positioning, inspection, repair and maintenance, material handling, and concrete placing and finishing (Ueno 1998). Attempts in the early 1990s to replace manual technologies with robotic building processes in the construction sector resulted in such automated bricklaying research projects as ROCCO (1994), ESPRIT (1995), and BRONCO (1996) (Andres et al. 1994; Bock et al. 2010; Pritschow et al. 1996). While automated bricklaying (masonry construction) projects figured in a little under 7 percent of the applied research work in robotics on construction sites, they have yet to be put to practical use (Warszawski and Navon 1996; Ueno 1998). The main reasons for this were, firstly, that the machines could not compete with manual labor, as they were, at that time, not economically feasible (a topic that is a research area on its own). And secondly, they did not fully address the fact that every building site is different or the dimensional tolerances involved in masonry construction. In order to justify the use of automated robotic processes on construction sites, it is clear that any such process has to be proven to be economically advantageous, though this lies outside the concerns of the present preliminary state of this research. Instead of developing a new automated robotic device, as such, this research has been directed toward the development of a robust design for a system that takes full advantage of the specific complementary strengths of both humans and machines. Throughout this research paper, it is assumed that for a robotic fabrication system to be of real practical use in the construction sector, it must enhance and make use of the cognitive skills of human workers in an efficient way. Together, this could help realize the wealth of latent and anticipated opportunities of the construction site.

figure 2

3 METHODOLOGY

In this research, the decision-making responsibility is shared between the human collaborator and the machine; as such, the machine autonomously solves problems that cannot be efficiently addressed by the collaborator. The mobile unit, then, comprising an existing model of industrial robot mounted on a mobile base, is able to fabricate algorithmically generated structures that would be prohibitively inefficient if built by hand, directly on the construction site at a 1:1 scale (Figure 1). The methodology of such a problem objective holds the following research sequence:

- experiment setup;
- iterative testing with mockups prior to 1:1 scale demonstrations;
- testing the software used to facilitate the design data as an active component in the in situ fabrication process;
- proof of concept (through three 1:1 scale demonstrations), in terms of (1) handling of tolerances, (2) human-machine interaction, and (3) mobility of the fabrication unit.

4 EXPERIMENT SETUP

The first task for the research was to assemble a customized mobile fabrication unit that would meet the requirements, in terms of the actual deployment of the unit in real contexts in addition to a stationary condition. The robot selected for this setup was an ABB IRB 4600, which was then mounted on a compact mobile track system sized to fit through a standard door frame on a construction site in its folded position (Figure 2).

- The experiment setup involved the integration of each of the following individual components to form a cohesive system:
- ABB IRB 4600, which is relatively lightweight, has a high load capacity, and provides a wide operational range and a 6 DOF;
- The engineered mobile track system, supported by side-hinged telescoping outriggers with integrated raising jacks and an attached diesel engine;

figure 2

The fabrication unit: an industrial robot (ABB IRB 4600) mounted on a compact mobile track system sized to fit through a standard door frame on a construction site.

figure 3

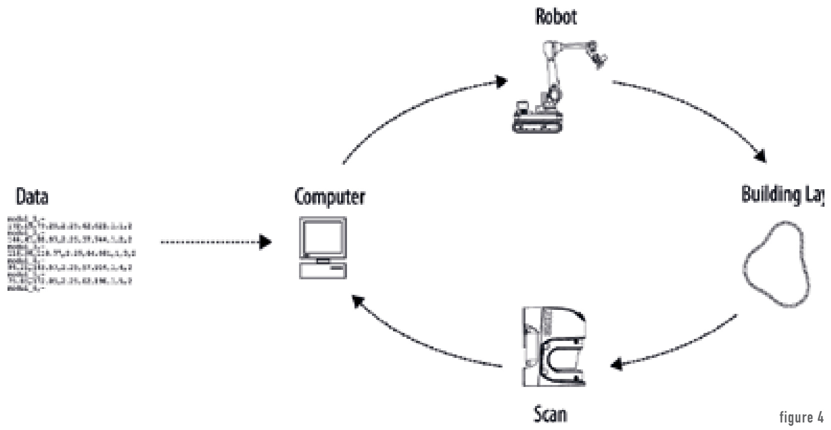

figure 4

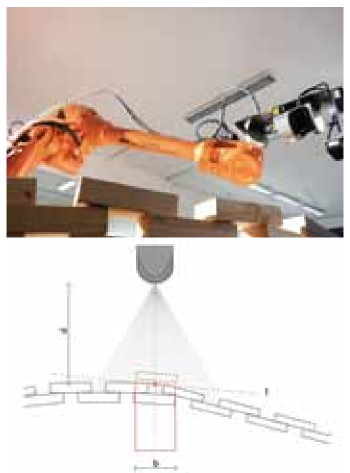

figure 5

- A 2D line scanner (Sick LMS500) for detection of dimensional tolerances and a 3D scanner enabling the detection of objects or obstacles in the workspace and facilitating human-machine interaction;
- Two vacuum grippers, which are installed on a multifunctional tool to enable the unit to grip bricks from different sides. This system includes a vacuum pump installed at the back of the fabrication unit.

5 HANDLING OF TOLERANCES

Every operation on a building site is unique in terms of the dimensions of the materials used and their range of tolerances, so this phase of the methodology is critical. A demonstration of a 1:1 scale building process was used (at the 2011 FABRICATE Conference, London) to test the handling of tolerances as part of the experimental application process of the mobile fabrication unit prior to its deployment on an actual construction site. Accordingly, based on a feedback strategy a reactive fabrication system was developed for the additive assembly of wooden blocks of varying sizes. The dimensions of the structure, shown in Figure 3, were derived directly from the robot's operational range. This test structure, circular in plan, was assembled from 1,330 timber building blocks of three different thicknesses, simulating the range of dimensional tolerances that would be faced on a construction site. This articulated timber composition displays an accumulated indeterminacy, which the system deals with by scanning each layer of blocks in turn and feeding the data back to the computer, which then adjusts the remaining additive assembly instructions.

5.1 2D Line Scanning of Differently Sized Elements

The issue of material and site tolerances was tackled by the use of different thicknesses of wooden blocks in the test application. During the fabrication process itself, the fabrication unit maps the indeterminacy by scanning each layer of blocks as it is laid (Figure 5). Rapidly and accurately measured, the indeterminacy is handled autonomously by the robot, an aspect that the human counterpart could not efficiently handle by himself or herself. The mapped measurements are then sent back to the design/control software, and the robot arm reorients itself according to the new set of height and angle data.

5.2 Design Tools and Control Software

As for the software, the design of the timber wall is at first simulated with CAD software. The articulation of the structure is created by defining the position of each block with a pixel image mapped onto the initial configuration (Figure 6a). This mapping places blocks of various sizes in position depending on the pixel value of the source image. Then, in the simulation, the aligned blocks are allowed in

figure 3

A 1:1 scale building process was initially implemented at the 2011 FABRICATE Conference as an experimental demonstration of the unit's handling of tolerances.

figure 4

The reactive fabrication system developed for the construction of an additive assembly of wooden blocks based on a feedback strategy.

figure 5

After laying individual wooden blocks, the fabrication unit can map the indeterminacy by scanning each layer of blocks.

(a)

(b)

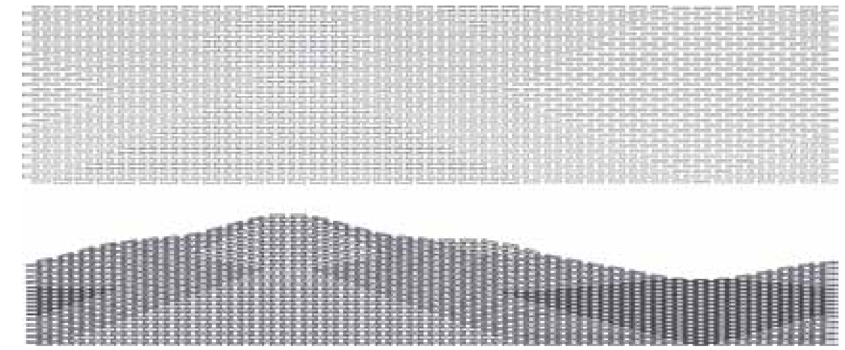

figure 6

figure 7

sequence to fall freely into place on top of one other, which creates the vertical articulation of the structure (Figure 6b). The process of data flow in the design is controlled by a plug-in developed for the CAD software used, enabling data to be exported from the digital model to the robot controller, once it has been converted into the programming language of the robot.

6 HUMAN-MACHINE INTERACTION

As the fabrication unit is intended to be employed directly on a construction site, it has to be able to operate in contexts and workspaces "unknown" to it, and to orient itself while recognizing obstacles or people working in its surroundings. The handling of tolerances is achieved through the use of integrated 2D scanning technologies, while for the recognition of the workspace, it is the innate orienting skills of the human counterpart that are called upon to lead the supervision of the robot. For this, a 3D scanning technology is integrated into the mobile fabrication system in order to map the hand movements of the human collaborator, which are then processed by the fabrication unit, allowing it to build in an unknown context such as a construction site. In this way, the system reacts in real time to visual instructions and accordingly applies an additive assembly strategy.

A demonstration at 1:1 scale of a fabrication cycle applying this interactive process was accordingly made at the 2011 Scientifica Exhibition in Zurich (Figure 7), in which audience participation was effectively employed as the human supervision. In this interactive fabrication process, the 3D scanning technology detects and processes hand movements, so that the human collaborator is able to "show" the robot its working area and building zone with reference to its relative position (Figure 8).

6.1 3D Scanning of Hand Movements

Before the fabrication process was tested at 1:1 scale, the 3D scanner on the mobile unit was tested using a smaller mockup, which explored the application of the human-machine interaction. In the

figure 6

(a) Initial configuration of the structure in which differently sized blocks are positioned according to a pixel image map. (b) The configuration after the blocks are allowed to fall freely on top of each other.

figure 7

The 3D scanning system, which is integrated into the mobile robotic fabrication unit, maps the hand movements of the human counterpart, and the new configuration of the wall stucture is built accordingly (2011 Scientifica Exhibition).


figure 9

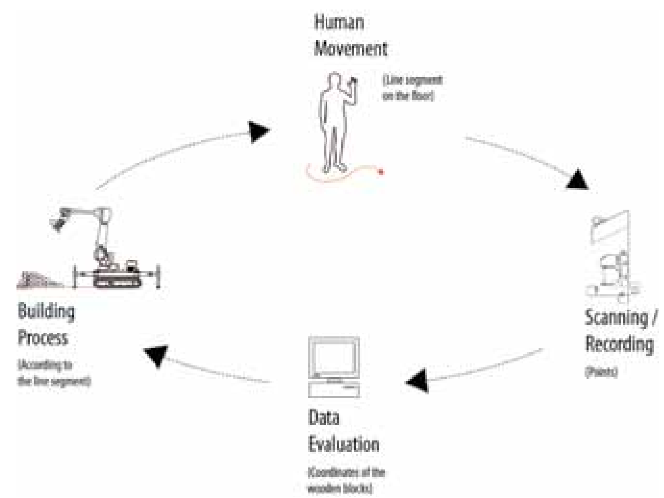

figure 8

test, the scanning system maps hand movements and translates this data into the virtual design medium, as shown in Figure 9. With the implementation of this recognition technology, the human counterpart, working in collaboration with the robot, leads the building process through freely made gestural instructions.

6.2 Design Tools and Control Software

On the software side, a feedback loop is programmed that provides continuous communication between the robot controller and the scanning system. This continuous exchange of information feeds into the fabrication process, with hand movements scanned and imported as CAD data into the design software (Figure 10). This data is then converted into robot code, with which the fabrication unit is continuously informed in real time. The CAD software acts as an intermediary in the communication between the fabrication unit and the human counterpart.

7 MOBILITY OF THE FABRICATION UNIT

Complementing the previous aspects of human-machine interaction and the handling of tolerances, the methodology for the on-site robotic fabrication developed includes the implementation of a cognitive strategy for self-positioning of the robot unit. A system was developed for the 3D scanning of local reference points in the workspace, which the mobile unit then follows when repositioning itself to further facilitate the fabrication process. This allows it to construct large building components in several sections, such as an eight-meter-long modular wall shown in Figure 11, for which the mobile fabrication unit repositioned itself several times. This represents another essential part of the in situ robotic fabrication process. It is a pioneering experiment on several levels, taking into account such features of the surroundings as ceiling height and inclination of the floor. The resulting building component was fabricated using a tool (the robotic unit) that was smaller than the end product (the wall).

7.1 The "Satellite" Concept

This phase of the methodological process is especially significant in translating the robotic operational capabilities from those of stationary conditions to the in situ production of a complex architectural component. On this subject, the conditions in the parking garage are used experimentally to represent those of a real construction site.

figure 8

Workflow showing the interactive fabrication process.

figure 9

The interactive 3D scanning system maps the hand movements and translates this data to the virtual design medium, which in turn informs the fabrication process.

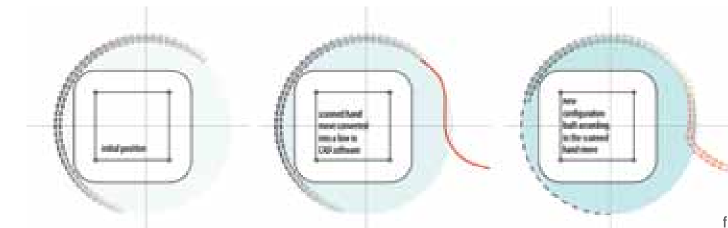
figure 10


figure 11

The 3D scanner integrated into the fabrication unit for the recognition of the workspace by following hand movements is also employed by the self-positioning system. With the help of a metal disk ("satellite"), whose center point is used as a local reference marker, the fabrication unit is able to reposition itself according to the scanned and mapped coordinates of this reference point. The scanning device finds/measures the center point of the "satellite," when is then set as the origin of the coordinate system that is defined in the CAD model for the current position (Figure 12).

After working in a sequence of positions, a fragile wall structure was fabricated in situ. It was designed and partitioned (Figure 12) according to the simulation studies carried out as part of the offline programming to establish the optimum positioning for the fabrication unit.

7.2 Design Tools and Control Software

The complexity of the fragile wall structure arises from the superposition of algorithmic rules, which cannot be applied easily in a manual fabrication process, while several aspects of the design are driven by the selected robotic fabrication method. The scale and modularity of the structure were

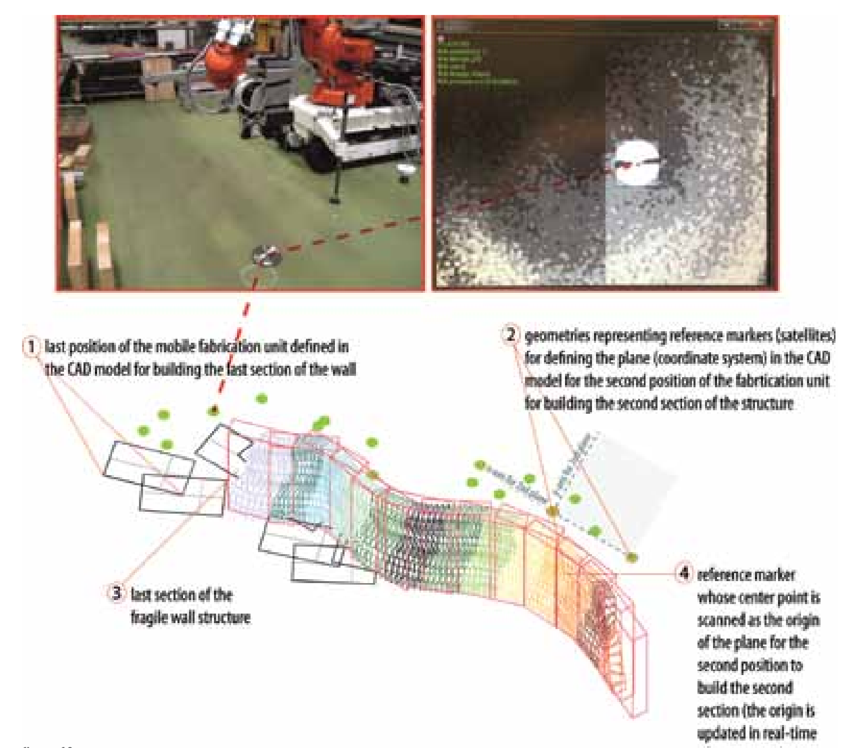

figure 12

figure 10

The hand gesture is scanned and imported into the CAD software as a line segment, and the new configuration of the structure is built accordingly.

figure 11

An eight-meter-long modular wall, fabricated in the parking garage of the Department of Architecture at ETH Zurich using an additive assembly method, for which the robot had to reposition itself several times.

figure 12

The CAD model of the wall structure. It was designed and partitioned according to the simulation studies carried out as part of the offline programming to ascertain the optimum positioning for the fabrication unit. The experimental scanning system is also visible here.

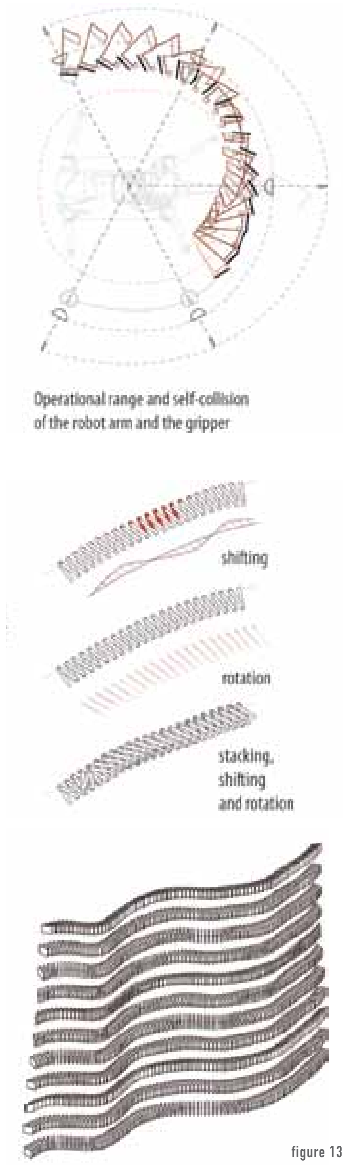

figure 13

directly derived from the surrounding spatial conditions—one, for instance, being the ceiling height. The structure was designed by the students taking part in an elective course, "The Fragile Structure," under the professorship of Gramazio and Kohler, which also investigated the self-collision and the positioning of the fabrication unit, in addition to the operational range of the robot arm (Figure 13). These are systemically used and simulated on the software side. Through a collaborative process in design scripting and offline programming, the fabrication data from the CAD model of the structure is exported to the robot controller.

The geometrically differentiated wall structure consists of more than a thousand individually positioned timber building blocks. In its overall assembly strategy, a new form of articulation in digital fabrication processes in architecture was intended.

8 CONCLUSION

The key contribution this in situ robotic fabrication potentially makes to architecture is the direct application of mobile units on construction sites; the intention here is to demonstrate the feasible objectives and potentials for the use of such a novel method of mobile fabrication.

Unlike in other sectors, the implementation of computer-controlled manufacturing has been relatively slow in the construction sector. Still, every building is designed with a unique complexity that is based on specific design drivers, and accordingly, the algorithmic description of complex architectural building projects demands more rapid progress in this field. The direct in situ application of mobile robotic fabrication units in response to these conditions is one way of providing accurate and customized solutions. To enable a deeper interaction and collaboration between humans and machines, the technical requirements and the interface for communicating with these robotic fabrication tools have also been simplified.

The work outlined in this paper was intended as a first step in the evolution of mobile robotics on construction sites. In contrast to previous research projects, the fabrication unit shown here is intended to be an open system that is adaptable to different applications and situations; accordingly, the main objective of our research has been to identify different application scenarios, in addition to additive strategies, and to illustrate various communication and data acquisition systems. The scanning systems integrated into the process aim to respond to changing conditions in the workspace or construction site, thus informing the building cycle in real time as a feedback mechanism, altering and adapting the outcome when necessary. This is intended as the extension of stationary digital fabrication processes to in situ fabrication.

The building system proposed in this paper can respond flexibly to the rapidly changing requirements of the construction industry and might help close the gap between the design and in situ construction of complex, nonstandard structures.

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figure 13

Diagrams showing the design concept. The design drivers include the operational range and the self-collision of the mobile unit (in particular the gripper), along with the superposition of algorithmic rules.

MORPHFAUX:
PROBING THE PROTO-SYNTHETIC NATURE OF PLASTER THROUGH ROBOTIC TOOLING

ABSTRACT

Morphfaux is an applied research project that revisits the virtually lost craft of plaster to explore its potential for producing innovative architectural elements through the use of contemporary digital technology. The research challenges the flatness of modern, standardized drywall construction and explores plaster's malleability as a material that can be applied thick and thin, finished to appear smooth or textured, and tooled while liquid or cured. If the invention of industrialized modern building products such as drywall led to the demise of the plasterer as a tradesperson, our research seeks alliances between the abilities of the human hand and those of automation. By transforming historic methods using new robotic tools, Morphfaux has broadened the possibilities of architectural plaster. While our research has produced forms not possible by human skill alone, it also clearly illustrates a symbiotic relationship between the human body and robotic machines where human dexterity and robotic precision are choreographed in the production of innovative plastering techniques (Figure 1).

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