The Informed Wall
applying additive digital fabrication techniques on architecture

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Abstract
In this work in progress report we present the results of a four week design studio with graduate students as part of a broader research project on investigating digital additive fabrication processes and their implications on architectural design.
In a simple test arrangement we realized the digital design and additive fabrication of two by three meters brick walls. The use of bricks, being the primary module for construction, and at a relatively coarse resolution, allowed us to concentrate on the design of completely programmed walls encompassing material-dependent parameters. The resulting prototypes depict the great potential of the integration of the design and the fabrication process. Non-standardized solutions can be easily accomplished as the design data is directly used to control the fabrication process. In using an additive digital fabrication process, a novel architectural product of the kind "brick wall" emerged, which could not have been conceived or fabricated manually.

Introduction
In the architectural context we understand digital fabrication as the possibility to directly fabricate digitally described building components in a real world scale by making use of computer numerically controlled (CNC) machines. This dramatically alters the production terms of architecture for both the design (i.e. the production of data) and the fabrication (i.e. the processing of material). By means of digital fabrication it is possible to directly couple the virtual and the physical reality. We can link information, being it data or procedures, to built architecture and vice versa. Design information has formally never been linked so directly to the physical production of architecture. We therefore refer to this process as informing architecture.
In our research we focus on additive fabrication of non-standard building components by means of digital tools. Additive fabrication in its simplest way can be described as three-dimensional printing. It allows for a smart embedding of differentiated information on a shape and material level during the build-up process of a building component. Through the selective placement of different materials, as well as via variation of their spatial
distribution it is possible to fabricate highly informed building components. For fabrication we make use of a six-axis industrial robot. Its flexibility enables us to experiment with different materials and fabrication processes.

In this work in progress report we first give a brief introduction to digital additive fabrication, followed by a description of the robot research facility we conduct our work on. In the second part we give a summary of a four week design studio entitled the programmed wall which illustrates the potential of the digital additive building principle and gives a perspective on its applicability based on a real world project of the digital design and fabrication of a brick wall façade, which will be completed by October this year. Finally we draw a conclusion of the present research results and give an outlook on our future research.

**Digital additive fabrication**

Applying digital additive fabrication techniques to architecture is mostly limited to design studies in a model scale (e.g. stereo-lithography). The use of additive principles for the digital fabrication of architectural building components is largely unexplored. This is surprising, because the construction and materialization logic of architecture itself builds on additive principles (e.g. the stacking of bricks or the pouring of concrete). Not only does the close relationship to common architectural practice make additive fabrication a promising field of research, it also offers dramatic advantages over already established subtractive or formative digital fabrication processes (cf. Soar, 2006).

Compared to subtractive processes, where material is removed from the initial work piece, additive build up processes deposit material exactly where it is needed and therefore they produce no waste. This is not only an ecological factor, but also fosters a cost effective production. Subtractive and formative fabrication processes limit the design of a component to the definition of the surface, whereas the additive principle additionally allows a differentiated design of the cross section of a component. Unlike a traditional layered building logic, where for instance a wall is build up in sequential layers (weatherproof outer layer, insulation, load bearing layer, installations, inside finish), the additive fabrication process permits to build up all these layers in parallel, incorporating different functional properties throughout the component. Additive fabrication processes in architecture will let the designer control the change of e.g. load bearing or thermal properties of a building component as they are needed throughout its cross section. Similar to Functionally Graded Materials, where the composition or the microstructure of a composite material is locally varied, a certain variation of the local material properties is achieved (cf. Hirai, 1996). In addition internal cut-outs as channels or ducts can be directly embedded in the building components macro structure during the fabrication process (Table 1).

The additive fabrication process is influenced by three key factors: the resolution of the deposited material, the performance of the built component and the speed of the production process. The resolution (and/or composition) of the deposition material has an impact on the performance of the fabricated...
A better resolution allows for a higher level of detail and thus a greater range of possibilities for the integration of functional properties into the component. On the other hand, the resolution directly affects the fabrication speed, which determines the cost of the components. These dependencies are true in both directions and as a whole significantly determine the design strategy as well as the accuracy and appearance of the resulting output.

**The robot research facility**

To conduct our research the chair of Architecture and Digital Fabrication of the ETH Zurich built a unique architectural research facility (Figure 1). In particular it consists of a six-axis industrial robot with a reach of 3x3x8 meters, which allows the fabrication of real scale building components. This fabrication environment offers a maximum of flexibility and is able to experiment with different materials, resolutions and deposition processes. The robot arm can reach any point in a given three-dimensional space and performs any action depending on the logic of its control program, as well as on the tool, called *endeffector*, it is equipped with.

Normally industrial robots are used to perform highly repetitive tasks (i.e.

![Figure 1: Robot research facility.](image)
in the automobile industry), yet most architectural buildings are unique artifacts and the need for customization is high. Therefore we developed custom software and hardware to make use of the robot’s flexibility to construct unique building elements that adapt to various demands.

The informed Wall

In a four week design studio with graduate students we investigated the digital additive fabrication of brick walls and its potential for the architectural design. The students’ designs were completely programmed and digitally fabricated using the robot research facility. In this initial setup we used standard bricks originally used for manually constructing onsite as the basic element. In terms of the three key factors affecting additive fabrication defined above, the bricks represent a relatively coarse resolution, which limits the possibility to inform a building component to its macro structure. On the other hand, a fast production process can be achieved. Bricks were chosen because they represent one of the primary elements of an architectural build-up process. In addition, using bricks allowed us to focus on the potential of the combination of digital design and fabrication and encompassing material-dependent parameters, without having to develop a complex fabrication process. The robot arm was equipped with a specially designed gripper tool, which is able to pick up a brick and lay it down in a defined position (Figure 2). Additionally a computer script was developed to translate the CAD data into control data for the robot, which allowed for a direct fabrication from the design.

The students were assigned to design a three by two meters brick wall, making use of the prerequisite, that the robot can position every single stone differently without an additional effort. Each wall of the given dimension contains about seven hundred bricks, and the students where challenged to develop strategies on how to apply information on a large set of elements (i.e. the alignment of the bricks).

In a first step the students dealt with the logic of masonry bonds and their criteria for assembly and static properties. Hands-on tests were used to verify their concepts and rules for assembly (Figure 3). In a second step the students developed a computer script on the basis of these rules to generate their wall designs. A classical masonry bond in itself follows discrete rules for its assembly and therefore already describes a simple but refined algorithm. In a bottom-up approach the students, who were all novices in programming, used these logics and altered them for their own designs. Through the definition of their own parameters the students were able to apply their own information strategies and gradually increase the complexity of their scripts.

As a developing surrounding we chose
the commercially available modeling and animation software MAYA with its embedded scripting language MEL. This allowed for a constant review of the consequences of a script on the computer screen. The combination of both physical tests and the geometrical examinations on the computer furthered an intuitive understanding of the potentials as well as the limitations of the fabrication process (Figure 4).

The three build prototype walls on the one hand reflect the archaic presence of the chosen material; on the other hand they depict the differentiated features of their procedural design. In informing an established element of architecture (i.e. the brick wall), through the definition of the spatial dispositions of its single members (i.e. the brick), a novel architectural component emerged (Figure 5-7).

Prototype application

Currently we are building up a test case to digitally design and fabricate a brick façade of overall 300 square meters. The façade is divided into 70 elements between 3.33 meters and 4.75 meters of length and 1.48 meters of height. Each element is built up on a concrete lintel to enable the transport to the construction site. The bond between the bricks is achieved using a two component epoxy adhesive. Load
bearing tests of the elements revealed a high performance making any additional reinforcement unnecessary.

For the prototype fabrication process we enhanced the hardware setup of the robot cell. Mainly we automated the application of the adhesive, as well as optimizing the robot control script. The current setup makes it possible for a single person to operate the production process. Currently we are at a cycle time of 30 seconds per brick. Introducing a professional metering system for the application of the adhesive would reduce the overall cycle time up to 50%, as spreading the glue takes up most of the time. However our focus lies on exploring the new design possibilities that emerge out of these novel fabrication techniques, rather than optimizing the atomization process.

**Further research**

In further steps we will apply different deposition resolutions, as well as different materials and their combination (composites) on the additive fabrication process. Our intention is to explore the possibilities of informing building components down to the level of their cross-section.

In addition, the above mentioned dependencies between the key factors of additive fabrication and their relation to both the design process and its physical materialization represent a crucial point of the investigations.
**Conclusion**

Digital fabrication with robots enables the architect to directly research the physical layer of construction. The students’ projects of informed walls point out the potential of interlocking the architect’s knowledge of production and construction methods with the design process.

Additive fabrication processes especially promise a high potential for architecture. Beside its close relation to common construction practice, additive fabrication allows for: the control of the micro and macro structure of a building component, performance optimization through the design of the cross section and it produces no waste. Yet, the application of digital additive fabrication in architecture and its implication on design are largely unexplored and are open to a wide range of research.

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**References**
