Digitally Fabricating Non-Standardised Brick Walls

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Abstract

This paper gives an insight into a current research project aiming at exploiting the potential of digital fabrication techniques for the architectural design. A prototypical application of digitally designing and fabricating non-standardised brick walls was developed and used as an example to explore design strategies that directly incorporate the logic of the fabrication process. An emphasis is laid on not only mimicking existing fabrication processes, but identifying possibilities of adding value to established building components. As a result a novel architectural product emerged that could not be fabricated manually.

Keywords: digital fabrication, computer aided architectural design, robotic masonry system

Background

Industrial Context

Digital fabrication of building components by the means of computer numerically controlled (CNC) machines is of high interest for architects and the building industry. At present, the building industry is facing numerous structural problems. Its alarmingly low labour efficiency, high accident rate and poor product quality, accompanied by the vanishing of skilled workforce, demand the adoption of new technologies. Modern CNC machines give the possibility of producing complex and unique products. Yet, examples of their application to architecture and the building industry are scarce and mostly limited to subtractive fabrication processes, such as laser cutting or milling (Kolarevic, 2003). Alongside subtractive processes recent research has emphasised on the high potential of applying additive fabrication processes on architecture (Soar, 2006, and Khoshnevis, 2004). Unlike subtractive processes, where the design of a building component is limited to the definition of the surface, the additive principle additionally allows a differentiated design of the cross section of a component during the build up process. Furthermore it produces no waste as the material is deposited where it is needed.

One of the fundamental additive processes in construction work is the stacking of bricks. In the 1990’s there have been several attempts to develop mobile bricklaying robots for construction on site, the most advanced of them being the ROCCO and the BRONCO project (Andres, Bock and Gebhart, 1994 and Pritschow, Dalacker, Kurz and Gaenssle, 1996). The motivation behind these researches was to improve the productivity and economy of masonry construction, mainly by utilizing the machines ability for handling an increased payload in contrast to a human being. Although already highly advanced these developments did not find access into the building industry.

Problem

In general, the building industry is very much reserved towards the application of new technologies. Despite the fact that the digital revolution has opened new doors in our ability to generate descriptions of buildings and to communicate this information to machines that will make components, our ability to construct has barely advanced at all (Cook, 2004). We believe that it is insufficient to merely mimic existing construction processes in
order to have an impact on the building industry. The stimulus for innovation is not only efficiency and cost effectiveness alone, but must result in novel building components - in their performance, as well as their aesthetic appearance.

The main focus of both robotic masonry systems referred to above was set on improving productivity of standard masonry construction. A further barrier proved to be the complex handling of dimension tolerances and repositioning of the robot on the construction site. Also, for a machine, which is designed to perform only one specific task - the layering of bricks, the investment costs of estimated 200.000-250.000 EUR is too high for small and medium-sized companies, which make up 80% the industry (Steinmetzger, 2002).

**Learning Objectives**

- Handling information
- Developing design strategies for digital fabrication
- Connecting design tools with the fabrication process
- Adding value to established building components

**Approach**

In our research we focus on incorporating the knowledge of digital fabrication processes into the design process of architecture. For an initial test arrangement we chose to digitally fabricate brick walls, one of the primary elements in construction. In order to concentrate on developing novel architectural design strategies the hardware setup of the fabrication facility was kept simple. Also, we concentrated on the design of facing masonry, which only needs to support itself, in contrast to load-bearing brick walls.

As a fabrication tool we apply a six-axis industrial robot. The brick walls are prefabricated off-site avoiding the difficulties arising with mobile units working on-site as described above. A two component epoxy adhesive acts as bond between the bricks and is able to take on the considerable tractive forces acting on the prefabricated elements during transportation. For the design of the brick walls we combine the commercially available 3d-modelling software MAYA with custom written software. We develop software tools to handle the information of the wall elements in the design stage, as well as for fabrication. Finally, we examined the commercial application of the developed process by applying it to the digital design and fabrication of a 400 square meters brick façade.

**Analysis**

In the analysis we discuss the software strategies applied to inform the architectural design, the chosen fabrication setup, as well as the prototype application of prefabricating façade elements.

**Software Information Strategies**

The main difference of a robotic masonry system compared to manual labour, apart from the fact that a robot can handle a higher payload, is its ability to position every brick differently without an additional effort. To take advantage of this capability the designer requires software tools in order to inform the bricks of their spatial disposition. This can only hardly be done manually, as a two by three meters wall already consist of over 400 standard bricks.

Until now we applied two different information strategies on the design. The first strategy operates with a predefined positioning of the single bricks. Spatial information can be mapped onto the wall, resulting in a rotation of each brick around its centre point. This allows for an algorithmic patterning, as well as mapping images onto the wall (figure 1). The second strategy has a more intuitive approach. The designer is able to create and deform surfaces in a 3d-modelling environment. A script then maps bricks onto the geometry of these surfaces, while incorporating simple static properties (figure 2).

The Design data of each wall is directly used to generate the control data for the robot, thus no additional
programming for fabrication is necessary. This is an important factor, as normally the planning effort scales disproportional with an increasing number of parts. In this case it is irrelevant how many bricks make up a wall element and how each single brick is positioned in space.

Figure 1+2, illustration and physical prototype, strategy 1 (top row), screenshot of 3d-modelling surrounding (MAYA) and physical prototype, strategy 2 (bottom row).

Fabrication Setup

The setup of the fabrication facility is mainly composed of commercially available hardware. In particular it consists of a six-axis industrial robot mounted on a linear axis resulting in a reach of three by three by eight meters. The robot arm has a payload of 110kg, which is more than sufficient when working with standard bricks. For handling the bricks the robot arm is equipped with a gripper tool. To ensure that each brick is picked up in a centred position two roll conveyors (full bricks and half bricks) supply the facility with material in a predefined position. The adhesive unit is build up out of a stationary installed pneumatic handgun, which is connected via a bus-system with the robotic control centre. As a bonding material a two component epoxy adhesive is applied. Load bearing tests revealed a high performance of the adhesive, withstanding an average of 8 kN/m² under horizontal tension. This made no additional reinforcement of the prefabricated wall elements necessary, which would be very complex to integrate into an automated fabrication process. The described fabrication facility allows for a cycle time of 30 seconds per brick. Thereby, most time is taken up by the application of the glue. Replacing the pneumatic handgun with a professional metering system would reduce the cycle time under 10 seconds per brick. Also, the current setup is in need of one person supplying bricks onto the roll conveyors. Nevertheless, an automated depalletizing as already described for the BRONCO project could easily be integrated. In using ready available hardware we are able to build a highly flexible fabrication facility with the reliability of approved components. As a mass product with its main domain in the automobile industry an industrial robot is also cost-effective. The above described facility amounts up to estimated 150.000 EUR. Furthermore, the robot is a universal tool, able to perform any action dependent on the given end-effector, the device that is connected to the end of the robot arm, making it adaptable to completely different processes and future developments.
Prototype application

In a prototype application we digitally designed and fabricated 400 square meters of brick façade for a functional building of a winery. The requirements of the façade were to shelter the interior from direct sunlight and still allow air to circulate. For the design we adopted the strategy described above, in which the single bricks are laid out in a predefined grid and are merely rotate around their centre points. There is a gap of two centimetres between each brick. The rotation of the stones allows us to control the width of these gaps, as well as applying a pattern over the whole of the façade, which constantly changes in appearance under the influence of the sunlight (figure 5).

The façade was divided into 72 elements of 3.33 meters and 4.75 meters of length and 1.48 meters of height. Each element was built up on a concrete lintel for ease of transportation. Fabricating in a controlled environment allowed for a just-in-time production, four elements were fabricated parallel each day and every second day eight elements were transported to the construction site and put in place. This reduced the stock location needed to a minimum.

The disposition of the single bricks is different for each element. The non-standardised design is made possible by directly connecting the design data with the fabrication process. Additionally, this allowed us to work on the design up to the last minute, without influencing the production schedule. Despite the fact, that the design of the elements would not have allowed for a manual prefabrication the price of the prototype application (110 EUR/m²) is already competitive to that of a standard manually prefabricated masonry wall (125 EUR/m²).
Results and Business Impacts

Key Findings

In applying a six-axis industrial robot as a fabrication tool we are able to fabricate non-standardised building components. In order to fully exploit the possibilities of these new technologies, specialised software is required to control the great amount of information that is being processed. In combining the knowledge of the fabrication process with the architectural design, novel architectural products emerge, that could not be fabricated manually. Through using a two component epoxy adhesive as bond between the bricks the automation of prefabricated masonry walls could be simplified to a great extend, as no additional reinforcement is necessary. As a side effect this bonding technique’s ability to withstand high tension while still maintaining a certain degree of elasticity makes it extremely interesting regarding the earthquake safety guidelines for masonry.

Business Impacts

Although, the elements in our prototype application also fulfil functional properties, the added value of digital fabrication is mostly of aesthetic nature. Nevertheless, this is seen as a stimulus for the building industry, demonstrating the possibilities of new technologies. The layout of the fabrication facility described above also allows for the fabrication of standard wall elements to a competitive price compared to manual prefabrication. Even more, the facility can be used to fabricate totally different products apart from brick walls. Using ready available hardware allows the industry to build up highly flexible fabrication facilities, which are cost-effective and technical reliable.

Conclusions

Taking the example of already highly developed robotic masonry systems it was shown, that it is difficult to establish new technologies in the building industry. Mimicking existing manual processes and making them more efficient is not alone sufficient to effect a revision of common practise. Information technology enables us to directly control the fabrication process. In order to utilise the potential that lie within the fabrication tools, their abilities have to be incorporated already at the stage of the architectural design. One of the main potentials of digital fabrication processes is the possibility to individually control a large amount of elements. To handle this vast amount of information the designer is in need of novel software tools. In this paper we describe software strategies to combine the design with the fabrication process of brick walls. The potential of the design approach and the practicability of the developed fabrication process were demonstrated on a prototype application.

In a further step we will work with different materials, mainly scaling the basic deposition element in size. Our intention is to explore the possibilities of informing building components down to the level of their cross-section.

Key Lessons Learned

- Automated fabrication techniques in the building industry must result in an added value for the building components
- To fully exploit the potential of digital fabrication techniques they must be incorporated into the architectural design
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