DIGITAL-MATERIAL FEEDBACK IN ARCHITECTURAL DESIGN

Introducing material feedback through computer vision in digital design and fabrication

FELIX AMTSBERG¹, FELIX RASPALL² and ANDREAS TRUMMER³
¹, ³ Institute for Structural Design, Graz University of Technology, Graz, Austria
{felix.amtsberg, andreas.trummer}@tugraz.at
² Graduate School of Design, Harvard University, Cambridge, USA
craspall@gsd.harvard.edu

Abstract. This paper studies the architectural potential of the implementation of material feedback using computer vision before and during an automated fabrication process. The combination of an industrial robot and a 3D camera is used to expand the typical one-way design and fabrication process (from a digital design to a physical output), to a feedback loop, where specific material information becomes the main trigger of design decisions and fabrication processes. Several projects developed by the authors and tested during a robotic workshop aim to unveil different aspects of material feedback in architectural design, opening a discussion for the benefit and challenges of this new approach to design and fabrication.

Keywords. Material feedback; robotic fabrication; computer vision; digital workflow; robotic workshop;

1. Introduction

The adoption of digital tools in design and fabrication has deeply changed the way architects and artists work. One of the most recent areas of research is robotic fabrication, focused on the application of robotic manipulators, previously limited to the manufacturing industry. In architectural academic research, the use of robots changed from mass-production applications to the
development of highly custom and one-off products (Bechthold and King 2013). The recent improvements in the interfaces to control robotic arms have opened the control of these machines to designer and artists. Many research groups are investigating opportunities for fabrication processes as main triggers of the design concept. Robotic controlled hotwiring of Styrofoam elements, weaving of frame structures or the assembly of brick walls, are just a few well known examples of the current explorations. They combine the accuracy and controllability of digital design with the versatility of industrial robots to enable new design and fabrication concepts. Therefore one focal point of investigation is the development of an end effector, designed specifically for the intended process. (Fig. 1)

![Figure 1. Versatility by tool development.](image)

2. Design to Fabrication as state of the art vs. Digital-Material Feedback

2.1. STATE OF THE ART

Current research on design to fabrication share the following workflow: The geometry is defined in a modelling environment, the production process developed or selected, the CNC instructions are created and the construction is executed. The production process and the final result are defined before construction. In this workflow, reactions to contingencies during construction are time consuming and expensive. For this reason, construction materials and fabrication processes are standardized and highly predictable. However, when construction materials and fabrication processes are non-standard and irregular, the specific material information becomes an essential part of the design process. Some industries are already addressing this issue, particularly when processing organic materials that carry inherent irregularities. For example the timber industry uses scanning x-ray systems to analyse logs on knotholes or other imperfections of the material. Sophisticated algorithms calculate the
cutting sequence to optimize offcuts according to parameters like quality and efficiency. An analogue process is used in the meat processing industry. 

On an academic level, several research projects have started to use work piece analysis before and during the fabrication cycle. The project “Band-sawn bands” (Johns, Foley 2014) uses the curved plank of an awry grown tree as an advantage and designs a divan suitable to the work piece. In that way, the number of cuts and the amount of waste can be reduced. The design is directly influenced by the irregularities of the available material. Other projects focus on fabrication processes that involve larger uncertainties. One example is the robotic steam bending using tracking sensors to measure the bending behaviour and adapt the motion of industrial robots in real time (Schwartz, Bard, et al.2014).

2.2. THE MOMENT OF DIGITAL-MATERIAL FEEDBACK

The implementation of sensor systems offers new perspectives to digital design and fabrication. The specificities of the actual construction materials and the actual fabrication processes become main drivers of the design (Raspall, Amtsberg 2014).

A relevant aspect in this research is the determination of the different time points of sensing. They can be distinguished in 3 stages: Before, during and while actuating. These sequences of sensing, analysis, design adjustment and fabrication define three levels of digital-material feedback:

1. Scan-Design-Production | Informed Feed forward process: The work piece or parts are scanned and analysed; using that information the design is adjusted and the fabrication process executed accordingly. After this process, the final product is accomplished. (Fig. 2)

2. Multiple cycle based Scan-Design-Production | Feedback loop: The project is divided into stages. The available work piece or additional parts are scanned and analysed; using that information the design of the current stage is adjusted, and the corresponding fabrication process executed. The process is repeated for all the subsequent stages until the completion of the final product. Scanning and actuation are separated processes. Decisions are made between the fabrication cycles. Iterative production is enabled. (Fig. 3)

3. Real-time feedback based Scan-Design-Production | Feedback loop: Differing from the second example the work piece is analysed while it is under actuation. The material feedback influences the digital model and the subsequent fabrication instructions in real time. This process requires a direct link between robot and design script. (Fig. 4)
2.3. RESEARCH ON “DIGITAL-MATERIAL FEEDBACK”

The use of actual material information before and during the construction process opens new opportunities for design. But, what benefits can designers get from material feedback? When and how should it be used? What kind of information is relevant? And how do new processes influence the design approach in architects, engineers and designers?

To answer these questions, three different experiment setups were designed, developed and tested during the 3-day workshop “Informal Material Formations”, ran by Felix Raspall, Felix Amtsberg, Martin Bechthold and Stefan Peters at Carnegie Mellon University form May 14th to 16th, 2014 in the framework of the “Rob|Arch 2014” conference. The aim was to test the feasibility of digital-material feedback in design and fabrication and to generate an initial understanding of its possibilities for architecture.

3. Experiments’ context, layout and programming

3.1. PHYSICAL LAYOUT

The layout consists of an IRB 140 industrial robot mounted on a table and equipped with a custom end effector (Fig. 5). The table is divided in two areas. The scanning area is used to “feed” building parts to the system. The as-
assembly area is the space where the robot assembles and manipulates the parts. The end effector combines the scanning and the actuation tool. It consists of an aluminium frame that contains a Microsoft Kinect 3D camera and allows the attachment of different effectors. The experiments use a suction cap and a clay stamping tool.

Figure 5. Physical Layout: the scanning table on the right of the robot and the assembly table in front of the robot. The image overlays the robot in the scanning position and the placing position.

3.2. DIGITAL SETUP

The experiments utilized a beta version of IDR, a plug-in for McNeel Grasshopper that coordinates camera control, computer vision and online robotic control. It is a platform currently under development by Felix Raspall as part of his doctoral research.

Figure 6. Example of the IDR interface for a simple script that scans the parts, calculates a linear organization and executes the robotic assembly automatically.
4. Case studies

During the workshop, three different experimental setups were investigated, aiming to prove the feasibility, reliability and potential of material feedback.

4.1. SETUP 1: FORM APPROXIMATION

The first setup investigates design processes in which the exact characteristics of the building parts are unknown before construction. The setup involves a collection of different parts with a large range of sizes and shapes. In the experiments, from a small pool parts are randomly selected from this collection, making impossible to anticipate exactly what the available materials to build the design are. The key challenge of the Setup 1 is understanding how to automate the design and fabrication of a predefined geometry when the actual available materials are unknown before construction.

The project “Scrap Wall”, developed by Antonia Dorn during the workshop serves to illustrate the process (see Fig. 7). The project develops a design and fabrication system that implements material feedback following the “Scan-Design-Production | Informed feed forward process” approach. The goal of the system is to automate the design and construction of a curvilinear wall of a predefined geometry using irregular building parts.

The system is designed to recognize the available parts, select those appropriate for the project, and calculate the arrangement of the parts in the predefined form. If the arrangement is successful, the system automatically executes the assembly, one row at a time. First, the system scans the parts, reading their geometry and position. Then, it attempts to fill the current row in the wall using the available parts. For this, a nesting tool (Geometric Global NestLib) is embedded in the system. The nesting process calculates the position of parts in the wall. If the nesting process is successful (in this case, success is defined as a ratio of parts area and row area) the robot starts to place them inside the geometry. At the end the physical result matches the desired geometry quite closely, and adds an expressive irregular texture.

![Figure 7. Digital model and realized wall of the geometry.](image-url)
4.2. SETUP 2: ASSEMBLY PROTOCOLS

The second setup also investigates design processes in which the exact characteristics of the building parts are unknown before construction. However, the key challenge of the Setup 2 is understanding how to automate the design and fabrication without predefining a geometry for the project. Instead, the project defines the assembly rules between parts.

The project “Scrap Column” developed by Pedja Gavrilovic during the workshop serves to illustrate the process (see Fig. 8). The project develops a design and fabrication system that implements material feedback following the “Scan-Design-Production | Informed Feed forward process” approach. The goal of the system is to automate the design and construction of a column-like structure using irregular building parts.

The system is designed to recognize the available parts, select those appropriate for the project, and calculate the arrangement of the parts in the predefined form. If the arrangement is successful, the system automatically executes the assembly of the whole column.

First, the system scans the parts, reading their geometry and position. Then, it sorts the parts by length, distributing them from longer to shorter to longer again. Then it calculates the 3D arrangement of parts, organizing them into pairs and stacking pairs, one perpendicular to the next one. The system executes the construction automatically. A waist profiled column is the result.

![Figure 8. Scanning and Pic and Place and realized waist profile column.](image)

4.3. SETUP 3: ITERATIVE FORMATION

The third setup investigates design processes in which the manipulation process involves high uncertainties, making unreasonable to create a single fabrication instruction. The setup involves the progressive deformation of a block of clay into a target geometry. In the experiments, a stamp tool is used to push the clay, but each pushing action affects the whole block of clay,
making it very difficult to anticipate the reaction of the block of clay after several pushing actions. The key challenge of the Setup 3 is understanding how to automate the design and fabrication of a predefined target geometry when the fabrication process is very hard to predict.

The project “Iterative Clay Formation” developed by the authors during the workshop serves to illustrate the process (see Fig. 9). The project develops a design and fabrication system that implements material feedback following the “Real-time Feedback” approach. The goal of the system is to automate the design and construction of freeform surface in clay.

The system alternates between 2.5D scanning and pushing actions. The system starts by scanning a block of clay placed on the assembly table. Then, it measures the deviation between the actual surface of the clay and the target surface and decides a pushing strategy. The system executes the pushing motions and rescans the results. Now, the block of clay is closer to the desired output. The pushing motion is calculated again and the process repeated until a predefined accuracy is achieved.

![Figure 9. Scanning and Deformation process and the final shape.](image)

### 4.4. EXPERIMENT ON HUMAN-MACHINE COLLABORATION

The effectiveness of the experiments in the Setup 3 enabled an extension of its scope, aiming to incorporate human labour in the fabrication process. The project developed by David Thomasson in the context of the workshop starts to address the possibility of human machine collaboration using material feedback. The project evolves the “Iterative Clay Formation” by using the scanning process as a means to introduce gestural commands to the system. By pointing on a specific area between the block and the camera (Fig. 10) the user informs the system the location, diameter and depth of a circle the system will then model. The system then runs the pushing action based on human instructions and waits for the next command.
5. Conclusion and Perspective

5.1 CONCLUSION

The presented projects demonstrate the feasibility and effectiveness of digital-material feedback in design and fabrication. The integration of a computer vision system within an automated fabrication process opens new avenues for architects. The use of irregular material sources and imprecise fabrication methods becomes possible, at the expense of embracing imperfection and uncertainty.

In the first setup, “Form Approximation”, a desired geometry is the crucial input parameter to which the available pieces are fitted as close as possible. The project embraces imperfection, as it is not possible to match the form accurately.

The second setup, “Assembly Protocol”, takes a different approach. Without a predefined geometry, the project is conceived as assembly rules that determine how parts are put together. The project embraces uncertainty, as the final form remains unknown, as it is calculated only when the parts are available.

The third setup, “Iterative Formation”, enables an automated production process via a feedback loop, which adjusts the fabrication based on the reaction of the materials to the manipulation process. The complete toolpath is never available, but it is actualized. This allows the manipulation processes that are not deterministic, like plastic formation of clay of elastic bending of wood.

Finally, enabling “Human machine collaboration” goes away from automation and links the fabrication process back to crafting, where the robot becomes an extension tool of the human. Intuitive, immediate reactions of the creator can be communicated to the system.
5.2 PERSPECTIVE

The described results have successfully proven the feasibility and reliability of the material feedback in architecture. There are several applications that can take advantage of feedback processes. For example, it enables the use of discarded materials, where the form, quantity and quality of the available construction materials are impossible to anticipate before construction. In addition, it expands the scope of digital fabrication beyond highly predictable and standard processes such as milling, embracing hard-to-predict fabrication methods.

The possibilities of material feedback in architecture are yet to be seen, but the initial explorations presented in this paper are promising.

Acknowledgement

The projects presented in this paper, are the results of the workshop “Informal Material Formations” hosted by Joshua Bard at the Carnegie Mellon University and part of the conference Rob|Arch 2014. The workshop participants included: Mahdi Alibakhshian, Padreep Devedass, Anita Dorn, Pedja Gavrilovic, Yasser Ibrahim, Brian Peters, Maximillian Seiferlein and David Thomasson.

The nesting library “NestLib” used in this research was kindly provided by Geometric Global and the ABB IRB 140 robot was provided by ABB.

References