
Cultural Performance in Robotic Timber Construction

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Figure 1 Detail of Lintel and Sill System

MIDDLEWARE

ABSTRACT

In the research presented in this paper, we investigate the architectonic potential of additive digital fabrication in timber construction through robotic processes. The goal of the project was to learn from traditional building techniques and to translate the cultural knowledge about performance requirements such as constructive weather protection and structure for today's tools and digital design systems.

1 INTRODUCTION

Material and production processes that inform design have come to interest architects over recent years (Kolarevic 2003). But still, geometry is at the core of today's digital design representation within standard software tools (Kilian 2006). Geometry alone makes it hard to capture the complex relationships among material properties, the constructive logic of building elements, and production. Current building scale digital fabrication technologies enable architects to integrate these often contradicting requirements through the direct link between code and fabrication, which not

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only yields new possibilities for the design, but also requires revising the usual top-down plan to the construction approach. In order to set up a link among design, fabrication processes, and material, the architect needs to control and manipulate his tools on the hardware side, as well as on the software side. This can be done through custom scripts, which, on the one hand, allow for the control of tailor-made hardware tools, and, on the other hand, integrate design-related parameters with process and material-driven properties.

For this research project, we were looking into component-based, flexible materials that can be processed into different shapes and lengths, and that are suitable for outdoor application. The material should be rooted in traditional artisanship in order to analyze culturally developed ways of construction and to test their relevance for today's digitally driven processes. For these reasons, wood was chosen as the preferred building material. Further, wood is inexpensive, and depending on the type of wood and how it is applied, it possesses great durability and strength compared to its weight. After all, it is a sustainable material that is easily available on the local market.

2 HARDWARE: MATERIAL AND FABRICATION

The object of investigation was the design of load-bearing, waterproof timber walls that integrate an opening (fig. 1). The walls needed to allow for insulation and were produced through an additive digital fabrication process. Wood was used for most of the constituent parts of the wall, such as the load-bearing structure and the exterior and interior cladding. The analysis of traditional wood construction such as carcass buildings or overlapping techniques for wood preservation found in vernacular farmhouses in the Swiss Alps informed the design systems used to organize the singular slats to form a wall.

2.1 MATERIAL SPECIFICATIONS

The projects presented here utilized standard spruce slats that are widely used, with a diameter of 4 cm by 60 cm. The length of the slats was allowed to vary between 15 cm and 120 cm [place all in mm or cm]. Besides the type of wood selected, constructive weatherproofing played an important role in the durability of wooden building elements (Schweizerische-Normen-Vereinigung 2007). These requirements led to the following guidelines: Face wood should not point in an upward direction due to its sensitivity regarding water absorption. Areas where rain water could accumulate were to be avoided, and an overall good drainage system should be achieved. These guidelines provided protection against fungus infestation and fissuring.

2.2 FABRICATION PROCESS

The fabrication tool we used was a six-axis industrial robot equipped with a custom gripper for handling and placing the slats at the right position in space with a specified angle (fig. 2). The robot arm can operate a workspace of 3 by 3 by 8 m.



Figure 2 Industrial Six-Axis Robot



Figure 3 Custom Air Suction Gripper

The custom gripper we developed was equipped with air suction nozzles, which grab the wood slat from the side (fig. 3). The nozzles could be switched on and off individually via the robot's control unit.

In addition to the placement tool, we used a circular saw to cut the wood slats to length. Since every slat can continuously vary from 15 cm to 120 cm, the robot was used to show the length of the slat for cutting. The cutting angles of the slats can be adjusted from -45 degrees up to +45 degrees. For exact angle cutting, the saw was connected to an automatic "turning table," which uses the same controller as the robot itself. This forms the seventh axis of the system. In this stage of the project, the cutting procedure had been kept semi-automatic, as this procedure can be handed over to a standard industrial trimming machine in later stages of automation.



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The connections between the slats were made through nailing on a per layer basis. The horizontal build-up process results in walls with the slats and their grain in a specific direction. The alignment of the grain is directly linked to the structural and weatherproofing performance of wood structures. A horizontal bricklike placement of slats is ideal for the fabrication process, but it is not suitable for the outdoor application of a wall. Horizontal slats would allow water to accumulate, and the vertical nailing is susceptible to horizontal wind loads due to pulling forces inside the structure. From this, it follows that for optimized water drainage and structural results, the walls should be turned over by an angle of 90 degrees after production (fig. 4).



Figure 4 Smooth Surface Ideal for Water Drainage in Wood Grain Direction

The stacking process and the nailed connections set the following constraints for the design:

- A minimum required overlap of half the slat's width between the slats of one layer to the slats of the next layer to allow for proper nailing connections.
- A maximum allowed cantilever of approximately 70 cm for the overall structure during production in order to avoid sagging and deformation.
- Placement logic for the slats either predefined or through optimization to prevent collisions between the gripper and the already built wall.
- An end angle that adheres to the ± 45 degree limit of the cutting machine to ensure closed flush placement of wood slats.

3 SOFTWARE TECHNOLOGIES

For the design and development environment, we chose a standard modeling and animation software package due to its integration of the Python (Python-Software-Foundation 2009) programming language and the flexible grouping mechanism for geometry. Additional technologies used were the Python vector library "Euclid" (Holkner 2009) for vector and matrix calculations and the "General Polygon Clipping" library, with the Python binding from Joerg Raedler for 2D polygon Boolean operations (Raedler 2009).

4 SOFTWARE: DESIGN TOOLS AND EXPORT

Design and construction parameters derived from physical testing should inform the data within the 3D modeling application. But the tools available within standard CAD packages did not allow for a flexible integration of this data. Therefore we developed a design setup that consisted of four parts. The first one was a set of design scripting tools written in Python which generate slats inside the 3D environment. The second part was a predefined data structure inside the 3D application. The third part was a custom export from the digital model to the robot, written in Python as well. It generates the fourth part the KRL code (Kuka Robot Language) which controls the fabrication robot.

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4.1 DESIGN SCRIPTING TOOLS

The design tools were comprised of several scripting functions that can be used to generate slats. They simplified the control over parameters such as location, rotation, and cut angles. Furthermore, they integrated production and construction logics derived from physical testing into the 3D environment by setting constraints for the generation of slats (e.g., the custom slat function did not allow for the generation of slats with a cut angle greater than the degree limit predetermined by the fabrication process).

4.2 DATA STRUCTURE

The data structure inside the 3D modeling application provides the basis for manual interaction during the design scripting process. From experience during previous research projects, we learned that about 90 percent of the design goals can easily be reached through direct programming, but around 10 percent are more easily solved through manual interaction. The data structure builds the interface between the scripting part of the work and the manual changes required.

The predefined hierarchical grouping logic within the 3D design package corresponded to the production logic of stacking. The top-level group formed the whole production piece and contained further subgroupings, which formed the layers. These layer groups held the actual slat components. In addition to geometric information, such as size, position in space, and cut angles, fabrication details were attached to the 3D slat objects. This information and the grouping sequence could be analyzed by scripts that already provided feedback about the production process in the 3D application. The designer could then modify the model and integrate necessary changes in an interactive process that did not stop after the generating script had finished.

4.3 EXPORT

The export optimized the design data structure for production and generated the machining code for the robot. The custom export functionality latched into the grouping hierarchy inside the 3D environment to extract layer data and to read out the location, rotation, and angle data from the slat components.

The ordering of the layers and of the components within the layers determined the basic placement sequence for production. Two critical aspects had to be solved during export for production. First, due to the shape of the gripper, which was predetermined by the picking of slat from the saw, virtual collision testing had to be performed to avoid collisions between the gripper and the already placed slats. Depending on the result of the collision test, the gripping position had to be modified until the algorithm found a solution. Second, in order for the walls to form a closed volume for insulation, the wood slat's face had to be placed flush, touching the other slats (figs. 5, 6).

Due to tolerances from cutting that could reach up to 1 cm, a final vertical move of the gripper could not serve to place the slats since, in some cases, this led to collisions. This fact required that we move the robot's gripper, a complex process whose placement was dependent on the already placed slats' orientation, the cut angle, and the orientation of the slat it was preparing to place. The Python code transferred this information via modified function calls to KRL.

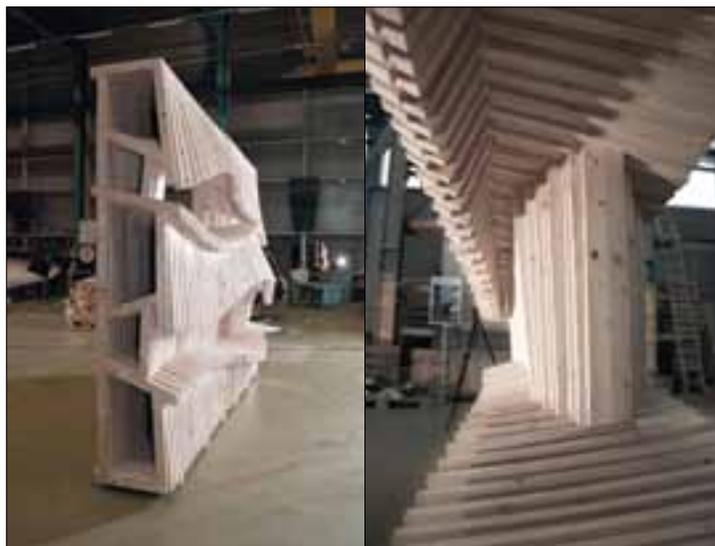


Figure 5 Flush Placement Section

Figure 6 Flush placement section

5 CASE STUDIES

The following case studies present some of the results developed and fabricated during a one-month student research course. The goal of the course was to develop a full-scale lintel and sill system, which would form the basic design for a wall prototype 4 m wide by 2.5 m high and with an approximate thickness of 30–60 cm. The intention was to have the prototypes serve as the building envelope and, therefore, had to allow for the addition of insulation in between two outer wooden shells. Further performance requirements were the structural feasibility of the design proposal and weather protection, either constructive or technical.

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We asked the students to analyze traditional wood building techniques and to evaluate their potential for fulfilling the aforementioned performance requirements. They specifically analyzed systems that would allow for the integration of openings or that already integrated an opening, with a special focus on constructive weather protection, insulation, or structure. In a second step, the students translated and adapted the artisan methods to today's requirements and to the digital fabrication process at hand.

The first case study reinterprets the traditional carcass system (fig. 7). The most important aspect of the carcass is that it integrates the opening in the structural system itself—no additional structural parts are required. The opening emerges naturally from the system. Another important characteristic is that the carcass can be built with relatively short wooden beams. Both of these facts translate very well to the production process, which works with short pieces of wood to form larger building elements with openings. The sill and lintel of this design form the basis for the structural system, which consists of large beams running through the whole piece (fig 8). Since many small pieces form the large beams, the beams are able to interlock easily with the reinforcing slats. The traditional filling material in between the beams of vernacular carcass buildings consisted of adobe and straw. The drawback of this technique is poor insulation performance due to air permeability. Thus, the students replaced the filling with a translucent ETFE shrink-wrap foil (fig 9). The small chambers between the wooden structure and the foil limit air circulation, enhancing the insulation effect.

The second case study uses the cantilevers in traditional Wallis sheds (fig. 10) as a basis for its design system. The gradual increase in width of the overhang is a simple means to achieve weather protection and to drain rainwater away from the structure. The students reasoned that the fabrication of small modular components that overlap and interlock with each other could solve the limitation of the slats' length. The slats can be assembled into one structure to build up the wall (fig. 11). By tilting the upper part of the component, the water drips from the tip of the horizontal slats. The inside of the components can be filled with cellulose-flake insulation. An opening can be integrated easily into the wall by leaving out select, individual modules (fig. 12).



Figure 7 Carcass



Figure 8 Wrapped Carcass

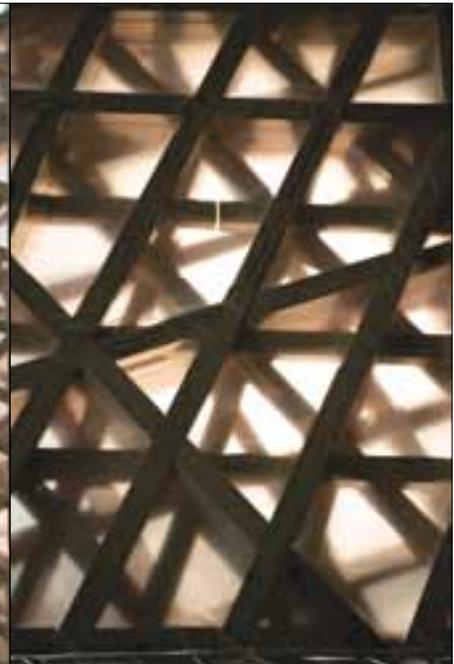


Figure 9 Detail

6 DISCUSSION

Between the material potential and the performance of a building component exists a direct relation that is influenced by the techniques and technologies used for production and assembly. In digital fabrication, the fabrication process data controls the transgression of a material component (slat) to a building component (wall). The selection of small components and a flexible connection technique (nailing) allows for the production of intelligent, monolithic elements. If we interpret the state of the feedstock as a system of high entropy, then the production process enriches the material with information that leads to a material aggregation that is functional, and whose design potential surpasses the possibilities of the singular small piece. The performance conceived during the design process can emerge only through the inseparable ensemble of the components as a whole building part.

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In traditional trades, the data that informed the building part was the knowledge about construction accumulated and passed on through generations of craftspeople. With the rise of the timber engineering industry, it became common practice to fabricate complex elements from larger boards of wooden composites.



Figure 10 Traditional Shed



Figure 11 Section
Overhang Structure

Figure 12 Elevation
Overhang Structure



The performance of such elements is often defined through the performance of the composites in use and less through how the original material is applied. Material properties of wood such as grain direction, shrinkage, or the sensitivity of face wood to moisture are, rather, interpreted as problems and are mostly solved on the material engineering level. In contrast to fabrication processes for derived timber products, the prototypical techniques laid out in this paper provide the possibility to work with raw wood. This requires responding to material properties and to the projected performance requirements. Together with the production process, this can enable a new freedom of design that generates an intrinsic expression that emanates from the interplay of the aforementioned physical and expressive facets of building. The characteristics of the wood are not ignored but integrated as the driver of the project from the beginning. This research tightly integrates material and technique, which bears similarity to pre-industrialization artisanship. Due to this affinity, the analysis of traditional construction systems is a rewarding starting point for the development of design systems for today's digital fabrication processes. Similar to the artisan who had to master his tools, the architect needs to master his software, as well as hardware, and to understand their relation to matter.

CONCLUSION

The research shows that it can be useful not to discard the cultural performance visible in traditional construction methods but to analyze and abstract these often sophisticated yet simple solutions for use with the tools of today. Until now, the focus was on very primitive constructive systems that could be easily analyzed and appropriated for a digital fabrication process. In a next step, there could be an evaluation of more complex systems that integrate different materials for specific parts of construction and for new types of connections.

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