The Framed Pavilion

Modeling and Producing Complex Systems in Architectural Education

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Abstract. According to the Encyclopedia Britannica [1] a robot is "any automatically operated machine that replaces human effort [...]". But it is much more than *just another tool*. It is an extremely adaptable machine open to any kind of task, when operated adequately. It is a complete new "medium", and as a result, there is a whole new "message". (Fiore and McLuhan 1967) Half a century after the introduction of robots to the manufacturing process that kinematical apparatus finally made its way into art and architecture. With a tangible example this paper tries to illustrate the opportunities for the contemporary building industries and the importance of teaching students the basic principles of interacting with robots. As a matter of fact, we will discuss the Design Master Studio *bot/log: Parametrics/Joints constructed/designed by/in Robots/Wood*.

Keywords. Project and practical application of Algorithmic Design; Computational approaches to Sustainable Design; 1:1 realization in wood; Rhino/Grasshopper.

Robots: The ultimate CNC machines

In a recent lecture at the Graz University of Technology (TUG) Martin Bechthold (2012), Professor of Architectural Technology at the Harvard Graduate School of Design, pointed out that the common architectural design strategy starts with a given problem, a problem to be solved. Subsequently one develops a tool or a system that could possibly solve that problem in a suitable manner. Therefore the outcome usually is unique, but in most cases rigid as well. As an example for that he refers to Japan's construction robot industry in the 1980s (Cousineau and Miura, 1998).

Opposed to this, the scientific approach of the Institute of Architecture and Media (IAM) [2] does not necessarily rest on a problem. We try to take a given tool and explore its capabilities. Our goal is to get to the bottom of that tool, make out the present limits of its employment and expand the borders of what's possible. And as we are currently working at the university we always feel the necessity to focus on the process, the research and the education of future architects rather than on the sheer result. In this context the head of our department Urs Hirschberg loves to quote Nicholas Negroponte (1994): "Don't Dissect a Frog, build One!"

Despite externally funded research projects in the field of geometric processing and non-standard architecture [3] the IAM is pursuing the idea of a research-based education of master students for several years now. We canvassed promising hardware tools like tracking systems [4], electronics prototyping platforms [5] and different rapid prototyping machines [6] [7] [8] [9] [10] in our Design Master Studios [11] with veritable success – including several exhibitions and publications. In 2009 the Faculty of Architecture [12] and the Faculty of Civil Engineering [13] joined forces to set up a new Robot Design Laboratory [14] in cooperation with ABB Robotics [15]. And the IAM started to delve deeply for new applications that are beyond the supplied industry solutions.

Apart from other obvious advantages over different CNC-machinery it is the manufacturing flexibility of robots that make them rewarding for any researcher and student. Since the robotic arm can manipulate any tool that is mounted on its flange, robots already take on a large variety of tasks – some taught online, but most of the fetching ones are programmed offline (Braumann and Brell-Cokcan 2011).

Quintessential for a picking and placing with a gripper could be Gramazio/Kohler's robotically placed bricks to form walls and columns [16] (Bärtschi et al. 2010) (Figure 1, left). Interesting examples for stamping, drawing and even painting might be robotlab's *autoportrait* [17], IAM's winter semester 2010 studio *papier peint* [18] and Richard Dank's *Chinese Ink Painting Robot* at the HDA panel discussion *Should buildings grow/adapt/repair themselves? And if so, why not?* [19] (Figure 1, center). And there are certainly a lot of welding, hot wire cutting and milling projects around, such as experiments at the smartgeometry workshops [20], designtoproduction's *SWISSBAU Pavillon 2005* [21] (Scheurer 2007) or the *ICD/ITKE research pavilion 2010* [22] (Kaltenbach 2010; Knippers and Menges 2011) and *2011* [23] (Fleischmann and Menges 2011) (Figure 1, right) envisioned at the institutes of Achim Menges and Jan Knippers in Stuttgart, just to name a few.

Figure 1
Gramazio/Kohler's brick laying robot in action (left). Dank's Chinese Ink Painting Robot (center). Menges/Knippers' ICD/ITKE research pavilion 2011 (right).

So the aim for architecture schools around the world is pretty obvious: Teach students to model parametrically and give them full algorithmic control over the robotic arm. When they grasped the principles and they know the instrument, they will be able to produce astonishing results while experimenting.

Code: The ultimate way to control the robot

In their paper *Parametric Robot Control* Braumann and Brell-Cokcan (2011) thoroughly analyze robot on- and offline programming respectively the common linear workflow. Usually there are several professions and platforms involved until the design of the architect finally disembogues in produced architecture: "A designer[…] to create an aesthetic surface in CAD", "a programmer then" applies "the geometric constraints to the predefined surface, […] followed by a technician who post-processes the geometric data output for the robot control data file". Additionally most projects require structural engineers and people/facilities who/which are able to produce and assemble the different pieces in the end. Due to all these different operations the whole object will gradually evolve.

This could be a good thing after all, but none the less the architect looses control over his/her composition eventually. What's even worse though: If the originally induced "aesthetic surface" needs to be changed for whatever reason, everything has to be done all over again. "The question arises here how to further customize the digital workflow to allow the user, i.e., the designer, to manipulate the initial CAD surface […] and the robot control simultaneously?"

We argue that all the external know-how from the collaborating partners must be incorporated into one single parametric model. So all the plans, figures and facts required can be directly exported. In addition even the robot code with all its parameters, from tool-data to tolerances, is written on the fly (Figure 2, right). So the process of designing is not frozen until one presses the play-button on the robot's pendant.

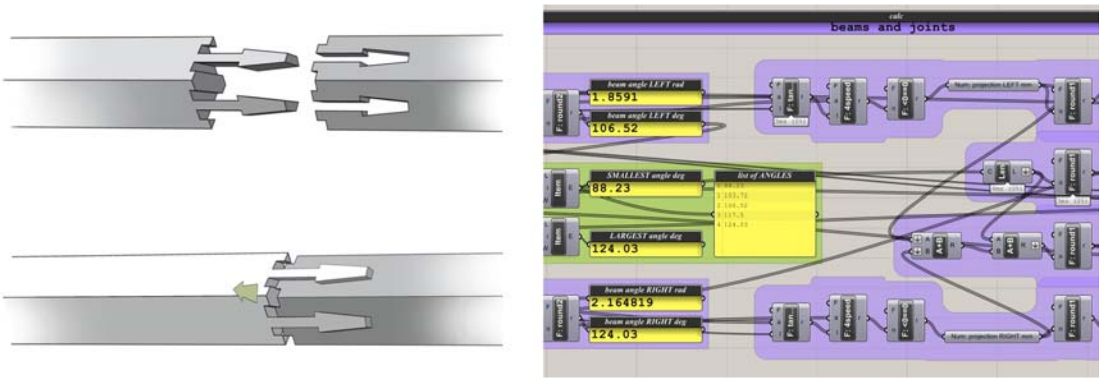

Figure 2
Traditional Japanese wood joint (left). Visual representation of parametric model generation (right).

As a consequence this means that future architects must be trained in designing the “aesthetic surface” as well as being able to formalize the process. They need to be programmers (to a certain extend) and know CNC technology with all its constraining and liberating features, so that there is no necessity to “dissect the frog”. The designer should be able to “build it” from scratch.

bot/log: Parametrics/Joints constructed/designed by/in Robots/Wood

This paper will present a case study just recently finished at the IAM. It started out as a Design Master Studio in winter semester 2011/12 with a group of students and the strong Styrian woodworking industry onboard.

The Objective: Design a structure and all joints solely made from timber, no glue or other fasteners or fixings allowed. For the realization use the capabilities of a 6-axes robot on an additional linear axis. Moreover the entire project must be applied parametrically! Start to analyze existing and traditional wood joints and test their possibilities to transform them to digital and parametrical models. Next step is to improve the parametrical models in consideration of producing all joints with our robot and the milling environment. The shown traditional Japanese wood joint (Figure 2, left) is a good example where production with cylindrical milling tools is not possible without redesigning the joint. With this developed data start to design and simulate a walk-in structure.

The Studio concluded with 18 individual full-scale algorithmic projects and one completely implemented and built structure – *The Framed Pavilion* (TFP). There were basically two main reasons why we finally chose to build exactly this structure. First the erection process does not require any scaffolding at all. And secondly everything can be put together without the equipment or the hands of professional workmen. The students could assemble the frames and blocks on their own. But the whole variety of projects and the evolution of TFP can be found on our bot/log webpage [24].

The Evolution of The Framed Pavilion

Sabine Lehner’s original design intention of was to build irregular pentagonal frames mutating along an axis. The implemented algorithmic process enables the user to convert any basic surface that seems appealing. The application assists to meet the restrictive parameters such as the positioning of the wooden dowels, the minimum and maximum beam length and joint angles. Thereby it was possible to generate a morphing shape between the interior and the exterior where height variations, gaps and openings define a special ambiance (Figure 3).

Figure 3
The completely implemented and built structure.

The Framework for the conceived design to production workflow was Rhinoceros [25] extended by its visual programming language Grasshopper [26]. These tools let us build a bridge between design, simulation and fabrication and give all the opportunities to enlarge their functionality by specially programmed Add-ons for our project. Due to performance and handling issues of large datasets we decided to split our parametrical process into two components that are linked together:

1. Definition of boundary conditions and design environment for the main structure.
2. Elaboration for the joint details with building and fabrication requirements including robot code generation.

The basic setup of the realized form is defined by multiple pentagons with variable interior angles. These curves define a lofted surface with straight sections. Afterwards we slice the surface in user defined distances for creating the square cross section wood frames (Figure 4).

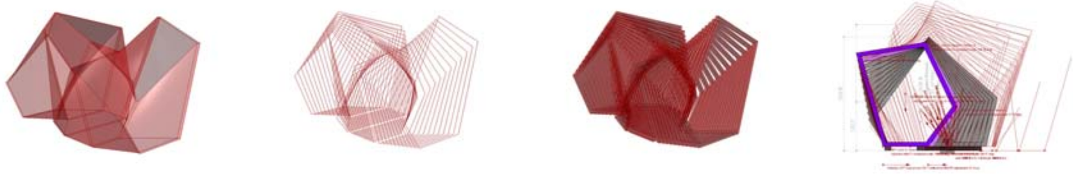

Figure 4
Evolution from designed shape to finally defined frames.

Beside aesthetics, transport dimensions, given wood measurements and other boundary conditions, structural analysis is one of the biggest influences to construct our rigid wood frame structure. In collaboration with the Institute of Structural Design (ITE) [27] it was possible to define maximum beam length according to its cross section and the crease angle range between each wooden beam inside the polygonal frame where our rigid joint design is carrying all loads without any external fastener and fixing. Therefore finite elements simulations with different load situations were calculated (Figure 5).

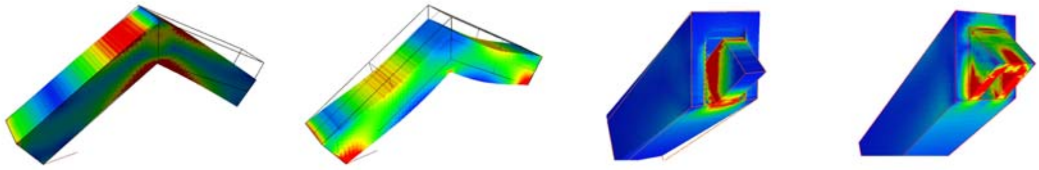

Figure 5
Simulating different load situations.

In addition to the final shape of "The Framed Pavilion" all drawings, production lists, mounting instructions as well as material nesting results were generated on the fly with our first design component. Generated output data for each beam, as well as for each joint is defining the input for our second component where all joint information is gathered and robot-milling code is generated. The joint design is inspired by Japanese wood joints where after assembling the composition is invisible (Figure 6).

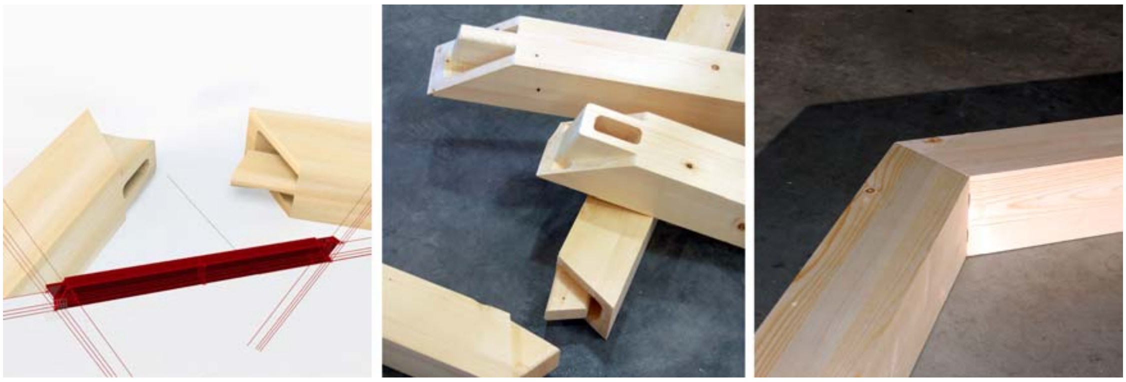

Figure 6
Comparison of digital parametrical model (left), milled joint parts (center) and assembled joint (right).

For the parametrically generation of all machining operations and tool paths following input parameters were considered:

1. Milling head for 6-axis robot with different cylindrical tool definitions.
2. Robot geometry including additional linear axis for reachability simulations.
3. Fastening structure for beams during milling.

4. Tolerance optimization between easy manual assembling and best values for friction and rigidity inside the joint.
5. Milling parameters like cut levels, path offset distances, point step density and additional tolerances to avoid collisions.
6. Optimization of tool paths and strategies to reduce production time

Based on these conditions all necessary machining operations were specifically developed to generate automated production data. Figure 7 shows the visual representation for different tool paths and associated tool orientations.

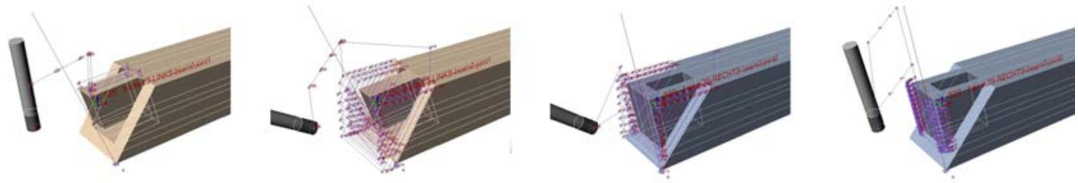

Figure 7
Different machining operations and milling path creation.

To keep different robotic production environments and robot manufacturer in mind we developed two gateways to communicate with the output devices. Our component is able to export apt milling files which are standard in exchanging milling information as example for robot post processors like Pi-Path for ABB robots. Pi-Path converts automatically 5 axis CNC code into multi-axis robot programs. The second output format creates the possibility to directly write and simulate entire ABB RAPID code in real-time without intermediate steps between design environment and production. Therefore all inverse-kinematics, target information, quaternions and configurations are calculated on the fly – see e.g. the Java-based simulation, code generator and live controller for ABB robots *Boot The Bot* for details [18].

The Production of The Framed Pavilion

In January 2012 over a period of three weeks our Design Master Studio students produced and assembled TFP within the production environment from the Engineering Center Wood (ECW) at the Holz Innovationszentrum in Zeltweg, Styria [28]. The prototype workshop includes an ABB IRB 6640 6-axis industrial robot on an additional 13.7 meter linear axis. This robot is equipped with a tool change unit combined with a 24.000 rpm milling head.

After nesting and cutting all wooden beams (including allowance), up to 10 beams were mounted side by side on an angular supporting structure during robot milling. The workflow was designed to pick, place and mill in one process. But due to technical and temporal requirements – automatic tool changing still consumes a lot of time – we had to fix the beams manually (Figure 8).

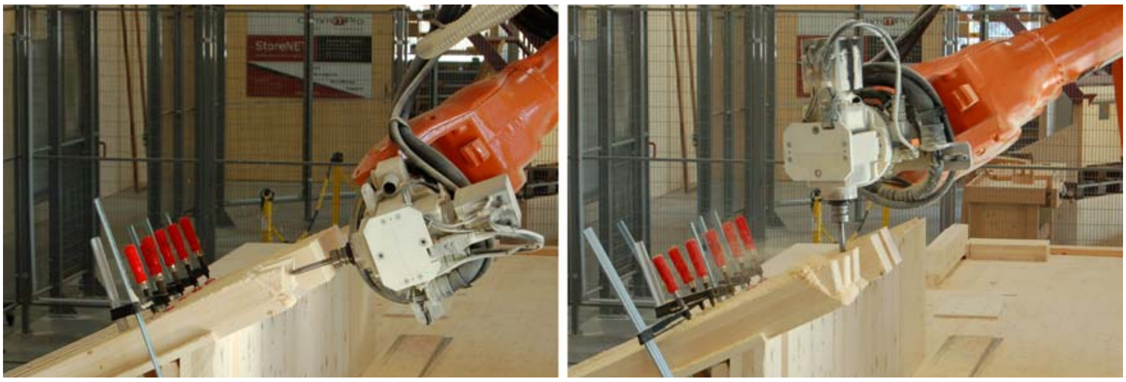

Figure 8
Positioned wooden beams and robot milling head during the production of the two different joint parts.

The final definition of the exact length for each beam and the milling process for all individual joints is done automatically afterwards. Although we could save about 48 hours of machine time due to milling path optimization, the production of one joint still took between 8 and 11 minutes – depending on its geometry. Several constrains needed to be taken into account as wood is obviously an anisotropic construction material.

In the next manufacturing phase, the pentagonal frames were assembled together (Figure 9). The precise production made it possible that the corners gained sufficient stability and stiffness just by being hammered together – no additional adhesion needed.

Figure 9
Assembling pentagonal frames.

Eleven individual frames are then successively placed on a cradle and doweled together – with wooden plugs driven in at the predefined skew drill holes – to transportable units (Figure 10). During those 12 days of fabrication we were able to produce four individual units which, when positioned together, finally resulted in The Framed Pavilion (Figure 11).

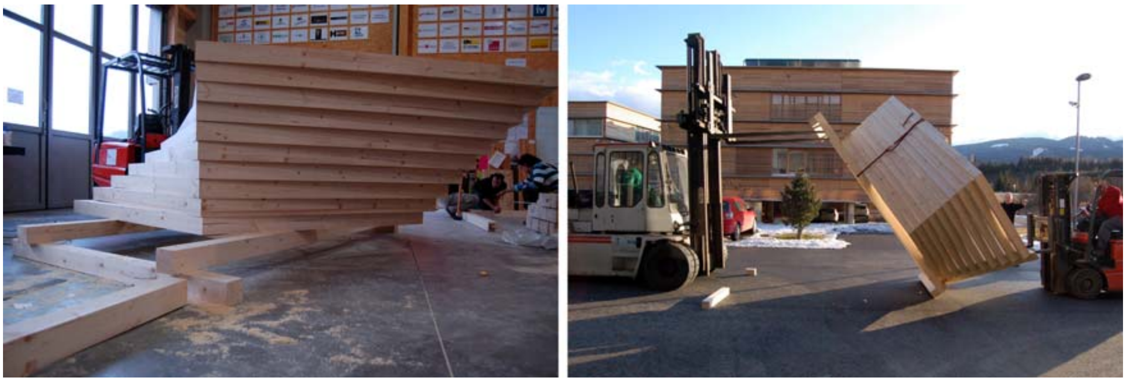

Figure 10
Combined transportable units (left) and the rolling into the upright position (right).

Conclusion and Outlook

Since completion TFP was transported across Austria, exhibited in public [29], discussed in architecture magazines (Colletti et al. 2012) and is now waiting for its final deployment in the city of Kapfenberg. However, the steep learning curve of all students during that semester and the affirmative feedback of the woodworking industry is even more gratifying. And the experience plus the algorithmic tools we built along the way are invaluable for us teachers and researchers.

51 years after the first Unimate joined the assembly line in Ewing Township, New Jersey [30] and almost half a century after UNISURF was introduced the automotive industry is still the powerhouse behind robotics. They have the money and they produce the turnover. Nevertheless they seem to have lost most of the innovative drive from the 60s (de Casteljau 1999) as they basically keep using their high-end equipment for recurring routines only – with exceptions of course. The animating spirit of mass customization has returned to the origins of industrialization and rationalization: the textile and garment industries. But they primarily use regular CNC machines.

“Non-standard design in architecture is rapidly evolving, and with the designs come a need for engineering and construction methodologies to support them. […] The most appropriate position for these new tools seems firmly set between the two disciplines of architecture and engineering, helping each rationalize and realize the project. The development of these digital processes not only presents the professions with a new set of tools, but also presents new challenges to the traditional working methodology. Perhaps the biggest challenge for the non-standard designer will be to accept that in order to optimize the processes, the designer will no longer detail the form of a design, but will design the process which generates the details." (Scheurer 2007) Maybe the new generation of architects that is now graduating from universities worldwide can close the gap between robotics and parametric design – or at least consign a substantial contribution.

Figure 11
Interior view of the four units forming "The Framed Pavilion"

Acknowledgements

The Design Master Studio bot/log would not have been possible without the generous support of Jörg Koppelhuber and Michael Lackner from the ECW and all partners of the Holzcluster Steiermark [31]. We would also like to thank the House of Architecture Graz (HDA) [32] for the opportunity to exhibit the findings to a large audience, our colleagues at IAM and ITE for

their stimulating collaboration and last but not least all of our students for their sublime commitment and their inspiring projects.

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