

Robotic Fabrication Techniques for Material of Unknown Geometry

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Abstract. Both natural materials such as timber and low-grade or recycled materials are extremely variable in quality and geometry in unprocessed state. Additive digital fabrication processes in robotics in combination with sensor feedback techniques offer large design freedom, high precision and material efficiency and enable a highly customized fabrication and calculation process. Separate studies have been made on scanning, efficient algorithmic arrangement and automated assembly of structures of variable timber elements. In this paper we explore a robotic fabrication process, in which we combine the techniques of scanning, digitally arranging and robotically assembling in one continuous real-time workflow. This means that the final design and appearance only emerge after a unique fabrication process, corresponding to the material used and the assembly sequence. We describe techniques for the simulation modelling and performance analysis using particle simulation, and demonstrate the feasibility through the realisation of the envelope of a robotically assembled double-story timber structure with hand-split wood plates of varying dimensions. We discuss a future use of natural, low-grade or waste material in the building industry through robotic processes. We conclude by analysing the integration of qualitative analysis, physical simulation and the degree of variability of input material and resulting complexity in the computation and fabrication process.

Keywords: Feedback process · Robotic fabrication · Particle simulation · Scanning · Real-time workflow

Introduction

Introducing natural variability in manufacturing processes rather than fabricating variable designs out of standardized products allows using local material (Stanton 2010), decreases processing operations, and can therefore save material and reduce the ecological footprint of construction. The natural variability in quality and geometry of raw timber products that is also found in low-grade or recycled materials makes their application in a controlled manufacturing process extremely challenging. Therefore, repeatable and standardized digital fabrication techniques are nowadays predominantly used to process highly engineered products. Additive robotic fabrication processes combined with sensor technology can be used for real-time feedback, e.g. in assembly processes. This opens up the possibility to integrate material variability through highly

customized analysis, calculation and fabrication processes. When using organic materials such as timber, the question arises at which state and format should the material ideally be integrated in additive robotic fabrication? A number of recent research projects have investigated the use of raw materials in digital design and fabrication workflows, such as the arrangement and positioning of irregular wood components through algorithmic techniques (Monier et al. 2013). Further studies show the possibility to physically scan and data process natural wood branches (Schindler et al. 2014), and connect them through robotic milling for architectural structures (Mollica and Self 2016; Self and Vercautse 2017). Autonomous assembly of standard wood beams using feedback processes was experimented with by Jeffers (2016). The “Mine the scrap” project (http://certainmeasures.com/mts_installation.html) investigated the use of scrap material. A computational interface was created in order to scan leftover wood plates of random geometry and arrange them algorithmically to match a given design envelope most closely. This paper investigates design modelling and fabrication techniques of how material variability can be directly integrated into a continuous real-time robotic workflow and how geometrical and functional performance can be strategically simulated and evaluated. In Section “[Methods](#)”, we describe the development of the design, analysis and fabrication process and the realisation of a large-scale demonstrator. In Section “[Results](#)”, we evaluate results of geometric generation, analysis and fabrication. We conclude in Section “[Conclusion](#)” by discussing a future use of robotic technologies for organic, low-grade and waste materials and analyse the incorporation of qualitative variability, physical simulation and the degree of variability and resulting process complexity.

Methods

In this section, we demonstrate design modelling techniques for façades of rectangular panels of variable size, analyse their ability to adapt to a range of surface typologies and evaluate water permeability using particle simulation (Section “[Design Modelling and Performance Analysis](#)”). In Section “[Real-Time Robotic Communication and Setup](#)” we explain the robotic fabrication setup and its communication protocols and continue to describe a large-scale demonstrator in Section “[Demonstrator Project](#)”.

Design Modelling and Performance Analysis

Traditional facades and roofs can be fabricated with timber panels without the need for additional waterproofing layers. When overlapped and mounted in certain angles and orientations, timber panels can last for up to 100 years depending on their wood type (<http://www.holzschindel.at/holzschindeln/ratgeber>). The fabrication technique plays an important role for the panel’s weather endurance. The traditional method is to split the timber chunks along the fibre direction. This keeps the fibres intact and creates a highly-textured surface, which allows split panels to dry much more efficiently than sawn panels (Niemiec and Brown 1993). Their varying size (in comparison to standard sizes) also allows the use of all parts of a naturally grown tree, limiting material waste (Fig. 1).

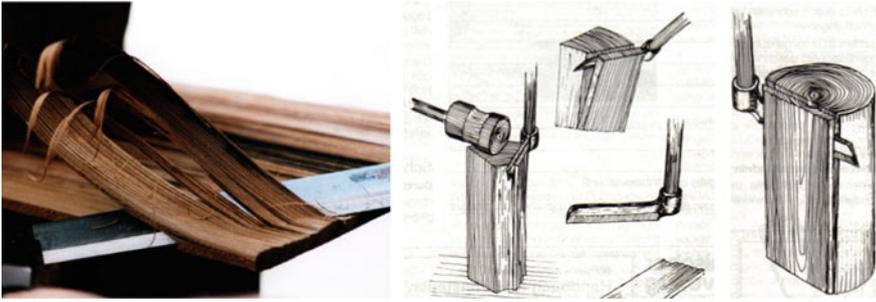


Fig. 1. *Left* Splitting of timber panels, image courtesy by Theo Ott—www.holzschindeln.de. *Right* Radial- and tangential splitting, image courtesy of Ludwig Weiss Holzschindelwerk

Panelisation Modelling. We investigated multiple geometric approaches for variable panelisation on flat and curved surface typologies with three design goals: (1) the pattern should be capable of adapting to double-curved surfaces while visual and geometric consistency remains. (2) It should be water resistant. (3) The facade should attach directly to the primary structure without additional sub-structures. The design space and its material, structural and geometric dependencies are summarized in Fig. 2. The primary structure consists of a geometric system of cuboids which are diagonally braced. Both horizontal as well as diagonal design patterns were therefore included in the algorithm. We also allowed horizontal as well as vertical overlaps between the panels. Since the algorithm had to function iteratively as well for the fabrication sequence, each panel is first placed at its ideal location and orientation along the surface curvature, and then subsequently rotated until it fits tightly to the precedent panels.

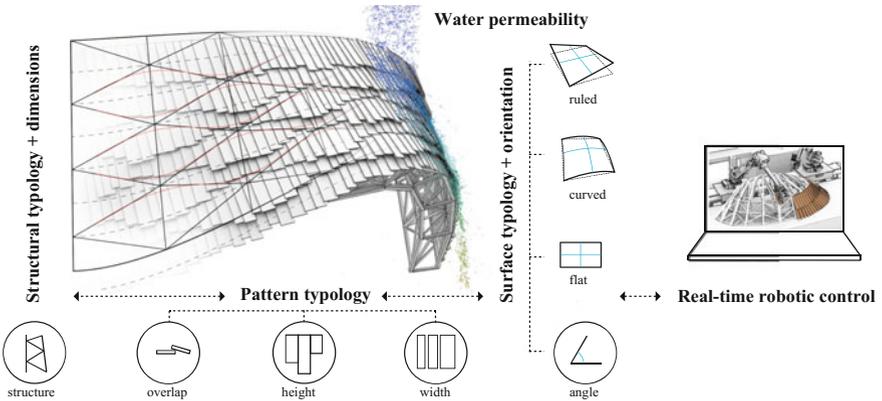


Fig. 2. Design space: overview of the relationship between the parameters and constraints of structural typology, pattern typology and variation, surface typology and angle, water permeability and fabrication system

Curvature adaptability. With these general constraints, a large number of patterns were generated. We evaluated a range of patterns for curvature and water permeability. Since the maximum distance between the panels and the driving surface already give an indication of the general surface tightness, our first step was to evaluate the variation of the parameters of height and width of the panel in relation to surface typology as well as a variation of “horizontal” or “diagonal” fixation lines (Fig. 3).

Water permeability. For the evaluation of the dependencies between the design pattern, parameter variation, surface typology, surface angle and water permeability,

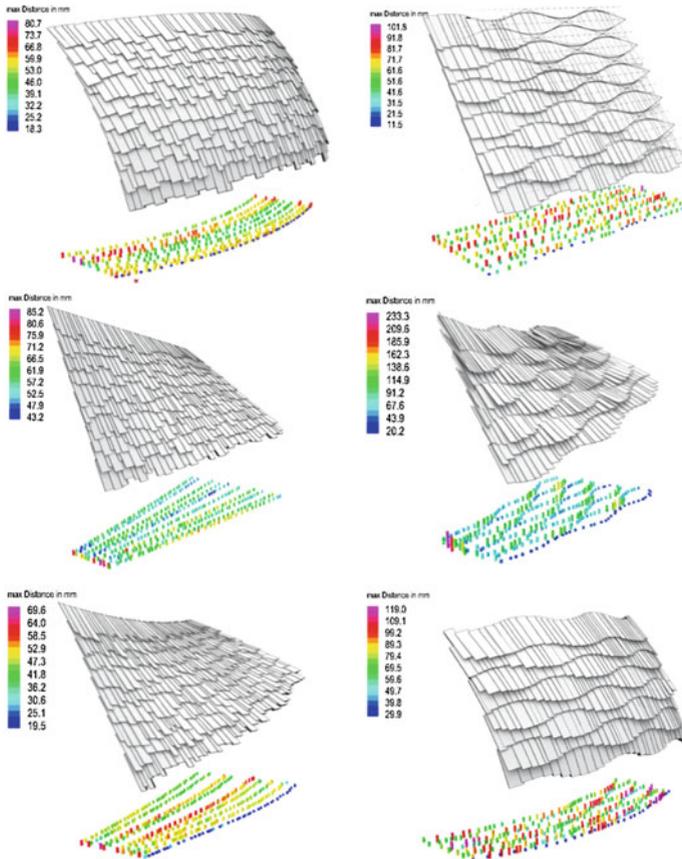


Fig. 3. Geometric adaptability: mapping of max. distance between panels and driving surface. *Left column* Horizontal rows 30 cm, width variation 8–25 cm, height variation 40–60 cm. Results for spherical curvature $r = 6$ m, double-ruled surface and simple-ruled surfaces, inclination 40° – 80° . *Left column* Diagrid panelling pattern on flat, ruled and spherical curved surfaces, panel width randomisation 8–25 cm, angle smoothing $r = 1.5$ m. Results show that randomisation can cause local disturbances. Variation of vertical overlaps as shown in the diagrid panelling introduces surface ripples on flat surfaces and can cause large irregularities on curved surfaces

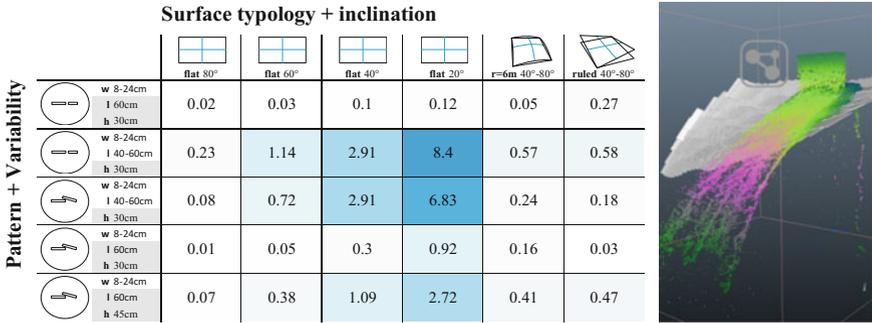


Fig. 4. *Right* Setup particle simulation in realflow: a rectangular dyverso-particle emitter emits a stream of particles on a panelised surface. *Left* Water permeability (in % of particles detected traversing the panels) in relation to panelisation parameters: width of butt-jointed and overlapped panels, panel height and row height in relation to drive surface geometry and inclination

we created an analysis setup using the particle simulation software Realflow (2017). Through large amounts of particles, fluid dynamics can be efficiently simulated for CG applications. The possibility to automate and trace particles through a scripting interface in Python also allows for a quantitative analysis for design and evaluation purposes (Tan et al. 2017). With a sufficiently high resolution and continuous collision detection the interaction of particles with values corresponding to the physical properties of water and a range of design patterns was simulated. Around 300.000 particles were emitted and traced for each pattern through custom Python scripts (Fig. 4). As the analysis shows, the row height can be increased by 50% without a significant increase of water permeability. Butt-jointed panels in combination with variable panel height show the highest values since a lot of joints stay open. The angle of the tested surfaces has a dramatic impact on the amount of water traversing the surface, since on lower angled surfaces, water can traverse in the opposite direction of the overlapping pattern.

Real-Time Robotic Communication and Setup

Here, the term “real-time” refers to a robotic fabrication system, which is able to react to new information acquired during the actual fabrication process rather than merely executing previously compiled machine code. Such a system relies on digital sensors and feedback processes that can react and calculate new instructions for the robotic system on run-time (Raspall et al. 2014). In order to establish a real-time digital fabrication process, it is necessary to have integrated sensors and to be able to constantly read and write on the controller in order to make geometrical calculations on an external computer. One approach is to use a custom socket connection between PC and controller (Dörfler et al. 2016). Our approach was to implement the Robotstudio PC SDK (Robotics 2015) within GH Python (Piacentino 2017). The PC SDK libraries allow developers to create applications that can directly communicate with IRC5 controllers (Csokmai and Ovidiu 2014; Dalvand and Nahavandi 2014). This has also already been demonstrated for high frequency applications as human-machine

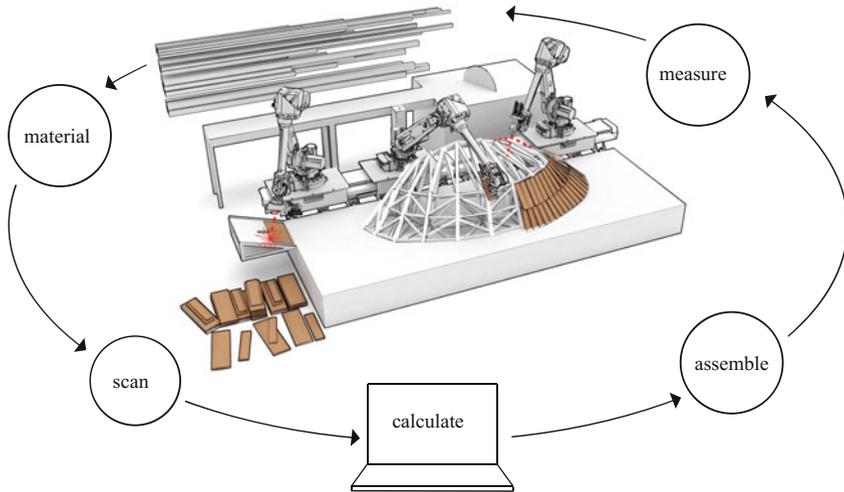


Fig. 5. Robotic fabrication workflow—Feedback process: wood panels of unknown dimensions are scanned, fabrication geometry and placement is calculated on an external PC, then written back to the robot controller in order to execute assembly. Reference points of the substructure are measured and calibrated with the numerical model in order to improve general fabrication tolerances

interaction for trajectory teaching using 3D-scanning (Landa-Hurtado et al. 2014). Our robotic setup features two robotic arms, which are able to move along a 5 m long linear axis. One robot was integrated to cut and assemble slats of variable cross-sections using an integrated CNC-circular saw, which was used for building the primary structure of building modules. The other robot was integrated to scan and mount rectangular wood panels of variable size, which was used to create the facade of the building modules. For this process, a feedback-loop of interactive operations was necessary.

In a first step, reference points of the primary structure are measured in order to calibrate the virtual model to fabrication tolerances. Then, a timber panel gets scanned and its dimensions can be read by an external PC. The parametric model described in Section “[Design Modelling and Performance Analysis](#)” was then able to calculate the position of each new element responding to architectural and fabrication constraints during fabrication. The new gripping and mounting position is then sent back to the controller while respective robotic movements are subsequently executed. Figure 5 shows the general digital fabrication workflow. We used a photoelectric sensor in combination with distance search movements of the robot to be able to determine the measurements of the plates (Fig. 6).

In order to adjust to the largely varying surface quality of the plates, we introduced a physical robotic softness through a custom end effector, featuring a vacuum gripper with elastic foam and a connection with adjustable springs. Even though all gripping and placing positions are different, the general sequence of operations is repeatable. This allows writing a general RAPID program with variables that can be changed for

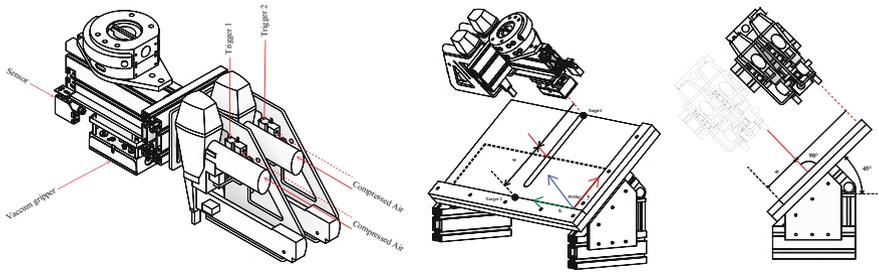


Fig. 6. *Left* Robotic endeffector design with two integrated nailguns. *Right* Feeding table for robotic scanning process

each fabrication loop. Updating of the variables occurs after the scanning process when the new positions have been calculated. We created a series of custom GH Python components which can scan the network for virtual and physical controllers, access variables and write new values. This allowed us also to simulate parts of the fabrication sequences with randomly generated panel dimensions beforehand. For movements in between the gripping and placement position, we created a standard retraction and orientation scheme that adapted to height and final positioning. The toolpath calculation remained therefore rather simple, since we could assure the building modules remained in a predefined zone, along which the robot could move freely.

Demonstrator Project

Within the course of a Master's programme in Digital Fabrication at ETH Zurich, we were able to create a double-story timber structure with an integrated timber envelope.

We investigated a design method in which the project is composed out of robotically prefabricated spatial building modules instead of a traditional fabrication method in which modules are manually assembled out of prefabricated components. The geometry consists of ruled surfaces, which creates multiple undulating ribbons that form variable vertical openings. The structure was based on a spatial truss, which was capable of adapting its geometry seamlessly between serving as wall, slab, roof and staircase. Over 4000 different wood beams were robotically cut and mounted (Fig. 7).



Fig. 7. *Left* Integrated saw cuts along robotic movements. *Right* Assembly of timber truss

We used four different cross sections of solid timber slats for structural differentiation and carbon-steel screws for fixation. The truss maximum vertical bracing distance on its envelope side was limited to 450 mm for surfaces between 90° and 40°, allowing fixation of the panels and sufficient water resistance (Fig. 4). Lower angled surfaces such as the roof have a denser diagonal bracing that allows double to triple vertical overlays in less inclined parts. A double and vertical overlap pattern was able to integrate horizontal (preferred by the algorithm) as well as diagonal patterns. Since the design of the primary structure was integrated with requirements of the envelope, we could directly attach the elements without additional substructures (Fig. 8). The building components could then be transported on site where they were connected to each other by steel bolts. Since each of the modules was unique and could only fit in one position, assembly errors were practically impossible (Fig. 9).

Results

We described digital modelling techniques incorporating variability in panelling dimensions and demonstrated how geometric and architectural performance can be analysed for design purposes. Patterns for irregular timber panels were analysed for geometric fitting to planar, ruled and spherical surface typologies. Water permeability was simulated through particle simulation and quantified through custom particle-tracing using Python. Results on a range of generated design patterns show that two-dimensional variability can be efficiently integrated. Overlaps in multiple directions can absorb greater geometric tolerances, but also allow for material savings through intelligently arranged overlapping patterns while keeping low values on water permeability. A robotic setup was developed for handling scanning, design calculation and mounting processes. We integrated the ABB PC SDK in a design interface of custom GH Python components, allowing the development of fabrication processes with direct interaction of geometric calculations in Rhino and robotic fabrication processes. In a large-scale demonstrator, we assembled over 2600 differently sized wood panels on a robotically-manufactured timber truss structure (Fig. 9) using a



Fig. 8. *Left* Robotic scanning and gripping. *Right* Mounting and fixation of timber panel. We used hand-split timber panels of variable widths between 8 and 30 cm and a fixed height of 60 cm

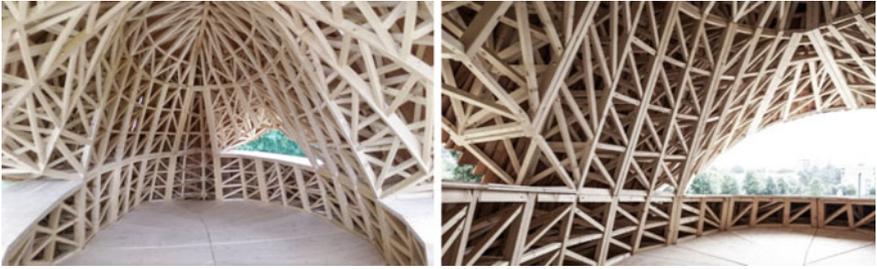


Fig. 9. Interior views of the upper floor. *Right image* courtesy of Kasia Jackowska



Fig. 10. Exterior view of the double-story structure

continuous robotic feedback process responding to the provided material size in real time. Therefore, the final panel arrangement appeared only after the final production process. Since we could apply a small amount of pressure by the robot during automatic fixation, we were able to slightly elastically bend each element. This helped to approximate a geometrically complex 3-dimensional form using a simple natural material (Fig. 10).

Conclusion

Although research for integrating natural variability in architectural construction is still only at the beginning, recent advancements in robotics and control promise feasibility and efficiency at industrial scale (Vähä et al. 2013). Local materials can be directly

employed, reducing the ecological footprint of construction. This can further be enabled by mobile systems for on-site digital construction (Bock 2007). While this study focusses on timber products, also other natural materials such as bamboo, straw bale, raw stones (Furrer et al. 2017), etc. and low-grade or recycled construction materials have great potentials for digital building processes. Research needs to be coupled with an investigation of functional and architectural expression for successful and profitable building applications. Furthermore, not only geometric variability, but also qualitative variability could be integrated in the design and fabrication process. Nowadays building codes account large safety values for the natural variability, which over-dimensions structural wood products. A closer computational examination might allow for a much more efficient classification and use of wood as a structural building material with large material gains. The integration of different material qualities, as found in recyclable building materials, could then be efficiently integrated. Further research needs to be done to integrate physical simulation in real-time fabrication processes. This could be used to analyse various architectural and engineering requirements also for each separate fabrication step. We deliberately excluded any sorting of material in order to simplify and streamline our fabrication process at maximum. This obviously creates constraints for the resulting geometry, which are mostly determining the visual appearance. Further studies could investigate the efficiency of a certain amount of sorting happening during the fabrication process for specific construction applications. The degree of variability of input material has a large impact on the resulting complexity of the fabrication process. In this study, the variability was constrained to two dimensions. The three-dimensional surface variation of the material (up to 20 mm on a 600×150 mm panel) was absorbed by the elasticity of the gripper. A similar effect could also be achieved by computationally liberating movements in certain directions of the robot (ABB Robotics 2011). Objects of unconstrained variability require three-dimensional scanning, which also leads to much more sophisticated processing techniques such as processing and mapping of large point clouds to virtual models (Tang et al. 2010). But since robotic processes are usually highly specific, our study demonstrates that functional, material and fabrication constraints can also allow the deduction of extremely simple and efficient scanning and processing techniques.

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