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# Robotic timber construction — Expanding additive fabrication to new dimensions

Jan Willmann [a,*], Michael Knauss [a], Tobias Bonwetsch [b], Anna Aleksandra Apolinarska [a], Fabio Gramazio [a], Matthias Kohler [a]

[a] ETH Zurich, Chair of Architecture and Digital Fabrication, Switzerland
[b] ROB Technologies AG, Switzerland

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ABSTRACT

This paper presents a novel approach to non-standard timber assembly – Robotic Timber Construction (RTC) – where robotic fabrication is used to expand additive digital fabrication techniques towards industrial full scale dimensions. Featuring robotic systems that grasp, manipulate, and finally position building components according to a precise digital blueprint, RTC combines robotic assembly procedures and advanced digital design of non-standard timber structures. The resulting architectural morphologies allow for a convergence of aesthetic and functional concerns, enabling structural optimisation through the locally differentiated aggregation of material. Initiated by the group of Gramazio Kohler Research at ETH Zurich, this approach offers a new perspective on automated timber construction, where the focus is shifted from the processing of single parts towards the assembly of generic members in space. As such, RTC promotes unique advantages over conventional approaches to timber construction, such as, for example, CNC joinery and cutting: through the automated placement of material exactly where it is needed, RTC combines additive and largely waste-free construction with economic assembly procedures, it does not require additional external building reference, and it offers digital control across the entire building process, even when the design and assembly information are highly complex. This paper considers 1) research parameters for the individual components of RTC (such as computational design processes, construction methods and fabrication strategies), and 2) the architectural implications of integrating these components into a systemic, unifying process at the earliest stages of design. Overall, RTC leads to profound changes in the design, performance and expressive language of architecture and thus fosters the creation of architecture that profoundly reinvents its constructive repertoire.



## 1. Introduction

Despite strong advancements in timber prefabrication using CNC systems, the timber construction sector is still characterised by a relatively high proportion of (manual) assembly tasks. Together with the inherently limited flexibility and working areas of conventional CNC machinery, this handicaps the sector when trying to take advantage of the rapidly spreading trend to use complex digital designs directly as input for comprehensively automated construction processes. Here, robotic systems are extremely useful — not only can their use lead to significant time savings, but their ability to transfer digital design data directly to 1:1 assembly operations enables the fully automated construction of non-standard timber structures. As a result, their use opens up entirely new possibilities for future timber construction that is not limited by the same constraints – such as, for example, work-intensive joinery and/or additional scaffolding – as manual assembly processes of pre-machined components; its most evident and radical consequences are therefore the ability to digitally oversee and control a large number of aspects of the design and construction (for instance the sequencing of the single elements and their assembly) and the ability to freely position building components in space.

Considering full-scale applications, Robotic Timber Construction (RTC) research is still in its infancy, and presents many theoretical, practical and methodological challenges to architecture. Obvious examples are wide-ranging and include, for example, the need for advanced computational design tools and novel constructive systems for automated construction processes, and the integration of robust and adaptive robotic fabrication technology. In order to develop a schema for addressing these challenges, the group of Gramazio Kohler Research at ETH Zurich started an in-depth investigation into robotic assembly of complex timber structures in the framework of the SNSF NRP 66 "Resource

* Corresponding author. Tel.: +41 44 6334611.
*E-mail addresses:* willmann@arch.ethz.ch (J. Willmann), knauss@arch.ethz.ch (M. Knauss), bonwetsch@rob-technologies.com (T. Bonwetsch), apolinarska@ethz.arch.ch (A.A. Apolinarska), gramazio@arch.ethz.ch (F. Gramazio), kohler@arch.ethz.ch (M. Kohler).
*URL's:* http://www.rob-technologies.com (T. Bonwetsch), http://www.gramaziokohler.arch.ethz.ch (M. Kohler).

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Wood" research programme and created first experimental demonstrations, which are presented in this paper.

This exploration is paralleled by a first full-scale building demonstrator, called "The Sequential Roof" (see Fig. 1), featuring a 2300 square metre large timber roof that is automatically assembled from alternately layered timber slats [1]. This multi-layered structural aggregation required many innovations (including the development of a computational design and construction framework, interfacing with structural analysis software and automated fabrication processes) and successfully illustrated the potentials of comprehensively automated construction processes at full architectural scale.

The paper is structured in 5 Sections. In following Section 2 we present the context of our work. Section 3 explains the technology and setup of RTC developed in the framework of the SNSF NRP 66 "Resource Wood" programme, focusing on parameters for investigation, including design strategies, connection and construction methodologies, features of robotic machinery and fabrication. In Section 4 we present a detailed description of the first industrial full scale implementation of RTC, "The Sequential Roof". Our conclusions are discussed in Section 5.

## 2. Context

Several attempts have been made to develop automated assembly systems in building construction [2]. This research projects date back to the early 1990s, and their main motivation was to improve the productivity and construction quality of building construction [3,4]. Although highly advanced by their time, these developments did not find access into practise since the developed robotic systems were not efficient and flexible enough to adapt and to react to different design situations [5]. While the wave of robotic automation radically penetrated many industry sectors [6], such as automotive manufacturing, and put into place entirely new, previously unthinkable standards of productivity and quality, the dissemination of advanced automated construction technology remained a marginal phenomenon in the building industry. However, a particular case is presented by the timber construction sector, which through the arrival of digitally controlled joinery machines for the automated fabrication of timber construction components by the 1980s gained the possibility of a radical technological reorientation [7]. Alongside the development of innovative, high-quality timber construction products, the associated transformation brought about a considerable increase in flexibility and manufacturing productivity.

In the course of the recent shift towards digital technologies and the introduction of computer-controlled manufacturing in architecture, universities such as ETH Zurich (2005) [8], Harvard GSD (2007) [9], Carnegie Mellon (2009) [10], University of Michigan (2010) [11], University of Stuttgart (2010) [12] and Princeton University (2013) [13] have followed this development and set up robotic research facilities for the empirical investigation of non-standard automated construction processes. They have fostered the development of promising robotic construction processes, resulting in robust, highly adaptable and sustainable building systems [14].

Concurrent to these advances in digital fabrication technology is a growing interest in robotic timber manufacturing. For example, the Gramazio Kohler Research group started in 2008 to develop non-standard robotic assembly processes where a large number of generic timber components are layerwise accumulated, enabling the implementation of additive manufacturing on a 1:1 scale (see Fig. 2). Seen against this background, robotic timber construction is fast becoming a mature technology, and is almost ready for large-scale assembly tasks. However, despite the use of automated robotic technology, a number of these structures (see Fig. 3) are largely built through "classical" CNC machining of components and subsequent manual assembly processes. This not only results in laborious fabrication routines and significant waste of human and material resources, but also heavily constraints the exploration of the full potential of novel automated timber construction systems, and, ultimately, prevents robotic fabrication technology to spread out into the timber sector at a larger scale.

## 3. Spatial timber assemblies

Central to our research into RTC is the assembly of complex spatial timber structures from a multitude of generic elements. Pursued in cooperation with the Bern University of Applied Sciences (Prof. Eduard Bachmann and Prof. Christophe Sigrist) [17], we have identified three complementary research trajectories: 1) assembly driven design processes, 2) material and constructive systems, and 3) integrated robotic fabrication. Here, the essential feature of RTC is to introduce the integration of specific design, material and robotic approaches, so that account is taken of their overall capabilities and limitations regarding the physical building performance. In order to conduct research with the most realistic impact possible, the experiments presented in this paper were implemented as full-scale architectural demonstrators (see Fig. 4).

### *3.1. Assembly driven design processes*

In the context of RTC, an essential goal is to foster design methodologies, which must be 1) informed by material, construction and fabrication criteria, and 2) be able to adapt to multiple functional requirements. This

**Fig. 1.** Computer rendering of "The Sequential Roof" – discussed in Section 4 – for the future Arch_Tec_Lab building of the Institute of Technology in Architecture (ITA), ETH Zurich (Image ©Arch-Tec-Lab).