Automation in Construction 61 (2016) 16–23

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

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

ARTICLE INFO

Article history:
Received 13 May 2015
Received in revised form 30 August 2015
Accepted 25 September 2015
Available online 20 October 2015

Keywords:
Non-standard timber structures
Automated assembly
Computational design
Industrial full scale implementation
Additive digital fabrication
Robotic Timber Construction

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).

http://dx.doi.org/10.1016/j.autcon.2015.09.011
0926-5805/© 2015 Elsevier B.V. All rights reserved.

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).

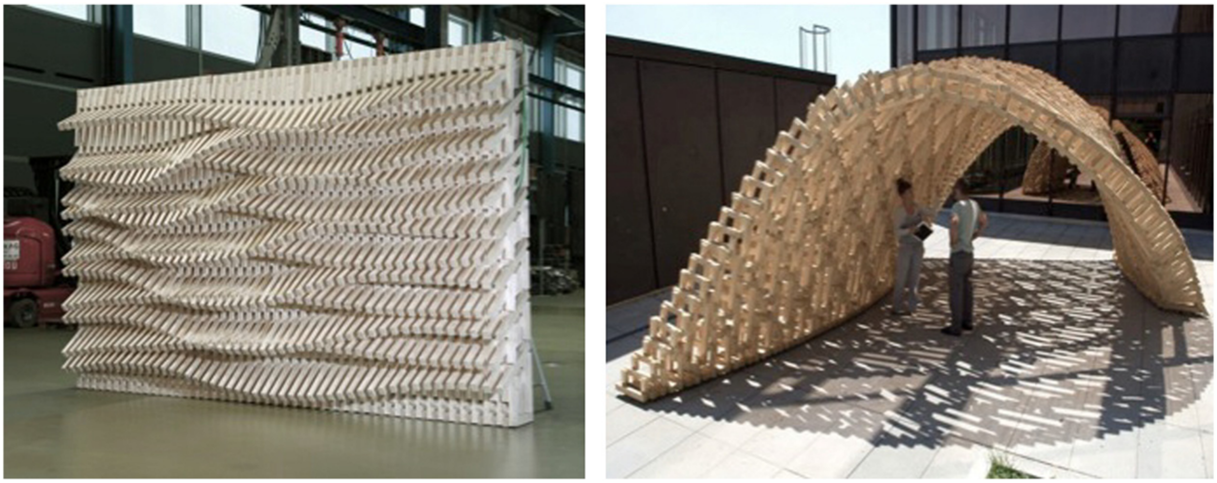

Fig. 2. Left: a 1:1 demonstration object of "The Sequential Wall" series, Gramazio Kohler Research, ETH Zurich, 2008; bottom: "The Sequential Structure", Gramazio Kohler Research, ETH Zurich, 2010.

requires the development of new computational processes, which allow to both evaluate the structural integrity of the final form and the evolving tolerances of the buildup process while maintaining an optimised economic performance. As an example, if a design does not allow to be successfully aggregated by the robotic system or shows substantial failures or unmodeled material effects during construction, the digital design tool must localise the problem in real time and propose possible solutions ensuring its integrity to the designer.

As a basis for the realisation of all three RTC demonstrators a custom digital design and fabrication workflow (see Fig. 5) have been developed and iteratively optimised. In this workflow, each timber element is defined as a logic entity including the specific information about its relation to neighbouring members from which to derive the end-cut information and the spatial sequencing of its robotic assembly.

At the same time, the design tool, which was written in the programming language Python and embedded within the CAD-platform Rhinoceros-3D, provided an interface to the structural analysis software RSTAB for the evaluation of the structural integrity and performance of the design. This digital design and fabrication workflow allowed for an intuitive design process of complex load-bearing timber assemblies by guaranteeing the breakdown of the form into an ideal number of components within a feasible spatial sequencing of the robotic assembly process. Additionally to the geometry (length and end-cut angle) of the individual timber members, all the relevant fabrication related information, as for example the geometry of the predrilled holes for the joining and the path planning of the robotic arm, was integrated into a comprehensive and coherent data model. The ultimate goal of such new (computational) design ontology is an architecture that is not defined primarily as a final geometric form, but as a complex and refined generative process of digital materialisation.

3.2. Material and constructive systems

While RTC enables the assembly of complex architectural artefacts from a large number of generic timber components it raises the problem of how these components are best connected to each other. As such, novel connection typologies have to be developed, which are suitable for the implementation as fully automated systems while taking maximal advantage of robotic fabrication by allowing for multiple degrees of geometric freedom.

A first approach to a constructive system accommodating these parameters has been identified in reciprocal frame structures (see Fig. 6). These supporting structures are interesting because of the simplicity and effectiveness of the reciprocally bearing elements. Based on a large number of rather short and simple timber members, which can be optimised according to the internal force flow of the structure, reciprocal frame structures are of particular interest in conjunction with digital fabrication techniques [18].

This connection typology has three fundamental advantages: First, by expanding the connection of three timber members at one single point in space into three separate eccentric connections between only two members, the components can be brought together once at a

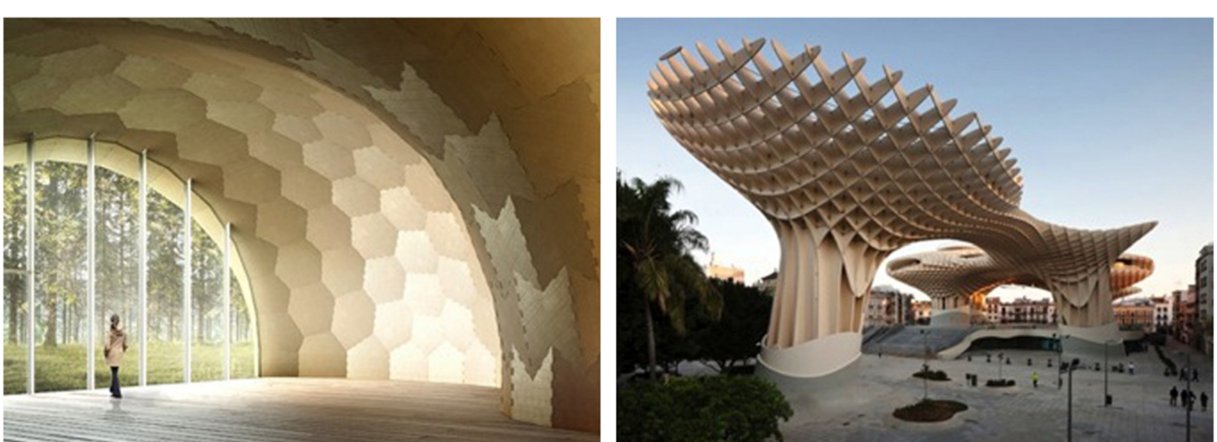

Fig. 3. Left: ICD/ITKE Research Pavilion, Landesgartenschau 2014 Exhibition Hall [15]; right: Metropol Parasol Structure, Seville [16].

Fig. 4. Initial robotically built prototype based on a material-efficient construction typology developed by Friedrich Zollinger during the beginning of the 20th century. Gramazio Kohler Research, ETH Zurich, 2012.

time, following a distinct assembly sequence which can be handled by a robotic arm. Second, as the individual members need only to be customised by an angled cut on both ends, this geometric adaptation can be carried out as an integrated step of the robotic process. And, third, the triangular arrangement of the node provides a simple mean to control the stiffness of the connection by varying its geometric eccentricity and thus allows to react to specific fabrication and structural constraints of an automated assembly processes.

For the connection of the single timber members, a novel gluing technique has been developed in addition to the more conventional nail-based solution. Based on a fast curing adhesive on a non-dispersion basis developed by Nolax AG, this experimental connection has the potential to leverage on the ability of the robotic arm to hold a member precisely in space without need for any scaffolding or additional measurement. In fact, the unique combination of an almost real-time curing adhesive, that gets injected under pressure in the connection which has previously been sealed with a custom neoprene gasket, and a speedy robotic assembly process that is able to position the members precisely in three-dimensional space according to a digital blueprint and releases them after only a few seconds from the injection of the glue, opens up new territories for automated timber manufacturing. A video documenting the demonstration can be found online [19].

3.3. Integrated robotic fabrication

In order to be able to build the three real-scale RTC demonstrators, we integrated all machining and assembly steps into one unified robotic fabrication system (see Fig. 7). In this prototypical process the single timber members were gripped, cut at their ends, perforated and moved into their final position within one consistent robotic fabrication workflow. The integration of all sub sequential steps into one single lean process was fundamental in order to preserve digital information integrity and to avoid complex logistics such as the intermediate storage of prefabricated specific parts.

The issues of precision as well as overall process and material tolerances, however, represent the main challenges. As a matter of fact, at this scale neither the (anisotropic) construction material, nor its robotic handling and positioning process are precise enough. In turn, tolerances in the buildup emerge, which through their accumulation, cause major problems to the assembly process. This limitation requires the implementation of sensor-based feedback mechanisms, which allow to register the actual geometry of the built structure in relation to the position of the timber member hold by the robotic arm and thus to adjust the digital blueprint and the pre-computed motion path of the machine to the factual material reality. Consequently, also the connection technology must be tolerant to incongruences between the physical reality and the digital model and allow for a range of geometric tolerances to be accommodated. At the same time, the real-time assessment of assembly tolerances during the fabrication process via a closed loop feedback system, represents an important step towards the implementation of fully adaptive building processes that are sustainable in their entirety, where computational tools allow not only for intuitive form finding while maintaining optimised structural and economic performance, but also enable smart and material efficient assemblies.

Here, current advances in sensor capabilities (optical sensors, cameras, etc.) and their growing performance are drastically improving the possibility of "smooth" real-time adaption of the assembly process. Moreover, the development of an RTC system requires advanced control capabilities. This includes cooperation among multiple robotic arms or external machines (such as, for example, sawing stations), trajectory planning and fault handling. Hence, the design of a particular assembly system is directly linked with the design of its fabrication process and the tools employed. Consequently, the infrastructural setup and material logistics heavily influence the buildup of an RTC structure, and hence its assembly performance.

4. First industrial full scale implementation

A first case for the industrial full scale implementation of RTC including automated assembly is presented by "The Sequential Roof" project, which is developed as collaboration between Gramazio Kohler Research at ETH Zurich, Arch-Tec-Lab AG, Dr. Luechinger + Meyer Bauingenieure AG, ROB Technologies AG and ERNE AG Holzbau [20].

However, since the spatial connection typology explored in the research described in Section 3 has not been developed at the time of the project start in 2010, the structure of "The Sequential Roof" still relies on a layered construction system, featuring twenty-four unique timber beams with a regular span of 14.7 m. Overall, more than 48,624 timber slats with a maximum length of 3.17 m were automatically assembled into a 2308 square metre large roof for the new building of the Institute for Technology in Architecture at ETH Zurich (see Fig. 8). As such, "The Sequential Roof" provides a first example for the realisation of RTC structures at full architectural scale.

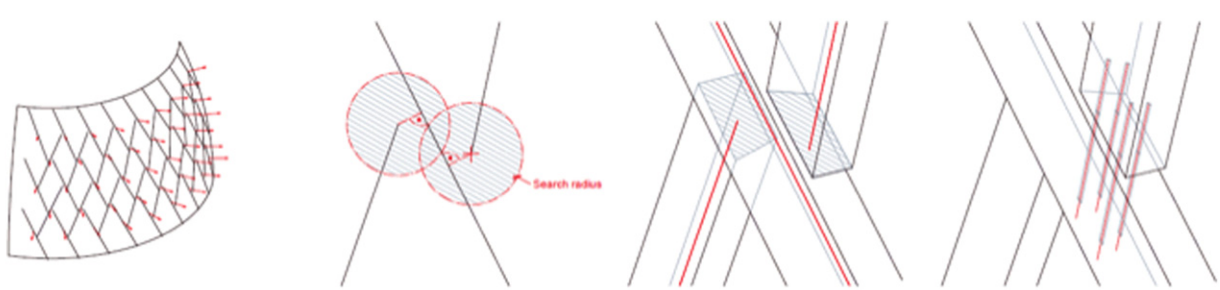

Fig. 5. Workflow diagram of the digital design and fabrication process. From left to right: a) generation of wood member axis and definition of member orientation; b) definition of neighbouring components; c) generation of volumetric geometry, and d) generation of connection detailing. Gramazio Kohler Research, ETH Zurich, 2014.

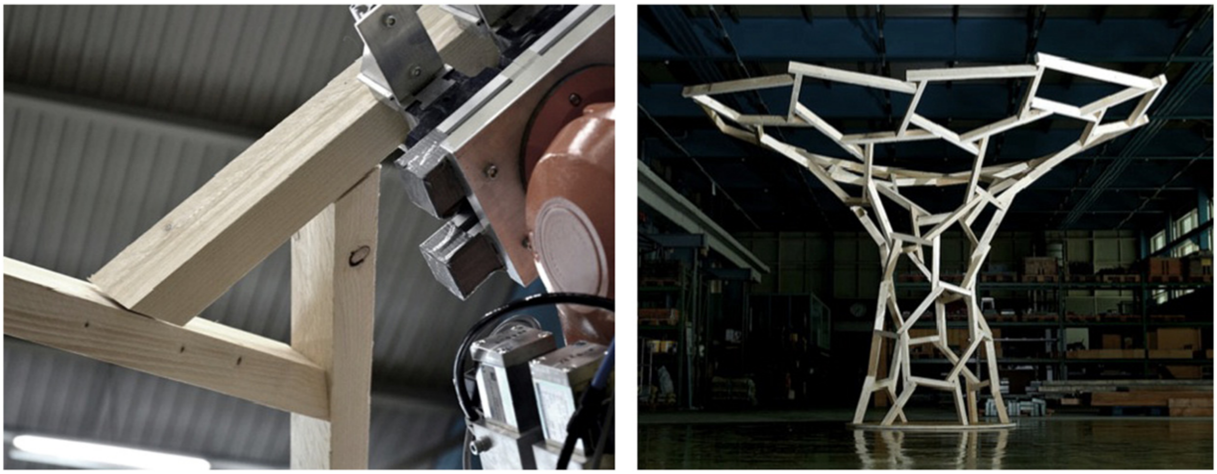

Fig. 6. Left: custom-developed spatial node connection for spatial robotic assemblies — by increasing or decreasing the size of its triangular arrangement, the stiffness of the connection can be individually adapted to specific local structural requirements; right: final 1:1 prototype, testing the feasibility of the connection according to tolerance compensation, structural performance and design freedom. Gramazio Kohler Research, ETH Zurich, 2014.

For the industrial full scale implementation of RTC a new multi-functional robotic setup was developed at ERNE Holzbau AG together with ROB Technologies AG, enabling the fully-integrated manipulation and aggregation of components through constant digital guidance. The core component of this RTC implementation is represented by a custom six-axis overhead gantry robot (see Fig. 9). It provides a workspace of $48 \times 6.1 \times 1.9$ m and consists of 3 translational axis in X, Y, and Z directions. Attached to the Z-axis is a mechanical wrist, featuring three rotational axes that allow the gantry system 6 DOF of orientation. As a consequence, the single working steps of each timber beam are fully integrated and automated, including an integrated quality monitoring by photographically checking for deviations or material errors. Cycle times – including gripping, trimming, positioning and nailing – are around 3 min per component. Overall, the large-scale setup would allow to handle timber components of a length between 500 mm to 10,000 mm and to manufacture building elements up to 48 m length.

As this kind of structural typology is not sufficiently covered by existing building regulations, a structural proof by means of empirical tests was required. This was performed through mechanical load tests of robotically fabricated real scale specimens (see Fig. 10), whereby the obtained data was fed back into the overall calculation model. The definitive design had to be validated again through load tests on 16 randomly chosen final trusses.

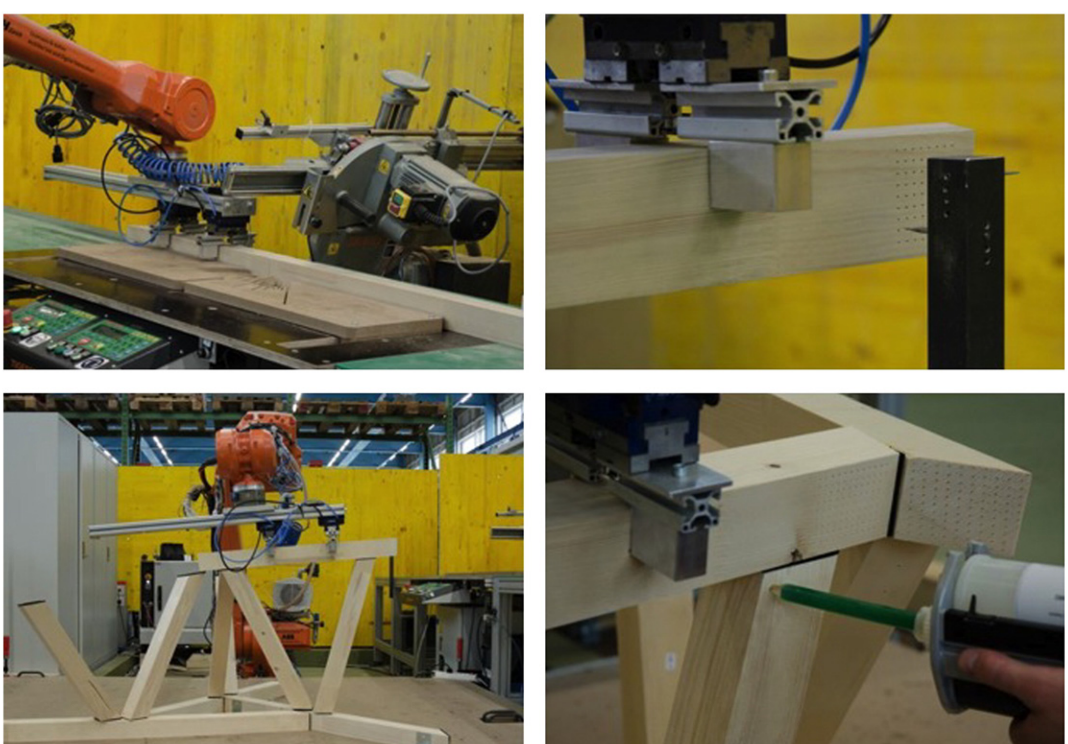

Fig. 7. Non-standard robotic fabrication system, featuring automated gripping and cutting, as well as robotic surface manipulation and spatial positioning. Gramazio Kohler Research, ETH Zurich, 2014.

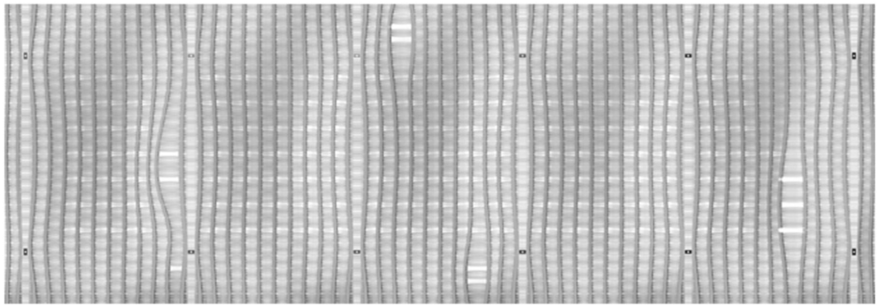

Fig. 8. Top view of the 2300 square metre large "The Sequential Roof", consisting of 168 robotically prefabricated lattice girders with a regular span of 14.70 m to form a continuously graded constructive arrangement (Image ©Arch-Tec-Lab).

The design of the roof has been encapsulated in a complex computational parametric model (see Fig. 11) developed especially for this purpose; it is iteratively refined according to specific formal, constructive and structural criteria (e.g. slat sizes, maximisation of the overlaps between the timber members, optimization of the nailing patterns of the connections) as well as to parameters deriving from the constraints imposed by the automated robotic fabrication process (e.g. element manipulation, layering logics) and by the integration of architectural subsystems, like sprinkler, lighting and openings. While the integration of all these diverse requirements left a very narrow solution space which had to be algorithmically explored, the RTC process allowed for the computational optimization of the design until the very last moment prior to the start of the physical fabrication process.

Against this background, the combination of strong custom computational tools and flexible industrial fabrication logics of this first industrial full scale implementation of RTC illustrates the potential of automated timer assembly processes. Even though "The Sequential Roof" will only be completed with the Arch-Tec-Lab [21] building by 2016, the performed tests have successfully demonstrated its feasibility and created knowledge that can be transferred to other RTC implementations.

5. Conclusion

In conclusion, the vision of RTC, in which the integration of digital design and automated fabrication is at the centre of both the final object and also the process of its construction, radically extends the traditional spectrum of timber construction and introduces the use of robotic assembly logics to this industry. Most of all, RTC pursues a radical shift in scales of application where complex and efficient non-standard timber structures can be realised from a multitude of simple timber members, fostering redundant, distributed and versatile constructions. In addition, this endeavour promotes new computational methods where design decisions orchestrate a multitude of structural constraints as well as construction and fabrication attributes from the very beginning of the design process onward up to the different stages of prototyping until its final realisation. Thus, RTC fosters information penetration across the whole process of construction, from the initial parametric design scheme to the machinic manipulation of single timber components to the constructive assembly of highly informed architectural structures, opening up new ways of thinking about architectural design and its materialisation [22]. However, RTC at full scale is still in its infancy, and presents many challenges not only to architecture, but also to integral structural engineering and the construction industry. And yet this approach is captivating: RTC not only creates a new vision for future timber construction, but also emphasises new possibilities for the exploration and understanding of it [23].

Acknowledgements

Most of the research presented in Section 3 results from the current research cooperation between Gramazio Kohler Research at ETH Zurich (Prof. Fabio Gramazio, Prof. Matthias Kohler) and the Bern University of Applied Sciences (Prof. Eduard Bachmann, Prof. Christophe Sigrist) in the framework of the SNSF NRP 66 "Resource Wood" research

Fig. 9. Custom six-axis overhead gantry robot of ERNE Holzbau AG, featuring a translational axis with a mechanical wrist and three additional rotational axes to perform fully automated fabrication tasks within an effective workspace of 48 × 6.1 × 1.9 m (Image ©Arch-Tec-Lab).

Fig. 10. Full-size load tests of automatically prefabricated lattice girders with a regular span of almost 15 m at the Bern University of Applied Sciences (Image ©Arch-Tec-Lab).

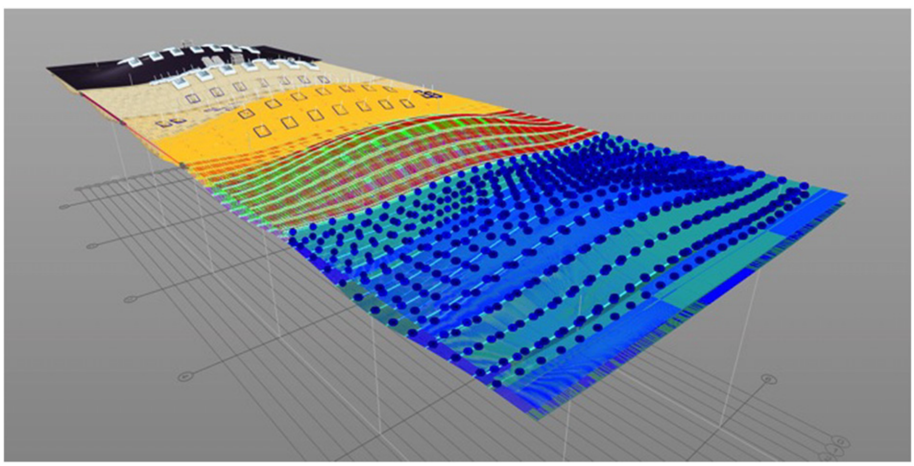

Fig. 11. The design of the roof is encapsulated in a computational model, where an object-oriented approach was used for computationally generating the "blueprint" of structure, based on Python as programming language for the integration of the original architectural design in the CAD-environment Rhinoceros (Image ©Arch-Tec-Lab).

programme. The authors thank the involved teams for their pioneering efforts on RTC, particularly Volker Helm, Dr. Thomas Kohlhammer, Stefan Sitzmann and Peter Zock. The authors are also grateful for the generous support of Nolax AG. An extra thanks goes to Luka Piškorec and his students for their efforts on teaching activities coupled to RTC. With regard to "The Sequential Roof", described in Section 4, the authors greatly thank all the collaborators – Jaime de Miguel (project lead preliminary project), Selen Ercan, Olga Linardou – at the Gramazio Kohler Research and particularly all cooperation partners for their generous support of the project. This includes the following cooperation partners: Execution planning: Arch-Tec-Lab; structural engineering: Dr. Luechinger + Meyer Bauingenieure AG; timber engineering: SJB. Kempter Fitze AG; manufacturing and realisation: ERNE AG Holzbau; digital integration and fabrication control: ROB Technologies AG; structural design consultancy: Prof. Dr. Josef Schwartz, Chair of Structural Design (ETH Zurich); timber structure engineering consultancy: Prof. Dr. Andrea Frangi, Institute of Structural Engineering (ETH Zurich); daylight studies consultancy: Estia SA (EPF Lausanne). Much of "The Sequential Roof" project would have not been possible without the valuable support of the Institute of Technology in Architecture (ITA) at ETH Zurich, which, in fact, initiated this exciting endeavour.

References

[1] Gramazio Kohler Research, ETH Zurich, "The Sequential Roof"accessed 26.02.2015 http://gramaziokohler.arch.ethz.ch/web/e/forschung/201.html.
[2] T. Bock, T. Linner, W. Lauer, N. Eibisch, Automatisierung und Robotik im Bauen, Archplus 198/199 2010, pp. 34–39.
[3] J. Andres, T. Bock, F. Gebhart, et al., First results of the development of the masonry robot system ROCCO, Proceedings of the 11th ISARC (International Symposium on Automation and Robotics in Construction), Elsevier, Oxford 1994, pp. 87–93.
[4] M. Dalacker, Schriftenreihe Planung, Technologie, Management und Automatisierung im Bauwesen, in: T. Bock (Ed.), Entwurf und Erprobung eines mobilen Roboters zur automatisierten Erstellung von Mauerwerk auf der Baustelle, Band 1, Fraunhofer IRB Verlag, Stuttgart, 1997.
[5] T. Bonwetsch, F. Gramazio, M. Kohler, Towards a Bespoke Building Process, in: B. Sheil (Ed.), Manufacturing the Bespoke, John Wiley & Sons, Chichester 2012, pp. 78–87.
[6] S.Y. Nof, C.N. Rajan, "Robotics", in Handbook of Design, Manufacturing and Automation, Wiley & Sons, London, 2007.
[7] R. Jordan, H. Kuechle, G. Volkmann, Holzwirtschaft im Wandel: Oekonomische und technologische Veraenderungen in der Holzbearbeitung und Holzverarbeitung, Cologne, Bund-Verlag, 1986 83–91.
[8] F. Gramazio, M. Kohler, Digital Materiality in Architecture, Lars Mueller Publishers, Baden, 2008 7–11.
[9] D. Schodek, M. Bechthold, K. Griggs, K. Kao, M. Steinberg, Digital Design and Manufacturing: Applications in Architecture and Design, Wiley, Hoboken, 2008.
[10] J. Ficca, Inclusion of performative surfaces material and fabrication research, in: L. Iwamoto (Ed.), Digital Fabrications: Architectural and Material Techniques, Association for Computer Aided Design in Architecture (ACADIA), New York, 2009.

[11] D. Pigram, W. McGee, Formation Embedded Design: A Methodology for the Integration of Fabrication Constraints into Architectural Design, The University of Calgary, Calgary/Banff, Canada, 2011 122-31.

[12] A. Menges, T. Schwinn, Manufacturing reciprocities, Architectural Design 82, No. 2 (2012), Wiley & Sons, London 2012, pp. 118–125.

[13] R.L. Johns, N. Foley, Bandsawn bands, in: Robotic Fabrication, in Architecture, Art and Design 2014, (Eds.), W. McGee and M. Ponce de Leon, Springer, Vienna/New York 2014, pp. 17–33.

[14] N. Dunn, Digital Fabrication in Architecture, Lawrence King Publishers, London, 2012 26–39.

[15] Institute for Computational Design, University of Stuttgart, Landesgartenschau Exhibition Hallaccessed 26.02.2015 http://icd.uni-stuttgart.de/?p=11173.

[16] J. Mayer H, Metropol Parasolaccessed 26.02.2015 http://www.jmayerh.de/index.php?article_id=19.

[17] Bern University of Applied Sciences — Division Architecture, Wood and Civil Engineeringaccessed 26.02.2015 https://www.ahb.bfh.ch/en/home.html.

[18] T. Kohlhammer, T. Kotnik, Systemic behaviour of plane reciprocal frame structures, Structural Engineering International 1 (2011), International Association for Bridge and Structural Engineering, Zurich 2011, pp. 80–86.

[19] Gramazio Kohler Research, ETH Zurich, Complex Timber Structuresaccessed 26.02.2015 http://vimeo.com/96060053.

[20] F. Gramazio, M. Kohler, J. Willmann, The Robotic Touch — How Robots Change Architecture, Park Books, Zurich, 2014 186–187.

[21] ETH Zurich, Arch_Tec_Labaccessed 26.02.2015 http://www.ressourcen.ethz.ch/projects/hib/index_EN.

[22] H. Adam, Holzkonstruktionen, digital fabriziert, Zuschnitt, 53 (2014), Ausgabe “Digitaler Holzbau”, proHolz, Austria, Vienna 2014, p. 20.

[23] J. Willmann, F. Gramazio, M. Kohler, An extended performative materiality, in: R. Oxman, R. Oxman (Eds.), Theories of the Digital in Architecture: A Critical Mapping of Theories, Models and Concepts, Routledge/Taylor & Francis, London 2014, pp. 307–319.