The CantiBox

Robotic Assembly of Interweaving Timber Linear Elements Using Bespoke Interlocking Timber-to-Timber Connections

Davide Tanadini, Giulia Boller, Pok Yin Victor Leung, Yijiang Huang, Pierluigi D'Acunto

In recent years, the building industry has increasingly promoted digital techniques, such as robotic manufacturing. Much scientific research has been conducted in the field of robotic assembly of timber structures, made of plates and linear elements (Robeller et al. 2017; Thoma et al. 2018; Leung et al. 2021; Hua et al. 2022). In this context, the robotically fabricated *CantiBox* project (Figure 1) presented here constitutes a novel application of the design and automatic assembly of interlocking timber-to-timber connections. The structure is composed of 60 linear elements of solid spruce interconnected through half-lap joints to form a reciprocal network.

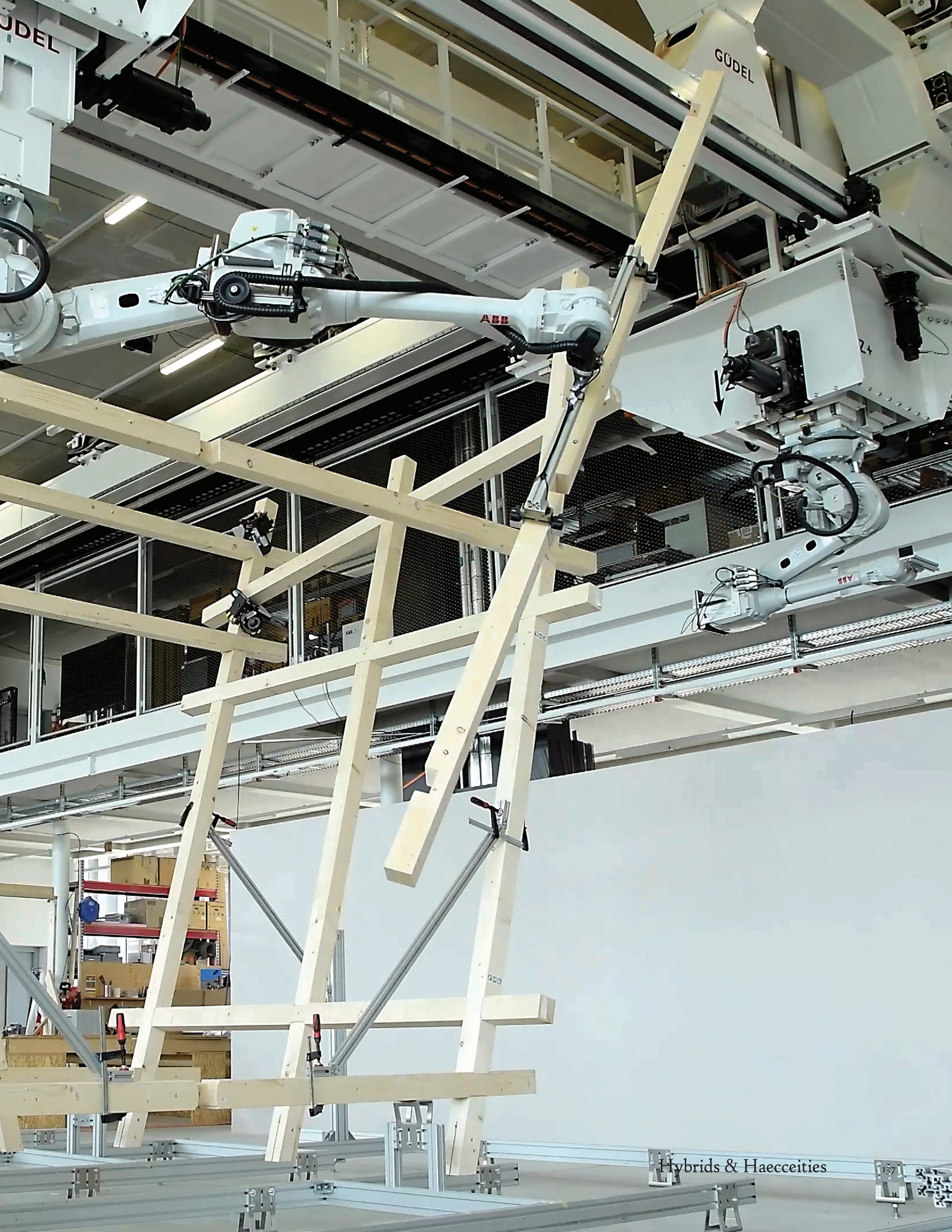
GLOBAL DESIGN

CantiBox consists of three independent units: two lateral boxes connected to the ground and a cantilevering central box, which is simply supported by the other units. Each unit is composed of 20 timber linear elements with a cross-section of 10 by 10 cm, which are automatically assembled via robotic fabrication. Each face of the boxes is made of six timber linear elements that are arranged in the plane to generate a reciprocal system (Figure 2). Equilibrium-based methods for structural design and Finite Element Analysis (FEA) are used to evaluate the global structural behavior of the *CantiBox*. In the analysis, each joint is regarded as a rigid connection. Since the project is built outdoors, both the self-weight of the structure and the wind load are considered according to the Swiss norms (SIA 2021). For each connection, the most disadvantageous load combination is evaluated.

PRODUCTION NOTES

Project Coordination:	Davide Tanadini, Victor Pok Yin Leung, Yijiang Huang
Structural Design:	Davide Tanadini, Giulia Boller, Pierluigi D'Acunto
Mechatronics and Robotic Execution:	Victor Pok Yin Leung
Robotic Task and Motion Planning:	Yijiang Huang
Robotic Screwdriver Design:	Marco Rossi
Location:	Zurich, Switzerland
Date:	2022

1 One of the timber units during construction, with the robotic arm positioning a timber element following the assembly sequence (©Gramazio Kohler Research 2022).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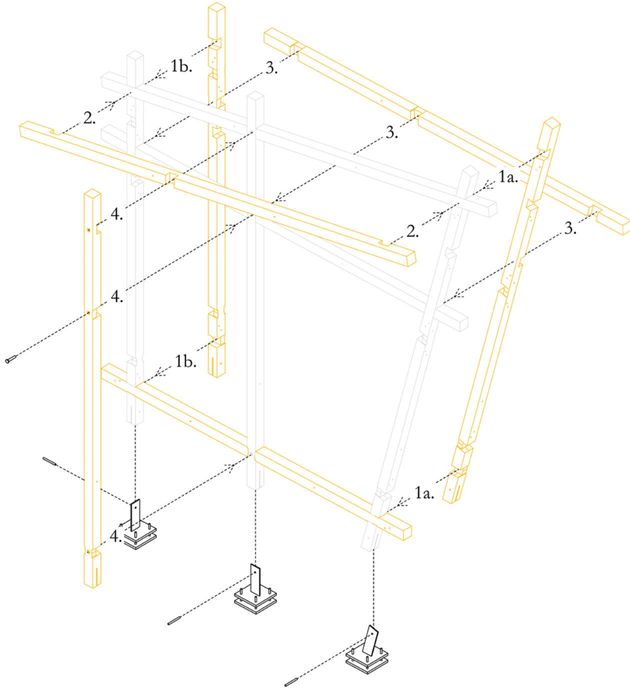
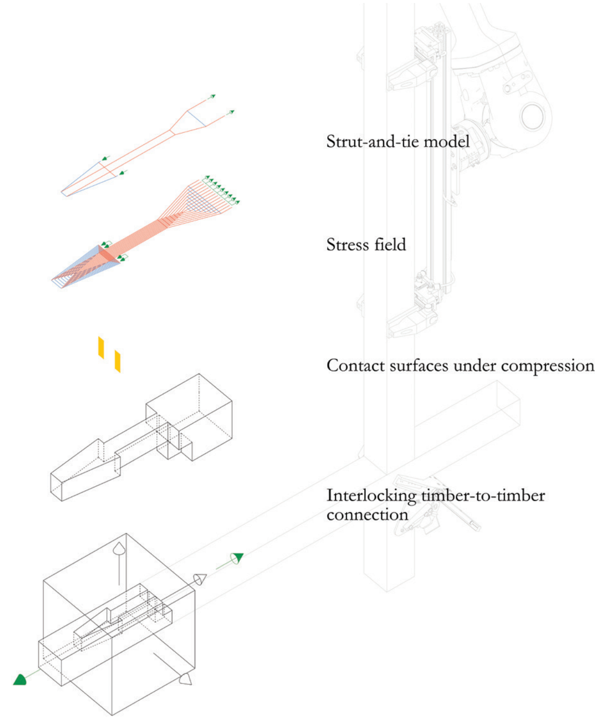


2 The interweaving logic used during the assembly allows the number of metal fasteners to be limited to one per face. In fact, only the last assembled element, the key element, requires the use of a screw to close the reciprocal system and prevent the system from disassembly. This screw does not have any structural function.



3 Step-by-step structural analysis and design of a generic interlocking timber-to-timber connection. Based on the initial geometry, the contact surfaces under compression required for force transfer are identified. The flow of internal forces is represented by stress fields or equivalent strut-and-tie models. The geometry of the joint and stress field is adjusted such that stresses do not exceed the yield conditions.

CONNECTION DESIGN

The static method of limit analysis, based on plastic theory, is adopted to determine the capacity of the interlocking timber-to-timber connections and for their design (Tanadini and Schwartz 2021). In each of the lap joints, forces are transferred between the elements by means of compressed contact areas. The capacity depends on two parameters: the size of the contact surface and the strength value associated with it (Figure 3). The contact surface strength indicates the maximum stress that a surface can withstand. The strength value is calculated thanks to stress fields and timber yield conditions, and then validated through mechanical tests.

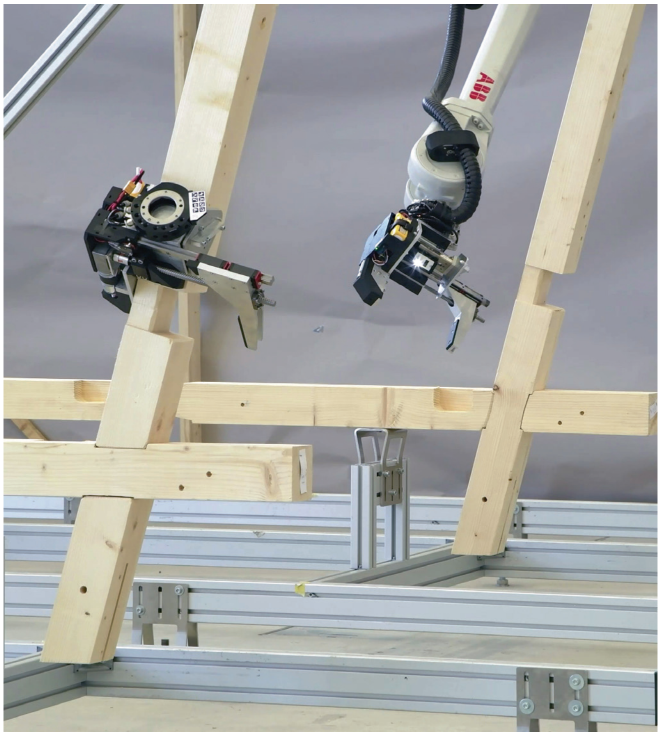
As each connection is subjected to different loads, it is possible to modify the contact surfaces required for load transfer by varying the geometry of the joints. The prototypical half-lap joint connection is therefore customized, whenever necessary, to adapt its capacity to the internal stresses. The parametric space for customization is carefully designed such that joints can be assembled by our robotic tools and are machinable by commonly available automatic joinery machines (Figure 7).

ROBOTIC ASSEMBLY

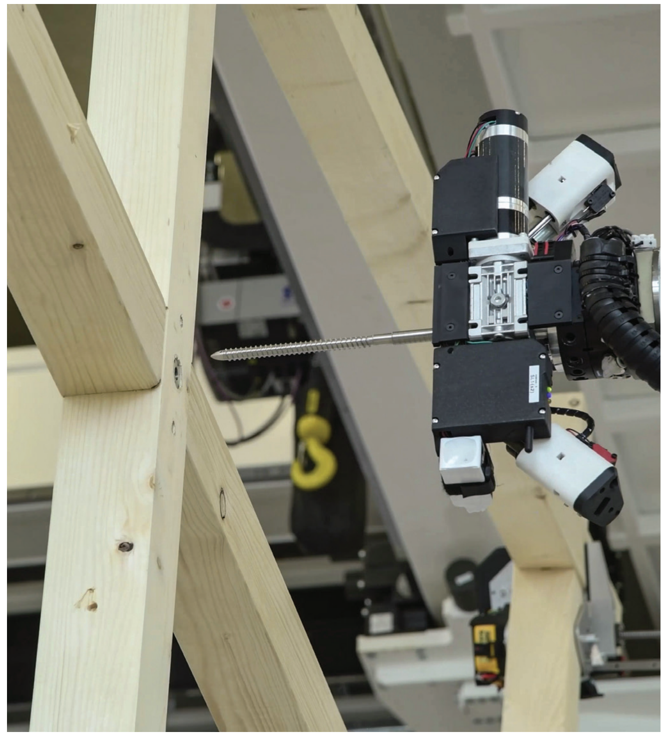
The structure is constructed through a fully automatic process (Leung et al. 2021), which uses a set of distributed robotic clamps (Figure 4) and screwdrivers (Figure 5) to operate in collaboration with an industrial robotic arm. Each of the three units is constructed spatially in an automatic process (Figure 1), as opposed to planar sub-assemblies. Robotic clamps are used for most joints that do not require fasteners. Robotic screwdrivers, which can be loaded with a left-in fastener, are used for the four key elements.

CONCLUSIONS

The *CantiBox* project demonstrates two cutting-edge approaches for jointed timber structures. First, the static method of limit analysis for timber-to-timber connection design, allows the adjustment of individual lap joint geometries based on real-time performance assessment. Second, distributed robotic tools are used to achieve a fully automatic assembly process. Both technologies complete an important knowledge gap that enables bespoke design and construction of spatial timber structures. Their flexibility



4 The robotic arm positions two robotic clamps to insert a new timber element in the structure (©Gramazio Kohler Research 2022)



5 A key timber element is assembled by a robotic screwdriver loaded with a left-in fastener (©Gramazio Kohler Research 2022)

6 General view of the *CantiBox*; the structure is partially covered with translucent fabric to provide shading (©Lukas Ingold 2022)

7 All the bespoke connections are machined with a Hundegger Robot Drive automatic joinery machine (©Gramazio Kohler Research 2022)

8 Thanks to its inherent spatial reciprocal configuration, the *CantiBox* project achieves high geometric complexity using only simple planar connections (©Gramazio Kohler Research 2022)

to accommodate custom design can be witnessed in the use of the interweaving logic to create a reciprocal network (Figures 7, 8).

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9 The *CantiBox* project leverages innovative approaches to structural design and robotic assembly to enable the development of a customized, spatial timber structure (©Lukas Ingold 2022)

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IMAGE CREDITS

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