# Towards an On-site Fabrication System for Bespoke, Unlimited and Monolithic Timber Slabs

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**We present the concept- and contextualization of a robotic fabrication system for bespoke, monolithic wood slabs for multi-story building structures.**

**Timber Construction is seen as the most promising technology for the sustainable development of continuously growing urban areas around the world, resulting in increasing legislative support. Although employing high levels of automation in prefabrication, wood building systems and construction techniques are currently hardly competitive outside of modular construction paradigms – restricting the material's use in the majority of building typologies. In many projects, the use of concrete is still preferred, as slabs can be poured into monolithic slabs of various geometries and steel reinforcement can be freely arranged according to structural requirements.**

**In order to allow engineered wood structures to be used across all building types, we propose a co-designed wood construction system. A respective robotic fabrication platform can be employed in two on-site fabrication scenarios. In both cases the mobile robot moves relative to a preinstalled wood-panel surface that serves as semi-controlled environment and is incrementally reinforced through iterative placement of wood laths using nail-press gluing.**

**This results in multi-directional, bespoke timber slabs of unlimited dimensions and continuous stiffness gradients.**

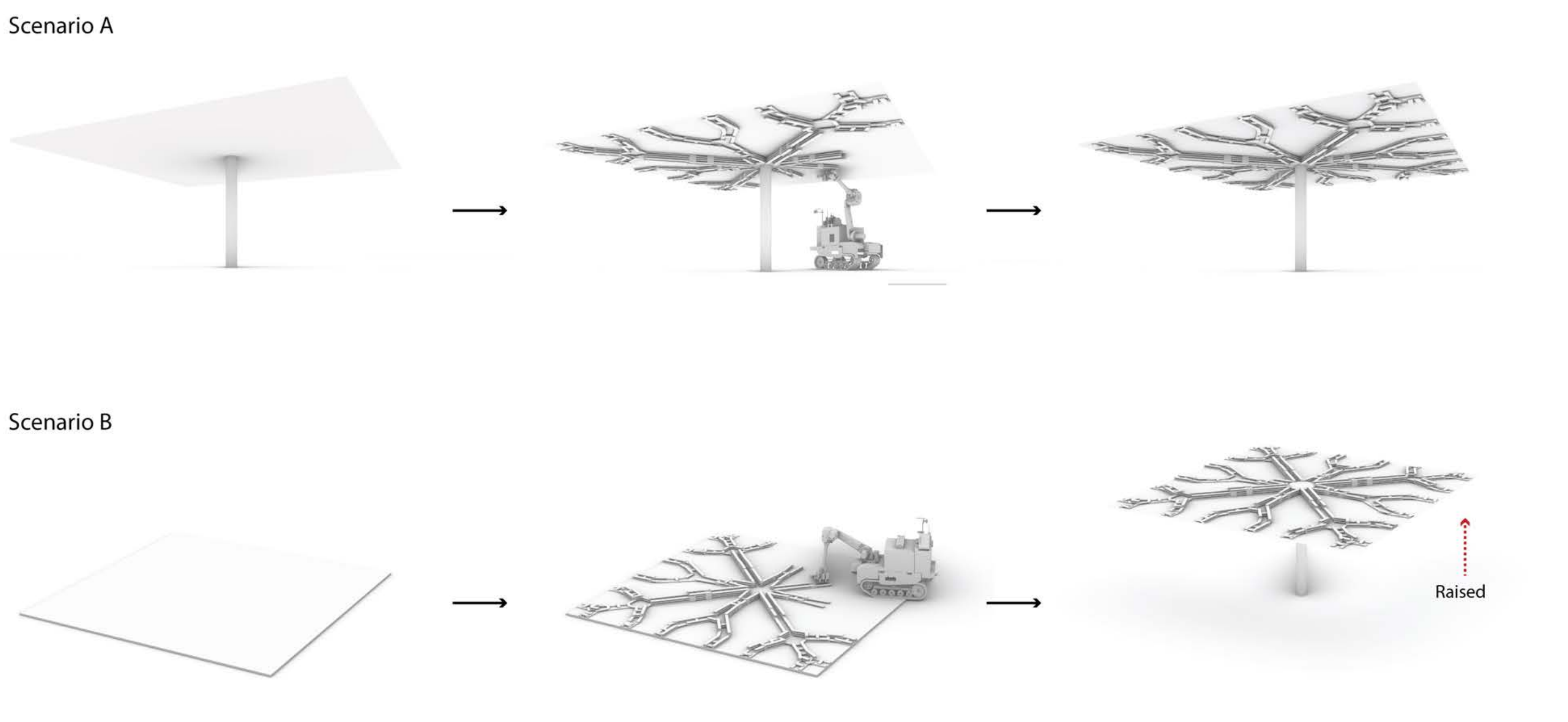

**Fig. 1.** Building system and fabrication concept: A mobile robot platform is used to incrementally nail-press-glue timber laths into geometrically unconstrained monolithic timber slabs that span in multiple directions. Two Scenarios are proposed in both of which an initially laid out preassembly of boards gets incrementally reinforced by a topologically optimized beam network made from glued together laths. In Scenario A the boards are fixed in place on top of the columns before beam fixation.
In Scenario B the boards are laid out flat on the floor and are lifted in place after completion of reinforcement.

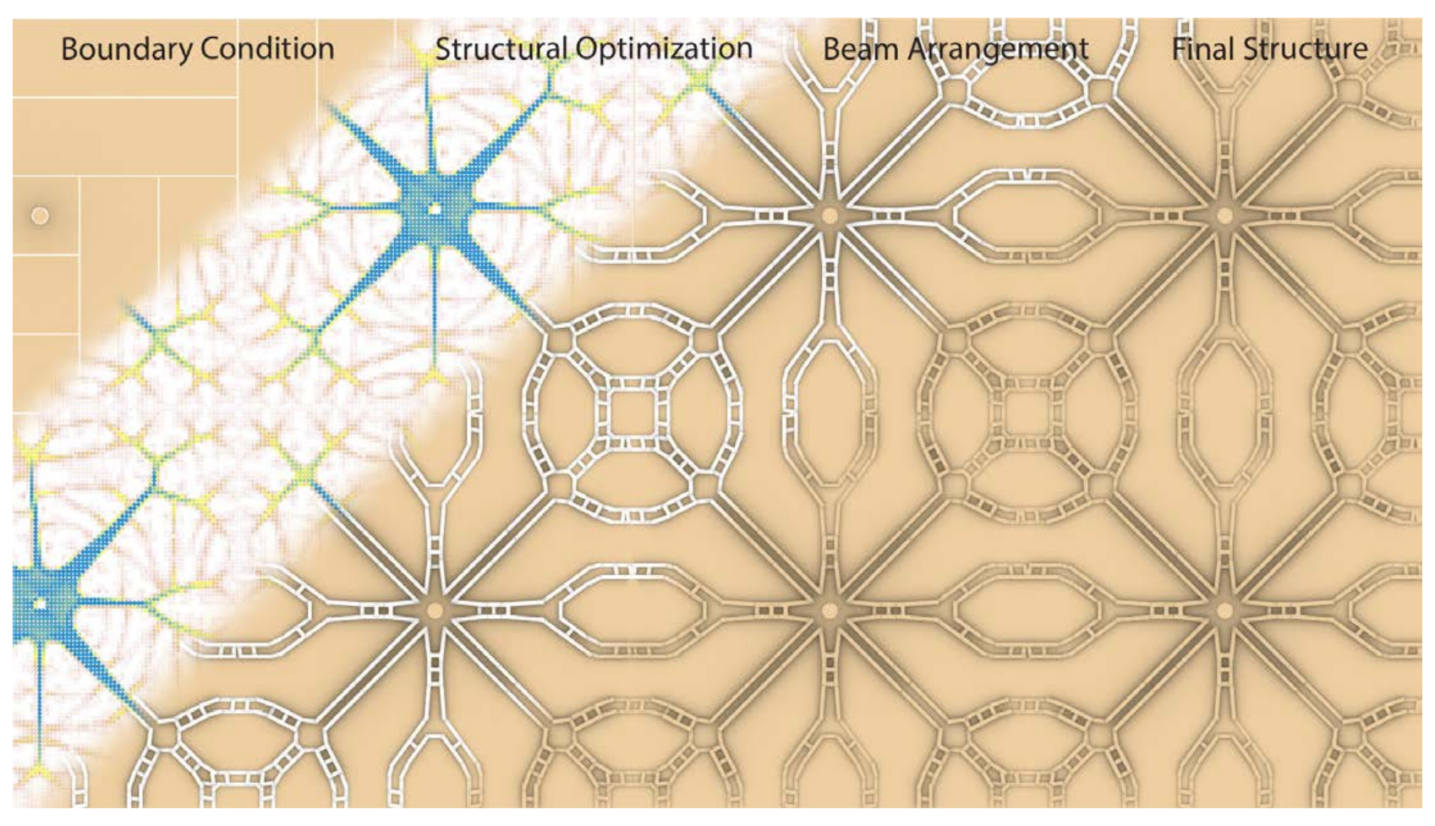

**Fig. 2.** The incremental assembly of discrete timber laths allows a bespoke network of beams that are all interconnected throughout the slab. A computational design algorithm takes into account the column positions and slab geometry as well as loadcases and the result of a subsequent topology optimization to generate a structurally performative beam arrangements.

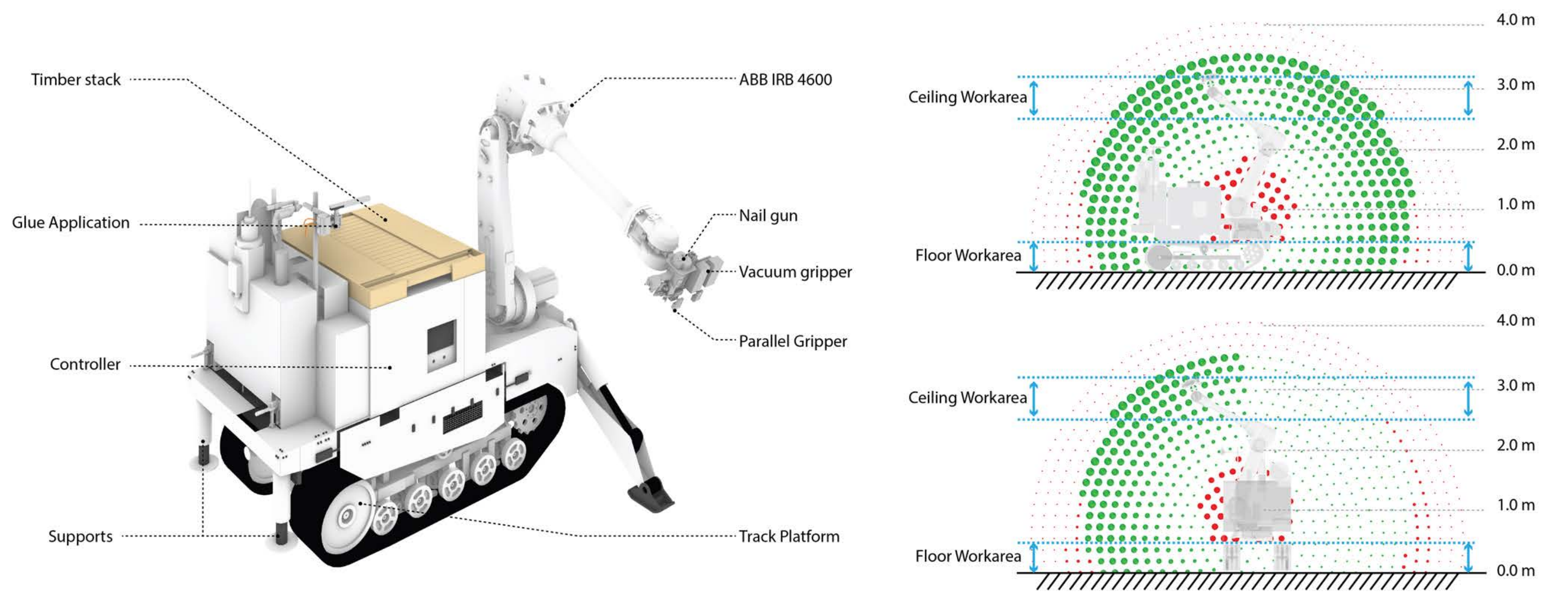

**Fig. 3.** The robotic platform was designed to be flexibly deployable for various timber construction tasks. It is equipped with a comprehensive set of tools (left).

To ensure ideal productivity in both fabrication scenarios its reach envelope needs to contain both typical ceiling and floor heights (right).

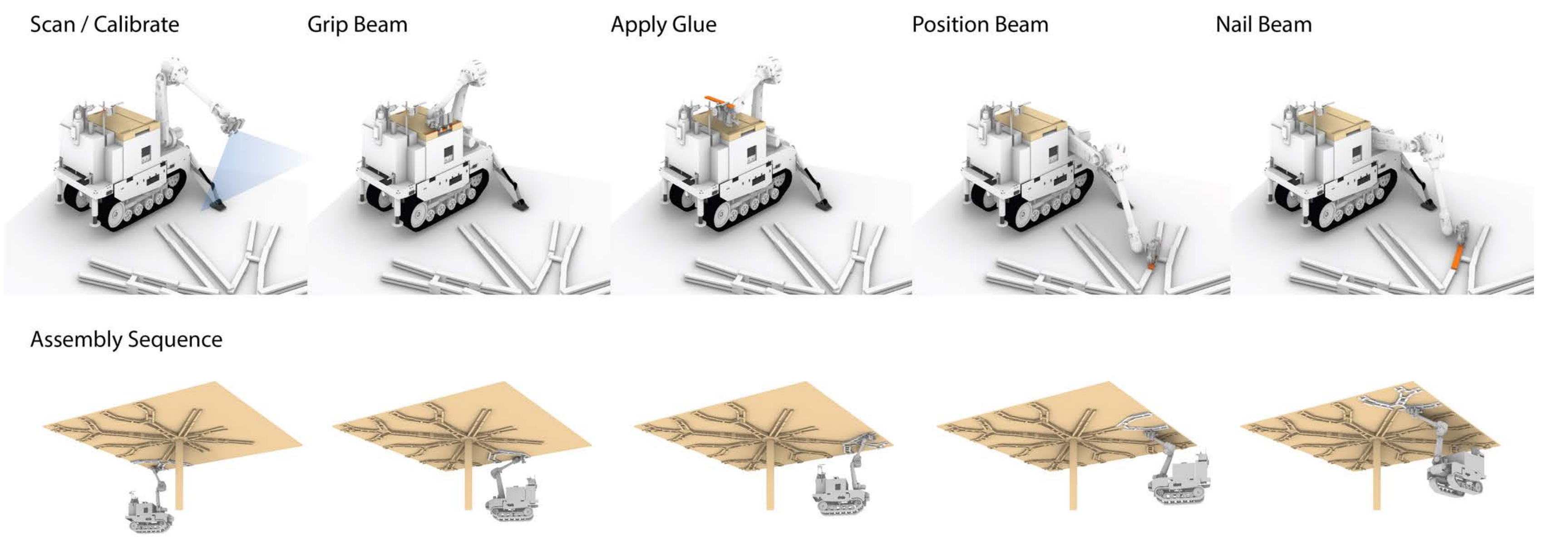

**Fig. 4.** Each assembly step the robot runs through a sequence of five routines (top, left to right). To minimize robotic repositioning during the slab assembly the beam network is divided into clusters that are reachable from a single platform position. (See supplementary video: https://www.youtube.com/watch?v=qyLQEb3iBOE&feature=youtu.be)

## I. RELEVANCE

Building construction is trapped inside a development dichotomy of highest public concern. It is currently responsible for roughly 30-50% of global energy consumption, waste production and greenhouse gas emissions [1]. Additionally a further increase in construction volume is necessary in order to house a rapidly growing global urban population [2]. This is still true in less dramatically growing populations of western countries – where skilled and unskilled construction labor is in short supply. The question is: How will we manage to build higher volumes with less labor while reducing negative effects on our planet's ecosystem? Timber construction will play a key role in developing sustainable solutions to address this grand challenge. First, building with wood stores sequestered carbon for long. Timber buildings could become the earth's biggest carbon sink [3]. Second, the resource wood lends itself to automation technologies due to its good machinability. Challenges such as the unreliability of the naturally grown wood was mostly overcome during the last decades through digital technologies such as image-based quality control, CT scanning, CNC manufacturing, 3D-modelling and prefabrication - making the timber construction sector one of the most digitally advanced within the field. Contrary to popular belief, there is currently little shortness of the resource wood. As an example, Europe could build apartment housing for its whole population of 750 million every 50 years, cyclically sourcing wood from only 30% of its sustainably managed forest areas [4].

As wood is still a valuable resource it is ideally used with a maximum of efficiency in construction to minimize material costs. High quality, material efficient construction implies increased manufacturing complexity that can only be achieved with advanced construction technologies. This makes the development of robotic fabrication technologies for wood construction an effort of highest global relevance.

## II. STATE OF THE ART

Current paradigms in timber construction adopted from manufacturing stress the advantages of off-site prefabrication. Building within factories benefits the quality of the working environment, increases construction quality as well as on-site erection speed and allows for the extensive use of fixed installed machinic equipment. As building assemblies need to be still transported to the building site, this technique is also termed "modular construction" – with the scale of each module being limited by transportation constraints (within urban areas roughly 3 x 3 x 12m). Such modular construction currently constitutes a rapidly growing industry – with its share of construction volume being predicted to possibly reach up to 13% of the building construction market within EU and US by 2030 [5] annually saving up to 22 billion dollar in construction costs through further optimization efforts within logistics and automation. Nevertheless, the off-site paradigm lends itself only to building typologies that offer an increased level of standardization, regularity and strict grid-based ordering systems and floorplan organization. Common examples are hotels, student dorms, possibly hospitals and elderly homes. For the majority of other construction projects, it is still more efficient to optimize the buildings through customization and directly react to project-based boundary conditions – through engineered-to-order construction efforts. In such situations – modular construction most often can't compete with on-site construction – as most commonly slabs are hardly divisible into repeating modules. Further challenges for modular construction in such projects are variations in span and span directions. Also connections of modules on site that do not constitute a common failure point, are yet to be found. Here the monolithic nature of steel-reinforced concrete slabs still plays out its main benefits: The material can be formed flexibly into almost any shape, while the rebar allows for the reinforcement of the slab in various directions and span dimensions. For timber construction a comparable and competitive on-site fabrication system for large-scale, monolithic, multi-directional slabs does not yet exist.

## III. CONTEXT - CONSTRUCTION ROBOTICS

The field of construction robotics saw a new wave of increased efforts that originated within the architectural schools around the world during the last decade [6] building up on earlier developments [7]. An increasing number of architectural research facilities are equipped with robotic setups. A common system used, are gantry robots [8], [9]. To ensure flexibility of use, location independence, on-/off-site use and the possibility of innovation diffusion into industry, the organization of robotic systems on transportable and/or mobile platforms becomes increasingly important [10]–[13]. As construction sites are generally unstructured environments that pose significant challenges on the employment of on-site robotic platforms, the applications of such are still limited – especially for the on-site fabrication of structural wood systems.

## IV. SCOPE

In the work presented here, we develop a fabrication system that integrates aspects of construction robotics, architectural building system design (including design, material tectonics, material science, structural optimization) and wood construction. Leveraging state-of-the-art technologies from all of these fields we develop a comprehensive fabrication system that contributes to the field through its integrative co-design: Through the intricate negotiation of potentials, constraints and boundary conditions of all fields we arrive at a tangible solution of a material efficient building system concept, it's computational design algorithms and respective on-site robotic fabrication platform.

## V. RESEARCH DEVELOPMENT

### A. Concept Definition

The proposed fabrication system allows the on-site construction of monolithic timber slabs with highly differentiated networks of beams composed of robotically assembled and glued discrete wooden linear elements. A mobile robot platform is developed, that can navigate on-site and is equipped with a gripper, material supply, adhesive application system, and an automated nail-gun. We propose two fabrication scenarios (Fig. 1). Both start with the two-dimensional arrangement of flat, thin LVL panels onto which the robot incrementally glues discrete timber laths - forming continuous reinforcement networks. In Scenario A, the panels are initially fixed on a set of columns. The robot then starts reinforcing the slab from below. In Scenario B on the other hand, the panels are laid out flat on the floor, which creates a semi-controlled environment for the mobile robot to locomote on while reinforcing the panels from the top. After completion of the full slab, it can then be raised using the columns as scaffolding. Both scenarios are to be tested in 1:1 scale during two upcoming workshops that the authors are conducting in 2020 at Tongji University (Shanghai) and Tsinghua University (Beijing) to test their feasibility through the construction of two large-scale demonstrator structures.

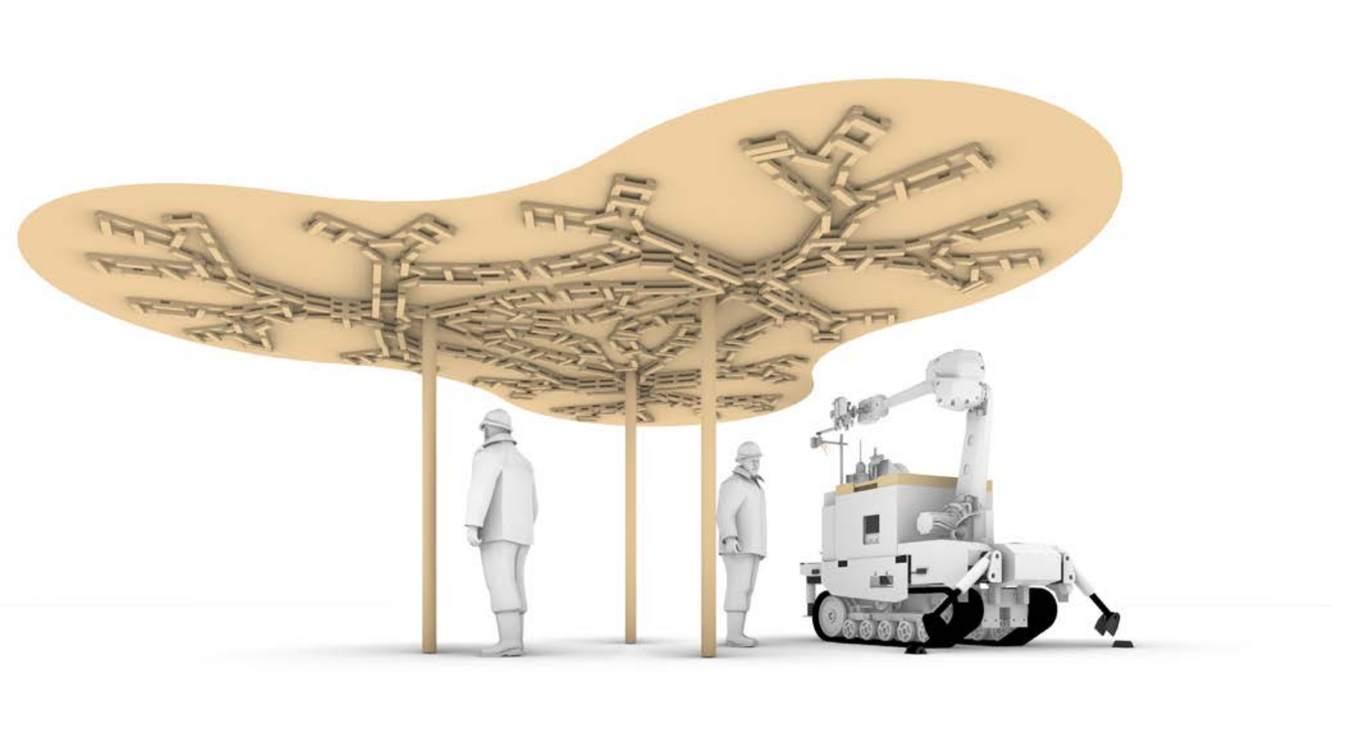

**Fig. 5.** The design of the proposed demonstrator structure to be fabricated by the authors at the DigitalFutures 2020 Workshop in Tongji University.

### B. Building System

Designing with wood is a highly challenging task, due to the internal anisotropy of the fibrous, natural material. Although the material has excellent structural characteristics challenges arise whenever elements need to be joined. Until now, only glued interfaces can establish a bond that allows for continuous stiffness gradients across the joint [4]. The proposed structural system dwells on the upcoming potential of on-site gluing through novel developments in material science and wood adhesive technology. Through iterative placement of linear elements and the subsequent fixation of the components with nails, the necessity of hydraulic- or vacuum pressing is avoided. The beam arrangements are organized in multiple layers, so that continuous force transfer is established at glued overlaps. These arrangements allow changes in direction of singular beams as well as branching and converging streams of beams within a multi-directional support network. Although the gaps between timber elements constitute a suboptimal situation for the flow of forces, such arrangements establish higher structural depths of the beams and allow for the integration of pipes and cables within the slab. The generation of beam topologies and tectonic geometries through computational design methods can directly implement results of structural optimization, boundary conditions and design inputs (Fig. 2).

### C. Robotic Platform

The mobile timber fabrication platform is composed of three parts, an ABB IRB4600 six-axis industrial robot arm, its control cabinet, a customized tool station for timber processing, and a track platform (Fig. 3). The platform has a width of 1100mm and length 2100mm and could well fit into a construction elevator. The ABB IRB4600 robot has a payload of 40kg and a reach of 2550mm. With the height of the mobile platform, the robot can reach a range from the floor up to 3432mm regardless of the effector. A gripper with nail gun is mounted on the robot, which can move a gripped piece below glue application head and then place and fix the piece in place. In addition to the adhesive application, the tool station also provides basic tools for wood processing including circular saw, spindle and drill to allow a flexible use of the platform beyond building system requirements. The control systems of all features are integrated on the platform. The controller generates the robot program in real time according to the position data received from the external locomotion system, and sends to ABB robot through ABB External Guided Motion (EGM). The track platform receives movements and speed control commands from the program through industrial Ethernet – passed through the programmable logic controller (PLC), driving the motor to accomplish forward, backward, and turning movements. During the fabrication process, all control signals for the fabrication tools, both in the tools station and the effector, are also given directly from the program through PLC.

### D. Fabrication Sequence

The fabrication sequence for both scenarios (Fig. 1) is based on the placement of identical elements and a repeating workflow of gripping an element from the part storage, application of glue, placement and fixation (Fig. 4). As the track-based locomotion system of the robot doesn't allow for an accurate positioning in absolute tolerances, a recalibration procedure needs to be implemented every time the robot is moved through vision based systems. As the base of the structure is defined by the initially placed boards, location identifiers (markers) could easily be embedded in the plates. These markers could be surveyed once per floor, and then allow the robot to easily detect its position. As the building system allows for certain tolerances (+- 10mm) marker-based localization is expected to be sufficient. To achieve higher relative accuracy for the positioning of elements and avoid tolerance accumulation, a cyber-physical workflow is conceptualized in which the robot scans the already built structure after each iteration and adapts the placement sequence of the next elements accordingly. Scenario A allows for a layer-based fabrication, but to avoid unnecessary repositioning, the elements can be assembled in clusters (Fig. 4). In Scenario B these clusters can be additionally sequenced in such way, that the robot is always able to move to the next position – avoiding the constructed beams to constitute an insurmountable obstacle.

## VI. FURTHER RESEARCH AND CHALLENGES

In the upcoming workshops we will explore the practical feasibility of the proposed fabrication. Fabrication tolerances and visual qualities of the structure can only be identified through prototype structures. Approval of structural glue interfaces is subject to stringent building codes around the world. For application in as certifiable fabrication system a process quality control system and routine could be implemented into the fabrication sequence to assure the quality of adhesive bonds. For fire safety considerations scenario B will have advantages, as the structural beams are protected by the boards below and the floor construction on the top. The structural simulation of the building system could be established only with advanced simulation software.

## ACKNOWLEDGMENT

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