Cyber-Physical Robotic Process for Re-Configurable Wood Architecture

Closing the circular loop in wood architecture

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The concept of circularity implies that materials, components, systems can be re-utilized to reduce their environmental impact by extending their life-cycle. This paper discusses an approach to circular construction that revolves around transformable wood architecture. What if we can make buildings that can be assembled, disassembled, and re-assembled by robots in infinite circular loops of reconfigurations? To explore this concept, a robotic process is developed to automate the reconfiguration of timber structures, considering the material, geometric and processual challenges involved in the operations. This method entangles establishing a cyber-physical process based on visual and force feedback, the development of wood construction elements suitable for the process, the deployment of design algorithms for semi-autonomous online construction. The paper describes this setup and demonstrates its functionality through a set of experimental prototypes conceived and evaluated in a three-phase collaborative process of assembly-disassembly-reassembly.

Keywords: *Robotic timber construction, Circular wood architecture, Cyber-physical systems, Robotic timber re-assembly*

INTRODUCTION

Material circularity is one of the critical challenges for the built environment of today and the future, which involves an in-depth reconsideration of our current practices for building (Sack-Nielsen 2018). Contemporary computational tools for design and fabrication offer opportunities to enable circularity at different levels (Studio RAP 2017, Jensen and Sommer 2018). Design for circularity extends the temporal horizon of architecture and requires considerations on how materials, components, and systems can be rendered reconfigurable in time. Along with this material agenda, architectural robotics plays a key role in this view by enabling automated, reproducible, and complex construction assembly, reconfigurable in time.

From an architectural technology standpoint, the idea of reconfigurable architecture, made of discrete parts, is considered a premise for enhancing the automation level in constructions by re-examining the whole production chain (Retsin 2019). The research in computational design and architectural robotics looks into automated reconfigurability of wooden constructions to shift the paradigm from a linear and deterministic to a circular and open-ended architecture. Innovative solutions are emerging in the design of building blocks which enable combinatorial and reconfigurable assembly logics (Retsin et al. 2017, Sanchez 2019) and in the conceptualization of assembly robots where building elements and robot mechanism work towards a symbiotic construction process to allow for continuous building and re-building of the structures (Leder et al. 2019, Tedbury 2017, Huang et al. 2018).

The CREATE Group at the University of Southern Denmark has been studying different approaches to computationally enhanced circular construction, involving the use of performative design (Naboni and Kunic 2019), reversible construction kits (Kunic et al. 2021), the use of robotics and humans for the assembly of reconfigurable and reusable structures (Naboni et al. 2021).

While most current research studies are focusing on the conceptualization of the new robot and building typologies without specific considerations of the material and construction challenges, in this study we investigate the possibility of a robotic circular construction process for assembly- disassembly-reassembly of complex structures based on vision and haptic construction feedback and human-robot collaboration. In particular, we focus on developing a cyber-physical robotic process that supports the continuous reconfiguration of timber structures while tackling in real-time emerging environmental and construction changes.

METHODOLOGY

This work explores the robotic re-assembly of transformable timber construction. We demonstrate a novel process where robots are autonomously assembling, disassembling, and reassembling sets of wood construction elements. While industrial robots are specifically well-performing in repetitive assembly routines, this task proves to be particularly challenging within the construction field because of the high level of customization, the material imprecisions, the assembly tolerances, the elements stability, and the forces applied during the assembly. Our approach involves using online design algorithms to compute assembly sequences based on assembly feedback obtained through camera vision. Design for disassembly principles has been implemented in designing the wooden elements to facilitate reconfigurability and assembly automation.

Robotic setup

The presented research is conducted using a collaborative robotic cell that allows for flexible and adaptive assembly and disassembly. Two UR10e robots are mounted on reconfigurable welding tables at a distance that will enable their workspaces to overlap and form a collaborative area (Fig. 1). Within this shared space, the robots can work on the same structure and perform assembly and consequent disassembly procedures.

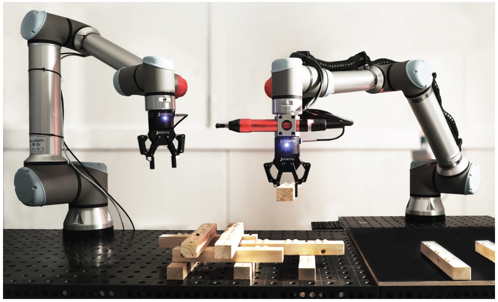


Figure 1
Collaborative robotic setup

The two robots are equipped with a multi-phase collaborative assembly tool, comprising an electric 2F-85 Robotiq gripper; a Robotiq Wrist Camera which is mounted above the gripper along the same axis; an electric Dessouter screwdriver which is mounted perpendicularly between the gripper and the camera in a custom-made holder; a custom-made wrist switch for human-robot interaction (Fig. 2). An additional 3D printed screw holder with an embedded magnet is attached to the screw bit to better hold and transport the steel bolts from the pick-up station to the assigned hole and vice-versa.

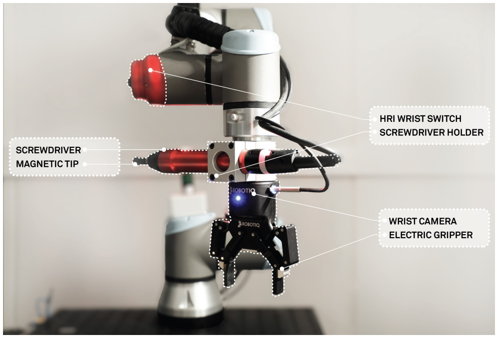
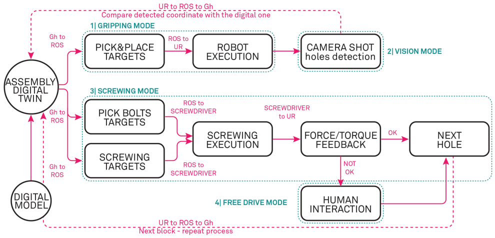


Figure 2
Multi-phase end effector

Figure 3
Cyber-physical workflow for adaptive reconfigurable construction

struction process is updated in response to this feedback. Finally, the robot and screwdriver controllers make possible the execution of the robot procedures and the communication of the inquired construction feedback back to ROS (Fig. 3).



Cyber-physical communication

The computational design environment of Grasshopper for Rhinoceros is used as the central planning and communication tool, where the data of both the physical construction setup and digital design are stored. A cyber-physical system is established based on a closed-loop, feedback-driven communication between the two domains to coordinate the digital and physical worlds and allow for their reciprocal dependencies.

The overall design-to-construction process is based on the information exchange between the three bodies: (1) Grasshopper, (2) Robot Operating System (ROS), and (3) the controllers of the two UR robots and the screwdriver. In the Grasshopper environment, the procedures for iterative design, robotic simulation, and generation of the robot targets are developed and communicated further to ROS through the Bengesht plug-in (Bengesht). These include the pick, place, and travel targets related to manipulating the blocks, the pick/unscrew, insert and travel targets related to the steel bolts, and the hole/bolt detection targets. The automated programs for screwing/unscrewing and hole/bolt detection are developed as robot skills in the ROS environment. Furthermore, the feedback received from the physical setup is managed through ROS, and the construction process is updated in response to this feedback.

Two types of feedback are inquired from the physical domain: (i) visual feedback from the wrist camera about the holes and bolts coordinates in the as-built construction; (ii) force/torque feedback from the screwdriver during the screwing and unscrewing operations. The new coordinates of the holes and bolts are sent back from ROS to Grasshopper, and the digital model is updated to facilitate further stages of disassembly and re-assembly. On the other hand, the force and torque feedback from the screwdriver is controlled only by ROS. This is used to understand if the bolt is inserted or removed correctly and call human assistance if the execution fails. The human interaction is well integrated into the digital workflow through the collaborative wrist switch, and its involvement does not interrupt the process but allows for its seamless continuation.

Construction system for robotic re-assembly

The developed assembly system is an evolutive step from the authors' previous works (Naboni et al. 2021). It is based on a generic set of discrete blocks that allow for reconfigurability and flexibility of the structural layout. These are intended to aggregate orthogonally with each other, and with differential density, as enabled by the connectivity patterns and the layout of the holes. The blocks are designed with pyramidal morphological features (Fig.4a), which facilitate the process of layered robotic assembly and disassembly in multiple ways:

- *Mounting precision*. The male-female interlock between two consecutive layers guides the robotic positioning, as the blocks tend to snap geometrically into the intended position (Fig.4b). This creates an intrinsic interdependency between the blocks that minimizes typical construction tolerances;

- *Rotational Locking*. In each connection slot are present three-dimensional pyramid-like geometries. These are used to prevent the blocks from spinning around the bolt axis or slightly rotating out of place during the screwing process.

- *Improved shear resistance and moment capacity*. As discovered in the authors' previous work, the developed features provide stiffness to the bolted connection and enhance the ductile behavior of the assembled blocks under applied loads. This significantly contributes to the reusability of the blocks.

- *Minimized fabrication toolpath*. The material wasted in the process of robotic milling is minimized to what is necessary to obtain a connection feature that would perform as desired mechanically and assembly-wise. The milling toolpath is programmed using a single round tool that moves along parallel contouring trajectories (Fig.4c). Both sides of the block are milled in a single robot program. In this way, there is no need for tool changing and additional operations, increasing the machining time.

The blocks are intended to aggregate orthogonally with each other with differential density, as enabled by the connectivity patterns and the layout of the holes.

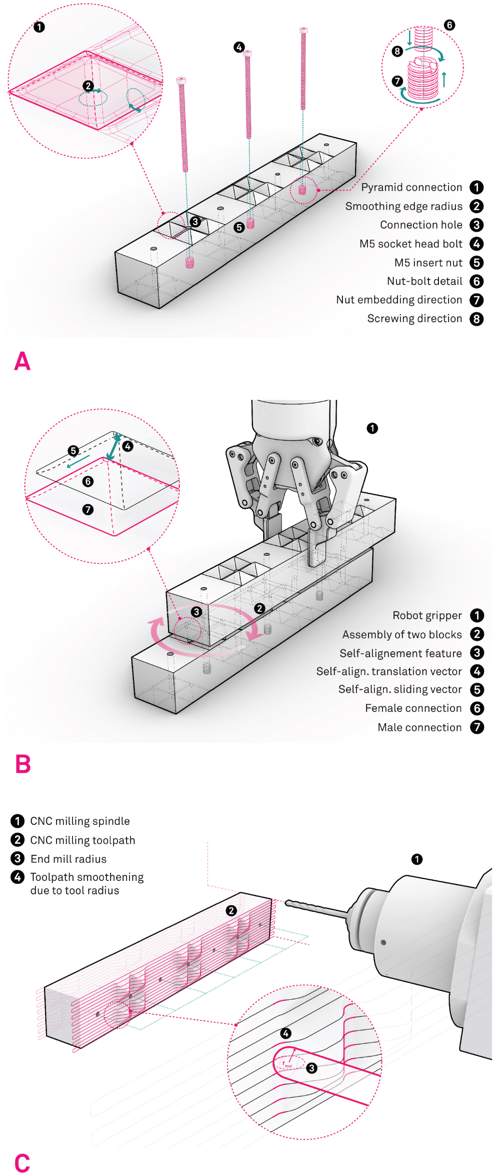


Figure 4
Performative features of the construction system

Robotic assembly / re-assembly experiment

The cyber-physical construction framework presented in this work is tested and evaluated on five experimental prototypes. The prototypes consist of twelve generic construction blocks which are aggregated in different randomly generated layouts, assembled through a layered sequence. The design, assembly, and disassembly procedures are performed through an adaptive and feedback-based construction process which operates as a bi-directional communication between the design environment and the real-time construction execution.

Assembly and Dis-assembly. The assembly sequence and commands are planned directly from the design model, simulated, and communicated to the robots. These involve the (1) picking and placing of the timber elements, (2) detection of the holes where the blocks are connected, and (3) the screwing procedures. Similarly, the disassembly process is based on scanning the pre-assembled structure, the robotic unscrewing, extracting the timber elements, and repositioning into a new layout, which is defined as re-assembly. These actions are performed in the following sequence to construct five consecutive prototypes:

Phase 01 - Robot 1 takes the blocks from the block positioners in the cell and executes the assembly steps previously described, i.e., pick and place, hole detection, screwing (Fig.5-A 1-2-3) to complete a structure.

Phase 02 - After this is completed, Robot 2 performs the disassembly of the structure, following defined steps, i.e., bolt detection on the assembled configuration, unscrewing, and releasing the bolts into the bolt-release mini gripper, pick and re-place of the blocks (Fig.5-B 1-2-3). The placing targets of the previous assembly cycle become the picking targets of the new dis-assembly cycle.

Phase 03 - The blocks are then re-assembled into a new structure, following the assembly sequence steps again.

The three phases are repeated to obtain five different prototype structures.

Hole Detection. The holes and bolts are detected through the Robotiq wrist camera, attached directly to the robot flange. The detection is based on: (1) the isolation of the hole or bolts through Morphological Image Processing methods, namely Dilation and Erosion (Efford 2000), (2) the hole detection through contour-based object detection method (Schlect and Bjorn 2011), and the (3) transformation of the pixel information to the real-world coordinates

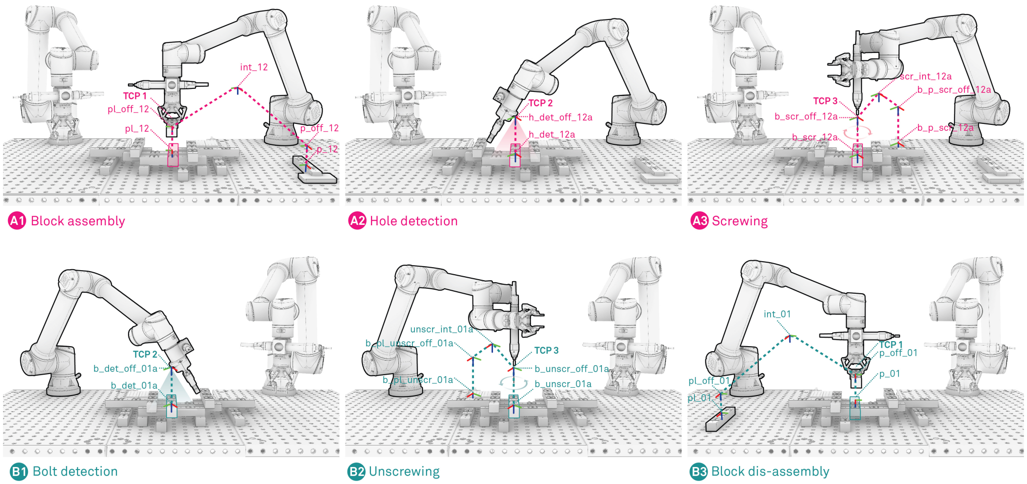


Figure 5
Toolpath planning and sequences for the assembly (A) and disassembly (B) of the timber blocks

of the hole by homography (Negahdaripour et al. 2005). Once the hole coordinates are detected, they are compared to the digital information, and an effective offset is calculated (Fig.6). This is further used as a new coordinate for the screwdriver, and the digital model is updated accordingly.

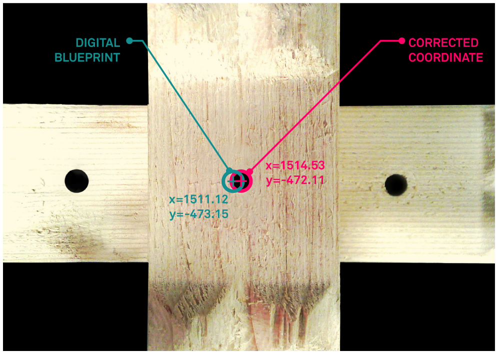


Figure 6
Hole detection from the wrist camera

Robotic Screwing and Unscrewing. The screwing and unscrewing processes are defined as robot skills inside ROS. The procedure is based on two principal flows, one which detects the hole and ensures its position is available for later use, and the second one which aligns the screwdriver with the detected hole. To understand if the screwing and unscrewing are performed correctly, force and torque values are monitored from the screwdriver controller. In case of failure, the robot automatically switches to the free-drive mode and allows an operator to assist the robot by dragging the tool to the corrected position. After this, a wrist switch button is used to resume the robot process without discontinuing communication between the physical and digital worlds.

RESULTS

Extending previous research from the authors, a novel process for collaborative robotic assembly, disassembly, and re-assembly based on a cyber-physical setup was developed and tested. The system successfully operates on different assemblies, five of which are presented in this paper as physical prototypes (Fig.9). Vision- and force-based feedback were successfully implemented to overcome typical assembly challenges due to unexpected physical changes, such as tolerances and material imperfections. Furthermore, human assistance was used as a secondary integrated level of target correction if the feedback-driven automatic execution failed to perform the tasks. This ensures a highly resilient system that is ready to adapt to various changes and conditions while keeping the level of automation high.

To facilitate the process of robotic assembly and at the same time assure advanced mechanical performance and reusability of the wooden blocks, a construction system with specific features was designed. Three-dimensional morphological features showed to be essential during the assembly processes, as the blocks were sliding in the correct position regardless of how the robot gripped them. They prevented the rotations and spinning of the blocks around the bolt axis while screwing was performed.

Both assembly and disassembly processes relied heavily on computer vision feedback and showed an average success rate of 88.7% and 83.8%, respectively. The disassembly procedure performance is sensitively inferior (Fig.7b) because of the more challenging camera detection task for the bolt socket head (3mm), in comparison to a 6mm wide free hole (Fig. 7a). The most common reason for needing human assistance is faulty hole/bolt detection due to wood knots or similar dark features that cause misleading vision. Therefore, the hole/bolt detection method will need further refinement to provide more robust performance.

Besides the minor flaws, the system is highly relevant and crucial to perform an autonomous robotic assembly and disassembly of discrete wood structures. The developed cyber-physical construction system was highly beneficial in realizing the presented prototypes. It was responsible for approximately 96% of the successfully performed assembly and disassembly operations - estimated with deviations higher than 3 mm, resulting in outside-the-hole projection (Fig.8).

Figure 7
Success rate of assembly and disassembly procedures

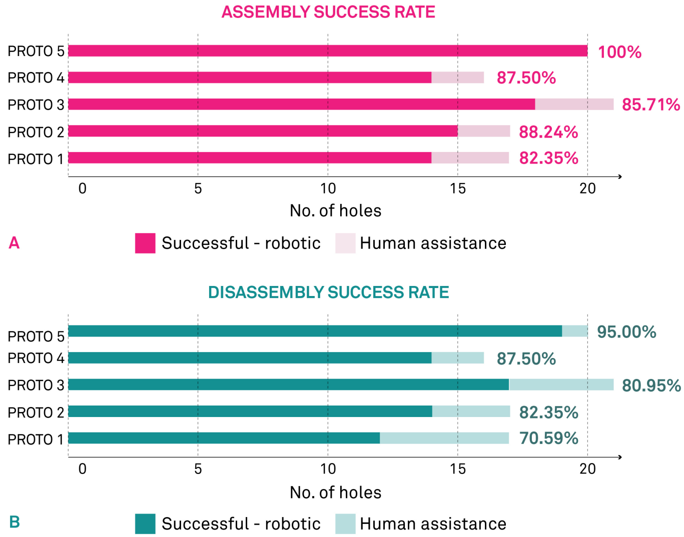


Figure 8
Distribution of deviation in the holes coordinates across the experiments

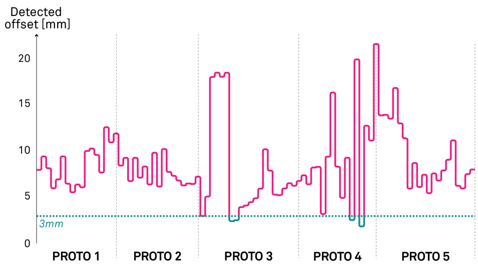
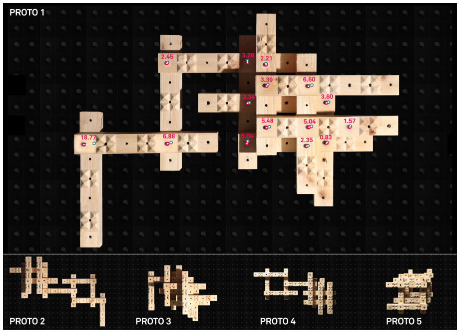


Figure 9
Three construction prototypes on which robotic collaborative assembly, dis-assembly and re-assembly were tested



CONCLUSIONS AND DISCUSSION

Circularity is a priority topic within the contemporary architectural agenda. A radical rethinking of the design and construction processes is required to achieve such an aim. Architectural robotics plays an important role in this, by providing instruments and workflows for the automation of circular construction. The joint application of design computing and a cyber-physical system of this research opens opportunities for easily reconfigurable wood structures. The presented research contributed in this sense by introducing a robot setup and an online process that performs complex assembly, and for the first time disassembly and re-assembly tasks, autonomously. The impact of such a demonstration is bifold. On the one hand, robots are measurably upskilled to take into account intrinsic material complexity during assembly processes, overcoming typically found assembly limitations. On the other hand, robots begin to acquire the capacity of intervening on existing structures, offering perspectives for future automation of building and structural reconfiguration and repurposing.

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REFERENCES

Efford, N (eds) 2000, *Digital Image Processing: A Practical Introduction Using JavaTM*, Pearson Education

Jensen, GK and Sommer, J (eds) 2018, *Building a Circular Future, 3rd Edition*, 3XN Architects, Denmark

Kunic, A, Naboni, R, Kramberger, A and Schlette, C 2021, 'Design and assembly automation of the Robotic Reversible Timber Beam', *Automation in Construction*, 123, p. 103531

Leder, S, Weber, R, Wood, D, Bucklin, O and Menges, A 2019 'Distributed Robotic Timber Construction', *Proceedings of ACADIA 2019: Ubiquity and autonomy*, Austin, Texas, pp. 510-519

Naboni, R and Kunic, A 2019 'A computational framework for the design and robotic manufacturing of complex wood structures', *Proceedings of eCAADe and SIGraDi 2019*, Porto, Portugal, pp. 189-196

Naboni, R, Kunic, A, Kramberger, A and Schlette, C 2021, 'Design, simulation and robotic assembly of reversible timber structures', *Construction Robotics*, 5, pp. 13-22

Negahdaripour, S, Prados, R and Garcia, R 2005 'Planar homography: accuracy analysis and applications', *IEEE International Conference on Image Processing 2005*, Genova, Italy

Retsin, G (eds) 2019, *Discrete: Reappraising the Digital in Architecture*, AD, Architectural Design

Retsin, G, Garcia, MJ and Soler, V 2017, 'Discrete computation for Additive Manufacturing', in Menges, A, Sheil, B, Glynn, R and Skavara, M (eds) 2017, *Fabricate*, UCL Press, pp. 178-183

Sack-Nielsen, T (eds) 2018, *Circularity City — Shaping Our Urban Future, 1st Edition*, Circularity City, Denmark

Sanchez, J 2019, 'Architecture for the Commons. Participatory Systems in the Age of Platforms.', in Retsin, G (eds) 2019, *Discrete. Reappraising the digital in Architecture*, AD, Architectural Design , pp. 22-29

Schlecht, J and Ommer, B 2011 'Contour-based object detection', *Proceedings of the British Machine Vision Conference*, pp. 50.1-50.9

Tedbury, I 2019, 'Semblr, 2017', in Retsin, G, Jimenez, M, Claypool, M and Soler, V (eds) 2019, *Robotic Building. Architecture in the Age of Automation*, DETAIL, pp. 84-85

[1] https://studiorap.nl/#/abnamro

[2] https://www.food4rhino.com/app/bengesht

[3] https://vimeo.com/304108480