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Design and simulation of an automated robotic machining cell for cross-laminated timber panels

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Abstract

Cross-laminated timber (CLT) is an innovative construction material that has brought advantages over traditional wood structures, reducing cost and lead time of buildings in recent years; yet CLT benefits primarily from offsite construction methods instead of automation or safety, while keeping the human onsite. The few advancements in automation for CLT panels have been in the implementation of dedicated CNC machines. Nevertheless, using CNC machines for machining CLT panels have disadvantages like clamping batches of massive panels with individual profiles, lacking the flexibility to access all acute machining angles, and struggling with the extraction of dust while the cutting spindle moves through large tight spaces. These disadvantages can be overcome with industrial robots' help, which the construction industry has not been traditionally favorable on their application, giving then the research gap in this study. This paper explores the introduction of a robotic cell for the machining of cross-laminated timber panels. The robotic cell is designed using 3D modeling and validated through motion simulation in a virtual environment. The proposed cell design is based on a minimum viable product and compared against a minimum throughput benchmarked on the Canadian market. This study aims to research the feasibility of CLT's automated machining by providing clear production characteristics of the designed robotic cell, such as material and tool utilization rates, lead time, or production efficiency.

Keywords: automation in construction; industrial design; offsite construction; cross-laminated timber; robotic simulation

1. Introduction

Cross-laminated timber (CLT) is an innovative construction material that has been arising in the last decades due to its advantages over traditional wood structures. CLT improves in cost and lead time on wooden building constructions; and has a lower environmental footprint, which is critical for construction to become more sustainable (currently providing 30% of the global annual greenhouse gas emissions and consumes up to 40% of the total energy [1]). Additionally, CLT is becoming a more popular construction material than concrete and steel based in the increase demand since 2010 [2]. CLT demand is estimated above one million cubic meters in 2018, implying that CLT-based projects are entering into mass production [3].

Such timber panels are manufacturing processed on different steps, lumber selection, flattening, adhesive application, and others [4]. Machining and cutting processes are crucial on the process because they define the panel’s shape. Architects desire to design buildings with more complex shapes, such as freeform structures, but these buildings cannot be developed without mechanical joints [5]. This joint type allows a degree of freedom for self-locking mechanism and builds rigid structures without excessive reinforcements. Still, machining interlocking joints requires more acute angles, requiring machines with 5-axis instead of current conventional 3-axis machines [6]. Nevertheless, using

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5-axis machines for CLT generates some problems: cutting spindle needs to move through large acute spaces, making dust extraction challenging; even with the additional axis, custom tools are required to achieve the prismatic geometry, and the clamping systems is difficult for large batches of individual plated, reducing the cutting velocity and quality [6]. Quality and productivity are selling points for offsite construction, and improved systems are needed to overcome the costumer bias against prefabricated components [7,8] .

Subsequently, the introduction of a robotic solution to CLT machining can overcome the challenges reported thanks to their great flexibility, adaptability, and accuracy. However, as shown in state of the art, there is no development in the academic literature of robotic machining cells for full-sized cross-laminated timber panels, being this the research gap to expand in this paper. Therefore, in this study, an automatic robotic cell for machining CLT panels is developed in a digital factory environment and simulated to validate its performance.

2. State of the art

The tasks robots usually perform for the wood manufacturing industry are of low accuracy; for instance, varnishing, and palletization [9]; and according to previous studies, barely 0.2% of all worldwide industrial robots are used for woodworking processes [10]. However, it is more often seen as the natural replacement of computer numerically controlled (CNC) machines. With the novel collaborative generation of robots, this trend is expected to continue, as they provide benefits like reduced product cost or better work-cell flexibility. It is important to mention the additional degrees of freedom an industrial robot provides, especially when contrasting against conventional CNC machines where increasing a degree of freedom is extremely costly [11].

There are studies about the forces a robot handle in the process of machining wood. On one side, Ayari et al. analyzed the machining behavior of cutting tools on hardwood and medium-density fiberboard (MDF) with a KUKA® Kr 210 L 180 [9]. The authors found a force of 69.94 N for beech and 38.7 N for MDF with an accuracy variation of 0.8 % and 0.6% respectively. Besides, Klimchik et al. did extensive research on families of KUKA®'s models, getting results showing an accuracy of 0.57 mm while sustaining a cutting force of 2000N for the robot KUKA® KR500 [11].

Contrary to steel and aluminum, machining wood is not as widely common researched problem, and it is considered a soft material in comparison; yet wood is different from other components because it is grown naturally and has different consistencies (soft, hard, or composite wood) and most of the knowledge in the woodworking sections comes from skilled craftsmen. Different authors have studied parameters as feed rate, spindle speed, and stepdown because an incorrect configuration will leave a poor-quality surface, generate chips, and cutting marks [12]. Krimpenis et al. optimized alder wood's surface quality for a musical instrument, where smooth surfaces and low roughness are critical [13]. The authors used genetic algorithms for this application; thus, a feed rate of 669 mm/min, a stepdown of 5.8 mm, and a spindle speed of 24,000 rpm gives the best surface quality [13]. Diversely, other researchers have taken a stochastic approach with the usage of the design of experiments to optimize machining parameters. Hazir et al. and Koc et al. ran studies with wood present on the furniture industry [10,11]. They obtained the following parameters as best: feed rate of 2 m/min, spindle speed of 18,000 rpm, and stepdown of 2 mm.

Efforts of automated machining robots for woodworking processes can be found in the literature, mostly covering off-site construction and pre-fabrication [14,15,16]. Nicolescu et al. presented a virtual robotic framework station for machining wood panel doors [17]. This station is equipped with an ABB® IRB 2600 robot, an ABB® IRBPK300/1000 workpiece positioner, and a stand for multiple tools, where the functionality of the robotic station is validated through a simulation on Catia® DMU Kinematics.

On the other side, Wagner et al. developed an in-site flexible robotic timber construction platform (TIM) equipped with functions of assembling, gluing, nailing, and machining [18]. TIM platform is dedicated to manufacturing "cassettes", hollow timber structures with individual shapes, which are assembled like a puzzle. With this in-site robotic platform, the construction time is improved because there is no waste translating the cassettes from the supplier, and any error can be fixed on-site. Moreover, the robotic platform has an average milling time of 15 minutes per operation, and it was capable of machining with a deviation of less than 0.5 mm against the ideal model, a critical feature for assembly of the BUGA pavilion building. The cases above prove the feasibility of robotic automation on wood machining processes and the advance they can represent from a performance perspective. Nevertheless, the surface quality required in construction is not as strict as for the final finishing, meaning that rough machining can be considered for similar robotic stations. Thus, a feed rate of 150 mm/s and a maximum 100 mm of stepdown for the point milling tool can be implemented accordingly to the guidelines [12].

The next step of the paper is to design the robotic station. For this objective, the methodology STCR-TMS is used. STCR-TMS ease the implementation of robots in the construction industry and formalize the development of the robotic cell. Some of the methodology's advantages are the issues included, like considering the know-how of stakeholders, best practices in the industry, and looks for a cost-effective approach to the design [19].

3. Robotic cell design methodology

This study focuses on developing a virtual automated robotic machining cell for cross-laminated timber panels with the methodology STCR-TMS (single-task construction robots – technology management system) [19]. Fig. 1 shows an overview of this methodology's layers and phases, where the first three layers belong to engineering and management systems, and the last layer are stand-alone elements. Similar to the Deming Cycle, STCR-TMS consists of iterative design cycles with four layers and four main design phases: requirement engineering, development sequence, implementation and prototyping, and performance evaluation.

The development of the robotic cell in this article covers only the first layer. Some elements as manufacturing, integration with current infrastructure, business model, economic performance are not included at the moment due to physical and time limitations but will be pursued in the future.

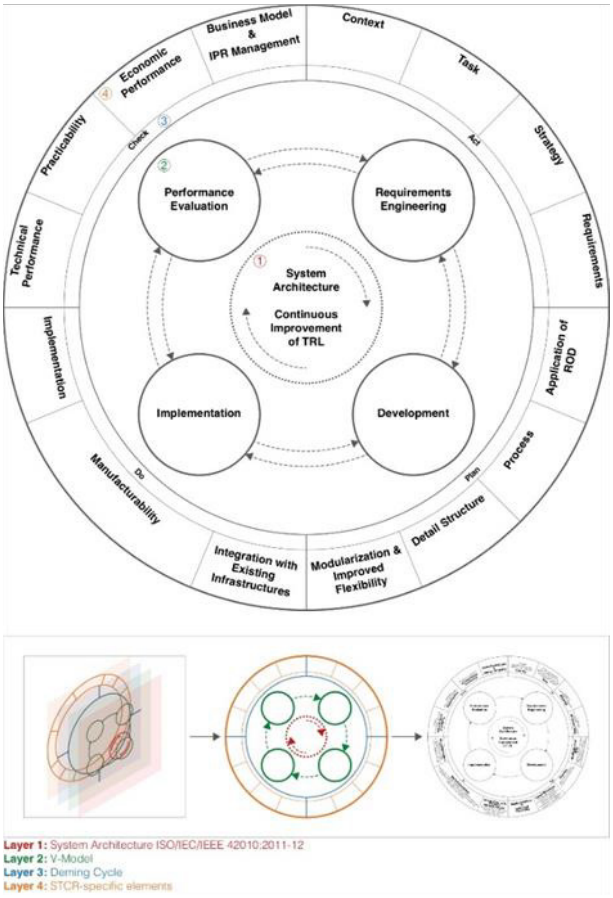

Fig. 1. Visual representation of STCR-TMS methodology. Picture used with the granted permission of the authors [19]

3.1. Requirements engineering

3.1.1. Context & Task

As stated from the literature review, robotic applications for machining of cross-laminated timber panels have an incredible potential to increase productivity, quality, and flexibility to the industry. For these reasons, a robotic cell is targeted to be designed in this paper. In this cell, the task of the robots is to remove the necessary material to shape the stock sized CLT panel as designed. Different tools, like saws and rough end mills, are used due to different geometrical shapes for windows or doors, and additional features proper to CLT building techniques.

3.1.2. Strategy & Requirements

From a business perspective point, the system must be able to cover a wide array of dimensions of CLT panels. As mass customization becomes a must in the offsite construction industry, this flexibility of design is hence required. Therefore, the automated robotic cell must cover two main requirements: 1) support the required cutting forces (minimum of 2000 N [11]); 2) adjust to the CLT panels characteristics (height = 2.5 – 3 m; thickness = 0.25 – 0.5 m; length = 10 – 18 m; density = 500 kg/m^3).

3.2. Development sequence

3.2.1. Application of robotic-orientated design

Given the**se** requirements, the industrial robot ABB® IRB 7600 is selected (see Table 1). Furthermore, a stand-alone robot cannot cover the length variation of the timber panels. Subsequently, the use of a track system to displace the robots along the work piece is necessary. For this, the track motion ABB® IRBT 7004 (see Table 1) is used due to its travel length up to 19.7 meters.

Table 1. Technical parameters for the ABB® IRB 7600 & IRBT 7004.

ABB® IRB 7600		ABB® IRBT 7004
Payload: 500 kg	Axis 1: ± 180°	Length: 1.7-19.7 m
Number of axis: 6	Axis 2: +85°/ -60°	Pos. time:1.7 sec @1 m 5 sec @5 m
Repeatability: ± 0.3 mm	Axis 3: + 60°/-180°	Acceleration: 1.8 m/s^2
Ctrl.: IRC5	Axis 4: ± 300°	Speed: 1.2 m/s
Weight: 2400 kg	Axis 5: ± 100°	
	Axis 6: ± 360°	

Now, CLT panels are of high density and the weight of the one working part can go up to 13.5 ton. Such load is unthinkable for an industrial robot. This rigorous requirement sets the need of an independent system to handle and clamp the working piece, leaving the robots alone for the machining operation.

3.2.2. Processes

The loading and unloading of the work piece to the designed robotic cell is not included in the scope of this article. It is assumed that conventional cranes can handle this part of the process. Then, once the system is loaded with stock, the independent system positions itself into an initial state and clamp the panel. With the working piece fixed, the robots take the tool required and start the machining process. The cutting patterns to be followed are pre-set based on the final panel design. The cutting process starts from inside-out and from the left to the right. Only once the robot finishes all the scheduled machining with the current tool, it changes to the next one. This iterative routine continues with the machining process until it completes all the cutting layouts. It is important to mention that the independent clamping system needs to be able to move to give access for all areas of the panel while machining. The desirable outcome is to avoid any interference and have flexibility for all kinds of panel designs and cutting layouts.

3.2.3. Detailed Structure

The robotic cell then consists of two robot arms mounted on the track motion rails and the independent system. All the components in the machining cell are placed directly on the floor to minimize installation costs. The CLT panel is then placed in a horizontal position, supported by the independent system (hereafter referred to as flexible clamping system, shown in Fig. 2). This clamping system is designed with a stochastic methodology from the industry, see Fig. 3, where the first step is to consider the design requirements and limitations. From this step, a "C" shape is selected to clamp the working piece due to its prismatic pattern.

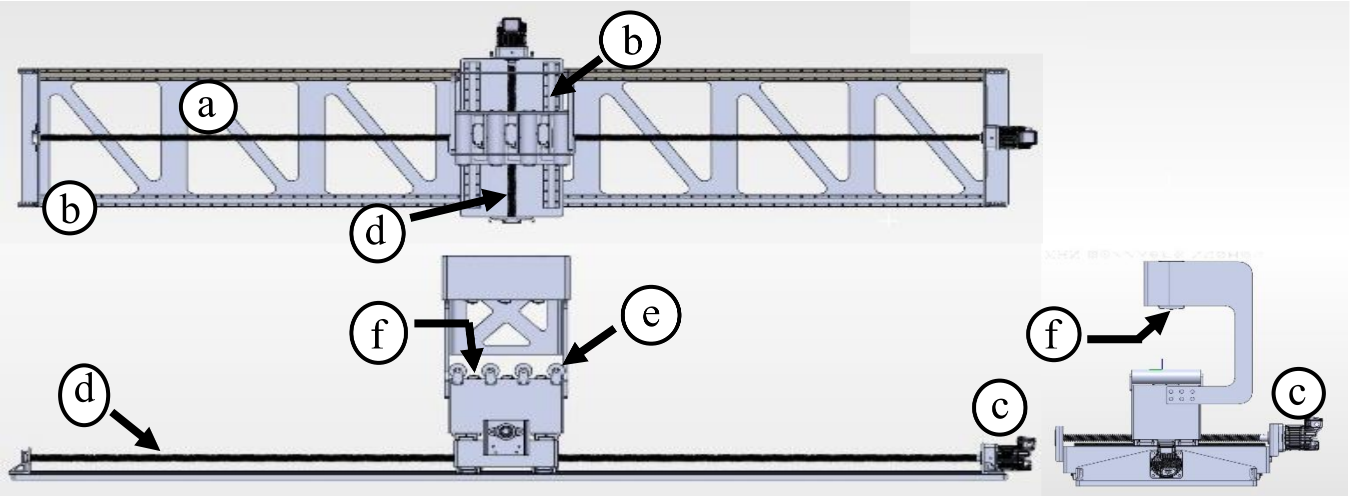

Fig. 2. Flexible clamping station: (a) Steel plate; (b) Wide ball bearing carriage and rail; (c) Servomotor CPM-MCVC-D1003P-RLN; (d) Worm gear; (e) Industrial polymer rolls; (f) Pneumatic cylinder SMC HYG50TFR-20

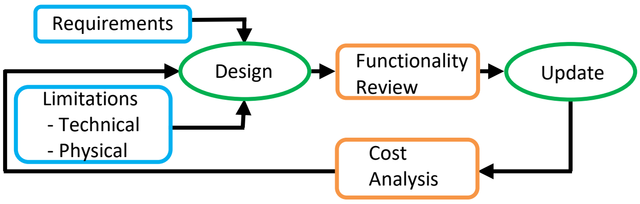

Fig. 3. Applied stochastic design methodology.

Additionally, industrial polymer rolls are considered in the panel's bottom contact to keep a degree of freedom, and six pneumatic cylinders are incorporated as the holding mechanisms. Then, checking the system's functionality, it is decided to split the mechanism into two sections to control the position in both axis, "X" and "Y." Similar to CNC machines, it is thought to control the displacement of the clamping system with servomotors and worm gears. Four linear bearing carriages and rails with a load capacity of 14,000 lbs. each is included per axis.

Moreover, thinking about the cost impact of the design, it is decided to limit the system to 6 meters of length, helping in the next phase's modularization. This flexible clamping system levels up the panel to an appropriate height that eases robot pathing and allows both robots to move along and across the working piece. The degrees of freedom are critical due to the high variation on the panel layouts. They will allow the robots to have access to all the machining features without interference concerns.

3.3. Modularization and flexibilization

The entire automated robotic machining cell is designed with modularization and flexibilization in mind. An overview of the proposed robotic cell is shown in Fig. 4. The robots are placed side to side on top of the track motion system enabling them to reach all the areas of the work piece. This setup allows the robots to machine in parallel, reducing the production time. Three flexible clamping systems are placed per side, making entire station flexible enough to cover the variations on the cutting layouts. Finally, each robot has a tool stand next to the start of its rail, giving quick and easy access to all the tools required without interfering with the clamping system.

3.4. Implementation and prototyping

The circular saws, the end mill tool, tool stands, and the flexible clamping modules are initially designed in the computer-aided design software SolidWorks® 2019. Once finalized, they are imported into the simulation software ABB® RobotStudio 2020, where the industrial robots and track motion systems are already included on the ABB® library. This simulation software is chosen because it includes real representative data from each of their industrial robots, and the simulations run within this software end with realistic performance using the same controllers that would be used in the industrial setup. The robotic station is kept only as a digital factory due to physical limitations.

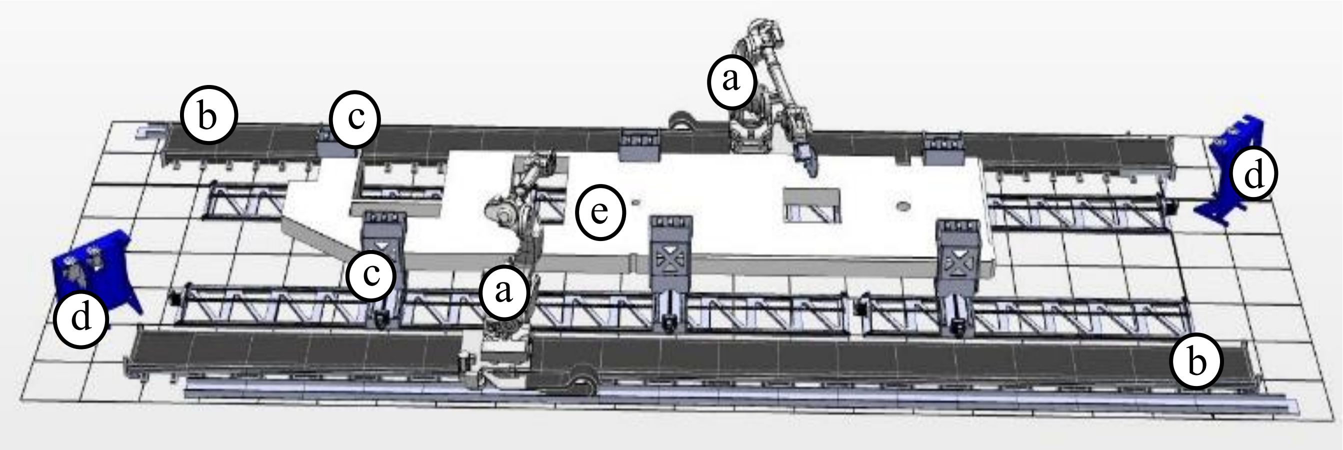

Fig. 4. Automated robotic machining cell for cross-laminated timber panels: (a) Robot ABB® IRB 7600; (b) Track motion ABB® IRBT 7004; (c) Flexible clamping System; (d) Tool stand; (e) Minimum viable product.

3.5. *Performance evaluation – Proof of concept*

To evaluate the feasibility of the proposed design, a simulation of the machining process for a CLT panel is implemented in RobotStudio®. This approach also enables the analysis of the performance of robotic machining cells for CLT panels. A CLT panel is designed that includes all kind of features found in most CLT panels, such as windows, doors, column anchors, and internal splines, among others. Such a panel is considered the minimum viable product for the robotic cell. Fig. 5 shows the manufacturing drawing with the cutting pattern for this panel. The simulation results and performance metrics obtained are presented and discussed in the following section.

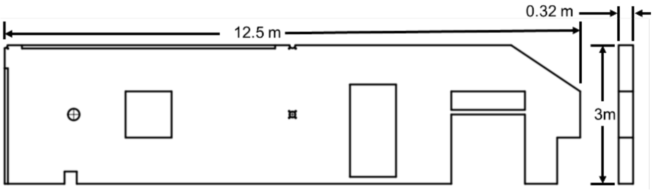

Fig. 5. Minimum viable product CLT panels.

4. Results and discussion

The proposed robotic machining cell for CLT panels timbers is fully simulated in RobotStudio®. The resulting cycle time required to finish the panel is 18 minutes and 20 seconds with an estimated a production rate of 22 sq. ft/min. Additionally, a lean mapping with value and non-value-added activities are discussed to showcase the efficiency of the design proposed. The value-added time is robots are performing machining operations on the panel, while non-value-added activities are any other tasks during the process, like changing tools or positional movements. Analyzing the simulation results, the proposed station has an efficiency of 83.3% from a LEAN perspective, see Fig. 6.

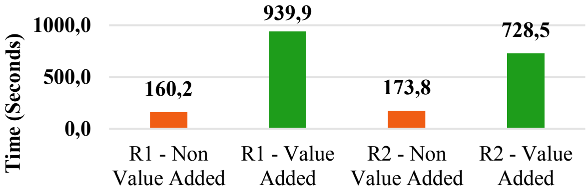

Fig. 6. Lean analysis over robotic cell operations.

Another metric to be considered showcasing the performance and behavior of the robotic cell is the total utilization of the tools. This is especially important to understand the maintenance needs of such a system. Based on the usage of each tool during the entirety of the machining process, the utilization graph is shown in Fig. 7. It can be observed that the milling tools are the most used. as milling covers more than 81.9% of the time in each robot. This might be explained due to the large amount of construction features required on CLT panels in column anchors and splines.

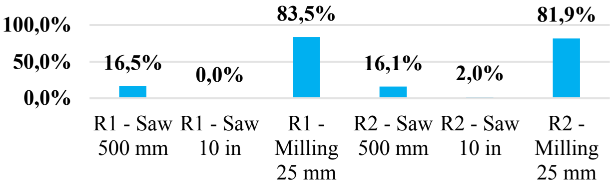

Fig. 7. Tool utilization per machining operation.

As future work, the physical validation of the automated robotic cell would be pursued. Following the virtual design proposed, a real prototype will be set up. Actual tolerances, the tool changer adapter, tool calibration, the tools' performance, surface finishing and other features are missing and can only be done with a physical system. CLT manufacturing is highly variable and finding the machining recipe and the limits for machining parameters is essential in the construction industry. For these reasons, implementing a pilot would be highly recommended before considering this work as a final production process.

5. Conclusions

Following the great capabilities of robotic cells for wood machining, this study proposes a fully automated robotic cell for the machining of CLT panels. Following the STCR-TMS methodology for the design of single robotic cells, a flexible and competitive solution is presented. The design is then simulated for validation purposes with a complex CLT panel that contains all the possible features that can be encountered during CLT machining processes. With the simulation in place, it was found that the robotic machining cell has a cycle time of 18 minutes and 20 seconds, a production rate of 22.02 sq. ft/min, and efficiency of over 83.3% from a lean perspective, and a high utilization of the end mill tool, over 81.9%.

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