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Robotic Cell Design and Simulation System for Cross-Laminated Timber Panel Post-Construction Operations

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Abstract: Mass timber, especially cross-laminated timber (CLT), is a sustainable and environmentally friendly construction material, that is attracting the attention of architects and engineers. Construction 4.0 is transforming the construction industry by integrating offsite methods and advanced technologies such as robotics and virtual simulation environments. Despite the current automation and use of machinery such as CNCs in construction sites, limitations arise due to the variability of construction projects. To address the gap in the precise cutting of CLT panels in the rapid offsite construction environment, this research explores the design process of a multi-robot cell using scaled components that mimic real-world construction scenarios within a controlled laboratory environment. To further ensure the efficacy of the design, this paper presents 3D models and simulations using © 2024 RoboDK software to validate the motion of the robotic cell in a virtual environment. Presented In this paper are the specifications of robotic cell development, along with a detailed analysis of the execution time the developed cell would take for real-time panel cutting.

Keywords: Robotic cell; Construction 4.0; Automation; Simulation; Mass Timber Construction

1 INTRODUCTION

Mass timber (MT) is a sustainable and environmentally friendly material that is increasingly used in the construction industry. MT construction is characterized by large pre-assembled panels and members. In 2020, the production of wood in Canada contributed 6% to the country's earnings, totaling CAD $653 billion (Paskoff, Boton, and Blanchet 2023). The conventional construction approach prevalent in North America involves the on-site assembly of wood frames, a process susceptible to errors due to human involvement, leading to variability and delays. Additionally, inclement weather conditions can further disrupt construction timelines. In contrast, offsite construction methods have emerged as a proven strategy to enhance productivity by prefabricating partial wood frames in dedicated facilities, with final assembly completed at the construction site. This approach significantly improves construction quality and efficiency (Villanueva, Martinez, and Ahmad 2024).

Particularly, Cross-Laminated Timber (CLT) stands as a beacon of sustainability and innovation (Villanueva, Martinez, and Ahmad 2024). CLT is attracting a lot of attention due to the increasing demand since 2010 (Villanueva et al. 2021) seeing that its first appearance the industry has considered it one of the best sustainable materials (Martinez Villanueva, Cardenas Castañeda, and Ahmad 2022). CLT panels are composed of multiple layers of solid lumber with alternating grain orientations bonded together with adhesive, offering remarkable strength to withstand substantial vertical loads despite their lightweight nature. Additionally, the unique properties of CLT enable architects, engineers, and developers to explore innovative building designs (Villanueva, Martinez, and Ahmad 2024).

Introducing robotic systems into CLT machining can provide significant advantages due to their flexibility and adaptability, effectively addressing the challenges previously mentioned. Furthermore, with innovative buildings featuring complex forms that require systems with mechanical joints, there's a need for more acute angles and machines with more than 3 axes. Having fewer axes limits the machine's mobility across large spaces and necessitates tool changes to fabricate prismatic geometry. Increasing the number of axes enhances productivity and quality allowing for batch processing (Villanueva et al. 2021). The construction 4.0 is undergoing a transformative phase with the integration of offsite methods and advanced technologies such as robotics and virtual simulation environments.

Through offsite construction, wall frames are prefabricated in a controlled factory environment before being transported to the construction site (An et al. 2020) to be later assembled on-site (Paskoff, Boton, and Blanchet 2023), providing a cost-effective solution (Ali et al. 2021). Panelization of buildings produced in offsite construction factories allows for the modularization of walls, roofs, and floors within a controlled manufacturing environment (Malik et al. 2021). This construction methodology significantly increases productivity, quality, product deliverability (An et al. 2020), sustainability, and labor safety (Malik, Ahmad, and Al-Hussein 2019). The traditional methods currently employed in the construction sector may not necessarily meet the demands for efficiency, productivity, and sustainability (Momeni et al. 2022); simultaneously, there is a pressing need to improve worker safety, as the diverse tasks they undertake pose potential health risks (Firth et al. 2022). Hence, the utilization of robots is considered a key innovation point in the construction industry (Momeni et al. 2022); thanks to their potential to perform repetitive tasks, they can reduce manual labor and enhance efficiency (You, Zhou, and Ding 2023), reducing the time required to complete a certain task (Chen et al. 2024). However, despite the benefits that robots could offer, the potential scenarios for their use in the construction sector have not been thoroughly and systematically explored. This is because robotics in the construction sector is not yet well-established due to limited experience in its usage and the lack of robust data from previous projects and applications (Momeni et al. 2022).

To address the gap in the precise cutting of CLT panels in the rapid offsite construction environment, this research explores the design process of a robotic cell using scaled components that mimic real-world construction scenarios within a controlled laboratory environment. This paper presents 3D models and simulations using © 2024 RoboDK software to validate the motion of the robotic cell in a virtual environment, ensuring the efficacy of the design. This study comprehensively explains the specifications of robotic cell development, along with a detailed analysis of the execution time the developed cell takes for real-time panel cutting. This research is novel because it is the first to explore the prefabrication of CLT panels by integrating two ©2024 Universal Robots A/S UR20, configured to operate simultaneously on a single CLT panel. The innovative approach includes a rail-based mobility system facilitating continuous movement and positioning within the working environment. This dual-robot, rail-guided configuration not only enhances the cutting process but also significantly improves overall precision and efficiency in Mass Timber CLT panel fabrication. Unlike other studies, this research uniquely combines dual-robot integration and advanced simulation to pioneer a comprehensive solution getting more experience in the field of construction automation.

The decision to employ parallel robotic functionality and rail-based mobility combines the accuracy of robotic arms with the flexibility afforded by rail-guided movement. It establishes an efficient workflow that addresses the unique demands of Mass Timber construction. Through an extensive series of simulation experiments, this study seeks to contribute essential insights to the ongoing discourse on the role of robotics in construction automation. The outcomes of our research are anticipated to illuminate new pathways for optimizing construction practices, marking a critical step towards a future where robotics serves as a foundation in reshaping and advancing traditional methodologies. As we navigate this exploration of innovation, we aim to pave the way for a construction landscape characterized by heightened efficiency, enhanced precision, and a renewed commitment to sustainable building practices.

2 State of the Art

The construction industry is undergoing a deep transformation, driven by the integration of advanced technologies, with robotics at the vanguard of this paradigm shift. Implementing robotics in processes offers users flexibility and simplifies what users aim to achieve through its utilization (Pires and Azar 2018). In the mid-2010s, significant strides were made in the implementation of robotic technology within the construction industry. Advanced systems leveraging robots are deployed worldwide, utilizing infrastructure production components and company networks to manage integrated systems that incorporate location design and industry-specific solutions (Linner et al. 2020). This is particularly crucial for small- and medium-sized enterprises (SMEs), which often possess limited human resources compared to larger corporations. Therefore, SMEs require thorough analysis from various angles regarding the challenges they face based on their business model and the adoption of new technologies such as robot integration. This is paramount, considering that SMEs represent 99.8% of companies globally (Pires and Azar 2018).

Currently, robotic cells are crafted utilizing digital software, specifically computer-aided design (CAD) packages and sophisticated simulation environments capable of replicating both the kinematics and dynamics. Under these circumstances, simulation encompasses geometric aspects and emulates the setup using the precise version of the robot control software. These tools possess the capability to generate code that is fully executable on the robot controller (Pires and Azar 2018).

Despite the current automation and use of machinery such as Computer Numerically Controlled (CNC) machines in construction sites, limitations arise due to the variability of construction projects. Currently, it's common to see a CNC machine performing machining activities, although a robot could perform these tasks in a more flexible manner or at a lower cost. Additionally, it's important to highlight the significant advantage that robots provide with their additional degrees of freedom compared to CNC machines. Adding more degrees of freedom to CNC machines would result in a significant increase in cost for additional flexibility (Villanueva et al. 2021). (Orlowski 2020) based on his review paper delves into the evolution of timber-based wall prefabrication, highlighting its transition from merely structural elements to fully complete walls incorporating façade, windows, insulation, and weatherproofing. They emphasize the significant role of automation technology in advancing this process, allowing for the integration of various processes into premanufacturing, resulting in essentially ready-to-install prefabricated walls. In addition, the concept of multifunctional bridges as an alternative to multiple stations for adding elements to timber wall panels, thus streamlining production.

Reviewing the literature concerning the state-of-the-art in this approach, several research articles on robotic cells for machining in offsite construction were identified. (Momeni et al. 2022) have developed a system comprising three robotic arms attached to a gantry structure, positioned upside down and capable of movement along the x, y, and z axes. Each robotic arm, specifically ABB® IRB1200-7/0.7 industrial robots, contributes 6 degrees of freedom (DOF), resulting in 8 DOF for each gantry-robot system. With three such systems combined, the full setup boasts 24 DOF, which can be controlled independently.

Additionally, the delivery system for rebars in the production cell includes a cut-and-bend machine and a fixture. To test the proposed algorithms, the authors implemented them as a plugin in © Copyright Coppelia Robotics AG., using its regular API. The gantry structures and robots were modeled in the software previously mentioned, with the robots imported from CAD models of ABB® IRB1200-7/0.7 and integrated into the setup. This allows for the simulation and testing of the system's functionalities and algorithms.

On the other hand, (Pires and Azar 2018) have developed a robotic cell designed to accommodate a robot, specifically an ABB® IRB140. The robot is outfitted with a simple tool capable of following the contour of a workpiece, which can be interchanged with other depositions. The goal is to produce high-precision parts from standard or innovative materials using both additive and subtractive manufacturing techniques. In addition, An et al. (An et al. 2020) have introduced a vision-based real-time inspection system tailored for steel frame manufacturing. Their framework aims to enhance the accuracy of framed panels by comparing actual geometries with nominal ones derived from Building Information Modeling (BIM) data.

In this context, our research focuses on the innovative design and simulation of a cutting-edge robotic cell specifically adapted for the precision cutting of Mass Timber Cross-Laminated Timber (CLT) panels. The following studies focused specifically on robotic cells for wood machining in offsite construction. (Wagner et al. 2020) developed research on a platform called TIM. It is a versatile timber construction platform that can be seamlessly integrated into local factories, temporary production facilities near the site, or directly onto the construction site itself, enabling a range of robotic fabrication tasks. The platform consists of steel plates with generic patterns of threaded screw holes, facilitating the mounting of robots, profiles, and other hardware. At its core, TIM features two high-payload KUKA® KR 500 Fortec industrial arms, directly mounted at two opposing corners, along with a two-axis KUKA® DKP-400 positioner positioned centrally between them.

Furthermore, (Nicolescu et al. 2018) are developing a wood machining application that integrates robotics. Wood processing encompasses a wide range of operations, including cutting, de-barking, treatment, assembly, painting, and finishing. For this purpose, they have selected an ABB® IRB 2600 articulated arm industrial robot. They have chosen the TMA4 end-effector produced by ©Copyright 2024 Elte srl., a tool stands with seven tool positions and an ABB® IRBPK300/1000 workpiece positioner with two workstations. Workpieces are transported into the cell via a ©Bosch-Rexroth AG 2014-2024 TS5 roller conveyor and automatically loaded onto workstations by © Güdel Group AG 1954-2024 a GudelZP4 two-axis gantry robot using a vacuum gripper and clamped in place. Control of the ABB® IRB 2600 robot and the workpiece positioner is managed by an ABB® IRC5 controller.

Additionally, our research follows a similar approach (Villanueva et al. 2021) to create a virtual automated robotic machining cell for CLT panels using the STCR-TMS (Single-Task Construction Robots - Technology Management System) methodology. The robots in this cell are tasked with removing material to shape the CLT panels according to design specifications. For this purpose, the authors have chosen the ABB® IRB 7600 industrial robot, a track system the ABB® IRBT 7004 is utilized to move the robots along the workpiece. Additionally, it has a circular saw, end mill tools, tool stands, and flexible clamping modules designed using SolidWorks® 2019 CAD software. Once finalized, these components are imported into ABB® RobotStudio 2020 simulation software. As a result, it helped identify the value-added time in this context and Non-value-added activities.

The state-of-the-art robotic cells for wood machining within offsite construction showcase a dynamic landscape of innovation and adaptation. Researchers have explored diverse avenues, from developing versatile timber construction platforms. Key studies have emphasized the need for collaborative approaches, leveraging the capabilities of advanced robotics alongside traditional skillfulness to optimize fabrication processes. Notably, recent advancements have led to the creation of virtual automated robotic machining cells tailored specifically for Mass Timber, utilizing methodologies like STCR-TMS to enhance precision and efficiency. As we navigate this evolving terrain, it becomes increasingly evident that the convergence of robotics, simulation technologies, and interdisciplinary collaboration holds immense potential for revolutionizing the construction industry’s approach to offsite manufacturing.

3 Robotic Cell Design Methodology

This section delineates the methodology for addressing the precise cutting challenge of Cross-Laminated Timber (CLT) panels in the rapid offsite construction environment. At this point of the project, the focus primarily resides on requirements gathering and design, employing the waterfall methodology, to ensure meticulous planning and execution. Waterfall project management, also known as traditional project management, remains widely used in construction. It follows a linear progression, where each phase must be completed before moving to the next. While limiting concurrent tasks, it offers a clear definition of project goals and budgets, focuses attention on milestones, thorough quality checks, and ensures details aren’t overlooked as progress only advances when a stage is completed (Project Sight 2023).

The five phases of this methodology, illustrated in Figure 1, enable a concise and planned workflow. In the first *Requirements* phase, all necessary information is gathered to develop the project. Subsequently, in the second *Design* phase, the required system is developed based on each requirement and its feasibility. Once the system is ready, the three *Implementation* phase is executed to set the designed system in motion. This leads to phase four, where *Verification* ensures that each part of the design aligns with the requirements and entire system functions correctly. Finally, in the five *Maintenance* phase, the goal is to ensure that each part of the system operates correctly, optimally and undergoes continuous improvement.

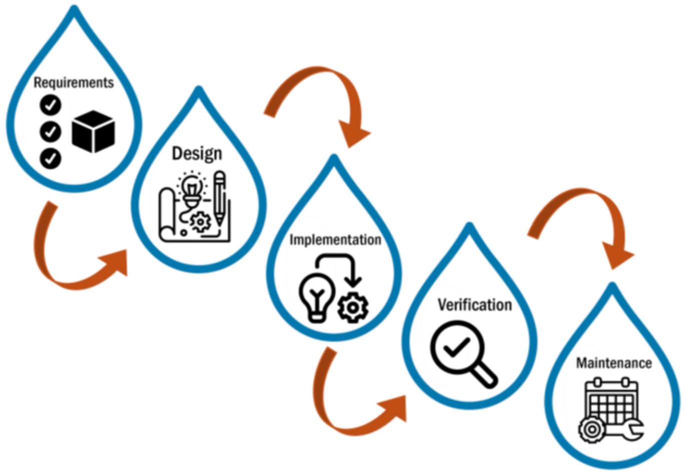

Figure 1. The waterfall methodology approach employed for the proposed robotics machining cell

The approach centers on developing a sophisticated robotic cell tailored to meet the unique demands of Mass Timber construction. Central to this system are two Universal Robots UR20, strategically configured to operate concurrently on a single CLT panel. Complementing this parallel robotic functionality is the integration of a rail-based mobility system, facilitating seamless movement and positioning within the operational environment. The rationale behind this dual-robot, rail-guided configuration lies in the fusion of robotic precision with the adaptability conferred by rail-guided mobility, thereby establishing an efficient workflow conducive to Mass Timber fabrication.

3.1 Requirements

The requirements for the engineering phase of the methodology (Linner et al. 2020) focuses on establishing a comprehensive understanding of the context and fundamental elements crucial for the development process. This involves analyzing the overarching context and industry trends related to the specific use case, streamlining the selection and decomposition of tasks pertinent to the robotic system, devising a business strategy, and delineating the stakeholder network. Additionally, it entails defining the system requirements and performance indicators essential for the effective functioning of the robotic manufacturing cell. This phase serves as the foundation for detailing the requirements of the manufacturing cell, ensuring alignment with organizational goals and stakeholder expectations while accounting for technological advancements and industry standards (Linner et al. 2020).

Furthermore, one of the facets of robotics that requires optimization is task management, which encompasses integrating motion planning within the context of the work cell, addressing technological process constraints, managing interfaces with external devices, and implementing automatic work cell calibration. Hence, it is evident that although crucial, existing robotic systems tend to address individual and specific requirements, lacking an optimal tool for designing a versatile robotic work cell (Tavares et al. 2020). The stiffness of the robot is also influenced by its location in Cartesian space or relative to the position of the workpiece. This technical consideration highlights the importance of understanding the robot’s spatial relationship to its surroundings and the workpiece for optimal performance (Iglesias, Sanchez, and Silva 2024).

Table *1* defines the requirements for the design and simulation of this robotic cell for CLT panel manufacturing. It is worth mentioning that these requirements are based on the objective of creating a controlled study environment for the use of robotic systems in the construction sector. One of the main challenges when implementing this technology in the construction industry is the variability of projects and the significant research gap in this area for the development of different areas. Thus, it represents an important developmental focal point for this system at scale.

Table 1. List of requirements for Robotics Cell

Context and Fundamental Elements	**Selection and Decomposition of Tasks**	**Business Strategy**	**System Requirements and Performance Indicators**
The primary objective of this robotic cell will be to facilitate research and development in the construction sector, addressing the numerous challenges associated with integrating technologies such as robotics. With a central focus on CLT panel processing, this system aims to advance the understanding and implementation of robotic solutions within the construction industry.	Initially, the task involves machining a CLT panel, as illustrated in Figure *2*. This panel incorporates distinct components earmarked for removal, delineating assembly apertures on the lateral surfaces alongside a door and window, among other critical elements integral to its functionality as a structural component of a structural wall system.	Utilizing robots in panel processing proves essential to address market demands more efficiently, quickly, and safely. This involves replacing repetitive tasks for workers in offsite construction, focusing on the pre-assembly and penalization of CLT. Additionally, it entails ensuring adaptability and flexibility to accommodate various projects.	The first requirement pertained to the dimensions of the laboratory space (9 mx7mx2m) for the research where the robotic cell would be installed. Additionally, it involved experimentation with two robotic arms working simultaneously in processing the CLT panel. These robots were required to have an additional degree of freedom to enable translation within the designed system.

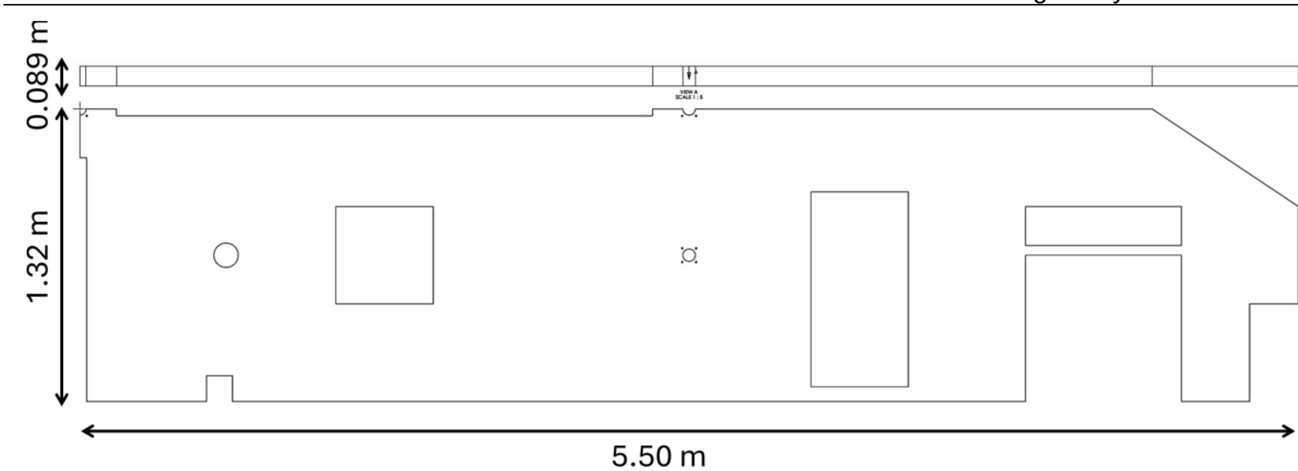

Figure 2. CLT panel used during experiments for the cutting tasks. Adapted from (Villanueva et al. 2021)

3.2 The Design

The primary step in the design phase involves a process analysis to ascertain the complexity distribution between the panel and robotic systems. This analysis informs the development of detailed operation sequences and task execution strategies, along with assessing their modularity and flexibility.

Based on the requirements and specifications outlined in the previous section, the design of the Robotic Cell was developed with the elements listed in Table 2. This table includes the name of the component, the supplier company’s brand, the key technical specifications crucial for this system, the specific functions they perform, and how they are implemented in this system.

Table 2. List of components selected for the robotic cell

Component	Brand	Technical specifications	Implementation in a robotic cell
UR20	©2024 Universal Robots A/S	• 20 kg payload • 6 degrees of freedom • Reach 1750 mm	Robotic Arm
7th Linear Axis	igus®	• 500 N payload radial • 250 N payload axial • 5,500 mm length	Linear rail for translation of the robotic arms
Compact Line Modules	ToolDrives GmbH & Co. KG	• 305 N Max. radial torque • 30,000 Max. rpm	An end effector for the robotic arms
Table	© Vention 2024	• 5,580 mm length • 1,530 mm width • 330 mm height	Worktable where the panel will be laid to be manufactured
Physical protection	© Vention 2024	• x2 Cell width – x4 (2,000 mm x 1,000 mm) • x1 Cell length – x7 (2,000 mm x 1,000 mm)	Shell protection for the whole robotic cell in the laboratory

Figure *3* shows the design of the robotic manufacturing cell, which features two ©2024 Universal Robots A/S UR20 robots (a) facing each other toward the worktable. Additionally, each of them is mounted on the rail (b) igus® 7th Linear Axis, adding a seventh degree of freedom to allow the translation of the robotic arms along the table where the panel will be mounted (mount and dismount of the panel on this system is outside of the scope of this robotics manufacturing cell). Moreover, the CLT panel intended for manufacturing, in this instance, lies upon the designated worktable (c), where the shapes obtained from the plan are cut accordingly; it was designed in © Vention 2024. As an end-effector (d), each robot is equipped with a tool consisting of a ToolDrives GmbH & Co. KG Compact Line Module, onto which the cutter can be mounted to perform the cutting task. Additionally, around the perimeter of the system, one can observe the protective barriers (e) of the robotic cell with its environment, designed in © Vention 2024.

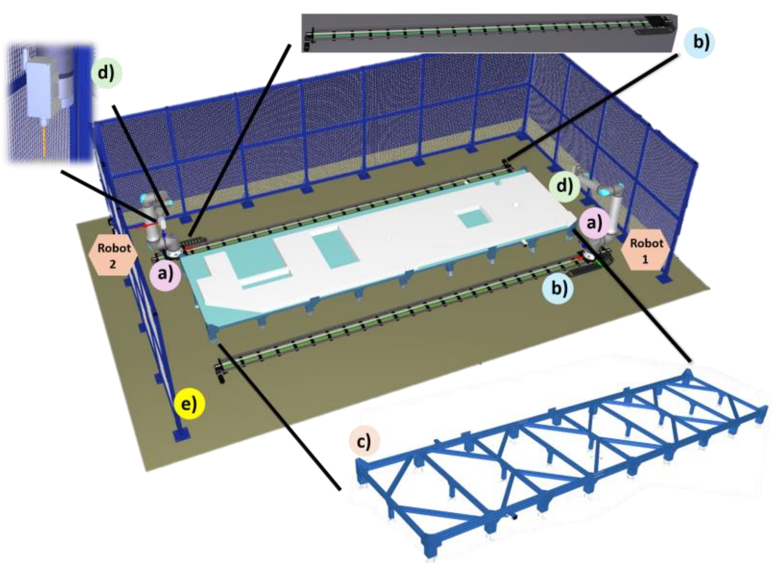

Figure 3. Robotic cell machining design & simulation using © 2024 RoboDK

- *UR20, 7th Linear Axis, and Compact Line Modules:*

For the development of the system, the selection of elements for the robotic manufacturing cell was carried out. Firstly, ©2024 Universal Robots A/S UR20 robotic arms, see Figure 4, were chosen because they meet the dimensional characteristics of the workspace in the laboratory and the payload to develop the planned task. In the design, it can be observed that there are two robots, one on each side, which will allow both robots to work in parallel within the robotic cell.

Next, considering the robots to be used, options for solutions with specifications were given specifically to components tailored for this brand of robot. This led to the selection of a rail igus® 7th Linear Axis, that acts as an additional freedom axis for each robot, allowing for their translation along the worktable. Moreover, within the solutions designed for the Universal Robot, the end-effector chosen was the ToolDrives GmbH & Co. KG Compact Line Module; this module comprises a tool holder onto which the wood router cutter can be mounted to execute a precise cutting operation as part of the robotic system's tasks.

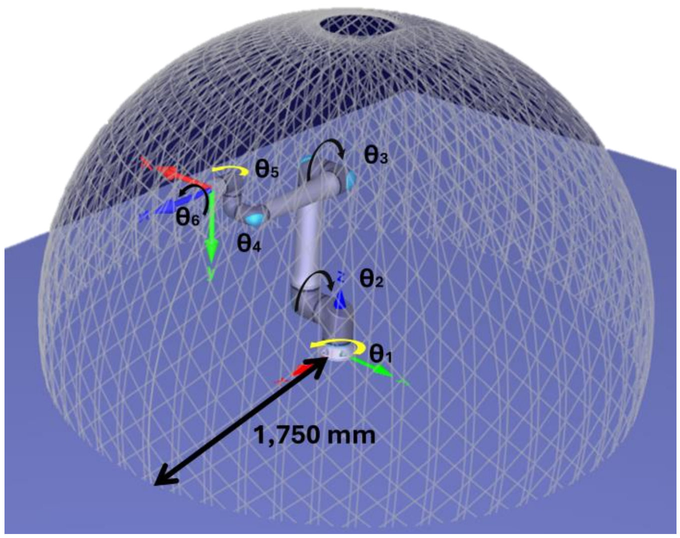

Figure 4. Individual Workspace needed for the ©2024 Universal Robots A/S UR20 robotic arm according to its joints, and the degree of freedom

- *Table & Panel:*

On the other hand, the design of a worktable was developed based on the force exerted by the panels it will be supporting, the dimensions of these panels and of the workspace in the laboratory, as well as an appropriate height to ensure that the robots can manufacture without any movement issues. This table was designed using the online interface provided by © Vention 2024, from which Aluminum Extrusion parts were selected, and the assembly of the design was developed using key connectors depending on the type of joint in the structure. Likewise, along the central structures, the table features holes that can be used as anchoring points, allowing for a wide range of sizes of CLT panels to be processed in this robotic cell. In other words, vertical stops can be inserted into these holes, acting as a barrier to keep the panel static during the machining process.

For experiments within this system, the panel shown in Figure *2* was used. This panel is based on the specifications and dimensions used in an industrial environment. The design and technical drawings of this panel were created using SolidWorks®, allowing us to obtain the necessary dimensions for its implementation in the system.

- *Physical Protection:*

Similarly, following the first principle of Lean Robotics, as explained (Bouchard Samuel and Couture Jérémy 2017) in the book Lean Robotics, "People before Robots," which means that the safety of individuals should take precedence over the robotic cell, both in stationary and operational modes. For this reason, a protective barrier was also developed using the online interface provided by © Vention 2024. This barrier utilizes Aluminum Extrusion parts and a Black Powder Coated Wire Mesh Panel grid to create a protective wall, around the robotic cell, safeguarding individuals from the system and vice versa, ensuring safe interaction with the environment.

4 Results and Discussion

This section presents the intricate details of the robotic cell design housed within the laboratory, providing a comprehensive examination of its components through a focused zoom lens. Additionally, we elucidate the system's behavior observed through a simulation study, shedding light on its efficiency and efficacy in executing the cutting task. Moreover, it presents empirical data elucidating the temporal dynamics involved in task execution, offering insights into the time required for task completion and the system's overall performance. For the development of this system, mounting and dismounting the panel are outside the scope.

In the realm of industrialized construction, simulation plays a vital role in optimizing various processes, comprehensive planning, scheduling, and operations. Simulation allows the exploration of diverse scenarios within a virtual environment before implementation. Additionally, the outcomes provide empirical evidence and quantitative analyses, aiding in informed decision-making (Martinez et al. 2020). For the simulation of this system, each target was programmed based on the design. This involved extracting a drawing with the precise measurements for cutting each section from the CAD model of the CLT panel. Subsequently, each target was selected according to these measurements, utilizing the frame of each robot as a reference relative to the worktable. The primary reference point of the system is located at the position of Robot 1, as depicted in Figure *3*. Therefore, the other components of the system are referenced based on this reference frame. This systematic approach facilitated the generation of a path of targets aligning with the process.

To streamline future enhancements in path planning, distinct programs were developed for each shape present on the CLT panel. In the current stage of the project, the targets were programmed based on the dimensions obtained from the panel drawings, using a coordinate system where each target is located at a specific point on the panel. This setup enables the creation of linear "L" movements in polygons, circular "C" movements in circles, and joint "J" movements for transferring the robot's tool to different points on the panel. This approach will allow for flexible manual rescheduling, enabling the allocation of cutting tasks to different robots based on efficiency, speed, and safety considerations.

Besides, to avoid collisions and ensure a balanced load of movements and tasks between both robots, a movement scheduling analysis was conducted manually. This analysis considered the cutting time for each shape, the robot's translation across the panel, and its approach based on the robot's reach constraints. Consequently, a master program can be formulated, integrating all the sub-programs designated for each robot.

On the other hand, non-value-added time is defined as the duration during which each robot is relocating to another point on the worktable to conduct milling in a different area than its current workspace. The milling process was consistently applied to the CLT panel, gradually removing material from the contour of each piece until it was completely separated from the main body. The selected tool for this experiment is a vertical cutter with a diameter of 12 mm, operating at a motor speed of 18,000 RPM, resulting in a movement rate of 15 mm/s. Each of the robotic arms, including the linear seventh degree of freedom, moves at a speed of 200 mm/s. Based on the methodology outlined in (Speiser Erez 2024), which highlights two critical iterative and learning data points on its website, the maximum depth the cutter can penetrate the CLT can be determined. This information allows for the calculation of the number of repetitions required for each shape on the panel, thus enabling the estimation of the total processing time. (Speiser Erez 2024) indicates that for large diameter cutters (above 3/4", 20 mm), the maximum depth of penetration can be up to 4 times the diameter (4D), while for small diameter cutters (below 1/8 “, 3 mm), it can extend up to 10 times the diameter (10D).

Table 3. Parameters for milling of CLT panel and cycle time

# Cutter and task	Axia depth (each pass)	Axia depth % diameter cutter	Milling passes	CLT Original thickness	Diameter cutter	Total simulation time
# 1 Shapes removed	0.12 mm	1%	742	89 mm	12 mm	1,282 min 25 sec
	2.4 mm	20%	38	89 mm	12 mm	65 min 40 sec
	6 mm	50 %	15	89 mm	12 mm	25 min 55 sec
	12 mm	100%	8	89 mm	12 mm	13 min 49 sec
	48 mm	400%	2	89 mm	12 mm	3 min 27 sec
# 2 Edges finished	0.03 mm	1%	2,967	89 mm	3 mm	1,997 min 46 sec
	1.5 mm	50%	60	89 mm	3 mm	40 min 12 sec
	3 mm	100 %	30	89 mm	3 mm	20 min 6 sec
	15 mm	500%	6	89 mm	3 mm	4 min
	30 mm	1000%	3	89 mm	3 mm	2 min

Taking into account the outcomes presented in Table 3 and adhering to the principles of lean manufacturing, we have defined tasks within the robotic cell as value-added activities, specifically when the robot is engaged in milling operations on the CLT panel. Furthermore, considering the ongoing milling development mentioned earlier, it is essential to factor in the tool diameter to accurately determine each pass’s depth. Thus, the preceding table illustrates the total time in seconds, varying according to different percentages of depth based on the diameter of the tool. Tool number one, utilized for defining the figures on the panel to be cut or removed, is compared with tool number two, which is known for providing finer finishing on corners of each shape as well as cutting circles of a specific size. The transition between cutters of different diameters is currently a manual process. Hence, the time taken for this change will not be factored into the simulation time.

As shown in Table *3*, if the maximum cutting depth allowed by the cutter diameter is taken into account, the total simulation time would encompass the sum of #1 shapes removed and #2 edges finished, resulting in a duration of 5 minutes and 27 seconds. Conversely, assuming a depth of 100% based on each cutter diameter, the total simulation time would similarly consist of the sum of #1 shapes removed and #2 edges finished, resulting in a duration of 33 minutes and 55 seconds. This analysis enables an examination of the impact of cutter diameter on the shapes to be cut, final finishes, and the robot’s movements across the panel, all of which define the manufacturing time.

As this manufacturing cell aims to research the implementation of robots in the construction sector, simulation times will vary based on different factors. These include varying thicknesses of the CLT panel, dimensions concerning length and width, and the diverse finishes and detailing required for the assigned project.

5 Conclusions

In conclusion, the design and development of the robotic manufacturing cell for CLT panel production has been a meticulous and iterative process. The integration of ©2024 Universal Robots A/S UR20 robots with a seventh linear degree of freedom has provided enhanced flexibility in panel handling and cutting, while the utilization of specialized tools, such as the vertical cutter, has yielded significant efficiency gains.

The simulation of the system, coupled with target programming based on the CLT panel design, has facilitated the optimization of the cutting process and the generation of precise route plans for each robot. Moreover, the ability to reschedule cutting tasks offers valuable flexibility for future enhancements in route planning, fostering synchronized, efficient, and productive operations. Determining the movement speed of the robotic arms and the seventh degree of freedom, alongside establishing the maximum cutting depth of the cutter, are critical factors in calculating the total process time and ensuring seamless and safe production.

In summary, the implementation of this robotic manufacturing cell represents the potential of using the simulation tools to help future processing of CLT using robots in efficiency and precision, particularly in offsite construction prefabrication. Furthermore, its potential for further improvement through future optimizations and adjustments underscores its significance in advancing manufacturing practices. Although these are initial results towards the automation of the CLT manufacturing process, we plan to integrate more operations, including milling, drilling, cutting, and inspection. Additionally, we aim to integrate software that links the panel design with the simulation, allowing for the automatic path-planning generation of targets which is optimal and improved.

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