Mobility-added multi tool end-effector for picking and nailing applications in robotic timber assembly

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Abstract -

Robotic timber assembly applications, such as nailing, often require the simultaneous execution of multiple tasks, necessitating the use of multiple devices and large working spaces. This poses a challenge for the development of transportable robotic manufacturing cells, which aim to bring the benefits of controlled environments closer to construction sites. Addressing this issue requires the design of manufacturing cells that optimize robotic resources and space by enabling multiple tasks to be performed simultaneously. In this work, the concept of Mobility-Added Multi Tool (MAMT) end-effector is introduced. Specifically, a MAMT end-effector designed for picking and nailing operations is proposed to eliminate the need for additional external devices during timber nailing processes. This end-effector is based on closed-loop linkages driven by linear actuators, providing ease of control, high force transmission, and structural stability. To demonstrate their practicality, application examples involving two-robot collaboration are presented and animated, illustrating the usability of the proposed end-effector in real-world scenarios. Future work includes the development of linkage kinematics and dynamics, as well as the exploration of alternative mechanisms to introduce additional mobility features, enabling the same robot to perform a broader range of tasks during the timber assembly process.

Keywords -

End-effector; Timber Nailing; Robotic Fabrication; Construction Automation; Linkages; Mechanisms

1 Introduction

Timber assembly plays a vital role in the construction industry. Timber is one of the most widely used construction materials globally and serves as the primary material in countries such as the United States and Canada [1, 2]. The construction industry is gradually transitioning towards greater automation, although at a slower pace compared to other industries [3, 4]. However, significant steps are being made in this direction. Among various construction processes, timber assembly is particularly well-suited for robotic fabrication due to the material's lightweight nature, flexibility, and ease of manipulation.

Currently, robotic timber assembly is predominantly carried out in off-site facilities, where robots are working collaboratively with other robots [5, 6] and automated devices such as stationary disc saws and CNC machines [7, 8, 9] to perform tasks like pick-and-place [10, 11], cutting [12], milling [13], drilling [14], screwing [15], and nailing [16]. These operations facilitate the prefabrication of small individual elements [17, 18] as well as larger products, such as complete building sections and facades [19, 20, 21].

While off-site timber assembly factories are advancing toward full automation, there is an urgent need to develop robotic manufacturing solutions closer to construction sites. Such solutions would retain the advantages of controlled factory-like environments while avoiding logistical challenges, such as transportation. Transportable and reconfigurable manufacturing cells have emerged as a promising solution [22]. To ensure portability and efficiency, these cells must optimize robotic and spatial resources, often relying on just one or two stationary robots equipped with the necessary capabilities to execute the entire manufacturing process, even for large timber products.

A significant challenge in timber assembly lies in the wide range of tasks required to complete a fabrication process. These tasks can lead to delays and increased human intervention for tool and material handling. To address this, additional automated devices have been incorporated into manufacturing cells for robot use [23]. Furthermore, robots have been equipped with the ability to perform multiple tasks by employing tool changers [24] or multi tool end-effectors [25, 26, 7]. While these innovations have improved timber assembly efficiency, they also present challenges. Adding more automated devices increases spatial and control system complexity, while tool changers and multi tool end-effectors often reduce robotic mobility. Crucially, these approaches fail to address the fundamental issue of performing multiple tasks simultaneously with a single robot. In many cases, tools remain fixed relative to the robot's end-effector, relying entirely on robot motion for operation.

Simultaneous task execution often requires multiple devices, such as robots or other automated tools, equal to the number of tasks involved. This is particularly problematic for applications like nailing, where at least two timber elements are joined using a nail, thus requiring the use of up to three devices during a single nail process. As a result, robotic nailing is challenging to implement with one or multiple robots. Currently, robotic nailing often involves a table—sometimes automated and equipped with additional Degrees of Freedom (DoF)—to hold timber elements while a robot performs the nailing operation [22, 27, 28, 29]. However, this approach limits manufacturing capabilities to the table's size and the robot's range of motion. Consequently, most robotic nailing applications are restricted to producing smaller products, such as panels and pallets, and transportable manufacturing cells are similarly limited to fabricating small-sized items.

In this work, the concept of Mobility-Added Multi Tool (MAMT) end-effector is introduced. This end-effector enhances robotic capabilities by providing additional mobility, enabling simultaneous execution of multiple tasks while optimizing resources, space, and time. The proposed MAMT end-effector allows a robot to hold a timber element and perform nailing simultaneously, with the ability to vary the nail's position and orientation. The MAMT end-effector is designed using closed-loop linkages driven by linear actuators, which enable precise adjustments to the nail gun's position and orientation. Additionally, these linkages provide high force transmission and structural integrity, which are characteristics of this type of linkages, meeting the demands of construction materials and processes. This paper describes the design and motion principles of the proposed MAMT end-effector. Furthermore, application examples involving collaborative tasks performed by two robots are presented to demonstrate their usability in real-world scenarios.

The remainder of this paper is structured as follows: Section 2 details the proposed MAMT end-effector and their mobility principles. Section 3 presents three application examples of timber nailing processes using the MAMT end-effector. Finally, concluding remarks are summarized in Section 4.

2 MAMT end-effector description

The general structure of the proposed MAMT end-effector is shown in Figure 1. This design is intended for installation on an industrial serial robot, specifically the KUKA® KR 250 R2700, as illustrated in Figure 1(a). The MAMT end-effector consists of four primary modules, depicted in Figure 1(b):

1. **Gripping module** (Module 1) for gripping timber studs.
2. **Linear translation module** (Module 2) for horizontal nail gun movement.
3. **Rotation module** (Module 3) for angular adjustments.
4. **Height variation module** (Module 4) for vertical positioning and nail gun triggering.

The main objective of this section is to present the MAMT end-effector concept and its operational principles without delving into detailed technical analyses. Synthesis, kinematic, and dynamic studies are beyond the scope of this work; however, key dimensions of the model are provided for reference.

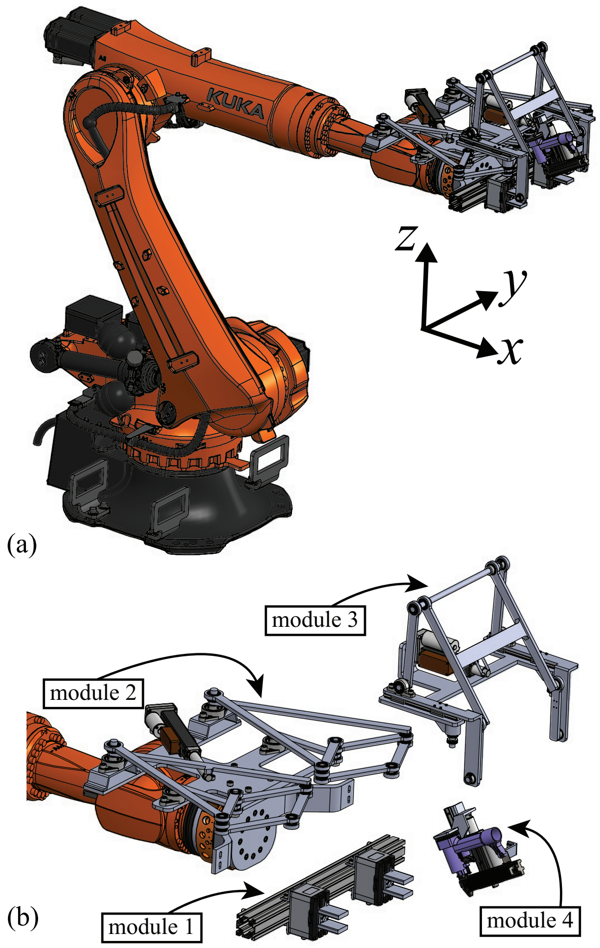

Figure 1. Proposed MAMT end-effector: (a) installed on a robot KUKA® kr 250 r2700, and (b) modules.

2.1 Module 1 - gripping

Module 1, shown in Figure 2, consists of two grippers symmetrically positioned along the end-effector's y-axis. This module enables the end-effector to pick and securely hold timber studs during the nailing process. The grippers' tips are fixed at a distance w_1 from the center of the robot's final link. Distances h_1 and v_1 can be adjusted by repositioning the grippers. The dimensions used in the computational model are listed in Table 1.

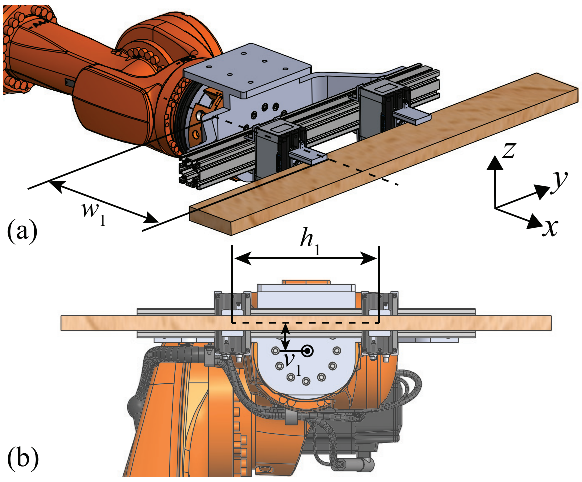

Figure 2. Module 1 - gripping: (a) isometric view, and (b) front view.

Table 1. Dimensions of Module 1 - gripping

Element	Dimension [mm]
h_1	300
v_1	56
w_1	447

2.2 Module 2 - linear translation

Module 2, shown in Figure 3, utilizes a double Peaucellier planar mechanism mounted in a plane parallel to the xy-plane of the robot's end-effector. The Peaucellier mechanism, a classic straight-line generator, comprises eight links and six revolute joints, resulting in one degree of freedom (DoF). Connecting two Peaucellier mechanisms, as shown in Figure 2(a), not only generates straight-line motion but also achieves straight-line body translation. This setup enables the nail gun to move linearly (parallel to the y-axis) over the gripped timber stud without undesired rotations, as illustrated in Figure 3(b).

The entire linkage maintains a single DoF and allowing to be driven by a single linear actuator. The Peaucellier mechanism's link dimensions are listed in Table 2. This double mechanism architecture provides a linear displacement d_1 of 700 mm with an output/input ratio of 3:1, meaning the nail gun moves three times the displacement of the linear actuator.

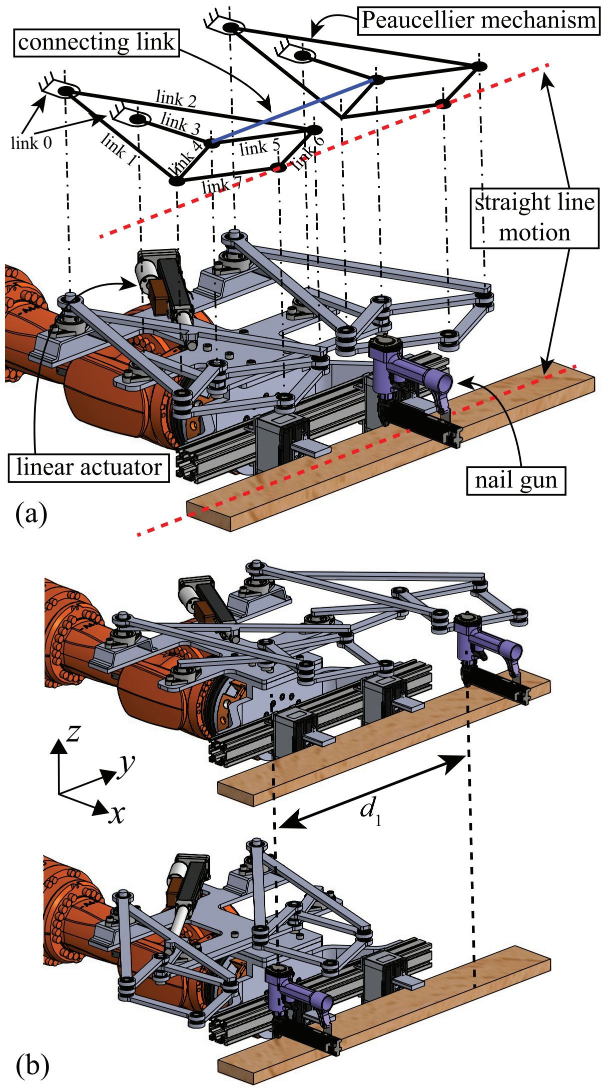

Figure 3. Module 2 - linear translation: (a) base linkage, and (b) displacement range. Modules 3 and 4 that physically connect module 2 with the nail gun are not included for better visualization of the base linkage.

Table 2. Dimensions of Module 2 - linear translation

Element	Dimension [mm]
link 0	200
link 1	530
link 2	530
link 3	200
link 4	210
link 5	210
link 6	210
link 7	210
connecting link	450

2.3 Module 3 - rotation

Module 3, shown in Figure 4, is based on two parallel four-bar planar mechanisms. Two design variants, to be used independently, are proposed:

1. **Variant 1** (Figure 4(a)): Mechanisms placed in planes parallel to the xz-plane of the robot's end-effector.
2. **Variant 2** (Figure 4(b)): Mechanisms placed in planes parallel to the yz-plane.

Each four-bar mechanism comprises four links connected by four revolute joints, resulting in one DoF, making it suitable for actuation by a single linear actuator. In these mechanisms, links 1 and 3 rotate about fixed axes. The nail gun is attached to link 3 in both variants, allowing rotation about axes parallel to the y and x, respectively.

The nail gun tips are positioned along these axes at a distance w_2 from the robot's last link. This distance can be adjusted using carriage and rail systems that enable translation along the x-axis between Modules 2 and 3. The link dimensions of the four-bar mechanism are listed in Table 3.

Module 3 provides a rotation range θ of 50° to 120° for variant 1 and 40° to 140° for variant 2. The rotation range of Variant 1 is shown in Figure 4(c).

Table 3. Dimensions of Module 3 - rotation

Element	Dimension [mm]
link 0	306
link 1	220
link 2	350
link 3	150
w_2	460

2.4 Module 4 - height variation

Module 4, shown in Figure 5, includes the nail gun and a linear actuator connected via a linear track. This module enables direct adjustment of the nail gun's distance d_2 relative to the gripped timber stud. In the initial position, as described in Section 2.3, the nail gun tip aligns with the rotation axis of Module 3.

Module 4 is rigidly attached to link 3 of Module 3, ensuring that any displacement produced by Module 4 moves the nail gun tip along an axis intersecting the rotation axis of Module 3. This functionality allows precise positioning of the nail gun tip close to the timber stud surface, regardless of the position and orientation defined by Modules 2 and 3. Additionally, Module 4 can trigger certain nail guns by moving the gun tip until it contacts the timber stud.

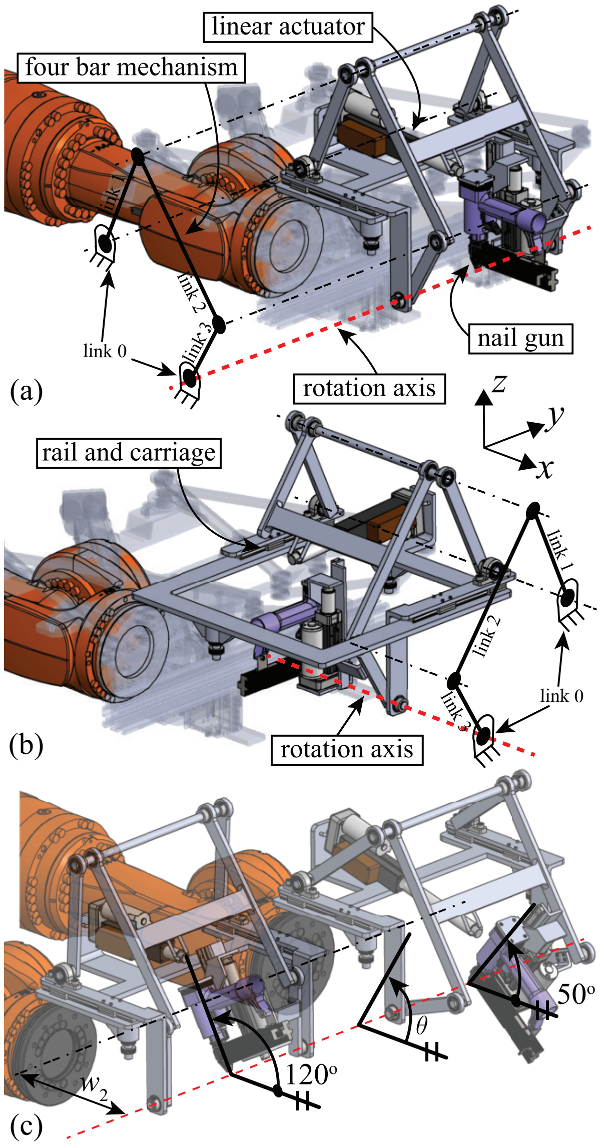

Figure 4. Module 3 - rotation: (a) base linkage of variant 1, (b) base linkage of variant 2, and (c) rotation range.

3 Application examples

This section provides visual demonstrations of the MAMT end-effector functionality in real timber nailing processes. Two robots in collaboration, each equipped with the proposed MAMT end-effector, were 3D modeled and animated to fabricate three types of timber-nailed structures:

1. **Straight on-plane structure**.
2. **Rotated on-plane structure**.
3. **Rotated off-plane structure**.

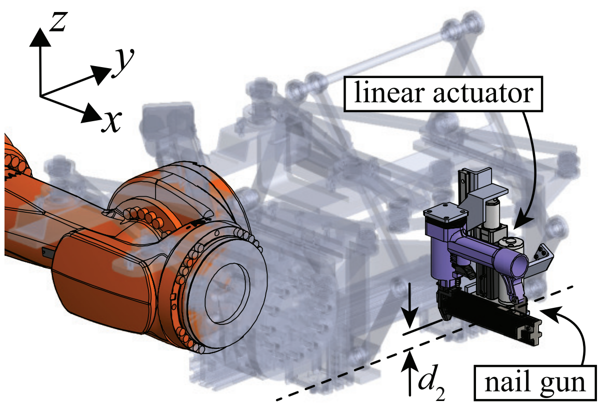

Figure 5. Module 4 - height variation.

The dimensions and configurations of these structures are illustrated in Figure 6.

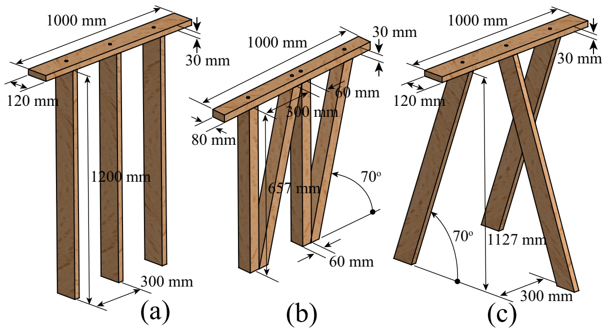

Figure 6. Timber structures: (a) straight on-plane, (b) rotated on-plane, and (c) rotated off-plane.

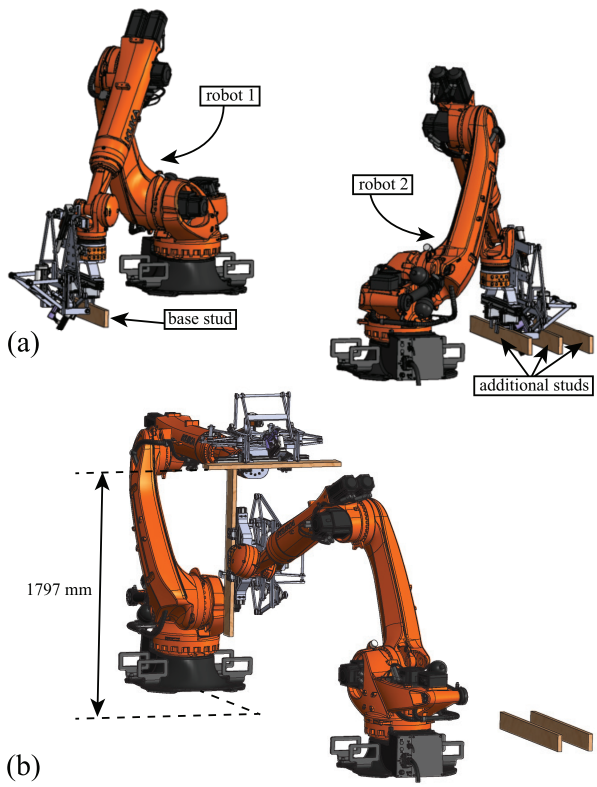

Figure 7. First stage of the timber nailing process with the robot team: (a) picking the timber studs, and (b) placing the timber studs.

The fabrication process begins with Robot 1 picking the base timber stud and holding it horizontally at a height of 1797 mm, as shown in Figure 7. Simultaneously, Robot 2 picks the additional timber studs and aligns them with the base stud for subsequent nailing. This process of Robot 1 holding the base stud while Robot 2 places additional studs is repeated for the entire assembly of the three timber structures.

The initial steps of the fabrication processes for the three timber structures are depicted in Figure 8. The procedures for each structure are described as follows:

Straight On-Plane Structure (Figure 8(a)): i) Module 3 fixes the nail gun at 90°, Module 2 translates the nail gun 300 mm along the negative y-axis from the center, and Module 4 lowers the nail gun to join the two timber studs. ii) Module 4 raises the nail gun, Module 2 translates the nail gun 300 mm along the positive y-axis to align with the next stud placed by Robot 2, and the nailing process is repeated.

Rotated On-Plane Structure (Figure 8(b)): i) Module 2 translates the nail gun 300 mm along the negative y-axis, Module 3 (Variation 2) rotates the nail gun to 90°, and Module 4 lowers the nail gun to join the two timber studs. ii) Module 4 raises the nail gun, Module 2 translates the nail gun 300 mm along the positive y-axis to align with the next stud placed by Robot 2, Module 3 rotates the nail gun to 70°, and Module 4 lowers the nail gun to repeat the nailing process.

Rotated Off-Plane Structure (Figure 8(c)): i) Module 2 translates the nail gun 300 mm along the negative y-axis, Module 3 (Variation 1) rotates the nail gun to 70°, and Module 4 lowers the nail gun to join the two timber studs. ii) Module 4 raises the nail gun, Module 2 translates the nail gun 300 mm along the positive y-axis to align with the next stud placed by Robot 2, Module 3 rotates the nail gun to 110°, and Module 4 lowers the nail gun to repeat the nailing process.

An animated video illustrating the assembly processes for all three timber structures is available at the following link [1].

[1] https://youtu.be/VaK4FC0Dgo4

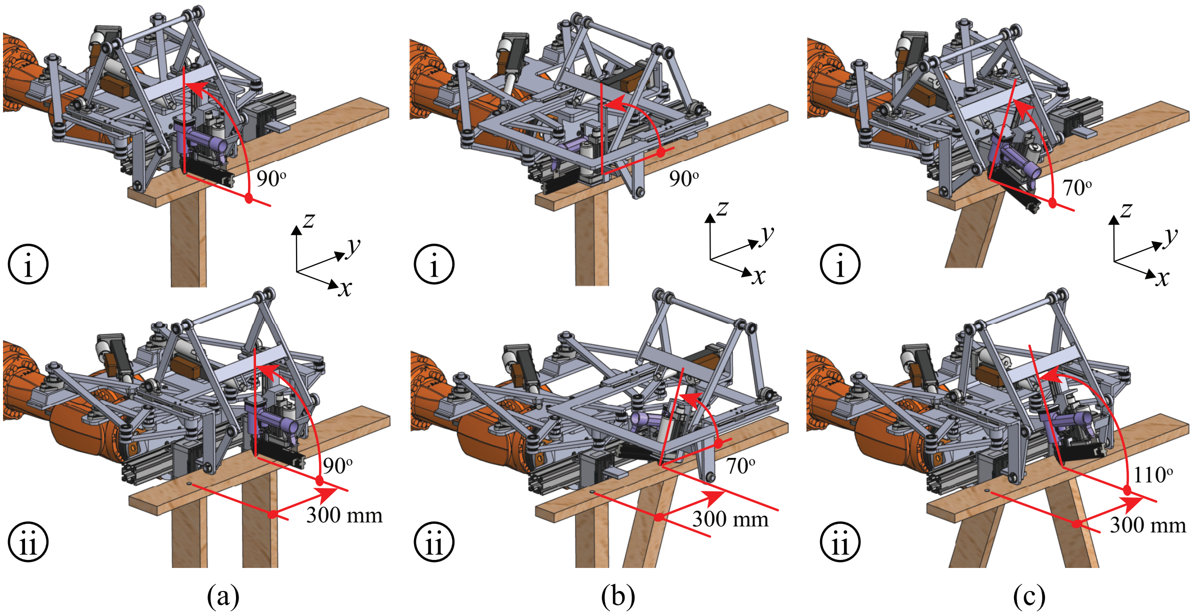

Figure 8. Fabrication processes for the three timber structures: (a) straight on-plane, (b) rotated on-plane, and (c) rotated off-plane. i) stands for first step and ii) for second step.

4 Discussion

Timber assembly is one of the most widely robotized construction processes due to the favorable characteristics of timber, which makes it highly suitable for robotic manipulation. However, specific operations such as nailing remain particularly challenging because of the wide range of tasks involved. This poses a significant obstacle to the development of compact and transportable manufacturing cells that can be deployed near construction sites.

This research introduces the concept of MAMT end-effectors for robotic timber assembly, addressing the need for more efficient and versatile solutions in nailing operations. By enabling robotic systems to perform multiple tasks simultaneously, the proposed MAMT end-effectors optimize space, time, and robotic resources.

The MAMT end-effectors leverage closed-loop linkage mechanisms driven by linear actuators, which provide high force transmission and structural stability essential for timber construction processes. Additionally, the mechanisms are easy to control, making them suitable for seamless integration into industrial robotic systems. The design includes four specialized modules: a gripping module for holding timber studs, a linear translation module for precise straight-line motion, a rotation module for angular adjustments, and a height variation module for accurate positioning and triggering of the nail gun.

The effectiveness of the MAMT end-effectors was illustrated through application examples, where collaborative two robots successfully fabricated three distinct timber-nailed structures: straight on-plane, rotated on-plane, and rotated off-plane. These examples showcased the system's ability to perform complex tasks with minimal reliance on external devices and within compact working spaces.

By eliminating the need for additional external devices during nailing, the MAMT end-effectors enable a more streamlined and efficient approach to robotic fabrication. Their modular and compact design enhances the adaptability and versatility, making them particularly valuable for applications where space and resources are limited. Furthermore, the linkage-based mechanisms ensures precise, robust, and reliable operation, even in demanding construction scenarios.

Some limitations of the proposed MAMT end-effector include the manual pre-setting of parameters h_1 and v_1, which requires prior knowledge of the timber stud dimensions. Additionally, the end-effector does not allow active translation of the nail gun along the x-axis. However, the nail position relative to the timber studs in this direction can be slightly adjusted by varying the portion of the timber stud grasped by the grippers.

While this work presents the feasibility and functionality of the MAMT end-effectors, further research will focus on conducting comprehensive technical analyses, including position synthesis, kinematic and dynamic modeling, and Finite Element Analysis simulations. Fabrication and experimental validation of physical prototypes are also planned as future work. Additionally, exploring alternative mechanisms to enable additional tasks such as cutting and milling is also planned as part of ongoing research.

5 Conclusion

The concept of MAMT end-effectors represented in this paper goes beyond the additional mobility seen in many existing robotic end-effectors. It emphasizes equipping the end-effector with the necessary capabilities to perform tasks independently of the robot's motion. This independence significantly advances the automation of timber assembly, offering a compact, efficient, and versatile solution for robotic systems. By bridging the gap between off-site prefabrication and on-site manufacturing, the MAMT end-effectors have the potential to address critical challenges in the construction industry, paving the way for more sustainable, scalable, and adaptable processes.

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