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Timber Construction Automation Using Industrial Robotic Arm Integrated with an Interactive Rail System

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ABSTRACT

Challenged by the prevalent workforce shortage, the construction industry is picking up interest in using robotic arms in construction operations, especially in the context of modular construction and prefabrication. However, the lack of systematic investigations into integrating robotic arms with mobile systems to enhance mobility and operational range has been identified as one main research gap. Stationary robotic arms have inherent limitations in their range, making mobility a critical need. To address that issue, in this paper, the authors proposed a mobile construction robotic system to facilitate their use in the automation of timber frame assembly operation. The authors simulated the system to assess the interactions and coordination among its various components, and to identify potential areas for improvement. This study showcased the effectiveness of the new system design in improving the timber construction automation process and reveals its potential for further exploration in the realm of mobile construction robotics.

INTRODUCTION

Different practices were recorded in literature for using robotic systems in large-scale off-site production of prefabricated components, such as the use of gantry robots, stationary robotic arms, and collaborative robots (Melenbrink et al. 2020). With the increased involvement of robotic systems in construction operations to help address workforce shortage, the user requirements for construction robots have also been growing. In this realm, the range limitations suffered by stationary robotic arms become apparent when used in construction operations. One recent study (Wong Chong et al. 2022) proposed a simulation of automated timber frame assembly using an industrial robotic arm. However, during this simulation, some studs were not successfully framed due to the limitations of the robotic arm's work envelope (i.e., the spatial volume encompassing the feasible motions of a robotic arm's end-effector). Robotics companies have designed mobile units/platforms (KUKA AG 2016) to enable mobile functionality for stationary robotic arms to facilitate their operation. Furthermore, research has expanded the range of robotic arms for applications in the installation of drywalls 6/29/2024 4:08:00 PM. Despite these advancements, research into the mobile capabilities of industrial robotic arms remains in its nascent stage, and there is a lack of research to systematically investigate the integration of robotic arms with mobile systems such as rail systems.

To address this limitation and enable robotic arms to move more freely while executing construction tasks, in this paper, the authors proposed a mobile construction robotic system built upon industrial robotic arms and a new rail system design, and simulated it in Webots (Cyberbotics

Ltd. 2022a). This enables us to evaluate the interactions and coordination between different components within the system, identifying needs and opportunities for refinement and optimization. This proposed robotic system has significant potential to advance the development of mobile construction robotics based on and beyond the off-the-shelf robotic arms, making it a valuable resource for future research on this topic. Through a systematic approach, we established the system architecture, defined the internal functionality of the system, developed the workflow, and preliminarily evaluated the proposed system in a simulated environment, for demonstrating its effectiveness in supporting the construction process.

LITERATURE REVIEW

Robotics system developments for construction date back to the 1960s and 1970s (Willmann et al. 2016). However, the construction industry, as a labor-intensive sector, has been slow in adopting robotics and other new technologies in general (Kim et al. 2015). The effectiveness of robotic systems in enhancing productivity and quality has been repeatedly demonstrated. For example, robotic systems have been adopted in construction operations such as steel-truss welding and assembly, bricklaying, concrete laying, facade installation, and wall painting, among others (Delgado et al. 2019). For better organization, Ardiny et al. (2015) classified construction robots into the following three categories: teleoperated systems controlled remotely by human operators, programmable machines with preprogrammed functions or the ability to learn new ones, and intelligent systems that operate semi- or fully autonomously.

With the increasing availability of technologies and their evolution, they are also being integrated into the construction industry at a faster pace. Specifically, 4D simulation and virtual reality (VR) have been applied to modular construction and prefabrication to improve construction efficiency and quality, which involves building modules in a factory setting and then transporting them to the final location for installation. For example, Pooladvand et al. (2021) developed an interactive virtual environment integrated with a database containing details of lift studies and crane path planning to improve crane lifting operations' safety and reduce the risks of accidents. Zheng et al. (2020) enabled the automatic location detection and movement of modules by virtual prototyping in BIM, which enhanced progress monitoring and safety management in modular construction. Kayhani et al. (2018) developed a VR environment to facilitate planning for heavy lifts.

The integration of modeling, simulation, and VR with construction robots represents a promising approach in facilitating modular construction, and game engines have played an important role in this context. Although originally intended for video game development, game engines are increasingly being applied in manufacturing, healthcare, and construction sectors. Applications in construction were limited to safety training at the start (Ezzeddine and de Soto 2021), but quickly evolved to support a variety of architecture, engineering, and construction (AEC) tasks such as virtual walk-throughs, design visualization, construction equipment training, and facility management, among others. A notable example of game engine application was the model proposed by Wong Chong and Zhang (2019), which aims to improve time efficiency, quality, and safety in modular construction. By integrating building information modeling (BIM), game simulation, and robotics, their approach demonstrates the increased flexibility and capacity of game engines to generate virtual scenes with realistic interactions. More recently, Yu et al. (2023) have proposed a framework for the collaboration of humans and robots in construction work, which aims to enable rich physical interactions while ensuring worker safety. Their framework includes a receiver grip state indicator, which captures grip strength and gestures by tactile haptic gloves, as well as a Learning from Demonstration (LfD) model designed to replicate reactive behavior norms for robots with regard to human grip state. The proposed approach by Yu et al. (2023) is expected to enhance worker safety and reduce human workload.

ROBOTIC SYSTEM AND SIMULATION APPROACH

This paper aims to evaluate the effectiveness of a mobile robotic arm system in addressing the issue encountered in a prior study (Wong Chong et al. 2022), where the placement of timber studs was limited due to the insufficient work envelope of the robotic arm used. To be consistent with the prior studies, we employed the same robotic system components (i.e., robotic arms) and simulation environment (i.e., Webots). Although prior research tested three robotic arms, because the focus of the current paper is not to compare different robotic arms but rather to improve the feasibility in the use of robotic arms, we selected one of the robotic arms to test, i.e., an ABB IRB 4600–40/2.55 (ABB Robotics 2013). We started with the same models of a gripper, a nailing gun and timber studs as in the prior study. To address the range limitation, we developed a rail system that enables the movement of the robotic arm base, and updated the entire architecture and workflow accordingly. The main parts of the proposed robotic system were then simulated in Webots, which provides a comprehensive set of tools and libraries for simulating the behavior of robots in complex environments, including physics engines, sensors, and actuators. Additionally, solid entities can be created in Webots by defining parameters such as dimensions, materials, etc. This enables us to simulate the rail system, and interactions and coordination between different components within our proposed robotic system design.

PROPOSED MOBILE CONSTRUCTION ROBOTIC SYSTEM ARCHITECTURE

This section outlines the four components in the architecture of the proposed mobile construction robotic system, namely, the rail system, the robotic arm body, the robotic arm head, and work environment (Table 1), with each component having distinct responsibilities (Figure 1). The separation of functions within each components provides several benefits, including the ability to make flexible calls in subsequent workflows and the establishment of a more coherent and structured work logic.

Table 1. Definition of proposed system components

Component	Definition
Rail system	A set of rectangular rails, wherein the middle ground serves as the workspace for the placement of components to be assembled.
Robotic arm body	The default configuration of robotic arm, consisting of joints and links.
Robotic arm head	The end-effector component of the robotic arm, which can be equipped with a gripper or a nailing gun.
Work environment	Workroom with construction materials, gripper or nail gun holder, etc.

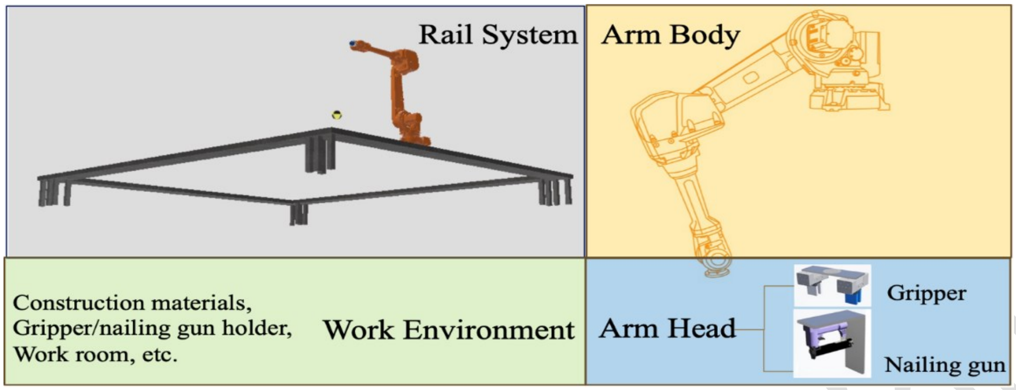

Figure 1. Proposed system components.

Functions are assigned to each component to achieve the automatic assembly of timber frames using the arm-based construction robotic system. The rail system is responsible for determining if a movement is required, and moving the robotic arm base to the calculated position if so. The robotic arm body performs the motion of the arm to the target point using inverse kinematics, while maintaining a secure posture to avoid collision with items in its work environment. The robotic arm head is responsible for grabbing and releasing objects using the gripper, as well as positioning the nailing gun to the intended nailing location and switching between the gripper and nailing gun. The function descriptions are listed in Table 2.

Table 2. Functions within each component

Component	Function	Description
Rail system	Check if movement is required	Define the work envelope of robotic arm, compare the distance between target and robotic arm relative to work envelope.
	Move robotic arm base to calculated position	Calculate the position closest to target on the rail system, change the coordinates of the robotic arm base to that position.
Robotic arm body	Move robotic arm to target	Utilize inverse kinematics to generate the appropriate motion for each joint on the arm to reach the target point while maintaining a fixed base position.
	Hold a safe posture	Hold a safe posture prior to initiating movement and maintain it in the movement to avoid collision with items in work environment.
Robotic arm head	Grab object	By opening and subsequently closing the two jaws of the gripper equipped on the robotic arm to grab the object.
	Release object	By opening the two jaws of the gripper equipped on the robotic arm to release the object.
	Nailing frame	Move the nailing gun to target nailing position.
	Change head to gripper	Unload the nailing gun and load the gripper in front of the holder.

	Change head to nailing gun	Unload the gripper and load the nailing gun in front of the holder.

PROPOSED MOBILE CONSTRUCTION ROBOTIC SYSTEM WORKFLOW

Based on the system architecture presented in the previous section, a complete workflow for the mobile construction robot was derived (Figure 2). The assembly work includes a framing stage and a nailing stage. In the framing stage, the robotic arm loads the gripper and moves between target positions to perform grabbing and releasing tasks. After completing this stage, the robotic arm switches head from the gripper to the nailing gun and proceeds to the nailing stage. Upon completion of the nailing stage, the entire workflow is concluded.

The presented workflow depicts the pre-defined logical operation sequences of the robotic arm using conditional statements. During the framing stage, the robotic arm checks if movement is needed before it grabs or releases an object. When the robotic arm is in a suitable and operable location relative to the target object, it proceeds to perform the subsequent tasks. Similarly, during the nailing phase, the system operates according to this same logic.

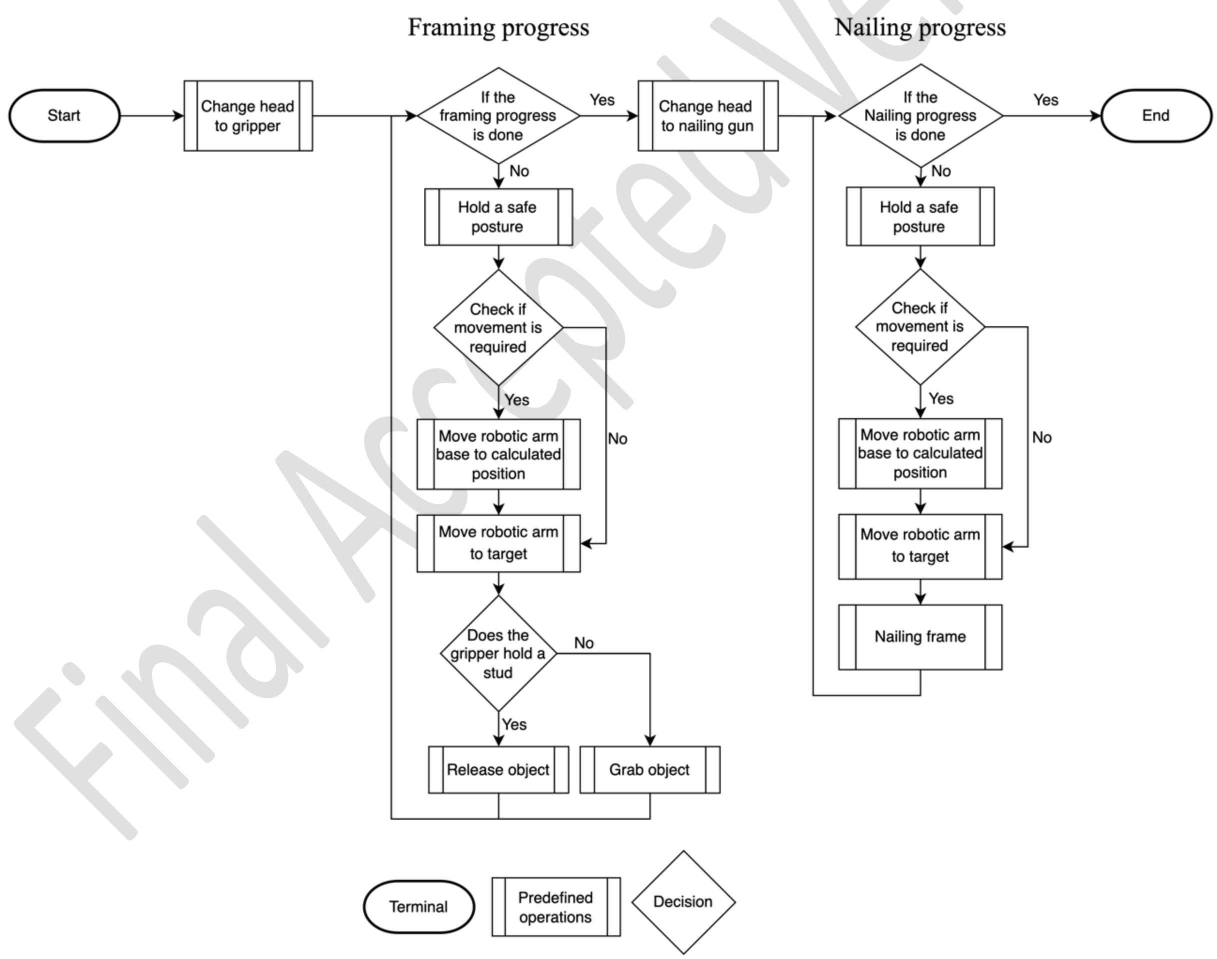

Figure 2. Proposed system workflow.

SIMULATION OF PROPOSED SYSTEM

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The feasibility of the proposed mobile robotic system was evaluated in Webots simulation environment (R2023a version, Cyberbotics Ltd. 2022). The simulated process involved the assembly of a timber frame by the robotic system, as well as its movement on the rail system. The assembly process comprised of several operations, including grasping, moving, and placing timber studs. Figure 3 specifies the proposed simulation method, which consists of six stages: (1) change head to gripper, (2) hold a safe posture, (3) grab object, (4) move robotic arm base to calculated position, (5) move robotic arm to target, and (6) release object. By referencing the background, the movement of the robot on the rail system can be observed by the reader. The nailing progress was not tested in the simulation, as the functions involved in the nailing process were already incorporated within the framing process.

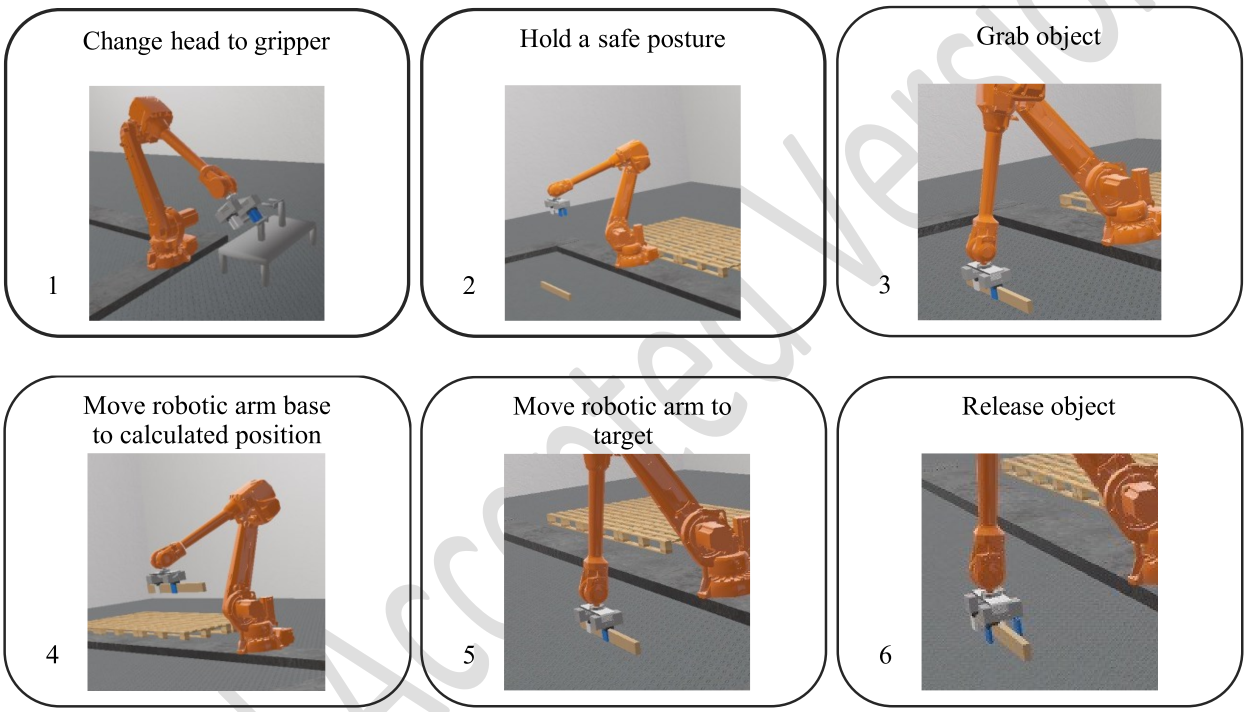

Figure 3. Proposed workflow operation simulation.

Simulation setup. An ABB IRB 4600-40/2.55 robotic arm, 'Two Schunk PEH 30 parallel grippers' (Schunk, PEH 2021), and a nailing gun (L. Hedges 2013) were used as test components in the experiment, as shown in Figure 1. The models of the construction materials were 2"× 4" wood studs, with a length of one meter. The controller used in this study was coded in Python and implemented as a supervisor in Webots (Cyberbotics Ltd. 2022b), which consistes of a collection of functions that enable the support module to access input information and robot's parameters during simulation (Wong Chong et al. 2022). Based on the architecture illustrated above, components, functions, and workflow were coded as classes, python functions within classes, and a queue of functions to be called according to the working logic hierarchy, respectively. Lastly, the robotic arm base's coordinates were altered using the supervisor controller to implement its movement.

Simulation evaluation. During the simulation, the robotic system executed target assembly operations utilizing the proposed workflow. Incorporating the rail system facilitated the robot's ability to perform tasks that were previously unattainable due to its limited work envelope. The process was accomplished without conflict, demonstrating the proposed mobile construction robotic system as a promising solution.

CONCLUSION AND FUTURE WORK

In this paper, the authors proposed a mobile construction robotic system that integrates a rail system to overcome the limited operational range of stationary construction robotic arms. The architecture of proposed system and its workflows have been successfully implemented and executed in simulation, demonstrating the potential effectiveness of the proposed system, with components working seamlessly in interaction and collaboration. The mobility offered by this approach holds substantial potential for future construction robotic systems to execute construction tasks and serves as a useful reference for researchers and practitioners interested in adopting and advancing mobile construction robotic systems and workflows.

Further research can be carried out in various areas related to the proposed system presented in this paper. First, a real-world practical comparison between the proposed system and previous stationary system can provide deeper insights and grounds. Second, evaluating the benefits and limitations of wheel-equipped mobile construction robotic arms, relative to the proposed rail-system robots can facilitate decision-making in selecting suitable robotic systems for future construction tasks. Finally, testing the effectiveness of the proposed system in tasks that involve materials other than timber frames, such as concrete or steel, can expand the applicability of the system to a broader range of construction projects. These future research directions can advance the development and implementation of mobile robotic systems in construction, which can ultimately help address the workforce shortage challenge, increase efficiency and reduce costs in construction.

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