Augmented reality for dynamic task sharing in human robot collaboration

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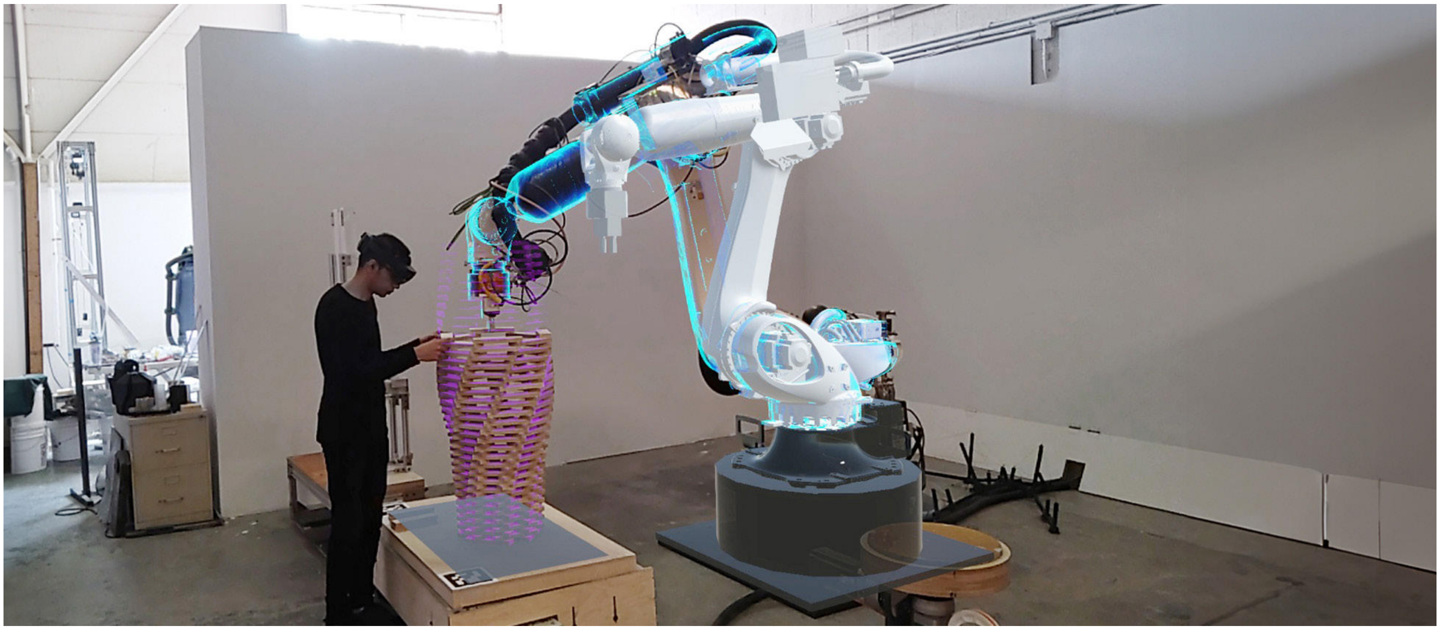
Real-time robotic control method for seamless task sharing in construction



1 Proposed AR-assisted dynamic task-sharing method. The robot and user can simultaneously pick and place elements without a predefined order.

ABSTRACT

This study presents an Augmented Reality-assisted method for real-time dynamic task sharing in human-robot collaboration in construction. This method consists of an AR immersive authoring platform combined with a real-time robotic controlling system that enables the user to dynamically share tasks between the user and a large-scale industrial robot for construction purposes. In this method, a custom-designed AR platform tracks the target object, allowing the user to do the construction task using visual guidelines and share the tasks in real-time with the robot, enabling uninterrupted collaboration. This collaborative framework facilitates the cooperation between humans and robots in a non-predetermined task-sharing environment, providing the user with greater freedom to allocate tasks. The performance of the proposed method is evaluated through a proof-of-concept case study. The results indicate that the task can be shared in a seamless procedure without any robot idle time. This research lays the foundation for the seamless integration of AR-assisted technologies into task-based human-robot collaboration in construction.

INTRODUCTION

Many processes in Architecture, Engineering, and Construction (AEC) aim to achieve full automation; however, not every architectural fabrication procedure can be fully automated, and in many cases, full automation is neither economical nor technically feasible (Mitterberger et al. 2023). Hence, human intervention is still necessary in certain construction areas to address challenges. One effective approach is to enhance these capabilities through digital augmentation tools (Alireza Fazel and Izadi 2018; A. Fazel et al. 2022). A subsequent step involves establishing collaborations between humans and robots. Human–Robot Collaboration (HRC) has been recognized as a feasible approach to incorporating robots in construction to increase productivity and decrease errors (Yu et al. 2023). This recognition points towards a more integrated and efficient construction process where humans and robots work together seamlessly. However, the implementation of such collaborative systems often remains cautious, with many studies focusing on maintaining physical separation and ensuring sequential interaction between humans and robots, primarily for safety reasons (Chemweno, Pintelon, and Decre 2020). Although there is an active field of research in the industry on physical interactions in HRC using Collaborative Robots (Cobots), they have also some limitations such as limited payload capacity, limited reach, and costs (Zentay et al. 2021). These limitations have restricted HRC in large-scale projects, such as construction, which require robotic arms capable of carrying heavier loads.

Recent studies in the field of Augmented Reality (AR) in construction show great potential for addressing these challenges by offering custom user interfaces (UI) independent of physical constraints (Mitterberger et al. 2020). By combining robotic fabrication and human augmentation through AR, it is possible to divide the construction tasks between the user(s) and the robot in a way that the advantages of each can be realized simultaneously. While numerous studies have investigated the use of immersive technologies for robot operation, their direct application to construction projects is still limited. This is because most existing systems are designed for small-scale tasks, involving small robotic arms manipulating small objects. These systems cannot be easily adapted to construction tasks where both the workspace and target objects are substantially larger (Xi et al. 2021). Therefore, it is necessary to investigate the integration of AR into HRC with large-scale industrial robots in construction.

To address this gap, this study investigates the incorporation of an AR-assisted method for real-time dynamic task sharing in HRC in the construction industry, specifically using industrial robots. This method not only facilitates seamless task allocation based on the strengths and limitations of each collaborator but also ensures a continuous workflow without interruptions.

BACKGROUND

HRC refers to scenarios where human workers and robotic systems operate simultaneously in a shared workspace to accomplish tasks (ISO/TS15066 2016). While robots excel at high-precision, repeatable tasks, human workers are better suited for tasks that require creative planning, perceptual understanding, experience, and improvisation (Sharif et al. 2017). There are various techniques for HRC in industry, which can be classified into five categories: physical HRC, teleoperation, gesture control, digital twins, and immersive technologies (Table 1).

Table 1. HRC technoques for industrial robot operation

Cat.	Techniques	Benefits	Risks	Reference
Physical HRC	Guiding robots via physical contact.	Reduces physical stress on human workers, retains human agility.	Potential safety hazard s from robot malfunctions.	(Ogenyi et al. 2021)
Teleop-eration	Remote opera-tion via joysticks cameras, haptic devices.	Protects operators from hazards and reduces physical exertion.	Limited field of view, high train-ing require-ments.	(Kha-sawneh et al. 2019)
Haptics, Gesture Control	Uses vision sys-tems and wear-able sensors for gestures.	Allows remote guidance of robots, intuitive interfaces.	Depends on gesture recog-nition accuracy.	(Suresh et al. 2019)
Digital Twins	Virtual represen-tations synchro-nized with the physical world.	Improves pro-gramming, enables dynamic tasks, boosts safety.	Limited applications in construction robotics.	(Liang et al. 2022)
XR Technol-ogies	XR for HRC in teleoperation and task setup	Improves visual-ization, design and safety training.	Limited practi-cal applications in construction.	(Mitter-berger et al. 2023)

Extended Reality technologies (XR), which offer immersive simulations for robot operation and planning tasks, have been a significant focus in the field of HRC. These technologies enhance the interface between workers and robots, providing visually rich and interactive environments for task programming and monitoring. Most of the literature on XR systems for human-robot interaction has utilized AR and Virtual Reality (VR) as a tool for robot teleoperation or programming interface. For instance, Rosen et al. introduced an AR system enabling users to set goal poses for a robot arm and preview its motion (Rosen et al. 2019). In the construction, there are extensive studies that utilize immersive technologies for data visualization, design (Song, Agkathidis, and Koeck 2022), safety (Chen et al. 2023), and training purposes (Pooya et al. 2022). Most existing XR and HRC systems are designed for small-scale tasks with robots manipulating smaller objects in controlled environments. Scaling these systems to construction tasks, where both the robot workspace and the target objects are substantially larger, presents significant barriers (Xi et al. 2021).

Despite the evident advantages of XR in sequential task sharing within a collaborative workflow, research has predominantly concentrated on robotic processes. Human labor is often relegated to tasks that are too challenging for industrial robots. Interaction and even structured, automated communication between human and robot units are often overlooked. Among the few studies that have explored dynamic task sharing using AR in HRC in construction, Amtsberg et al. (2021) made a significant contribution by introducing a method for AR-informed human-machine collaboration in timber prefabrication (Amtsberg et al. 2021). Their method uses a computational framework to provide an interface between human and robotic fabrication units via a mixed reality head-mounted display. This approach promotes a dynamically adaptive workflow where tasks can be shared between human and robotic units. Nonetheless, it relies on a task list interface in the AR environment, which can limit the immersive workflow of HRC by requiring users to manually select tasks for collaboration. To address these gaps, there is a need for new methods that support real-time dynamic task sharing. The proposed AR-assisted method seeks to contribute to this effort, fostering smoother collaboration within the construction industry.

METHODS

The proposed method integrates three frameworks: AR framework, computational framework, and robot control framework (Figure 2). This integration facilitates dynamic allocation and management of tasks between human operators and industrial robots. In the following sections, each framework is described in greater detail to illustrate its specific contributions and functionalities within the overall system.

AR Framework

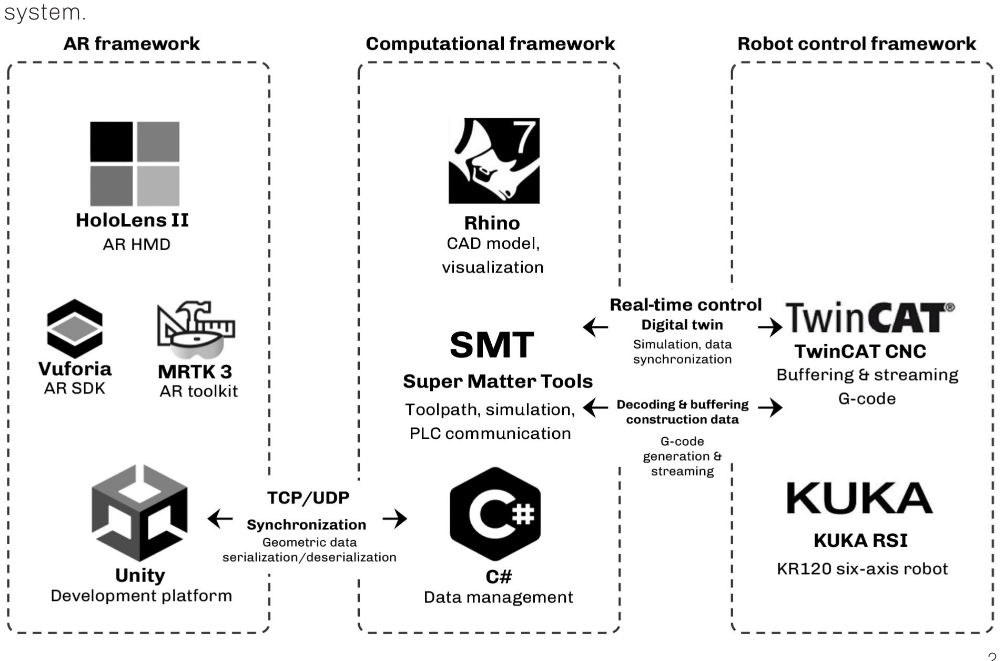
The AR platform is designed to facilitate communication between the user and the robot. It consists of four modules including communication module, design module, simulation module, and object tracking module. All modules were developed in Unity and are compatible with Microsoft HoloLens 2, based on MRTK3.

Communication module

In this study, we established a real-time communication link between Unity and Rhinoceros 3D, leveraging WiFi to facilitate data exchange. This system utilizes both the User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) to optimize the trade-offs between speed and reliability. UDP was selected for scenarios where low-latency updates were crucial, such as during real-time geometric modifications. In contrast, TCP was employed for scenarios requiring reliable data transfer, such as during the initialization of construction sequences and the transmission of complex mesh geometries. To ensure seamless interoperability between Unity and Rhinoceros 3D, we implemented data serialization, using JSON to encode and decode the transmitted data.

Design module

The design module, developed using Unity, functions as an immersive authoring platform that enables users to engage with 3D design features directly within an AR environment, eliminating the dependency on predefined models. Prior research showed the significant potential for integrating immersive AR platforms during the early design phases (Song, Agkathidis, and Koeck 2022). Such integration fosters

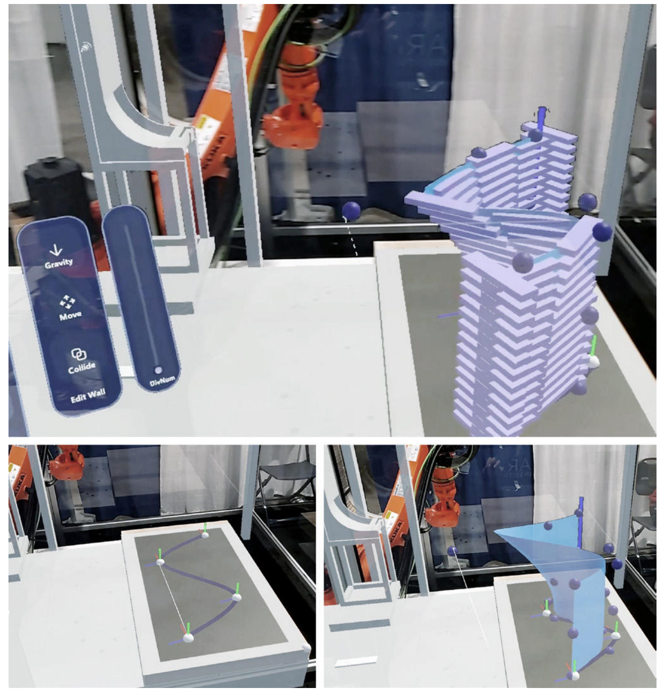


2 Software system architecture of the proposed AR-assisted HRC method.

a more consistent collaborative environment by allowing users to stay within a single AR environment for the entire design process, thus avoiding the need to switch between different software for designing 3D models. Furthermore, this module supports the use of gesture, gaze, and voice commands based on MRTK3 to design construction objects, enhancing user interaction and efficiency in constructing the target structure (Figure 3).

Simulation module

The simulation module incorporates both a virtual robot simulation and a real-time digital twin of the robot (Figure 4). The virtual robot simulation allows users to visualize and validate robot movements before construction, making necessary adjustments easier. Alongside this, the digital twin enhances robot communication by providing real-time updates on its position, orientation, and gripper status. The simulation data for these components is generated using Super Matter Tools (SMT), a custom computational design tool developed for offline programming and simulation (Pigram and McGee 2011).



3 Design module of the AR framework (HoloLens view).

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Tracking module

The tracking module integrates spatial mapping and image recognition technologies to accurately identify and monitor the position and orientation of objects in real-time. Utilizing the Vuforia Model Target System (VuforiaEngine 2024) we developed an algorithm that tracks the position and orientation of construction objects and compares it with the 3D model. This capability is crucial for accurately aligning digital content with the physical construction site, thereby enabling seamless interaction between users and the robot. By eliminating redundant task selection procedures, such as navigating through task list menus, this approach streamlines interactions. As a result, it allows users and robots to share and execute tasks more efficiently, minimizing the need for manual intervention.

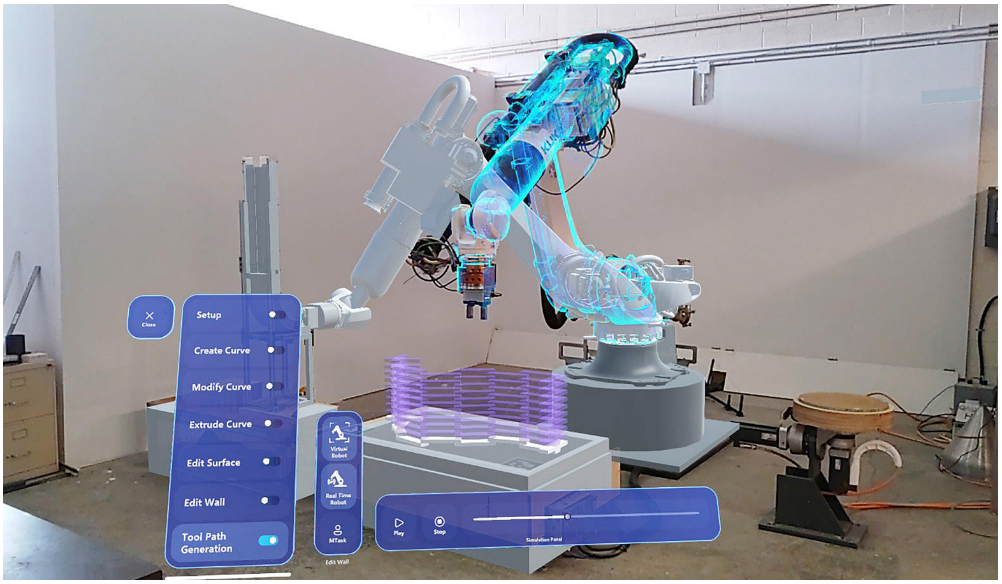
Computational Framework

The computational framework serves as the core for data processing and simulation within our AR-assisted method. This framework is built around SMT and Rhinoceros 3D, with all scripts and parametric computations developed in C#. The parametric data originates from the AR framework and the communication module described before, enabling seamless data exchange between Rhino and Unity. This integration allows for the finalization of designs within our system. Upon completing the design, the user transitions to construction mode, where toolpaths are generated. Throughout the construction phase, these toolpaths are dynamically updated to reflect changes in task allocations. In this study, we assumed identical tasks for the human and robot. Thus, when one party completes a task, the system automatically tracks the completed task and updates the toolpath accordingly. These capabilities are crucial for maintaining continuous alignment and updates between the computational model and the physical construction activities, facilitated through a real-time control loop with the Robot Control Framework.

Robotic Control Framework

The robotic control framework developed for this study specifically employs KUKA robots, which are mainly controlled through their exclusive KUKA Robot Language (KRL). In standard setups, commands are often pre-programmed and loaded into the robot's controller, which can limit flexibility in dynamic construction environments. This is particularly restrictive in HRC scenarios, where task conditions can change rapidly. While some manufacturers like ABB and UR enable streamed robot instructions via buffer, KUKA's KRC4 controller accommodates this through a lower-level feature, the Kuka Robot Sensor Interface (RSI). RSI allows for the streaming of Cartesian or joint positions with update rates of 4 or 12 ms.

To overcome these limitations, we utilize an industrial CNC motion controller that decodes and dynamically plans synchronous Cartesian motion trajectories. It supports the robot’s six degrees of freedom, manages joint velocity limits, and performs kinematic transformations to joint space in real-time, typically 1 ms. This capability is essential when navigating near the robot's kinematic singularities.



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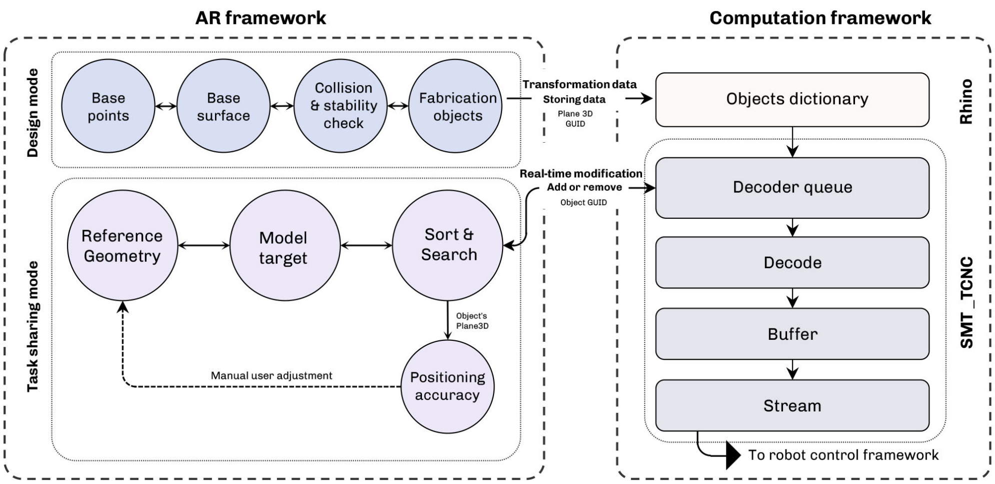
4 Simulation module including the virtual robot simulation, real-time digital twin, virtual assets, and UI (HoloLens view).



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We model this motion controller as a "virtual" robot, which allows streaming of planned joint positions to the KUKA KRC4 controller via the EtherCAT fieldbus. This setup is processed through the RSI interface. Utilizing Beckhoff's TwinCAT technology, which acts as a digital twin, enhances the system by enabling bidirectional communication with external software like Rhino or ROS (Liang et al., 2020). The TwinCAT CNC controller's streaming interface supports buffering and real-time interpolation of g-code instructions, facilitating adaptive fabrication processes.

Real-Time Data Streaming and Task Synchronization

The system's ability to adapt to real-time changes is facilitated by the "virtual" robot model which simulates the robot's kinematics and dynamics for preemptive adjustments to motion trajectories. This is particularly useful near robot singularities or when task conditions change unexpectedly. The EtherCAT fieldbus, employing Beckhoff's real-time interface, manages data streaming and synchronizes Cartesian and joint positions with update rates of 1 ms. This high-frequency update capability is critical for maintaining movement fluidity and precision in task execution, which is essential for safety and efficiency in shared operational spaces between humans and robots.

Dynamic Task Allocation and AR Integration

The integration between the robotic control system and the AR platform is mediated through real-time communication protocols that ensure seamless task sharing. A key feature of our method is its support for non-predetermined, flexible task sharing, which allows human operators and robots to collaborate seamlessly. The collaborative framework is designed to be adaptive, supporting spontaneous task reallocation and synchronous operations without causing downtime or delays in the construction process. Communication between the human and robot is facilitated through the AR interface, which provides a continuous feedback loop and updates on task progress and adjustments.

The communication module, connects the AR platform in Unity to SMT and TwinCAT CNC. This module ensures that both platforms AR for task visualization and robotic control for execution—operate in complete sync, thus facilitating a dynamic task-sharing environment (Figure 5).

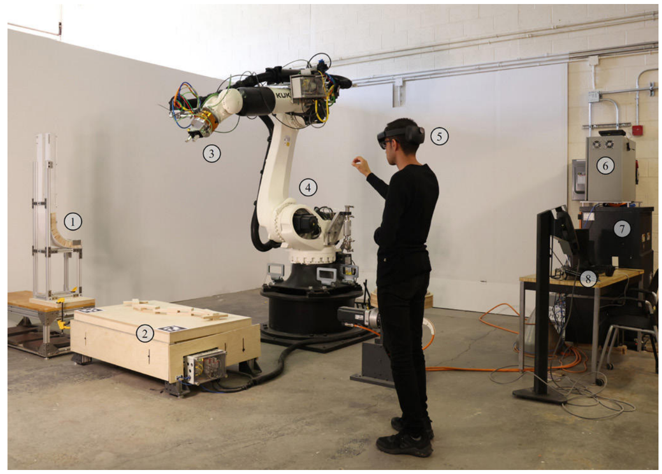
CASE STUDY

To validate the performance of the proposed method, a proof-of-concept construction experiment was implemented. This experiment involved the assembly of a modular wall structure, requiring both precise alignment and the ability to adapt to on-the-fly design changes. The fabrication testbed for this research comprised a KUKA KR 120 R2700 6-axis industrial robot arm, equipped with a Schunk EGU 50-EC gripper on the robot side and a Microsoft HoloLens2 for the human participant (Figure 6).

The basic pick-and-place process, serving as the main procedure for this study, begins with a human operator designing a free-form modular surface in the AR environment using hand gestures. After confirming the stability of the wall through a gravity check, the user initiates construction within the same AR environment. Concurrently, the robot starts to pick up 200×30×18 mm wooden elements from the feeder and places them on the testing bed. To demonstrate the dynamic task-sharing capability of the system, this test assumed the same task (pick-and-place) for both the robot and the human without any predefined schedule. Thus, the user was able to place subsequent elements concurrently while the robot functions seamlessly. An object-tracking algorithm aids the user in verifying the correct positioning of each element (Figure7). Once an element is positioned accurately, the system automatically relays the target object's data to the computational framework (Figure 8). This framework then updates the toolpaths for the remaining elements autonomously, eliminating the need for manual intervention. The construction of the wall, which involved the placement of 188 elements by both the robot and the user, was completed as a continuous, collaborative effort in 105 minutes (Figure 9).

DISCUSSION

This paper presents the initial deployment of our AR-assisted method for real-time dynamic task sharing in HRC within construction settings. We demonstrated the system's capability to manage basic task sharing effectively in a controlled environment. The results showed the average time of 20 seconds for the user, and 36 seconds for the robot to place a single element. This preliminary test is crucial in establishing a robust framework for more complex interactions in future studies. It confirms that simultaneous, dynamic task sharing between humans and industrial robots, without



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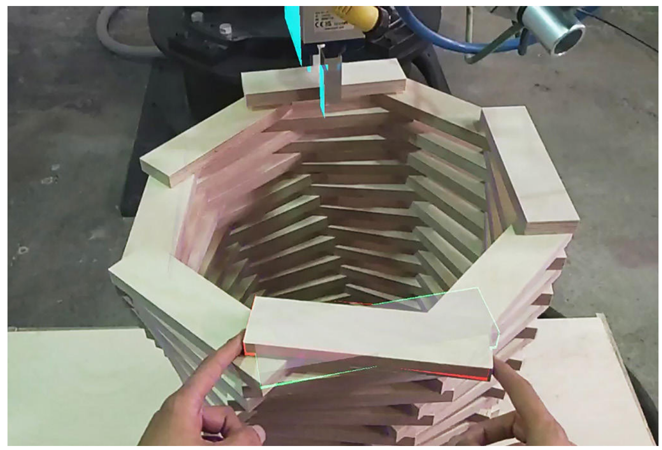
6 Fabrication setup, (1) Feeder, (2) ArUco Marker, (3) Gripper, (4) KUKA KR 120 Robot, (5) Microsoft HoloLens II, (6) PLC, (7) KUKA Controller, (8) Main Computer.



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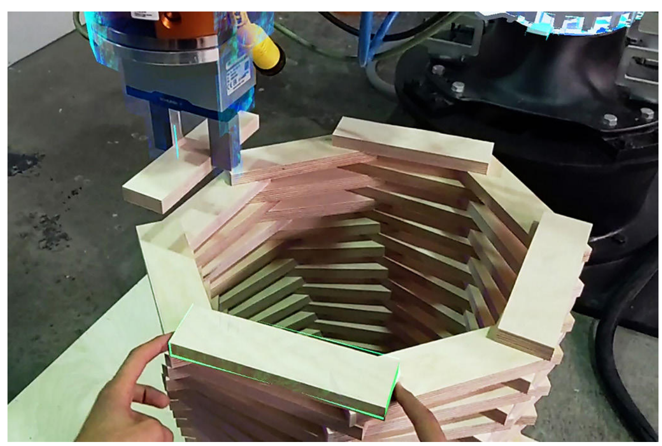
7 Object tracking module. (a) User adjustments are based on the virtual edge curves. A real-time algorithm compares the positions of the physical object's plane and the virtual object's plane and returns the results to the system (HoloLens view).



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8 Object tracking module. (b) Final position. Once the user begins placing the element, the robot skips that element automatically (HoloLens view).

interruptions, is achievable. The integration of AR with robotic control has laid the groundwork for a continuous, coordinated workflow, illustrating the platform's potential for more sophisticated systems. Our approach has improved the interaction between human operators and robots, creating a more intuitive and responsive collaborative environment. The dynamic task allocation system, supported by real-time data exchange and AR feedback, has enabled seamless cooperation without the delays typically associated with manual task coordination.

Limitations and Challenges
Several limitations were noted during the experiment. The system's dependence on the accuracy and robustness of the AR technology means that discrepancies in data or hardware malfunctions can disrupt workflow. Additionally, other feedback control systems need to be integrated to improve safety features for more complex dynamic task-sharing scenarios. Furthermore, although the proposed object tracking algorithm based on Vuforia target tracking technology can track objects with complex geometries in real-time, it increases the computation load and is limited to tracking one object during task execution. Therefore, developing a target tracking algorithm with less computational load will enhance the ability of the system to be implemented for more complex tasks where the user needs to perform more than one task simultaneously.

9 Final assembly of a modular wall structure

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Future Directions
Looking ahead, exploring more sophisticated algorithms for object recognition and tracking that can reduce sensitivity to environmental factors will be beneficial. Further developments will also seek to integrate machine learning techniques to dynamically adapt to real-time construction variations. Expanding the range of tasks that can be dynamically shared and exploring the scalability of the system for larger and more complex construction projects are also critical areas for future development.

CONCLUSION

This study introduced an AR-assisted method for real-time dynamic task sharing in HRC within the construction industry. By integrating an immersive AR platform with a robotic control system, we developed a framework that enhances flexibility and enabling seamless cooperation between human operators and industrial robots. Our proof-of-concept case study demonstrated the practicality of this method in facilitating uninterrupted collaboration and dynamic task allocation, resulting in no idle time for the robot and continuous workflow optimization. However, this study is not without its limitations. The current dependency on the precision of AR technology and the need for robust tracking mechanisms highlight areas for further research and development. Therefore, future explorations will focus on addressing the technological challenges identified, such as improving object tracking, refining data communication protocols, and expanding the system's ability to adapt to complex construction tasks. Furthermore, ensuring the safety and reliability of human-robot interaction will remain a paramount objective. This study lays a foundation for the seamless integration of AR into the future of construction robotics, aiming to create a symbiotic ecosystem in which human expertise and robot precision come together.

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