Advancing Construction Efficiency Through Collaborative Robotics: A Scalable Multi-agent-Based Logistics Solution

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Abstract. This research introduces a multi-agent-based logistics system for collaborative construction robotics to address challenges in efficiency, sustainability, and labour shortages. The system consists of and integrates human and robotic agents, creating redundancy and scalability within the construction process. By leveraging digital twin technology and Building Information Modelling (BIM), the system streamlines the entire logistics chain, from material arrival to construction activities. A key innovation is the integration of a modular space concept, in the present case construction container for material preparation and organization. The multi-agent-based approach controls complex logistics, gathering data from BIM and utilizing the data exchange platform Speckle, ensuring seamless collaboration between human and robotic agents. This research has the potential to significantly impact the construction industry by increasing efficiency, reducing waste, and improving project outcomes. The fully integrated workflow enables a high degree of automation in task planning. The proposed method offers a promising outlook for reshaping construction processes and contributing to a more sustainable and resilient built environment.

Keyword: Collaborative construction robotics · Multi-agent-based logistics · Construction container

1 Introduction

The construction industry is witnessing transformative changes due to robotics and automation, though implementation challenges persist due to the sector's complexity and fragmented logistics. These challenges often lead to delays and cost overruns, attributed to labour-intensive tasks such as material handling, which also pose safety risks. Various issues in site management and logistics complicate the deployment of automated technologies aimed at optimizing time, cost, and safety. Furthermore, the lack of structure in construction sites and the high cost of automation systems necessitate specialized personnel. Despite these hurdles, robotics could address industry issues such as labour shortages, safety concerns, and efficiency. This paper introduces a novel multi-agent-based logistics system that combines human and robotic agents for improved material

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and tool management. Our system leverages a digital twin and a modular construction container to enhance site logistics, bringing increased efficiency and resilience. This innovative approach has significant implications for the future of construction robotics and the industry overall.

2 Literature

The integration of robotics in construction has gained considerable attention in recent years, with numerous studies investigating various aspects of robotic systems in construction applications. Research has explored the use of multi-agent collaboration for building construction [1], BIM-integrated construction robot task planning and simulation [2], and human-robot collaboration in construction [3]. Further studies have delved into the adoption of automated facility inspection using robotics and BIM [4] and addressed the industry-specific challenges for adopting robotics and automated systems in construction [5]. Moreover the research has covered the current task management process and state of control systems in construction sites, related digital tools and similarities with systems of the autonomous intralogistics sector [6, 7].

The use of multi-agent systems has been explored in various domains, including supply chain risk management [8] and logistics robot scheduling [9]. Learning-based methods of perception and navigation for ground vehicles in unstructured environments have also been reviewed [10]. However, the literature lacks a holistic concept that integrates collaborative robotics in construction logistics, covering the entire process from material transportation to placement and utilization.

While some studies have explored BIM-integrated collaborative robotics for application in building construction and maintenance [11, 12] and BIM-based semantic building world modelling for robot task planning and execution [13], they do not provide a comprehensive approach that includes logistics, since the only creation of three-dimensional site layout plans and 4D coordination of site processes for updating the 4D logistics [14, 15] are not sufficient for an automatic construction logistic management (CLM). Additionally, the concept of digital twins in construction has been investigated [16, 17], but its integration with collaborative robotics for construction logistics remains unexplored. In particular the work preparation is not targeted and limited literature can be found on the topic of on-site fabrication in a modular concept [18, 19]. The on-site production models reviewed, even BIM-based, focus on safety stocks for material and time predictability but are affected by loss of a clear logistic planning where also space is a resource [20].

In summary, the existing literature provides valuable insights into various aspects of robotics in construction and multi-agent systems. However, a holistic approach that combines collaborative robotics and construction logistics, with a focus on both human and robotic agents, is yet to be explored. This paper aims to address this gap in the literature by presenting a comprehensive concept for multi-agent-based logistics for collaborative construction robotics and introducing a modular construction container that is used for work preparation.

3 Method

The proposed approach for multi-agent-based logistics for collaborative construction robotics combines a digital twin concept, a modular construction container, a multi-agent control system, and an advanced task planning application. The method leverages the Speckle platform [21] for data exchange, Building Information Modelling (BIM) integration, and the creation of a fully integrated workflow and unique data source for all stakeholders. The following sections provide a detailed overview of each component of the method:

Modular Construction Container
The modular construction container serves as a flexible and adaptable system for material preparation, storage, and transportation (see Fig. 1). Modules can be attached or detached depending on the project requirements, enabling material preparation tasks such as cutting bricks or insulation panels. Prepared materials are then packed in the correct order for efficient use on the construction site. Thus, the modular container system enables a streamlined transportation of materials to different levels or areas within the construction site, either by crane or robotic agents, minimizing delays and maximizing productivity.

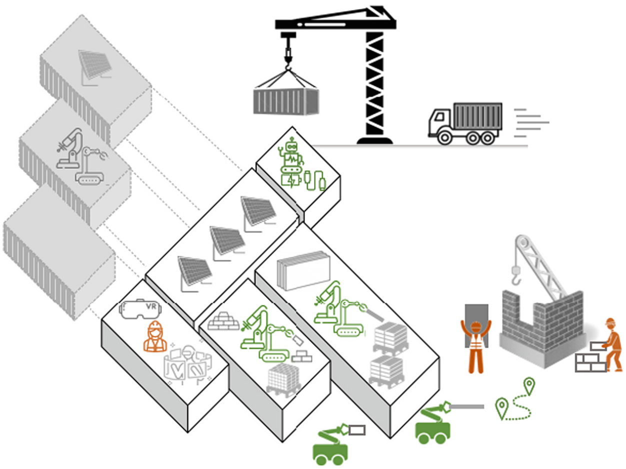

Fig. 1. Modular construction container system.

Integration with Speckle Platform Applying the Digital Twin Approach
The digital twin concept enables the creation of a virtual representation of the construction site, including materials, tools, robotic agents, and human personnel. This virtual model is continuously updated based on real-time data collected through sensors and IoT devices, ensuring accurate and up-to-date information for decision-making and task allocation. The digital twin model also allows for better communication, coordination, and visualization among stakeholders, leading to improved overall project management and automated progress monitoring. The establishment of a digital twin framework for

construction site management requires several core components to work together [22]. a physical environment, a digital environment containing the digital model enriched with multi-source data to construct a real-time representation of physical objects, and a communication mechanism used to transfer bi-directional data between the digital and physical twins with real-time data obtained through IoT state synchronisation (see Fig. 2).

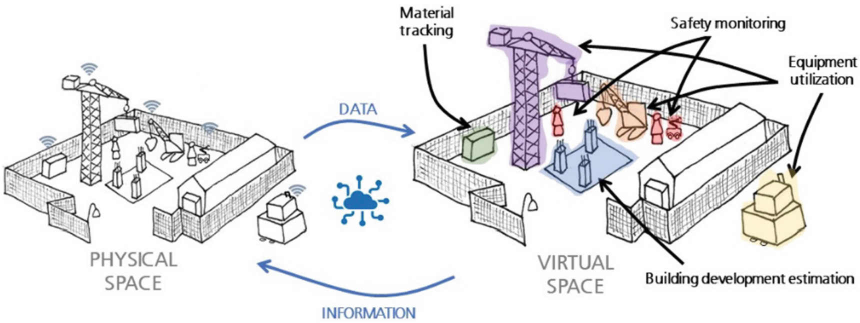

Fig. 2. Digital Twin concept for construction site

The Speckle platform, an open-source data exchange platform, facilitates seamless communication and data sharing between different software tools and applications used in the AEC (Architecture, Engineering and Construction) industry. By developing the task planning application on the Speckle platform, the proposed method willbenefit from seamless integration with existing BIM workflows and software tools, creating a fully integrated workflow and unique data source for all stakeholders involved in the construction logistics chain.

The open-source nature of Speckle allows for easy customization and adaptation to the specific needs of different construction projects. Moreover, the platform's ability to store processes, tasks, and pre-calculated trajectories enables efficient data management and sharing among all stakeholders involved in the logistics chain.

Task Planning Application

The task planning application, built on the Speckle platform, will be designed to streamline the process of assigning tasks to both human and robotic agents (see Fig. 3). The application leverages the digital twin concept and real-time data from the construction site, intelligently allocating tasks based on factors such as agent availability, skills, and the urgency of tasks. The application will provide a user-friendly interface for monitoring progress, making necessary adjustments to the task schedule, and visualizing the current status of the project. The task planning application will incorporate advanced automation features, reducing the need for manual intervention in various aspects of task planning. For example, the application can automatically generate laying patterns for insulation panels based on the BIM model and construction site data, ensuring that materials are placed in the most efficient and effective manner. Additionally, the application can optimize task sequences and schedules, considering the interdependencies between tasks and the availability of resources such as tools, equipment, and agents. This level of automation enables seamless coordination between human and robotic agents, ultimately leading to more efficient and productive construction processes.

Fig. 3. Task Planning Application.

Multi-agent Control System
The multi-agent control system coordinates the actions of both human and robotic agents involved in the logistics chain. It utilizes a data-driven approach, gathering information from the task planning application and the Speckle platform. Robots receive information about upcoming tasks to their control systems, while humans receive tasks through mobile or smart devices. This coordinated approach ensures that tasks are allocated effectively, taking into account agent skills, workload, and priority, leading to a more efficient construction process. Figure 4 shows potential agents in the presented concept of the modular construction container.

The construction container is a separate agent (here A), the crane (likely to be controlled by a human person is agent B. The tasks of transport (within a storey) and the construction (here of a brick wall) are done by robots (agent C and D). In our concept all agents can be represented either by a human being or a robot. This increases the resilience of the construction process, i.e., to replace a defect robot or to resolve a bottleneck in logistics by adding an additional agent for a limited time. For the multi-agent based control approach we will work with methods and results presented in [23] and [24], based on decentralized systems composed of several modules and cores.

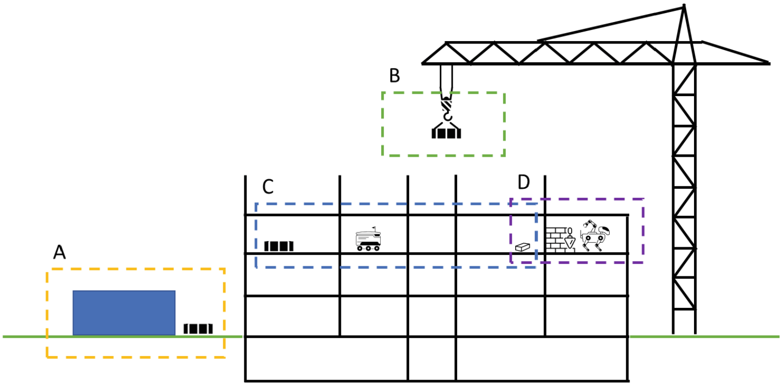

Fig. 4. Agents on construction site.

4 Expected Results

The proposed method for multi-agent-based logistics for collaborative construction robotics is anticipated to yield several significant results, which are expected to revolutionize the construction industry and contribute to a more efficient, resilient, and sustainable built environment. The presented parts are currently under development and realization. The expected results include:

Increased Efficiency and Productivity: The seamless integration of human and robotic agents, automated task planning, and the digital twin concept will streamline construction processes, minimizing delays, and optimizing resource allocation. By automating repetitive labour-intensive and time-consuming tasks, such as material handling, transportation, and placement, the method will allow human workers to focus on more complex and value-added activities, ultimately leading to higher productivity levels, enhanced efficiency and accuracy and reduced construction time.

Enhanced Resilience and Adaptability: The multi-agent control system and modular construction container enable the method to adapt to changing project requirements and unforeseen challenges. Since robotic systems can collaborate with human workers, providing complementary skills and capabilities to enhance logistics on construction sites, the system can dynamically allocate tasks to different human or robotic agents based on their availability and skill set, ensuring that the construction process continues even in the face of unexpected disruptions. This adaptability contributes to a more resilient construction process, better equipped to handle uncertainties and fluctuations in the construction environment.

Improved Communication and Collaboration: By creating a unique data source and fully integrated workflow through the Speckle platform, the proposed method facilitates better communication and collaboration among all stakeholders involved in the construction logistics chain. This enhanced collaboration will contribute to more effective decision-making and streamlined project management, ultimately leading to a more successful project outcome.

Cost Savings and Waste Reduction: The advanced task planning application, automation features, and communication technologies for real-time monitoring, data collection and data analysis can contribute to optimize resource allocation and to more efficient material usage and waste reduction. By optimizing material handling, transportation, and placement, the method will minimize waste generation and help reduce overall construction costs. In addition, the improved efficiency and productivity offered by the method can lead to shorter construction times and cost savings.

Safer Working Environment: The integration of robotic agents in the construction process can help reduce the risk of accidents and injuries on the construction site. By automating tasks that involve heavy lifting, working at height, or exposure to hazardous materials, the method will help create a safer working environment for human workers and reduce the potential for workplace accidents.

Scalability and Futureproofing: The proposed method, built on the open-source Speckle platform, offers a high degree of scalability and adaptability to meet the evolving needs of the construction industry. The modular construction container concept, the multi-agent control system, and the task planning application can be easily adapted and scaled to accommodate new technologies, tools, and construction methods, ensuring that the method remains relevant and effective in the face of ongoing technological advancements.

5 Outlook

The future of collaborative construction robotics through multi-agent-based logistics is promising, with potential to revolutionize the construction industry. Key research areas include technological advancements, interdisciplinary collaboration, standardization, education, and sustainability. Embracing innovative technologies like AI and machine learning will enhance decision-making and efficiency in construction processes. A holistic approach that fosters collaboration between architecture, engineering, and construction management is necessary to effectively integrate human and robotic agents. As construction robotics gain popularity, establishing industry-wide standards for safe and effective implementation is crucial. It's also essential to consider potential sustainability contributions, such as waste reduction and resource optimization, while assessing the social impact on employment and worker safety.

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