Integrating Automation into Construction Site: A System Approach for the Brick Cutting Use Case

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Abstract –
The integration of robotics, automation and digital technologies into construction processes offers opportunities for increased efficiency, adaptability and sustainability. However, a comprehensive integration of these technologies is still missing. This paper proposes an integrated systems approach using collaborative construction robotics, a modular construction container and an advanced tasks application connected to a multi-agent control system to address challenges in efficiency, sustainability and labour shortage in construction site to optimise construction workflows and processes. The focus is on establishing on-site factories and using mobile manufacturing technologies to revolutionise traditional construction methods. The methodology includes modular construction containers, collaborative construction robotics and advanced task applications to streamline construction operations. A case study of automated brick cutting illustrates the feasibility and potential benefits of the proposed approach. The multi-agent control system coordinates human and robotic agents to increase the efficiency and resilience of construction processes. The paper concludes with insights into future research directions, emphasising safety, efficiency, adaptability and scalability in addressing the dynamic nature of construction environments. Through this integrated approach, the construction industry can achieve improved productivity, safety and sustainability, paving the way for transformative changes in construction practices.

Keywords – Construction container; Construction processes Automation; Collaborative Construction Robotics; Advance Task Planning; Multi-agent-based system

1 Introduction

Robotics and automation are transforming the construction industry, but implementation challenges remain due to the sector's complexity and fragmented logistics. The deployment of automated technologies and prefabrication is hindered by various site management and logistics issues, which negatively impact productivity in terms of time, cost, and safety. Construction automation is challenging in the construction industry due to the need for on-site operations and the absence of a fixed workspace like most manufacturing sites have. Moreover, the high cost of automation systems and the unstructured nature of construction sites require specialized personnel. However, robotics offers a promising solution to address issues relating to labour shortages, safety concerns, and efficiency. Customizing construction elements, such as bricks or insulation panels, or replacing parts of existing structures, poses a high level of risk on-site, as it often requires of saws, cutters or drills and is carried out frequently throughout the working day. One possible solution is to automate established design processes, employing programmable machinery and robotic equipment to load machinery and transport components to the assembly location. This would improve working conditions and enhance procedural accuracy by partially relieving workers of hazardous, monotonous, and physically demanding tasks.

This paper introduces an integrated systems approach based on an initial prototype employing robotics and multi-agent-based strategy aimed at automating construction tasks. The prototype integrates human, production equipment, and robotic agents to streamline material preparation and tool management. Employing an advanced task planning application alongside a modular construction container, the system aims to bolster on-site production, fostering enhanced efficiency and resilience. This early prototype serves as a crucial step in identifying and addressing open issues within construction automation, setting the stage for more targeted and specific research in the field.

2 State of the art

The integration of robotics in construction has received considerable attention in recent years, with numerous studies investigating different aspects of robotic systems in construction applications. The current state of automation and robotics in construction, coupled with BIM-based task planning and multi-agent control platforms, reflects a transformative shift towards efficiency, precision, and adaptability in the industry. 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]. In addition, the research has addressed the current task management process and state of control systems in construction sites and associated digital tools [4] to understand how using Industry 4.0 enablers and interconnection on a construction site can improve productivity [5]. Task planning and control activities can meet the information needs of workers and preparation of materials, thus optimising the time for installation work [6].

The use of multi-agent systems has been explored in various domains, including supply chain risk management [7] and robot scheduling [8]. [9] advocate for a platform-based approach to automation in construction, emphasizing the need for integrated systems to optimize resource allocation and project coordination highlighting the potential for automation to streamline on-site construction processes. Some studies have explored BIM-integrated collaborative robotics for application in building construction and maintenance [10, 11] and BIM-based semantic building world modelling for robot task planning and execution [12] so that the use of automated or robotic tools combined with BIM, which provides positioning data for automated or semi-automated assembly, can speed up the construction process [13].

In addition, the concept of digital twins in construction has been explored [14], [15], together with its integration with collaborative robotics for construction tasks in generating realistic simulations to prototype robotic solutions suitable for specific tasks [16]. Recognizing the recent advancements related to applications of machine learning and digitalization, [17] propose to open the perspective from the discussion of single construction activities (e.g. additive manufacturing, automated installation, assembly or bricklaying) towards an integrated robotized construction site including innovative materials, improved robotic hardware and streamlined construction workflows.

In particular, component assembly requires workers to repeatedly measure and calibrate, resulting in low construction efficiency. Using on-site factories and automated tasks can create opportunities for improved productivity, profitability, and sustainability compared to manual labour and traditional off-site prefabrication, unrealistic and expensive. [18] discuss the challenges and opportunities for digital in situ fabrication in architecture and construction. Their research underscores the transformative potential of robotic technologies in redefining traditional fabrication methods. This approach aims to mitigate waste, predominantly resulting from transport, rework, and storage, by maximising outputs from enhanced inputs [19, 20]. [19] advocate for the establishment of on-site factories to support lean principles and industrialized construction practices. Their research highlights modularization and prefabrication as strategies for enhancing project scalability and adaptability. Implementing a process of low to high-level fabrication and assembly of components on a site using fixed or mobile automated machines/robots, instead of traditional construction methods, has the potential to automate construction processes [21]. [22] present mobile additive manufacturing, a robotic system for cooperative on-site construction exploring the potential of additive manufacturing technologies to enable on-site fabrication and construction for greater flexibility and adaptability in building processes.

The construction industry is characterised by greater uncertainty and variability of operations and requires modern organisational models based on lean principles for small, flexible and scalable production units that can be moved directly to the construction site [23], reducing lead times and waste in the construction processes, minimising the use of materials to ensure excellent mobility and on-time delivery. The reviewed on-site manufacturing models, even those based on BIM, focus on safety stocks for material and time predictability, but suffer from a lack of planning of workers and resources, where space is also a resource [24]. In particular, work preparation has not been targeted and there is limited literature on the topic of modular on-site fabrication [17, 25, 26]. However, the literature lacks a holistic concept that integrates collaborative robotics into construction processes, covering the entire process from material transport and preparation to placement and use.

Despite recognizing the potential synergies between BIM-based task planning and multi-agent control platforms, existing research reveals significant gaps in integrating robotics and automation into construction processes comprehensively. These gaps encompass various aspects, including task planning, control, collaboration, and the absence of holistic methodologies that address the entire construction lifecycle from planning to execution. Addressing the identified gaps in the literature and advancing the understanding of the integration of robotics, automation and digital technologies in construction processes requires answering critical research questions. These questions include how on-site factories and mobile manufacturing technologies can revolutionise traditional construction methods, enabling greater flexibility, adaptability and sustainability in construction processes. Additionally, methods and strategies to improve material preparation, workforce planning and resource allocation within construction projects must be explored. An integrated systems approach using robotics, automation, BIM-based task planning and multi-agent control platforms would result in streamlined construction workflows and processes to optimise material preparation and resource utilisation. A new systems approach, together with the implementation of flexible production units, would enable agile and responsive construction operations, leading to improved project scalability, adaptability and sustainability.

3 Implementation

The scope of this research is limited to providing and testing a system approach and methodology for handling heterogeneous and dynamic processes and data in the construction industry, specifically for some common and hazardous tasks on construction sites.

3.1 Modular approach

The integration of collaborative construction robotics, modular construction containers, and advanced task applications linked to multi-agent control systems an attempt at a paradigm shift in construction methodologies and processes. This section describes the methodology adopted to realize this integrated approach, aimed at generating a seamless workflow that enhances construction efficiency and adaptability. At the core of this integrated approach lies the modular construction container as a flexible and adaptable system designed to facilitate material preparation, storage, and transportation.

This modular approach supports the idea that on-site factories can be used on different projects and be scalable according to the project needs. Modules can be attached or removed according to the project requirements, enabling material preparation tasks such as cutting bricks or insulation panels. The prepared materials, resulting from a single assembly line with a low-mid level of automation, are then packed in the correct sequence for efficient use on the construction site (Figure 1).

By using a task planning application specifically designed for allocating tasks to both human and robotic agents, we can use the digital twin concept and real-time data from the construction site to allocate tasks intelligently. This process considers factors such as agent availability, skills, and the urgency of tasks. For instance, an application could generate brick laying patterns based on BIM model and construction site data, optimizing material utilization. The same application could optimize task sequences and schedules, taking into account task interdependence and the availability of resources like tools, equipment, and workers.

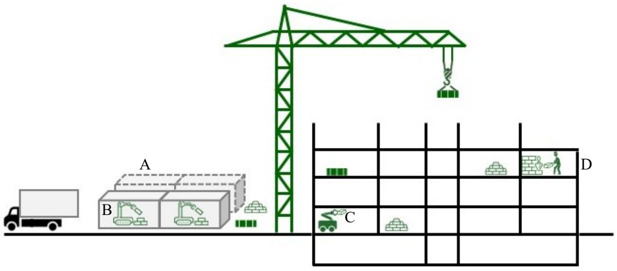

Figure 1. Modular construction container and multi-agent system

The methodology consists of several steps. A pivotal phase is included, focusing on software development and integration to digitally manage equipment, including robots and machinery, to fulfil the identified use cases of the on-site factory. The first step was the implementation of the on-site factory and configuring the container and its equipment. Subsequently, an automated and programmable system is developed to equip the machines for semi-automatic operation. Next, focus on software development and integration to digitally manage equipment (robots and machinery) to fulfil the tasks for the on-site factory's identified use cases. Achieving integration between the various technologies required to streamline a system and an adaptable approach and process flow that could, in the future, with specific research, meet the standards of rapid reconfigurability, accuracy and performance required by the industry.

3.2 Case study

The construction industry has historically underinvested in technology and appears to be resistant to change. The use of technology in planning, delivering, and operating construction projects carries great potential for saving costs, enhancing quality, and increasing speed.

Brick cutting is a relevant use case because modifications are frequently necessary. Brick cutting is a common task on a construction site, as walls are often not multiples of brick sizes. This requires adjusting the dimensions of one or more bricks to achieve the correct size. Additionally, changes to the dimensions of openings or other structural elements during construction also necessitate brick cutting. Unfortunately, this task exposes workers to significant health risks. The implementation of programmable machines, along with robotic tools for loading and unloading the work surface, offers a high degree of flexibility and automation. As a result, it enables customisation and automation of a significant proportion of the work executed on-site, which is currently performed by on-site workers, frequently outdoors and near the building site.

From the BIM model data, precise element dimensions and placement details essential for construction can be obtained. This information is crucial as it informs the cutting parameters for the machine and coordinates the final delivery of the finished part on the robotic platform. Creating an isolated and controlled area, monitored by the workers, for this activity that utilizes high-risk equipment will enhance the safety and working conditions of the workers by enabling better control. By relocating this task to a secure and closely monitored facility and enabling robotic machinery to carry out the task instead of or in support of the worker, the aim is to achieve greater precision and efficiency with a focus on safety. The handling of the bricks cut-out by machines can be passed on to robotic platforms, which precisely deliver the parts to the operator on-site when and where they are required. This process saves time by enabling the worker to stay on site instead of interrupting operations to cut and transport bricks, while also enhancing safety by reducing the number of workers working at the site.

3.3 Proposed framework

3.3.1 Definition of the requirements

The challenges of the system approach based on a construction container for the automation of construction tasks and integrated agents' management include a restricted working area, complications in handling various brick shapes and weights, unpredictability regarding agents' collaboration in the operational environment, and task variability, which requires operations and activities to be performed through motion and interaction control. The definition of functional and technical requirements of the systems involved interpreting the needs of the end users, so they were organically derived from the use cases in terms of reliability, consistency, productivity safety and accuracy.

- Configuration: provide a system, software and control framework related to the configuration required by the use case.
- Operation: provide a system for planning and executing the use case.
- Safety: provide a comprehensive safety management system for the use case.
- Planning and monitoring: provide a system for planning and monitoring the execution of the tasks through an intuitive GUI linked to the digital twin of the construction container.
- Accuracy: the accuracy needed by the operation has been defined by improving the quality of the component information provided by the BIM model.

3.3.2 Agents definition

The multi-agent control system coordinates the actions of the human and robotic agents involved in the construction tasks. This approach ensures effective allocation of tasks, taking into account agent skills, workload, and priority. As a result, the construction process becomes more efficient. The construction container, represented as agent A, customizes and stores bricks. Agent B, a separate robot, sets up the brick cutter (agent C) and separates usable bricks from rejects. The transportation and construction tasks, specifically constructing a brick wall within a storey, can be efficiently performed by robots - agent D (Figure 2).

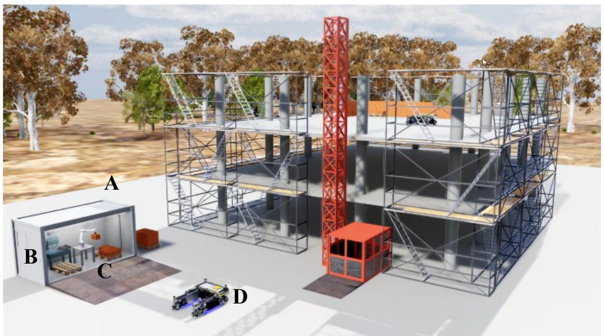

Figure 2. The multi-agent control system

This increases the resilience of the construction process by replacing a faulty robot or resolving a bottleneck in carrying out a given task with an additional agent for a limited time. The data-driven approach gathers information from the task planning application, enabling robots to receive updates about upcoming tasks on their control systems while humans can receive tasks through mobile or smart devices.

3.3.3 Hardware Architecture

The construction container consists of a 4.8x2.4m on-site container housing the automated production system. The development of the automated production system involved compiling a list of components and tools based on defined requirements and desired features.

The completed setup included a 6-axis collaborative robot arm (Universal Robots UR10e) with a two-finger gripper (Onrobot RG6) and a brick-cutting machine (IMER M400 Smart). The machine has a water-cooled saw with a diameter of 400 mm and a pusher that moves independently via a linear actuator. In addition, the machine is enclosed in a Plexiglas structure to prevent splashes that could damage electrical components. The elements communicate via a private Ethernet connection within the container, with each component assigned a unique IP address. This communication is facilitated by a central switch (D-Link DGS-108).

The gripper was integrated using the MODBUS communication protocol. The saw was chosen for its compatibility with the automation, which was achieved by incorporating a DC motor moving a linear guide connected to the saw carriage by an Oldham joint and controlled by a DC brick (Tinkerforge).

3.3.4 Software Architecture

The construction container's software architecture comprises three main elements: one for robot motion planning, another for controlling the brick-cutting machine, and a third for the User Interface (UI). These components are connected via an MQTT broker, enabling message exchange in JSON format, as illustrated Figure 3.

The robot's trajectory has been planned for brick handling using the ROS Moveit framework. The Pilz Motion Planner performs the planning using a Python program for simulation in RViz to provide visualisation and validation.

The robot is capable of performing four distinct pick and place tasks, depending on whether brick cutting is necessary. These tasks include transferring items from the source pallet to the machine, transferring items from the source pallet to the destination pallet, transferring items from the machine to the destination pallet to unload the desired part, and transferring items from the machine to the warehouse to unload the remaining part. The machine can move both forwards and backwards. An error management protocol has been integrated to handle any failures. The user interface enables communication with the backend using the three.js JavaScript library.

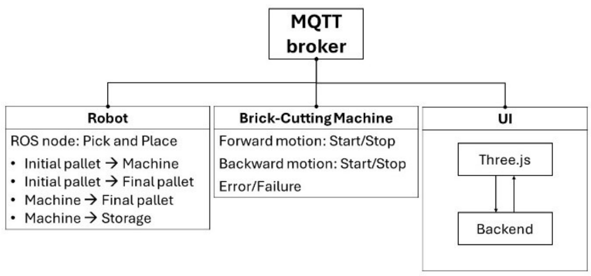

Figure 3. Software architecture

Figure 4 presents an example of agent communication. The scenario illustrates the UI indicating that one brick requires cutting, while another brick needs to be placed directly on the final pallet as a whole brick. The UI initiates communication by sending a message that includes the dimensions of the bricks, the specific tasks assigned to each agent, and the predetermined order in which these tasks are to be performed. The manipulator loads the brick onto the machine. Once the task is complete, it sends a message to load a brick directly onto the final pallet and another message to the machine to start cutting. After the cutting process, the machine sends a message to the robot to unload the two parts, which then informs the UI that the task is complete.

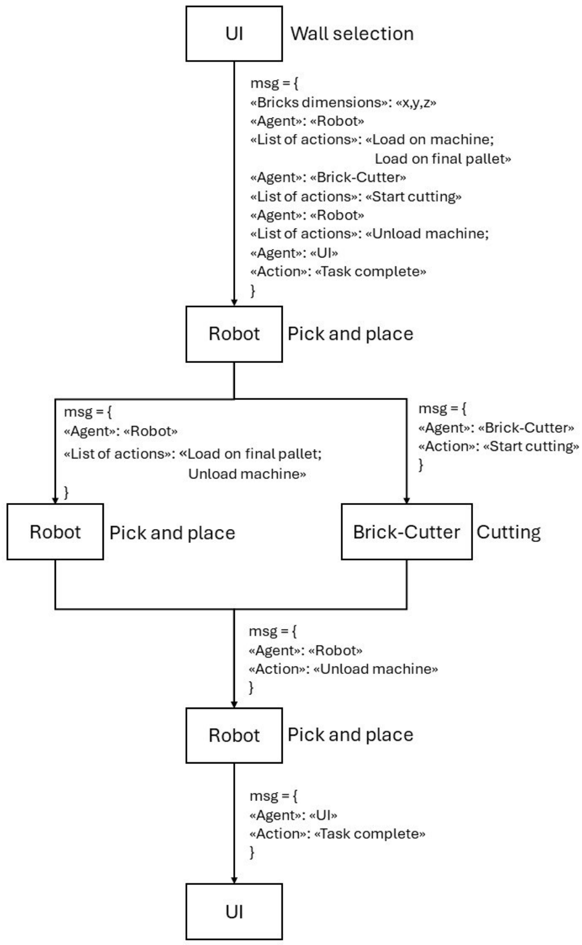

Figure 4. Agent communication

3.3.5 Task planning application and User Interface

Effective communication among the agents involved in the on-site construction phase is a crucial factor for project success. Planning and control actions that facilitate construction work include tasks such as organising production areas, coordinating material transportation, and setting up tools.

The implementation of process automation and robot operations has led to the creation of a task planning application. This tool effectively manages the necessary information sources for executing tasks and the available actors for completing them. It generates multiple tasks from the building's BIM file and assigns them to the most appropriate and available actor (either a robotic arm, a human worker, or manufacturing equipment) via an intuitive graphical interface (Figure 5). The application integrates machines and robots to manage and prioritize tasks, cooperatively handling more complex tasks, thus facilitating on-site coordination and communication.

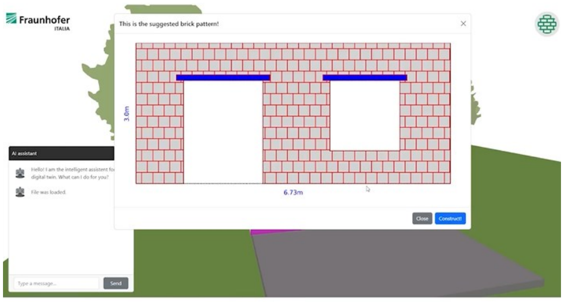

Figure 5. Task Planning Application User Interface

The system consists of a high-level planner which identifies tasks and robot base positions, and a basic planner, which computes a collision-free trajectory.

4 Results

The feasibility of the first prototype for the proposed integrated system approach for automating construction tasks using collaborative construction robotics and multi-agent control systems has been tested. The results indicate that it could be adopted as an alternative workflow, with the potential to revolutionise the construction industry and contribute to a more efficient, resilient, and sustainable built environment if the remaining issues are addressed by specific research. The study suggests that this approach has the potential to be a game-changer in the construction industry, but measurable benefits have yet to be demonstrated. The presented work is currently undergoing further development since its initial presentation at the DiSC - Digital and Sustainable Construction Conference 2023 in Bolzano. A dedicated showcase session was held to gather feedback from participants. The test carried out suggests that it may be possible to automate labour-intensive and time-consuming tasks, such as brick cutting, material customisation, and placement. This could lead to improved working conditions on construction sites, as workers can focus on more complex and value-added activities, potentially resulting in improved safety, productivity, efficiency, and accuracy.

4.1 The construction container - Automated on-site prefabrication

Due to the interdisciplinary nature of construction engineering and research, and the innate challenges of conducting studies in real-life settings, validating construction domains poses various challenges.

Figure 6. The construction container - Automated on-site prefabrication

The construction container (shown in Figure 6) acted as a mobile factory shell, serving as an external laboratory for testing and verifying the feasibility of the proposed approach and its applications in real-world environments such as construction sites. The feedback provided reliable information on the consistency of the method and process, as well as immediate feedback on critical issues. It also has the potential for resolution or future development. Automating operations that involve exposure to hazardous equipment or materials can create a safer working environment for human workers and reduce the potential for workplace accidents. The presented system approach has been shown to be effective in achieving these goals.

The multi-agent control system and modular construction container allow for adaptation to changing task requirements and unforeseen challenges. The task planning system can allocate tasks dynamically to human or robotic agents located in different containers based on their availability and skill set. This ensures the construction process continues even in the face of unexpected disruptions. This flexibility could help to make the construction process more adaptable to uncertainties and fluctuations in the workforce on site.

4.2 Automated brick cutting system

Due to the high degree of customisation in the construction industry, it is challenging to apply standardisation and prefabrication techniques off-site without requiring frequent revisits and modifications on site. Therefore, the possibility of establishing mobile factories on site has emerged to meet the demand for customised special pieces, including bricks and insulation panels. An automated system for cutting bricks has been developed and tested with the aim of producing tailor-made building materials.

Robot tasks involve (Figure 7a/b):

1. Brick grasping from their initial position.
2. Loading the machine to execute the task

and to match brick dimensions.
3. Unloading the cut parts.
4. Loading entire bricks onto the final pallet.

The waste can be reused in the construction process if its dimensions match the need for other special pieces to build walls on the site, as derived from the BIM model. By optimising material consumption and placement, this method would minimise waste generation and would help to reduce overall construction costs.

Figure 7 a/b: Automated brick cutting system

The integrated system approach consisting of the modular construction container concept and the task planning application could be easily adapted and scaled to meet the needs of other tasks or to accommodate new technologies, tools and construction methods. The test carried out showed that the approach remains relevant and worthy of further development in the face of ongoing technological advances.

5 Conclusion & Outlook

The aim of this paper is to outline the proposed system approach for addressing automation and collaborative robotics in an integrated workflow to manage performance and safety issues related to specific construction site tasks.

The modular system approach focused on the on demonstrating the feasibility of using a fully automated workflow to perform tasks on site, using task planning and execution BIM-based and collaborative robotic arms. The results indicate that automated brick cutting workflow is faster than the manual process, where workers have to go to the point, measure, and return to the cutting machine to execute the task. However, so far, no measurable data has been collected in terms of final accuracy and overall performance.

Research indicates that the path is feasible, but it can be further improved to fulfil the requirements for safety and efficiency, and for demonstrating a high level of adaptability and versatility in response to the constantly changing and dynamic nature of the construction site.

Issues regarding speed and performance must be addressed while prioritising safety. Enhanced grasping capabilities can be achieved through the implementation of advanced vision object recognition algorithms based on deep learning and the development of custom machines and tools. This will lead to increased speed and greater robot efficiency.

Future research should also consider the complete process, including the delivery of bricks to the construction site. This would address the challenges of handling and transporting pallets loaded with bricks.

Additional insights should therefore concentrate on fulfilling container space requirements that meet market demands, coordination of multiple on-site factories, and testing the automated system's speed limits to optimise productivity.

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