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REGULAR PAPER

Robotics in assembly-based industrialized construction: a narrative review and a look forward

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Abstract

The significant quality and productivity improvements realized through the adoption of robotic systems in the manufacturing industries have sparked the interest of construction researchers and practitioners to explore their potentials in the construction industry. However, the lack of technical and financial knowledge among construction practitioners concerning robotic applications, the unique nature of construction projects, and fluctuating demand limit the widespread implementation of robotic systems in construction projects. The research present in this paper conducts a narrative review of state-of-the-art and state-of-the-practice of the application of robotic systems in the construction and manufacturing industries to augment automation in industrialized construction by identifying the limitations and potential directions of robotics. The proposed mapping system connects the identified robotic systems to offsite assembly and onsite installation tasks of industrialized construction. The study results revealed that robotics in industrialized construction is considerably under-researched, leaving significant room for improvement. Indeed, only six out of the twenty-five identified industrialized construction tasks, namely panel framing, boxing station, drywall installation, inspection, excavation/site rough grading, and surveying, have been sufficiently explored in the literature. This research intends to educate and inform construction practitioners about the potential integration of existing robotic systems into industrialized construction.

Keywords Industrialized construction · Robotics · Construction automation · Offsite assembly · Onsite installation · Literature review

1 Introduction

According to International Data Corporation (IDC), the worldwide spending on robotics systems and drones amounted to $128.7 billion in 2020 and is expected to reach $241.4 billion by 2023 (IDC Media Center 2021). In 2020, about 2.7 million robots were in operation; an impressive 100-fold increase from the number four decades ago (IFR presents World Robotics Report 2020). Indeed, robots have a strong presence in many sectors such as automobile, electronics, and metal industries, where they perform a wide range of tasks from welding to material handling and assembly (Tani 1989; Graetz and Michaels 2018). The rise in robotic adoption stems from high demand for productivity and quality improvements in different manufacturing sectors (Graetz and Michaels 2018; Ishitani and Kaya 1989), with a proven record of achieving the sought-after improvements (Edwards 1984; Bock 2015; Ballestar et al. 2021). For example, in the automobile industry, the need for reduced production times and the necessity of movement of heavy parts have been aiding the robotic expansion in this industry (Edwards 1984; Seliger 1988).

Although robots have been introduced to the construction industry since the 1980s (Skibniewski 1988; Bock 2007), their integration remains low (Bock 2015). This can be attributed to the lack of in-depth knowledge of construction robots and the risks associated with robotic adoption (Pan and Pan 2020; Davila Delgado et al. 2019; Wuni and

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Shen 2020). de Soto et al. (2018) argue that the research into robotics applications in the construction industry is fragmented, which impedes the much-needed transition to full automation (Willmann et al. 2016). Furthermore, the distinct characteristics of construction projects and the diversity of construction elements add to the complexity of technology adaptation in construction practices (Bock 2015).

Despite the slow start, there are signs of enthusiasm among construction researchers toward integrating robotics in construction. Prefabrication and assembly of large timber structures (Willmann et al. 2016; Eversmann et al. 2017), applying foam concrete to vertical walls (Lublasser et al. 2018), 3D mapping and surveying of construction sites, and construction progress monitoring using unmanned aerial vehicles (UAVs, i.e., drones) (Álvares et al. 2018; Mahami et al. 2019) are some examples of robotic applications in the construction industry.

These promising results have driven researchers to review the current state-of-the-art of robotics applications to investigate their impact on construction automation. Melenbrink et al. (2020a) conducted a literature review on robotic applications in site preparation, prefabrication, onsite assembly, and 3D printing. Buchli et al. (2018) discussed the opportunities and challenges of in-situ fabrication using robotics and proposed an in-situ fabricator for finished building shells. Orlowski (2020) reviewed robotic utilization achievements in the field of timber panelized wall systems. Dadhich et al. (2016) limited their literature survey to challenges in automating earth-moving practices. Albeaino et al. (2019) reviewed the application of UAVs in construction and architecture domains, while Rakha and Gorodetsky (2018) reviewed the use of UAVs for building inspection via thermal imaging techniques.

While these review studies investigated a specific application(s) or a specific robotic type(s) in the construction industry, they overlooked industrialized construction (IC) that can be the prime of robotics applications in both assembly-based offsite and onsite settings specifically volumetric offsite assembly and onsite installation. To address this knowledge gap, the objectives of this research are:

(1) To conduct a narrative review of the literature on the use of existing robotic systems in the construction and manufacturing domains in order to identify their application trends and potential for use in assembly-based IC tasks;
(2) To develop a robotic mapping system that links relevant robotic systems to assembly-based IC tasks, specifically modular construction tasks, in both offsite assembly and onsite installation settings;
(3) To develop a future outlook for robotics in assembly-based IC by highlighting the limitations of the literature.

The focus of this paper is on assembly-based IC since it offers innovative technologies and automation that provide a more productive, efficient, and flexible environment in both offsite assembly and onsite installation settings (Li et al. 2020a; He et al. 2021). Overall, efficiency and quality are mainly proven to improve in IC compared to that of the traditional method (Bock 2015; Orlowski 2020; Zhang et al. 2020). Offsite assembly, where building components are fabricated as modules or panels in an offsite factory, can save time, cost, and reduce material waste in projects (He et al. 2021; Thai et al. 2020). Onsite installation, which refers to the use of robotics in onsite construction, helps reduce injuries and can be used for repetitive tasks such as masonry and structure fabrication (Melenbrink et al. 2020a; Chea et al. 2020).

The remainder of the paper is structured as follows. Section 2 discusses the methodology used in this study, as well as the paper selection filtering process. Section 3 discusses paper categorization based on the reviewed literature and various robotic systems in each of the offsite and onsite settings. Section 4 presents the results and identified challenges of the reviewed studies, maps current robotics systems to IC tasks, and discusses limitations and future directions. Section 5 wraps up the paper by summarizing key findings.

2 Methodology

This paper identifies existing robotic systems for potential use in IC by conducting a narrative review of robotics state-of-the-art, with a special focus on assembly-based robotic systems. A narrative review was selected because it covers a variety of topics (Collins and Fauser 2005), which is necessary to explore the potential applications of existing robotic systems in the offsite assembly and onsite installation tasks of IC.

As illustrated in Fig. 1, the methodology process has three stages: (1) literature review, (2) robotic analysis, and (3) robotic mapping. We retrieved relevant literature from a narrowly defined number of journals using a set of keywords. We then identified robotic types, respective tasks, and challenges of robotic systems in the construction. Finally, we mapped the identified robotic systems to a list of modular (i.e., volumetric) construction tasks.

In the ***literature review*** stage, we initially conducted a trial search using a set of specific application-driven keywords such as “robotics and component installation” or “1D element installation”. However, the results obtained through searching these keywords were too limited and did not provide sufficient literature to review. Therefore, we selected a new set of generalized keywords to expand the pool of identified literature. The selected keywords

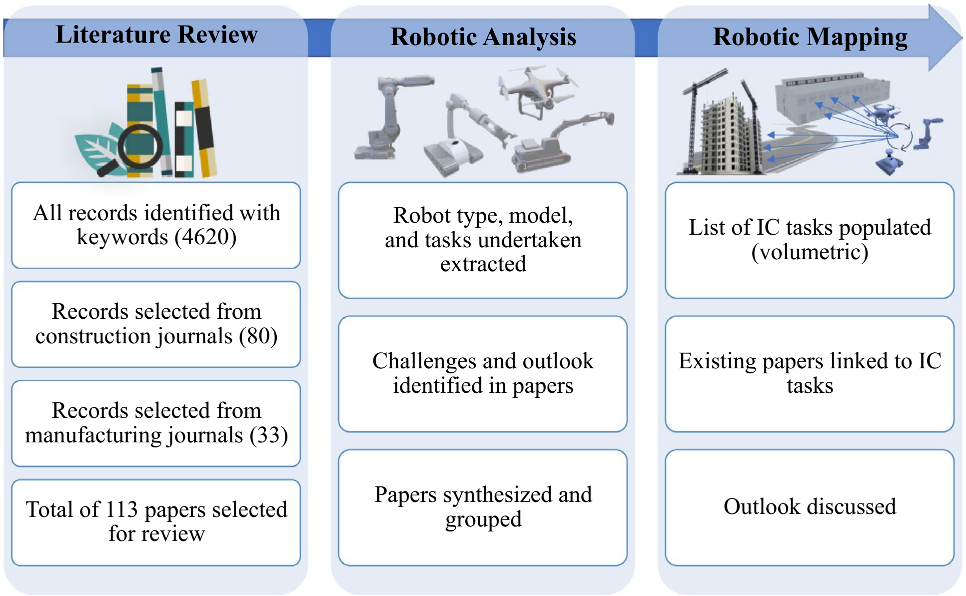


Fig. 1 Methodology overview and the proposed mapping system

are "*robotics and construction*", "*digital fabrication and construction*", and "*unmanned aerial vehicle*".

Relevant academic journals focusing on assembly-based automation, robotics, and emerging technologies were selected based on various metrics, including impact factor and popularity in the construction industry. Web of Science, the American Society of Civil Engineers (ASCE), Google Scholar, and Elsevier were among the databases/search engines used to locate the journals needed for the review. The selected keywords were then searched in these journals (see Table 1). Despite the fact that there is a great deal of research in books, conference proceedings, reports, and other sources, we only chose peer-reviewed journals to avoid collecting a large number of papers and to ensure the quality of the selected articles for the review process. It is worth mentioning that to expand our search horizon on the application of robotics in construction, a selected number of peer-reviewed journals from the manufacturing industry were included in our search sources as well. In total, 4620 articles were identified from the search of 13 journals using the selected keywords.

The next step in the literature review is the selection of inclusion criteria for screening the obtained results. As shown in Table 2, only English-written, peer-reviewed publications between 2010 and 2021 were considered to capture the trends in robotics technologies in assembly-based construction within the last decade. These articles must use actual robotic systems (commercial or custom-built) in their experiment, case study, or test. Figure 2 lists the robotic types included in this study. Studies that used robotic systems chiefly for 3D printing tasks, such as contour crafting and cable-driven parallel robots, were excluded from this review since the focus of this study is on assembly-based construction. Furthermore, articles should focus on the application of robotics in the construction and manufacturing domains rather than on foundational research and methodology development (e.g., when a paper only focuses on a robot's control architecture).

Table 1 Sources searched in this study

Manufacturing domain	Construction domain
J of Robotics and Computer-Integrated Manufacturing	J of Automation in Construction
J of Robotics and Autonomous Systems	J of Construction Robotics
J of Intelligent and Robotic Systems	J of Computing in Civil Engineering
International Journal of Advanced Manufacturing Technology	J of Construction Engineering and Management
J of Autonomous Robots	J of Construction Innovation
J of Industrial Robot	
IEEE Transactions on Robotics	
IEEE Transactions on Automation Science and Engineering	

Table 2 Criteria of paper filtering

No	Inclusion criterion description
1	Publications between 2010 and 2021
2	Used a form of robotic system i.e., commercial/customized robots (e.g., UAV, robotic arm, mobile robot) in their experiment/case study/test and must not rely solely on simulations in their research
3	Peer-reviewed journal articles only
4	Articles should focus on the application of robotics in construction/manufacturing rather than just foundational robotics research
5	Articles should be written in English

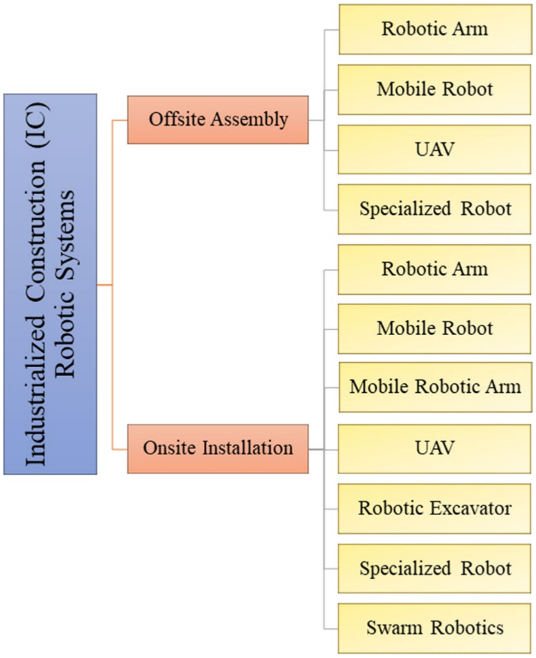


Fig. 2 Robotic types and distribution in two main categories

The implementation of the proposed inclusion criterion results in the selection of only 113 journal papers (80 papers from construction journals and 33 papers from manufacturing journals) out of the 4620 papers obtained from searching the identified journals.

In the ***robotic analysis*** stage, the second stage of the methodology, robotic type, robotic model, and task(s) in papers are identified. Further, challenges and future opportunities in robotic systems are extracted. Finally, papers are grouped into two categories of offsite assembly and onsite installation based on the application mentioned in the literature and according to the robotic system used in the paper.

In the ***robotic mapping*** stage, the last stage of the methodology, the identified robotic systems are linked to a list of modular construction tasks in order to augment the automation in IC. The linking step is based on the application of a paper (i.e., matching the task or experiment undertaken with a specific IC task) and the capabilities of the robotic system used in the paper (refer to Sect. 4.2 for details).

3 Application contexts and robotic types

The identified robotic types are categorized according to two high-level categories, offsite assembly, and onsite installation, as illustrated in Fig. 2. These categories are based on the authors' interpretations of the applications found in the searched publications, as well as the robotic system(s) used in each publication. Then, based on the robotic system used, we identify and elaborate on each category to realize each robotic system's potential for use in IC, as detailed in the following section (see Sect. 4.2). Tables 3 and 4 present a summary of papers reviewed for offsite assembly and onsite installation, respectively. It is worth noting that some papers have applications in both offsite and onsite settings; these papers are included in the offsite assembly category (Table 3).

Figure 3 shows the annual number of publications in each of the previously mentioned categories. Overall, both categories are trending upward, and the number of publications in both categories increased from 2015 to 2020, reflecting researchers' growing interest in using robotics for various construction applications in recent years.

3.1 Robotics in offsite assembly

The application of robotics in offsite assembly is limited in the literature. Mainly, the articles that address the use of robotic arms are prevalent in the offsite construction category. Below subsections elaborate on some of the robotic types and their applications in offsite assembly.

3.1.1 Robotic arm

Robotic arms in assembly-based offsite construction have been used in timber construction, welding, drilling, and painting. One of the prominent applications of robotic arms is in the prefabrication of complicated timber elements. Eversmann et al. (2017), for example, designed

Table 3 Summary of reviewed papers in offsite assembly

Paper	Robotic type	Application	Material	Scope
Eversmann et al. (2017)	Robotic arm	Fabricating timber structures	Timber	Offsite
Naboni et al. (2021)	Robotic arm	Fabricating timber structures	Timber	Offsite
Chai et al. (2021)	Robotic arm	Fabricating timber structures with robotic band saw cutting (double-curved glulam)	Timber	Offsite
Rossi et al. (2021)	Robotic arm	Fabricating acoustic walls using bricks	Ceramic brick	Offsite
Heimig et al. (2020)	Robotic arm	Welding in steel structures	Steel	Offsite
Tish et al. (2020)	Robotic arm	Fabricating spandrel panels	Masonry	Offsite
Søndergaard et al. (2018)	Robotic arm	Abrasive wire cutting for complex concrete structures	Concrete	Offsite
Larsen and Aagaard 2020)	Robotic arm	Restoring wood logs for roof assembly (sawing)	Timber	Offsite
Gomez Ortega et al. (2011)	Robotic arm	Assembly of vehicle headlamp	Plastic	Offsite
Hultman and Leijon 2013)	Robotic arm	Cable winding in electric machines	–	Offsite
Paoli and Razionale 2012)	Robotic arm	Data collection on large surface (measurement process)	–	Offsite
Hultman and Leijon 2014)	Robotic arm	Cable winding in electric machines	–	Offsite
Pellegrinelli et al. (2017)	Robotic arm	Welding in metal panels	Metal	Offsite
Li et al. (2021)	Robotic arm	Drilling on large panels	–	Offsite
Liao et al. (2020)	Robotic arm	Milling on freeform surface	Aluminum alloy	Offsite
Krebs et al. (2016)	Robotic arm	Handling large cut pieces	Non-crimp fabric (NCF)	Offsite
Arrais et al. (2020)	Robotic arm	Coating of large customized parts	–	Offsite
Qu and Zong 2014)	Robotic arm	De-stacking circulation boxes	–	Offsite
Tavares et al. (2019)	Specialized robot	Welding in steel structures	Steel	Offsite
Malik et al. (2019)	Specialized robot	Fabricating light gauge steel framed wall-panels	Light gauge steel	Offsite
Willmann et al. (2016)	Specialized robot	Fabricating large timber structures	Timber	Offsite
Chang et al. (2012)	Specialized robot	Welding in steel structures (hazardous environments)	Steel	Offsite
Yang et al. (2016)	Specialized robot	Prototype "REMORA" developed for manufacturing tasks in large workspaces	–	Offsite
Wu et al. (2015)	Specialized robot	Welding in large and complex structures	Aluminum alloy	Offsite
Lindsey et al. (2012)	UAV	Fabricating structures using multiple UAVs	Special cubic elements	Offsite
Canfield et al. (2019)	Mobile robot	Inspection on a large tank	Steel	Offsite/onsite
Bruzzone and Fanghella (2014)	Mobile robot	Prototype "Mantis" developed for surveillance and inspection (indoor/outdoor)	–	Offsite/onsite
Liu et al. (2021)	Mobile robot	Remote teleoperation of robotic systems for bricklaying	Brick	Offsite/onsite
Yang et al. (2021)	Mobile robot	Automated material transportation for heavy tasks	–	Offsite/onsite
Dritsas and Soh (2019)	Mobile robot and Robotic arm	Subtractive fabrication processes and welding in steel pipe structures	–	Offsite/onsite
Fascetti et al. (2021)	Robotic arm	Fabricating structures (e.g., shelters) with special material	Droxel	Offsite/onsite
Wagner et al. (2020)	Robotic arm	Fabricating timber structures	Timber	Offsite/onsite
Duque Estrada et al. (2020)	Robotic arm	Fabricating lightweight non-regular fibrous space frame structures	Filament	Offsite/onsite

a robotic cell that included two 6-axis ABB industrial robotic arms and a CNC machine to fabricate customized shaped elements. Wagner et al. (2020) developed the “TIM” timber prefabrication system, which includes a robotic cell (two 6-axis KUKA robotic arms and a two-axis positioner between the two arms) for rapid integration within factory settings. In another endeavor, researchers developed a computer vision system that includes all the necessary workflow for picking, placing, and assembly of materials by mounting an RGB-D camera on the end effector of the arm for position estimation, image recognition, and object identification (Tish et al. 2020). Søndergaard et al. (2018) proposed a method for manufacturing spatial concrete structures using a heavy payload robotic arm

Table 4 Summary of reviewed papers in onsite installation

Paper	Robotic type	Application	Material	Scope
Le et al. (2017)	Robotic excavator	Excavating and dumping soil to fill a fixed container	–	Onsite
Bender et al. (2017)	Robotic excavator	A hydraulic mini excavator developed for automated task execution	–	Onsite
Johns et al. (2020)	Robotic excavator	Fabricating dry stone walls	Stone	Onsite
Jud et al. (2021)	Robotic excavator	Autonomous excavation of trench and assembly of dry stone walls	Stone	Onsite
Asadi et al. (2018)	Mobile robot	Inspection/surveying in construction site (outdoor)	–	Onsite
Detert et al. (2017)	Mobile robot	Removing dangerous materials from construction site	Asbestos	Onsite
Tsuruta et al. (2019)	Mobile robot	Marking free access floors for installing floor pedestal bases	–	Onsite
Kim et al. 2018)	Mobile robot	Surveying in construction site (indoor)	–	Onsite
Adán et al. (2020)	Mobile robot	Surveying in construction site (indoor)	–	Onsite
Cebollada et al. (2018)	Mobile robot	Application of foam insulation in underfloor voids	–	Onsite
Melenbrink et al. (2020b)	Mobile robot	Driving posts and piles into the ground	–	Onsite
Mantha et al. (2018)	Mobile robot	Surveying/data collection in construction site (indoor)	–	Onsite
Beckett and Ross (2017)	Mobile robot	Mechanical testing of HVAC fire curtain	–	Onsite
Kasperzyk et al. (2017)	Mobile robot	Assembly and disassembly of an N-by-N stack of single Jenga blocks with two wall designs	Jenga block	Onsite
Li et al. (2020b)	Mobile robot	Intelligent hoisting system for precast concrete floor slabs during the process of assembly	–	Onsite
Yan et al. (2019)	Mobile robot	Inspection and quality assessment for construction defects (indoor)	–	Onsite
Prieto et al. (2017)	Mobile robot	Surveying in construction site (indoor)	–	Onsite
López et al. (2013)	Mobile robot	Surveillance/data collection in construction site (indoor)	–	Onsite
Soleymani et al. (2015)	Mobile robot	Fabricating building protective barrier using filled bags	Amorphous material	Onsite
Chen et al. (2018)	Mobile robot and Robotic arm	Welding inspection on large pipe structures	–	Onsite
Kim et al. (2019a)	Mobile robot and UAV	Surveying/data collection in construction site (outdoor)	–	Onsite
Asadi et al. (2020)	Mobile robot and UAV	Surveying/data collection in construction site (indoor)	–	Onsite
Park et al. (2019)	Mobile robot and UAV	Surveying/data collection in construction site (outdoor)	–	Onsite
Stumm et al. (2018)	Mobile robotic arm	Fabricating timber structures	Timber	Onsite
Lublasser et al. (2017)	Mobile robotic arm	Disassembling multi-layered façade panels	–	Onsite
Wang et al. (2019)	Mobile robotic arm	Automatic waste recycling (nail and screw recycling system)	–	Onsite
Yousefizadeh et al. (2019)	Mobile robotic arm	Cooperating with a human operator to lift, transport and install glass panels	Glass	Onsite
Lublasser et al. (2018)	Mobile robotic arm	Application of foam concrete onto bare walls of existing buildings to gain a façade finish	–	Onsite
Yun and Rus 2014)	Mobile robotic arm	Delivery of materials and assembly of truss structures	3D printed elements	Onsite
Saboia et al. (2019)	Mobile robotic arm	Fabricating structures in an unstructured environment using foam blocks & bean bags	–	Onsite
Dörfler et al. (2019)	Mobile robotic arm	Fabricating steel rebar mesh for concrete structure (wall)	Steel/concrete	Onsite

Table 4 (continued)

Paper	Robotic type	Application	Material	Scope
Giftthaler et al. (2017)	Mobile robotic arm	Fabricating brick wall and steel rebar mesh for concrete wall	Brick/steel	Onsite
García de Soto et al. (2018)	Mobile robotic arm	Fabricating steel rebar mesh for concrete structure (wall)	Steel/concrete	Onsite
Dawod and Hanna 2019)	Robotic arm	Fabricating complex structures of high tolerance objects with distinct typologies (wall)	–	Onsite
Reinhardt et al. (2019)	Robotic arm	Fabricating structures attached to the ceiling	Carbon-fiber-reinforced polymer (CFRP)	Onsite
Dharmawan et al. (2017)	Robotic arm	Welding in pipe structures	Steel	Onsite
González Böhme et al. (2017)	Robotic arm	Milling on building joints and elements	Timber	Onsite
Lundeen et al. (2019)	Robotic arm	Joint filling in a foam board and a door frame	–	Onsite
Feng et al. (2015)	Robotic arm	Assembly of construction components (curved and circular wall)	MDF blocks	Onsite
King et al. (2014)	Robotic arm	Tile installation	–	Onsite
Jovanović et al. (2017)	Robotic arm	Fabricating complex structures (wall)	Foam	Onsite
Loing et al. (2020)	Robotic arm	Fabricating complex structures (wall)	Brick	Onsite
Gil et al. (2013)	Robotic arm	Cooperating with a human operator to lift, transport and install glass panels	Glass/plastic	Onsite
Morse et al. (2020)	Robotic arm	Fabricating complex structures (struts)	Timber	Onsite
Cortsen et al. (2014)	Robotic arm	Fabricating steel rebar mesh for concrete structure (wall)	Steel	Onsite
Zhou et al. (2019)	Robotic arm	Fabricating structures with lunar bricks for lunar habitation	Lunar regolith	Onsite
Zhou et al. (2020)	Robotic arm	Fabricating structures with planetary LEGO brick for lunar habitation	Lunar regolith	Onsite
Vasey et al. (2020)	Robotic arm & UAV	Fabricating long-span structures (winding process)	Fiber	Onsite
Chu et al. (2013)	Specialized robot	Assembly of construction elements (steel beam)	Steel	Onsite
Brunete et al. (2012)	Specialized robot	Inspection of piping systems for defects using microrobot (indoor)	–	Onsite
Chung et al. (2010)	Specialized robot	Cooperating with a human operator to lift, transport and install glass panels	Glass	Onsite
Činkelj et al. (2010)	Specialized robot	Assembly of façade panels	–	Onsite
Gui et al. (2014)	Specialized robot	Welding in steel structures (climbing on a cylindrical product)	Low-carbon steel	Onsite
Moses et al. (2014)	Specialized robot	Fabricating structures from the same type of components they are made from	Plastic	Onsite
Goessens et al. (2018)	UAV	Fabricating structures (conical and rectangular concrete dricks materials)	Concrete/timber	Onsite
Bang and Kim (2020)	UAV	Data collection in construction site for resource planning (outdoor)	–	Onsite
González-deSantos et al. (2020)	UAV	Contact inspection for large structures (indoor/outdoor)	Metal	Onsite
Siebert and Teizer (2014)	UAV	Surveying in construction earthworks (outdoor)	–	Onsite
Bang et al. (2017)	UAV	Data collection in a construction site (outdoor)	–	Onsite
Freimuth and König (2018)	UAV	Inspection/surveying in a construction site (outdoor)	–	Onsite
Moon et al. (2019)	UAV	Surveying in construction earthworks (outdoor)	–	Onsite
Roca et al. (2013)	UAV	Inspection in construction site (outdoor)	–	Onsite
Guo et al. (2020)	UAV	Surveying in construction earthworks (outdoor)	–	Onsite

Table 4 (continued)

Paper	Robotic type	Application	Material	Scope
Xiong et al. (2020)	UAV	Surveying in construction site for damage assessment after earthquake (outdoor)	–	Onsite
Bang et al. (2020)	UAV	Surveying in construction earthworks (outdoor)	–	Onsite
Zhong et al. (2018)	UAV	Inspection in construction site (outdoor)	–	Onsite
Aguilar et al. (2019)	UAV	Surveying in construction site for seismic performance assessment of buildings (outdoor)	–	Onsite
Zhang et al. (2015)	UAV	Data collection in construction site for workforce planning (outdoor)	–	Onsite
Li and Lu (2018)	UAV	Surveying in construction earthworks (outdoor)	–	Onsite
Wang et al. (2020)	UAV	Inspection in construction site for seismic damage assessment of building (outdoor)	–	Onsite
Mahami et al. (2019)	UAV	Data collection for construction progress monitoring (outdoor)	–	Onsite
Álvares et al. (2018)	UAV	Surveying in construction site (outdoor)	–	Onsite
Kim et al. (2019b)	UAV	Data collection for construction workforce safety (outdoor)	–	Onsite
Kim et al. (2020)	UAV	Data collection for construction earthwork machinery safety (outdoor)	–	Onsite
Punzo et al. (2019)	UAV	Inspection in construction site under safety constraints (outdoor)	–	Onsite
Cafolla et al. (2020)	UAV	Inspection in cultural heritage site (outdoor)	–	Onsite
Haus et al. (2014)	UAV	Data collection in construction site (indoor)	–	Onsite
Ortiz et al. (2014)	UAV	Inspection on large ship vessel hull	–	Onsite
Wang et al. (2015)	UAV	Surveying for construction quality control (outdoor)	–	Onsite
Quenzel et al. (2019)	UAV	Inspection of industrial chimney and smoke pipe	–	Onsite

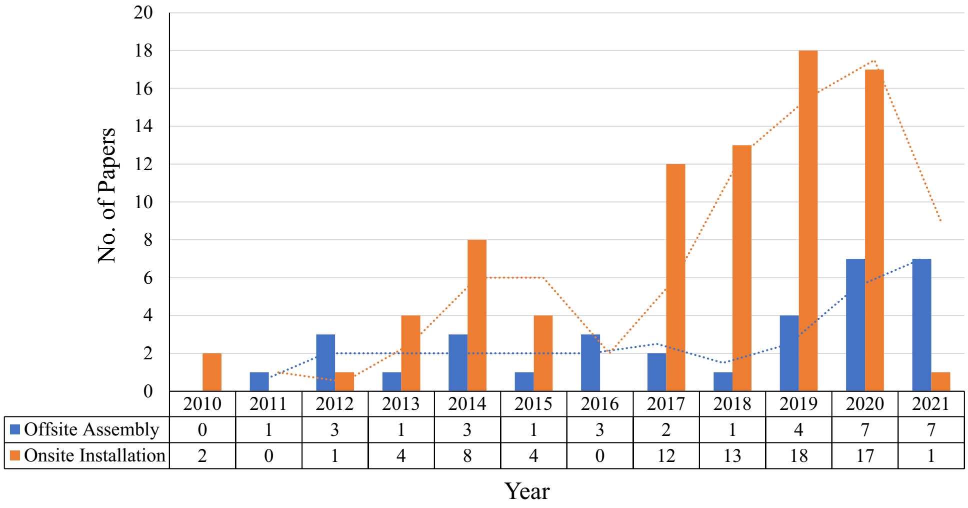


Fig. 3 Annual number of publications (2010–2021)

for abrasive wire cutting of the formwork system. Their system was tested for fabricating a 21 m structure out of six prefabricated modules. Pellegrinelli et al. (2017) used robotic arms in a coordinated robotic cell for the assembly of metal panels using spot welding. Their approach involved optimizing cell design and motion planning to reduce project time and error. Researchers also used a 6-axis KUKA robotic arm and a welding torch as an end effector for incremental point welding (Heimig et al. 2020). In the same study, a photonfocus HDR camera was used to monitor and control arc-welding and a computer vision image processing to analyze the process and material deposition.

3.1.2 Mobile robot

Mobile robots have been used mainly to support inspection tasks in offsite construction. In their effort to improve vertical inspection operation in offsite construction, researchers developed a customized Skid-Steer Mobile Robots (SSMRs) in manufacturing applications for climbing on steel surfaces to scan along with large-scale tanks (Canfield et al. 2019). In another work, a custom-built, small-sized (350 × 300 × 200 mm) mobile robot named "MANTIS" was introduced for indoor inspections environments (Bruzzone and Fanghella 2014).

3.1.3 Unmanned aerial vehicle

Using the proposed search criteria outlined previously, we managed to find only a single study on the application of UAV in offsite construction. The study discusses the construction of simple 3D structures with a group of a small 6-sided cuboid with a magnet (node) to be attached to six members (rectangular prism) to form a module (Lindsey et al. 2012). The authors used Hummingbird quadrotor and developed algorithms such that the UAV used its controller systems to autonomously assemble a pyramid-shaped structure with other quadrotors in a group.

3.1.4 Specialized robot

This category refers to the robots that are specifically designed to perform assembly-based tasks such as fabricating timber, light gauge steel (LGS) structures, and welding. Willmann et al. (2016) developed computational design processes, construction methods, and fabrication strategies for the assembly of non-standard timber structures. For the implementation, they used a custom-built 6-axis gantry robot to automatically fabricate timber structures in a large space where it allowed prefabrication of structures for up to 48 m in length. Other researchers developed a prototype machine that allowed a semi-automated system to take shop drawings as input from Building Information Model (BIM) and transferred them to manufacturable information for production. It eventually allowed workers to assemble LGS wall framings (Malik et al. 2019).

3.2 Robotics in onsite installation

Robotics applications in onsite setting have a stronger presence in the reviewed literature. Examples range from welding to inspection, surveying, and assembly. The following subsections present some of these applications.

3.2.1 Robotic arm

Researchers used robotic arms for in-situ welding of large structures (Dharmawan et al. 2017). The mentioned study proposed an agile robotic system concept, where a robotic arm is mounted on a moveable platform for welding on jack-up oil rig legs. Their portable platform used UR10 robotic arm (from Universal Robots manufacturer) mounted on a scaffold rail system to work at height. In another robotic arm application, researchers used them to handle and install heavy-duty panel glass on a construction site using a human–robot collaborative approach (Gil et al. 2013). The operator, in the proposed system, chooses the axis for the panel's linear and rotational motions while the robot handles the mass of the glass.

3.2.2 Mobile robot

The most frequently reported uses of mobile robots in onsite construction activities are to support inspection, surveying, and pile driving tasks. Researchers used laser scanning technology and a mobile robot platform to navigate and scan indoor construction environments (Kim et al. 2018). Their system is composed of a hybrid LiDAR system and an autonomous custom-built mobile platform and benefits from 2D Hector Simultaneous Localization and Mapping (SLAM) technique that allows robots to operate in real-time. A vision-based system mobile robot capable of autonomous navigation in real-time was proposed by Asadi et al. (2018). Their approach utilizes monocular SLAM for path planning and object detection, a commercially available mobile robot (i.e., Husky A200 unmanned ground vehicle), a Microsoft Xbox controller, and a camera for autonomous navigation and surveying in the unstructured environment of construction. Melenbrink et al. (2020b) discussed a custom-built autonomous mobile robot named "Romu" that used its mass and vibratory hammer to drive sheet piles into the ground. Romu uses a gripping system that can also drive steel rebars T-posts, and wooden posts into the ground.

Overall, the use of autonomous mobile robots in construction opens new doors in construction automation, particularly, where there are accessibility issues and potential hazards for human workers to operate.

3.2.3 Mobile robotic arm

The mobile robotic arm category here includes any robotic system that combines two previously discussed robotic systems, i.e., robotic arm and mobile robot. Researchers have combined these two robotic types to broaden the application of robotics in assembly-based construction. The main features of mobile robotic arms are increased flexibility and extended working area. Earlier lab-scale studies have shown the application of mobile robots with small manipulators in fabrication and assembly tasks in construction using 3D printed materials and filled bags (Yun and Rus 2014; Magnenat et al. 2012; Soleymani et al. 2015). Indeed, such studies provided the ground for the recent 1:1 scale applications of mobile robotic arms in construction. For instance, recently, an onsite in-situ fabricator (IF) was developed by researchers to fabricate non-standard reinforced concrete structures on the job site (Dörfler et al. 2019; Giftthaler et al. 2017). IF is designed to fabricate steel rebar mesh walls known as "Mesh Mould" with a length of 12 m. IF is composed of a robotic arm with a reach of 3.2 m in height and payload capacity of 40 kg with a tracked hydraulically driven mobile base and a vision-based system for localization and monitoring the fabrication process. IF can fabricate an s-shaped steel rebar mesh wall (2.8 m height and 11.8 m top length) with 22,000 welding nodes in 125 h.

Mobile robotic arms can also assist in demolishing operations. Lublasser et al. (2017) developed a mobile robotic arm system to assist in the deconstruction of façade layers. The experiment focused on the external thermal insulation composite systems (ETICS) based on expanded polystyrene foam (EPS) insulation panels. The system is comprised of a KUKA iiwa robotic arm with the mobile platform KUKA KMR.

3.2.4 Unmanned aerial vehicle

UAVs are mainly used for inspection, surveying, and data collecting tasks. For instance, a commercially available UAV (DJI Phantom 3) was used to acquire point clouds data for earthworks quality and productivity management in large construction projects (Moon et al. 2019). The study proposes a new method for the creation of models of earthworks using image processing and data optimization techniques that combine point cloud and photogrammetry data for equipment operations in earthworks activities. Similar studies in earthworks activities showed the potential of using UAV images for construction resource allocation and equipment detection for safety-related issues on the construction site (Bang et al. 2020; Guo et al. 2020).

In a different context, a micro-aerial vehicle was used to automatically inspect large vessels in the shipyard (Ortiz et al. 2014). Using a lightweight laser scanner and sensory system, and by adopting self-localization and mapping algorithms, the micro-aerial vehicle proved to be a viable option to help human surveyors in visual inspections.

3.2.5 Robotic excavator

The application of robotic excavators has been very limited in the construction domain. Le et al. (2017) proposed an observation method for teleoperated control of excavators using a portable control station. A hydraulic excavator (S015 model) with a total weight of 1.5 tons was reconfigured with a hydraulic system, target controller, and observation system. Digging and leveling tasks were performed to examine the proposed smart observation system, and the study used a head-mounted display on an operator to control the process. Another study focused on the in-situ construction of a dry stone wall by using a customized autonomous hydraulic excavator (Menzi Muck M545 12 tones) (Johns et al. 2020). Multiple sensory systems and LiDAR scanners were attached to the excavator to make the system adaptable to different terrains and help its localization, scanning, and geometric and motion planning. The excavator built a stone wall with 3 m height and 5 m length for a total average mass of 757 kg.

3.2.6 Specialized robot

Chu et al. (2013) developed a robotic automated steel beam assembly system used in a real-world construction project. Their system was found to be both safe and time-efficient. Chung et al. (2010) developed a specialized device for the task of fitting large glass windows on the construction site, which was used to install a heavy glass curtain wall in collaboration with a human operator. Gui et al. (2014) designed a wall climbing welding robot for the fabrication of large steel structures, and their results indicated that their automatic welding system with high payload capacity is a viable option for onsite manufacturing.

3.2.7 Swarm robotics

Swarm robotics (or multi-robot collaborative systems) are used to increase the flexibility of performing construction tasks. For example, expanding the working space of robotic arms is one of the incentives to use robotic arms in conjunction with UAV. A study investigated the collaboration between UAV and robotic arms in fiber laying processes to support fabricating large structures (Vasey et al. 2020). A custom-built UAV collaborated with two six-axis KUKA KR 210 robotic arms for fiber composite filament winding. The UAV was responsible for fiber transport, while the robotic arms winded the glass fiber around fiber anchors that were mounted to a rigid metal frame. Another application of the UAV and mobile robot collaboration is collecting data on construction sites. Asadi et al. (2020) used vision-based mobile robots for autonomous navigation in conjunction with a UAV to broaden the system's observation of the construction scene and for more efficient navigation in indoor surveying. In their study, the UAV served as an extra eye for the system, which intervened when sensory data on the mobile robot was inaccessible. In a similar study, researchers proposed a framework for operating mobile robots in outdoor environments with the assistance of a UAV (Kim et al. 2019a). In their method, the UAV scanned the area of interest and generated point cloud data that feeds into an optimized model back to the mobile robot to navigate, avoid obstacles, and collect data for surveying purposes. Another study presented collaboration of UAV and mobile robot with more focus on the algorithms required to register the developed point clouds model through different sensory systems (Park et al. 2019).

3.3 Statistics of robotics in construction

Overall, the results from the literature review show that in both offsite and onsite activities combined, robotic arms have the most significant share with almost 30% of the robotic systems. This can be attributed to the ability of robotic arms to be computer programmed to execute computationally generated motions accurately in Cartesian space and their efficiency in performing repetitive tasks (Vasey et al. 2020). Mobile robots and mobile robotic arms together account for 23% of all robotic systems. Mobile robotic systems add high flexibility and mobility to the system (Dörfler et al. 2019), which is why they have been used for inspection and surveying tasks in both indoor and outdoor environments, and as a base platform for robotic arms (Asadi et al. 2020). UAVs account for 23% of the total reviewed papers. One of the main features of UAVs is their ability to approach places inaccessible to humans from an aerial perspective, and UAVs can accomplish construction tasks such as inspection, surveying, and assembly at a lower cost and with greater safety (Rakha and Gorodetsky 2018; Martinez et al. 2021). The rest of the robotic systems, including specialized robots, robotic excavators, and swarm robotics together comprise about 24% of the whole papers. More details are discussed in Sect. 4.

4 Results and discussion

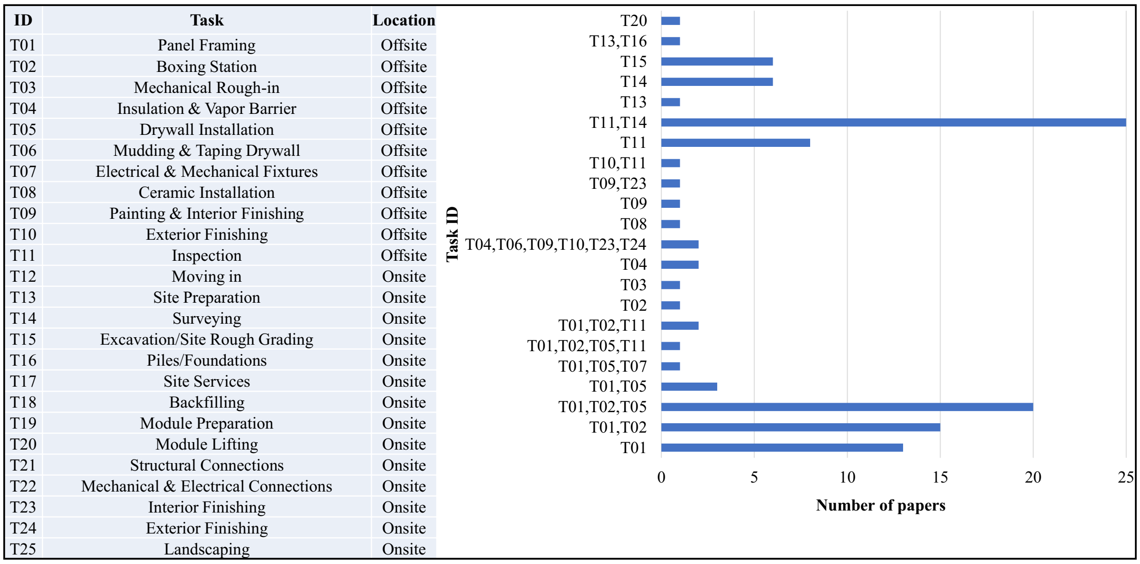
4.1 General results

With the studies presented, it is evident that there is more traffic on robotics applications in onsite installation than in offsite assembly. Only 33 out of the identified 113 papers have addressed applications in an offsite environment (offsite and offsite/onsite papers in Table 3), with the remainder focusing on onsite activities. Given the numerous advantages of offsite assembly, including high production quality, workplace safety, and eliminating the impact of poor weather conditions on construction progress (Malik et al. 2019), a shift to offsite assembly will not only contribute to addressing the labor shortages and low productivity issues in conventional construction but will also expedite projects. The automation of offsite assembly tasks can further improve productivity and safety. Recent research studies on human–robot collaboration and autonomous robots have been setting the stage for robotics adoption in offsite facilities. For example, Liu et al. (2021) proposed a remote robotic control system using mobile robots in a collaborative human–robot bricklaying task and found that hands-free robotic control was possible. Yang et al. (2021) investigated automated material transportation and found significant potential for fully autonomous material transportation on real-world dynamic construction sites. Dawod and Hanna (2019) used BIM models for object recognition in conjunction with a robotic arm to assemble building components autonomously. As a result, combining wearable sensors, vision-based systems, BIM models, and Artificial Intelligence (AI) with robotics has greatly aided recent robotic applications in construction, and their use is expected to expand in future studies and aid in the augmentation of robotics in offsite facilities.

4.2 Mapping papers to IC tasks

As illustrated in Fig. 5, this paper maps robotics applications with volumetric assembly-based modular construction activities to further augment automation in IC. Each reviewed paper is assigned to one or more of the tasks depicted in Fig. 4. Given that not all offsite and onsite construction tasks activities are covered in the literature, and in order to expand the mapping process of papers to a wider range of tasks listed, papers are assigned to the tasks according to two main criteria. First, based on the paper's application (i.e., task conducted or experiment undertaken). Second, based on the capabilities/specifications of the robotic system presented in each paper. Indeed, most current applications of onsite robotic systems can be utilized in offsite assembly. For instance, assembly of timber structures, welding in steel structures, and inspection tasks with robotic systems (categorized as onsite in Sect. 3.2 based on the paper's application) can be applied to respective offsite assembly tasks of modular construction where automated robotic systems can boost productivity and efficiency in a factory-based environment (Dharmawan et al. 2017; Stumm et al. 2018; Reinhardt et al. 2019). It is also worth mentioning that the proposed mapping of the robotic systems onto IC tasks accounts for all the identified robotic types that can be used in the defined task.

According to Figs. 4 and 5, most of the papers are classified under only six major tasks in offsite assembly and onsite installation activities. These six tasks are panel framing (T01), boxing station (T02), drywall installation (T05), and inspection (T11) in offsite assembly. Surveying (T14) and Excavation/Site Rough Grading (T15) in onsite installation. It is worth mentioning that there is no application of



ID	Task	Location
T01	Panel Framing	Offsite
T02	Boxing Station	Offsite
T03	Mechanical Rough-in	Offsite
T04	Insulation & Vapor Barrier	Offsite
T05	Drywall Installation	Offsite
T06	Mudding & Taping Drywall	Offsite
T07	Electrical & Mechanical Fixtures	Offsite
T08	Ceramic Installation	Offsite
T09	Painting & Interior Finishing	Offsite
T10	Exterior Finishing	Offsite
T11	Inspection	Offsite
T12	Moving in	Onsite
T13	Site Preparation	Onsite
T14	Surveying	Onsite
T15	Excavation/Site Rough Grading	Onsite
T16	Piles/Foundations	Onsite
T17	Site Services	Onsite
T18	Backfilling	Onsite
T19	Module Preparation	Onsite
T20	Module Lifting	Onsite
T21	Structural Connections	Onsite
T22	Mechanical & Electrical Connections	Onsite
T23	Interior Finishing	Onsite
T24	Exterior Finishing	Onsite
T25	Landscaping	Onsite

Fig. 4 Distribution of mapped papers in IC tasks

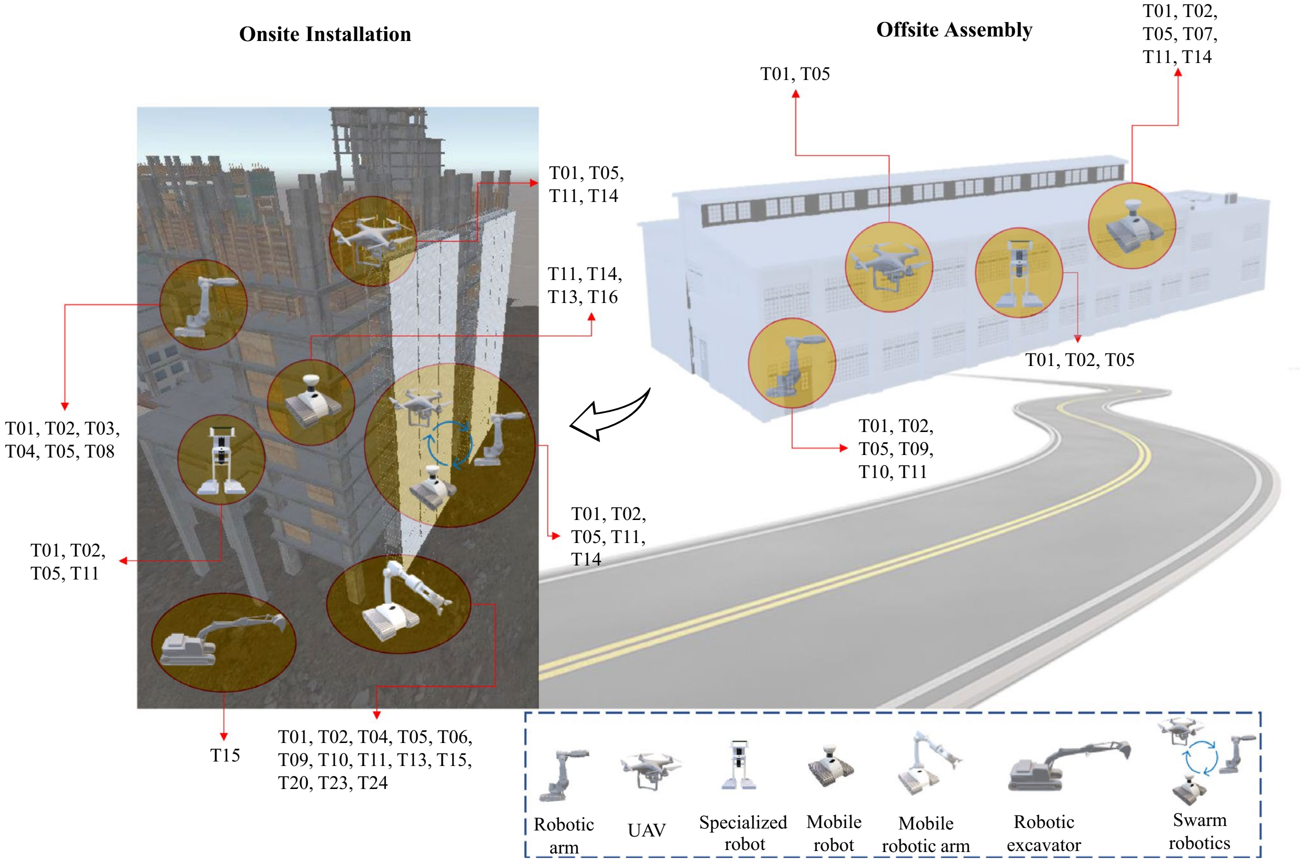


Fig. 5 Mapped robotic systems in onsite and offsite settings

robotic systems in a number of tasks in Fig. 4. For instance, there are no existing robotic systems for the following onsite tasks: Moving in (T12); Site Services (T17); Backfilling (T18); Module Preparation (T19); Structural Connections (T21); Mechanical and Electrical connections (T22); and Landscaping (T25). Furthermore, very limited studies investigated the use of robotics in some tasks such as Ceramic Installation (T08), Painting and Interior Finishing (T09), Site Preparation (T13), Piles/Foundation (T16), and Module Lifting (T20).

One conclusion that can be derived from the examples given to widen the application of robotics in IC is that there is a need for the production of commercially available robotic systems suitable for construction environments. It is also worth noting that additional research is needed for using robotic systems in tasks other than the six major tasks previously discussed, as there has been little research in the application of robotics in modular construction. The present mapping process augments the automation in IC by explicitly highlighting the applicability of current robotics in offsite assembly processes.

4.3 Discussion

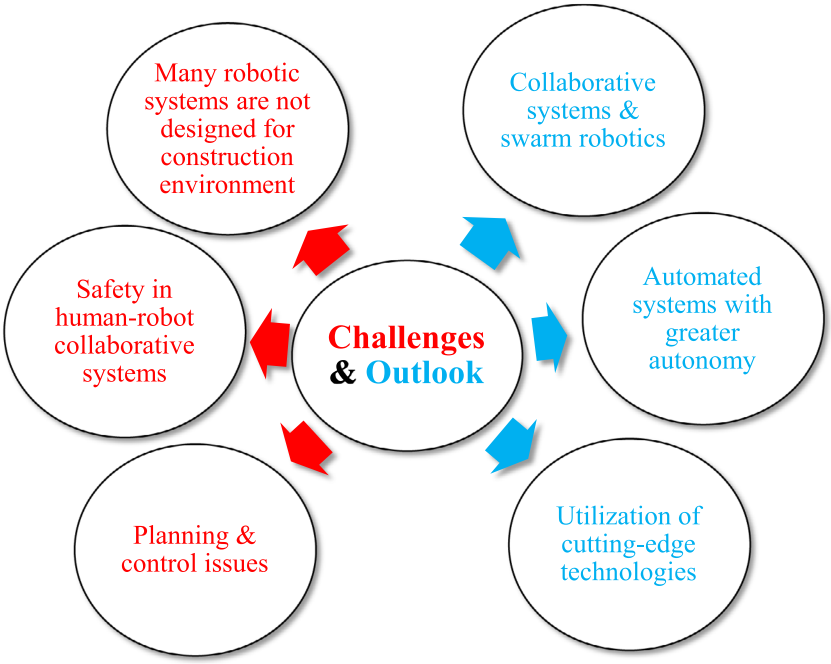
4.3.1 Identified challenges and outlook

The identified challenges and outlook are summarized in Fig. 6. Planning and control of robotics systems present one of the key challenges facing the integration of robotics in construction tasks. Surely, efficient planning and control require high integration between robotics' software and hardware and utilized sensing technologies, which is currently done using basic-level programming methods (Dritsas and Soh 2019). For instance, identifying efficient robotic procedures capable of meeting all relevant building code requirements for the fabrication of large timber structures (such as thermal insulation and air-tightness) remains a challenging task (Eversmann et al. 2017). Similarly, in light gauge steel frame prefabrication, the need for faster screw fastening time, as well as having a vision-based system to assure accurate panel assembly before and during the framing sequence, remains to be implemented in the future (Malik et al. 2019). Real-time adaptive workflows reduce production time while enhancing quality (Rossi et al. 2021). However, the domain of efficient planning and control needs to be assessed further in the future.

The future of automated systems will rely on human–robot collaboration, and given the dynamic nature of the construction industry, it is critical to provide a safe environment for human workers. Establishing a safe human–robot collaboration, on the other hand, continues to be a challenge in automated assembly workflows. Advanced technologies, such as adopting vision-based systems, can significantly improve safety in human–robot collaboration systems and large-scale fabrication processes (Wagner et al. 2020). Liu et al. (2021) proposed using a remote emergency safety system by humans in human–robot collaboration tasks on a construction site. Overall, human–robot collaboration in construction has been understudied, leaving a large gap for future research.

Another under-researched area is the application of multi/swarm robotics, and there are still challenges to overcome

Fig. 6 Summary of challenges and outlook



before these can be fully realized in construction. The use of multi robots or swarm robotics with different robotic types whose technical features complement one another can increase the flexibility of construction processes. For example, robotic arms have highly unidirectional kinematics and a high stiffness but a small working area in comparison to the size of a building (Vasey et al. 2020). The combination of a robotic arm with other types of robotic systems, such as UAVs, will allow for the completion of a broader range of construction tasks. However, UAV applications in the construction industry are still limited (mostly inspection and surveying tasks). While there are already instances where UAVs have been used in assembly tasks to lift and transport concrete blocks (each block 20 kg) (Goessens et al. 2018), UAVs have caused inefficiency in the other instances when used in collaboration with other types of robots due to their low payload capabilities. In the work presented by Vasey et al. (2020), for example, a fully automated system was less efficient than a manually assisted process in the fabrication of long-span composite structures. Due to the UAV's limited payload, only a single filament from a single spool could be transported between landing stations at a time. As a result, the entire production cycle took longer (Vasey et al. 2020). In the future, it would be ideal to see UAVs with larger payloads used in construction tasks, specially IC tasks. Another issue with UAVs is the use of multi-directional obstacle avoidance systems. Adoption of visual-based obstacle avoidance systems and ultrasonic sensors can assist UAVs in multi-directional obstacle avoidance and expand their applications in construction sites (Asadi et al. 2020). Likewise, adopting other robotic types, such as mobile robots, can also provide mobility, flexibility, and larger working space to the overall robotic system. Furthermore, to supplement the use of swarm robotics, coordinated control strategies can be developed for only distributing high-level goals to each robotic agent to achieve greater autonomy. As such, the robots will be capable of autonomously modifying their behavior (i.e., IC task or sub-task) within their local context in order to achieve a specific goal (i.e., completion of a project or main task).

Overall, more automation is needed in IC, and robotic adoption is expected to boost productivity and safety in both offsite assembly and onsite installation settings.

4.3.2 Limitations and future work

One of the limitations of this study is the selected number of journals. Although selected journals are the leading ones in robotics and automation that provided sufficient information for this review study, other relevant publications may exist in other journals and conference proceedings or even beyond the selected time frame of this study. More specifically, we did not conduct an in-depth analysis of some areas such as 3D printing and additive manufacturing due to the focus of this study on assembly-type manufacturing. As such, the authors will continue to update the developed robotic database as part of ongoing research in smart industrialized design and construction.

The high-level mapping of the robotic systems onto IC tasks represents the second limitation of this work. While this study attempted to cover a wide range of robotic systems and mapped robotics onto IC tasks, no information is provided on how to best incorporate a robotic system(s) into a specific application or task. Indeed, this study is a first step toward connecting robotics and IC. Incorporating robotics into specific tasks can be accomplished by developing a decision support system (DSS) to create a systematic guideline for robotics selection based on a variety of IC tasks, robotic specifications, and the investor's financial capacity. This will be accomplished in future research.

5 Conclusions

Robotic adoption has significantly improved the productivity and efficiency of the manufacturing industries. Nevertheless, the construction industry is yet to witness a widespread implementation of robotic systems due to multiple factors, including unique attributes of construction projects and lack of technical and financial frameworks for integrating robotic systems. This paper examines the literature on robotic system applications in the construction and manufacturing domains, with a focus on studies with applications relevant to IC tasks. A mapping system connected the existing robotic systems to the tasks in volumetric modular construction to identify the best robotic system for each task. The proposed mapping system can assist construction professionals in augmenting automation in IC by better understanding the potential of using existing robotic types in the offsite assembly and onsite installation of IC.

According to the findings of the review, the use of robotics in offsite assembly has received less attention than onsite installation. Overall, it has been determined that more automation in IC is required. It is specifically suggested that in the future, robotics planning and control, human–robot collaboration safety, and the potential for swarm robotics with different robots, be further investigated to increase the likelihood of application of robotics in IC in real-world examples.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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