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Review

Recent advancements of robotics in construction

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ABSTRACT

In the past two decades, robotics in construction (RiC) has become an interdisciplinary research field that integrates a large number of urgent technologies (e.g., additive manufacturing, deep learning, building information modelling (BIM)), resulting in the related literature being both fragmented and vast. This paper has explored the advances in RiC in the past two decades using a mixed quantitative-qualitative review method. Initially, 940 related articles (170 journal articles and 770 conference papers) were identified by keyword-searching in Scopus and then fed into a bibliometric analysis to build science maps. Following this, a qualitative discussion highlights recent achievements in RiC across three dimensions: tasks, algorithms, and collaborations. Moreover, four future research directions are proposed: 1) in-depth integration of BIM and robotics; 2) near-site robotic fabrication; 3) deep reinforcement learning for flexible environment adaption; and 4) high-level robot-to-robot collaboration. The contributions of this research are twofold: 1) identifying the latest research topics and trends concerning robotic technologies in construction; and 2) providing in-depth insights into the future direction of RiC. The findings from this research can serve both academia and industry in terms of promoting robotic algorithms, hardware, and applications in construction industry.

1. Introduction

The construction industry is one of the most important industrial sectors in North America, contributing 958.8 billion dollars of the United States' gross domestic product in 2021 [1]. Despite this, the construction industry is suffering from labor shortages, high safety risks, and low automation worldwide [2]. Robotics has emerged as a revolutionary technology in the construction industry with the potential to improve productivity and occupational safety [3]. The Robot Institute of America defines a robot as "a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks" [4]. A rapidly expanding literature field of robotics in construction (RiC) has made proposals covering construction equipment with robotic features (e.g., robotic excavators), using robots from other industrial sectors for construction purposes (e.g., drones), and robots customized for the construction industry (e.g., façade cleaning robots). However, adopting robotics in the construction industry still facing many challenges due to the unique characteristics of the construction process. Especially when compared with the manufacturing industry (where robotics has been highly adopted and its influence is the driving force for the adoption of robotics in the construction industry), the construction process has a lower level of standardization and controlled working environment [5].

Today, RiC has become a highly cross-disciplinary research field that integrates robotics with many urgent technologies including additive manufacturing, building information modelling (BIM), and deep learning. As a consequence, the RiC scientific literatures is vast, diverse, and fragmented. Questions associated with RiC that still remain largely unanswered include the following: 1) what are the latest research topics and trends in RiC? and 2) what are the future directions for applying robotic technologies in the construction industry? To answer these research questions and provide in-depth insights into the development of RiC, a comprehensive and up-to-date review is needed. In recent years, several review studies [6–10] have been offered in the field of RiC. For example, David et al. [9] have reviewed robotic inspection systems in the built environment and Pan et al. [10] have reviewed the state-of-the-art construction robot adoption from the perspective of building contractors. However, the existing overview studies are based on manual reviews and are therefore prone to be subjective or even

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biased [11].

To clarify the abovementioned uncertainties, this paper introduces a comprehensive mixed review (i.e. with quantitative and qualitative components) of the development of robotic technologies in the construction industry over the past two decades. First, a bibliometric analysis (a quantitative review) is enacted to create a science map of the RiC literature and explore the latest research topics and trends. A bibliometric analysis can provide unbiased results from a process of retrieving information from a considerable number of existing literature [12]. Following this, a qualitative review has been conducted to provide an in-depth insight into the urgently required RiC research in terms of three dimensions: tasks, algorithms, and collaborations. Through this, the research gaps and opportunities for applying robotic technologies in construction are identified. This mixed review is expected to provide researchers in the construction automation community with a state-of-the-art understanding of the RiC field.

The remainder of this paper is organized as follows. In Section 2, the research methodology is presented in terms of data collection, bibliometric analysis, and qualitative discussion. Next, Section 3 illustrates and discusses the results of the bibliometric analysis. Subsequently, Section 4 provides a qualitative analysis of the RiC literature as well as identifying future research directions. Finally, Section 5 concludes this paper by highlighting the contributions made.

2. Methodology

To explore the domain knowledge on the topic of RiC, this research employs a mixed literature review method, an approach that has been largely used in previous studies [13–15]. An overview of the method utilized is presented in Fig. 1. This review method consists of, first, a data collection step to retrieve the related publications from a selected database, followed by a bibliometric analysis to form a science map of the existing literature, and finally a qualitative discussion on selected sub-topics to present an in-depth understanding of the current research status with final outputs of suggestions for future research directions. The following subsections describe the methodology in more details.

2.1. Data collection

The quality of the input data is the foundation of any literature review and, thus, a comprehensive database and a rigorous searching strategy are required before moving on to the bibliometric analysis and the qualitative discussion. In this research, widely used databases, such as Scopus, Web of Science, and Google Scholar, were compared, and Scopus selected as the best database for retrieving relevant publication information. Scopus has been selected as a data source in many previous literature reviews focusing on topics related to the construction industry [14,16–18] due to its wide coverage of construction engineering-related research [19]. Scopus also has a wider coverage than many of the alternatives in terms of interdisciplinary research [20] and journal publications [21].

As for search strategy, several keywords related to the topic of RiC were identified for retrieving publication information in Scopus within a time period from the start of this century onwards (i.e., January 2000 to May 2022), reflecting the period of the development of RiC. The terms used in our research process were as follows:

("robotics" OR "robot") AND ("construction engineering" OR "construction management" OR "construction project" OR "construction automation" OR "building engineering" OR "building project" OR "modular construction" OR "modular building" OR "offsite construction" OR "off-site construction" OR "industrialized construction" OR "prefabricated construction" OR "precast construction").

The search field in Scopus was set as "title/abstract/keywords" to retrieve all publications containing the keywords in the title, abstract, or keywords sections. Keyword selection related to the theme of robotics is relatively straightforward and covered by using the two keywords of *robotics* and *robot*. However, keyword selection related to the theme of construction is much more complicated. If only the word construction is used as a keyword, then many publications with no relation to the construction industry will be included in the search results. Therefore, the authors used a strategy including the keywords indicated above such that publications identified would be related to the construction industry. The selection of keywords related to the theme of construction was developed by referring to several literature review studies in the construction research field, such as [13,22].

A further refining process was conducted after the keyword searching. Publications falling into categories such as arts, medicine, nursing, agriculture and biological science were excluded since they were not related to the research topic. In addition, only publications in English were to be included in the further bibliometric analysis. Finally, a thorough check of the source titles was conducted to exclude papers from irrelevant journals or conference proceedings. After this filtering process, the remaining publications serve as inputs for the bibliometric analysis.

2.2. Bibliometric analysis

A bibliometric analysis was carried out to present the overall trends in this research field, as well as to draw a comprehensive picture of the knowledge domain on the topic of RiC. This approach was selected in

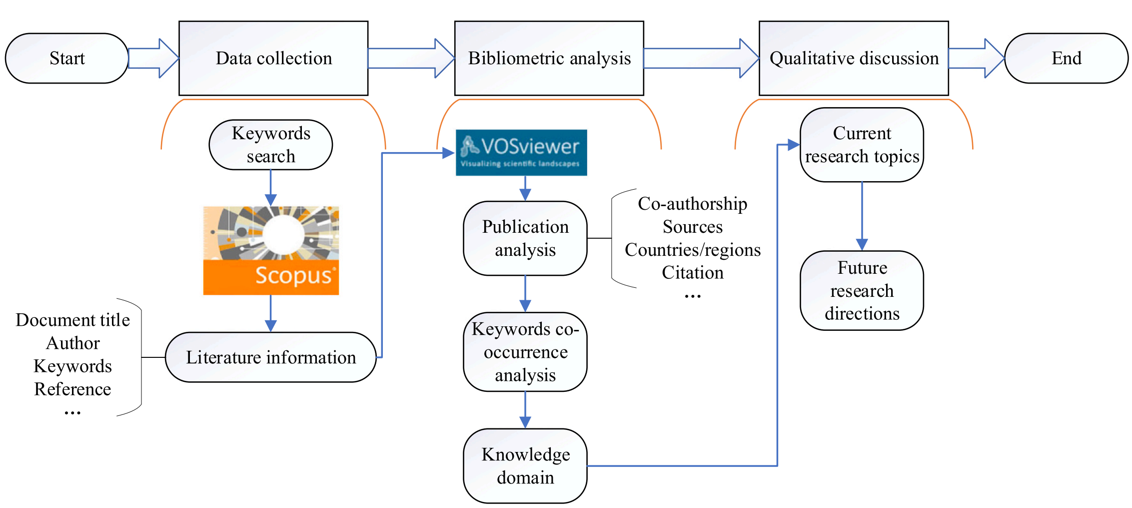

Fig. 1. Overview of the research methodology

previous studies and indicated that bibliometric analysis can provide unbiased results regarding information in existing publications on the main research foci through using appropriate input data [13]. To realize this objective, a bibliometric analysis tool VOSviewer [23] was used to analyze the bibliometric data and produce tables and figures that facilitate science mapping of the knowledge domain. VOSviewer has been widely used in previous quantitative literature reviews, such as [14,15,24], to generate distance-based maps that visualize internal relationships among targeted publications in terms of co-authorship, keyword co-occurrence, co-citation, etc. [25,26]. The bibliometric analysis results are presented in Section 3.

2.3. Qualitative discussion

While a bibliometric analysis presents the knowledge domain regarding a specific research topic at the macro-level, a qualitative literature analysis facilitates a deeper understanding of that topic by providing in-depth discussion at the micro-level. As represented in Fig. 1, the qualitative analysis triggers a further discussion regarding the main research topics linked to RiC. Challenges in developing and deploying robots in the construction industry and the current research limitations linked to RiC are also identified in this step. Finally, opportunities for future research and the development of robotics in the construction field are discussed. The results of the qualitative discussion are presented in Section 4.

3. Bibliometric analysis

3.1. Overview

Follow the procedure described in the data collection section above involving keyword searching and refining processes, 940 related publications, including 170 journal papers and 770 conference papers, were retrieved from the Scopus database (the data were last accessed on May 21, 2022). The publication numbers, based on year of publication, are plotted in Fig. 2(a). A rapid growth in the number of related publications occurred between 2003 and 2006, after which the annual publication number remained relative stable (around 50) in the period up to 2017, followed by an increase with over 70 publications in each of the next four years. The publication total for 2022 is much lower since the data only covers the initial months of the year. From Fig. 2(a), it is difficult to predict the future trend in research publications on the topic of RiC given the steady output over the middle decade of the data collected and the apparent step change to a higher level since.

For comparison purposes, a preliminary search was conducted to retrieve publications related to robotics in all research domains in the Scopus database by setting the search field to “title/abstract/keywords” using keywords of “robot” or “robotics”. The publication totals by year are plotted in Fig. 2(b). This shows that the number of published studies related to robotics has increased continuously since 2000, with an especially rapid growth seen since 2015. This comparison suggests that the development of robotics in construction industry has been relatively slow, and the potential for growth is substantial. In the following subsections, the results of a detailed analysis regarding the reporting of robotics in the construction literature are described.

3.2. Publication cluster analysis

3.2.1. Publication versus citation

In order to identify the most influential sources of publications related to RiC, information about the journals that published most of the related studies is summarized in Table 1. The number of citations and the average citations per paper are also presented in the table. It can be seen from the table that *Automation in Construction* has by far the most publications on the topic of RiC, with 36 papers in the period from 2000-2022. *Automation in Construction* also has the highest citation number

Table 1
Journal publications versus citations related to RiC.

Journal title	Documents	Citations	Average citations
Automation in Construction	36	1835	50.97
Journal of Construction Engineering and Management	8	80	10.00
Advanced Materials Research	7	5	0.71
IEEE Transactions on Automation Science and Engineering	5	230	46.00
Journal of Computing in Civil Engineering	5	152	30.40
Procedia CIRP	5	28	5.60
Advances in Intelligent Systems and Computing	4	16	4.00
Applied Mechanics and Materials	4	4	1.00
IEEE Access	4	11	2.75
Industrial Robot	4	47	11.75
International Journal of Advanced Robotic Systems	4	92	23.00
International Journal of Robotics Research	4	168	42.00
Journal of Management in Engineering	4	51	12.75
Mechanisms and Machine Science	4	28	7.00
Autonomous Robots	3	80	26.67
Computer-Aided Civil and Infrastructure Engineering	3	16	5.33
IEEE International Conference on Intelligent Robots and Systems	3	45	15.00
IEEE Robotics and Automation Letters	3	20	6.67
IEEE/ASME Transactions on Mechatronics	3	40	13.33

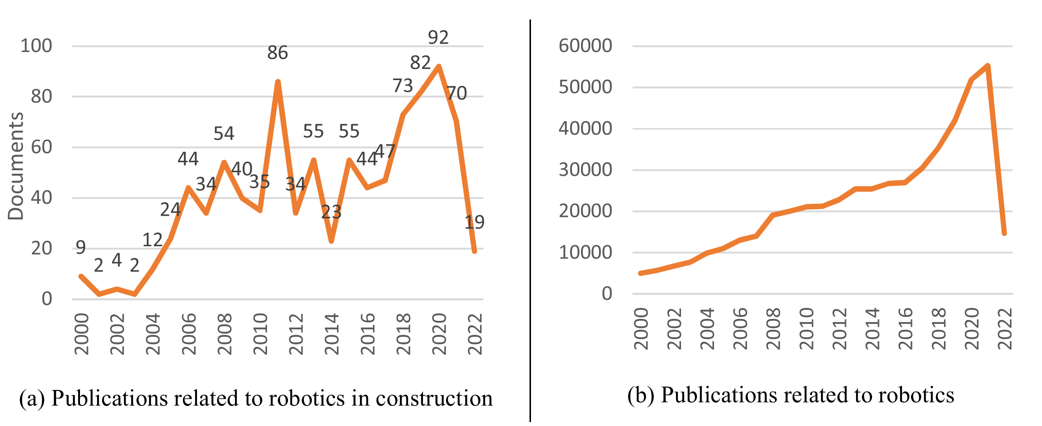

Fig. 2. Number of published studies from 2000-2022: (a) on the topic of robotics in construction, (b) on the topic of robotics

among the identified journal sources, with a total of 1835 citations, and the highest average number of citations at 50.97 per paper. As such, this journal is clearly the most important and the most influential journal in terms of RiC research. Many of the other journals listed in Table 1 have had multiple publications on this topic (e.g., *Journal of Construction Engineering and Management, Advanced Materials Research*). Although some journals have only a few related publications, these have often been widely cited (such as the *International Journal of Robotics Research, Autonomous Robots*) and thus may have had a significant impact.

3.2.2. Co-citation analysis

Co-citation refers to two documents that are cited together by a third document. If two papers are frequently cited together, then both papers will also each have high individual citation numbers. Frequently cited papers tend to present *key concepts, methods, or experiments* in a field [27]. Furthermore, if two papers are cited together in many other papers, it can be concluded that these co-cited papers have a close relationship and high impact in the research domain [28,29]. As a result, a co-citation network is able to visualize the relationships among key publication sources, key documents, and highly influential authors. In this research, a co-citation analysis on the bibliometric data retrieved from Scopus was conducted in VOSviewer. The co-citation function was used to generate co-citation networks related to different aspects to explore the most influential publication sources, authors, and documents in the RiC domain.

3.2.2.1. Co-citated publication sources. To generate the co-citation network of publication sources, the minimum citations for a source was set at 20 in the VOSviewer setting field, and 21 out of the 8212 sources met the threshold. The threshold set took account of two factors: (1) the practice of previous bibliometric literature review research, such as [15,17]; (2) the need to produce visually comprehensible maps containing clearly readable information, which requires some trial and error to fine-tune the parameters [13]. These two factors were taken into account throughout the presented study. As recommended in similar research [21,29], "fractional counting" (a normalization method) was adopted in conducting the co-citation analysis.

The co-citation network of publication sources is depicted in Fig. 3. The size of a circle represents the number of citations and, thus, the larger the circle, the more citations. It is clear that *Automation in Construction* has the most co-citations, followed by the *Journal of Construction Engineering and Management* and the *Journal of Computing in Civil Engineering*. Nodes that are in the same color are categorized as in the same cluster by VOSviewer. The detailed information of clusters, links, total link strength, and citations are summarized in Appendix 1. Note that, the links column indicates the number of links between nodes, and the total link strength reflects the total strength of links between one node and others [30]. The higher the number, the greater importance of the item in the co-citation network.

The software identified four clusters as shown in Fig. 3 and Appendix 1. Cluster 1 is on the right of the figure and shown in red, with the largest item in this cluster being the *International Journal of Robotics Research*. Compared with the other clusters, journals in this cluster, such as *IEEE Transactions on Pattern Analysis and Machine Intelligence* and *Science*, do not focus on the construction industry. Cluster 2, located in the lower left corner of Fig. 2, is shown in green with the *Journal of Construction Engineering and Management* as the largest item. The journals in this cluster mainly publish papers focusing on managerial topics in the construction industry, such as *Construction Management and Economics* and the *Journal of Management in Engineering*. Cluster 3, in the upper left part of Fig. 2, is shown in blue with *Automation in Construction* as the largest item. Finally, cluster 4 is the smallest cluster (shown centrally in yellow), with the *Journal of Computing in Civil Engineering* as its largest item. Clusters 3 and 4 are close to each other and feature journals such as *Advanced Engineering Informatics*, *Computer-aided Civil and Infrastructure Engineering*, and the *Journal of Information Technology in Construction* that focus on technical issues in the construction industry.

3.2.2.2. Co-cited authors. As with co-cited publication sources, authors that are co-cited tend to be the most influential in a research domain. Therefore, a co-citation analysis to identify the most influential authors was carried out and is reported in this section. Feeding the bibliometric data into the VOSviewer and using the co-citation analysis function results in the co-citation network of authors plotted in Fig. 4. As with the earlier publication co-citation analysis, a fractional counting method was used to obtain a normalized network. The minimum number of citations for an author to be included was set at 35 using the criterion outlined earlier, and 37 authors met the threshold. The information displayed in Fig. 4 is summarized in Appendix 2, sorted by the number of co-citations.

Fig. 4 and Appendix 2 show that five clusters of authors were identified. Authors in the same cluster are the most frequently co-cited by other researchers, indicating that their research has more in common than with authors in other clusters. Appendix 2 shows that the most cited author is Haas, C.T. (with 149 co-citations) who is placed in cluster 1 (in red in the lower-left corner of Fig. 4). Next is Bock, T. with 117 co-citations placed in cluster 5 (in purple to the right of the figure). The most cited author in cluster 2 (in green, top-center) is Wang, X. with 90 co-citations. In cluster 4 (in yellow, top-left), the most cited author is Al-Hussein, M. with 77 co-citations. Cluster 3's (blue, bottom-middle) most cited author is Lee, S. with 60 co-citations.

3.2.2.3. Co-cited papers. The last part of the co-citation analysis focuses on the most co-cited academic papers in the RiC research area. If certain articles have been co-cited by different papers multiple times, it means that the papers are probably among the most influential papers for the targeted research area, thus, the top co-cited papers are tabulated in Table 2 to present the important papers in the RiC research area. The

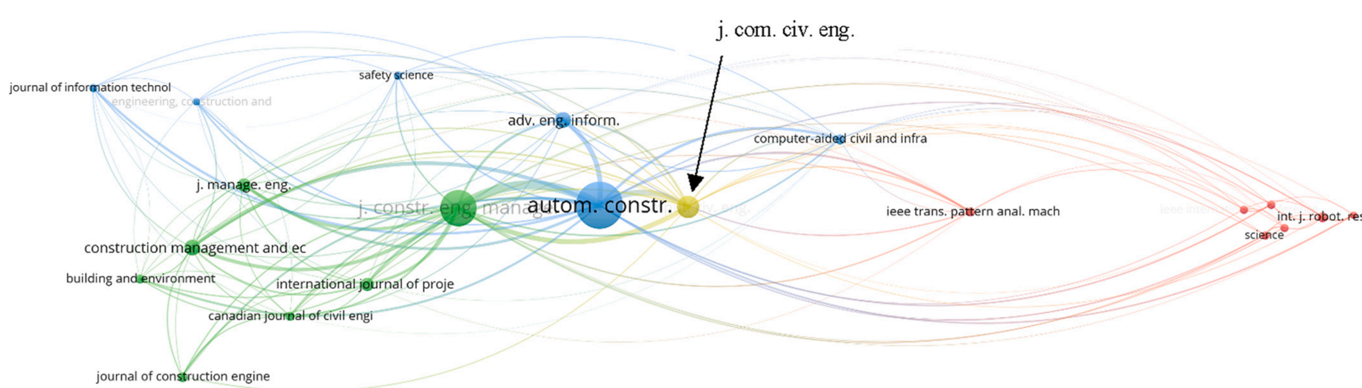

Fig. 3. Co-citation network of publication sources.

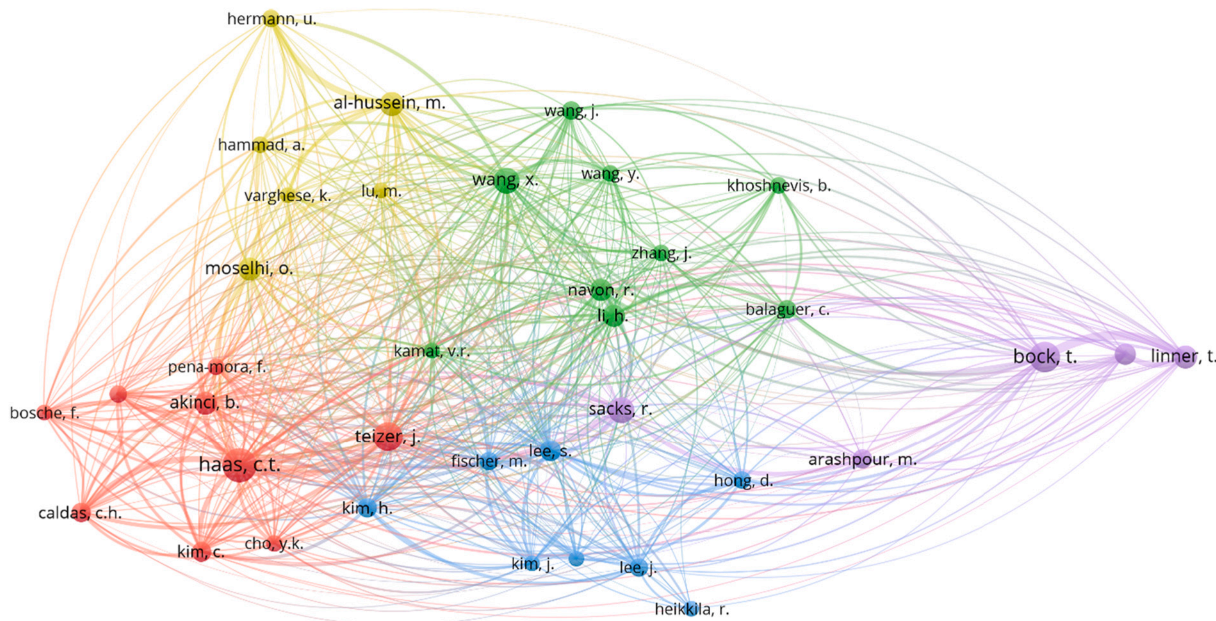

Fig. 4. Co-citation network of authors.

information from Table 2 was also retrieved by the VOSViewer co-citation analysis function. The minimum number of co-citation number was set to 5, and 12 papers met the threshold out of a total of 18,510 cited references. It can be seen from the table that Bock [31] outstands all the identified top co-cited papers, with a co-citation number of 19 followed by Oestrreich and Teuteberg [32], Song et al. [33], Warszawski and Navon [34], etc. To be noted, most of the papers are published in renowned journal sources in the construction engineering domain (i.e., Automation in Construction and Journal of Construction Engineering and Management), with the exceptions of [32,35,36], which are published in journals out of the domain of construction engineering. In summary, the papers listed in Table 2 most likely provide fundamental knowledge for RiC research, and that leads to the high co-citation numbers of these publications.

3.2.3. Multinational co-authorship

A co-authorship analysis based on individual authors' geographic area (country/region) is presented in this section to identify geographical collaboration networks. The co-authorship function of VOSviewer was adopted to analyze the bibliometric data accordingly, with the minimum number of publications per country/region set at 5, resulting in 28 areas out of the 59 countries/regions included in the dataset meeting this threshold. The co-authorship network is shown in Fig. 5. The figure includes only 26 areas (rather than 28) since neither the Netherlands or Poland was linked with other countries/regions in the clusters. The detailed information of these 28 countries/regions is tabulated in Appendix 3, sorted by the number of published documents.

Countries/regions with the same color in Fig. 5 are in the same cluster, meaning they have closer collaboration with each other than with other areas. For example, researchers in Canada, Australia, and India are all placed within the same cluster, indicating that authors in these countries closely collaborate in the RiC research domain. The most productive country regarding RiC is the United States with 153 published documents that have gained a total of 2004 citations (also the highest citation total in the list). Many other countries/regions have published considerably and been widely cited in this field, for example South Korea (130 documents, 574 citations), China (104 documents, 359 citations), Japan (39 documents, 639 citations). Interestingly, in terms of average citations per paper, Spain, despite only having 8 publications in this field comes top, achieving 23.88 citations per paper. The average publication year column gives a crude indication of when a region was most active in producing publications in this field. This suggests that South Africa, Hong Kong, and United Arab Emirates have been most active in recent years, while Japan and the Netherlands were more active earlier.

3.3. Research cluster analysis

Author-determined keywords have been recommended in many previous studies, such as [43,44], as an important source for identifying key research areas in a certain topic. Consequently, this subsection presents the results of an analysis of keyword co-occurrence using the VOSviewer tool. The keywords co-occurrence network was generated by feeding the bibliometric data on RiC research into the VOSviewer in order to facilitate a better understanding of current research patterns and relationships [13]. The threshold for the minimum occurrence of a keyword was set at 5. A further step of combining keywords with similar semantic meanings was performed to achieve a readable and meaningful map. For example, keywords such as "construction", "construction management", "construction engineering", "construction automation", "automation", and "construction project" were merged under an umbrella term construction automation/management ("const. auto./manag." for short). From this process, 40 keywords emerged that are displayed in the co-occurrence map (Fig. 6) from the 2088 keywords found in the included publications. In the figure, the size of the node reflects the occurrence of a keyword: the larger the node, the more occurrences of the keyword. Nodes shown in the same color are categorized as falling within the same research cluster, and the distance between nodes shows the strength of the relationship between them (a greater distance reflects a weaker relationship) [45]. The detailed information shown in Fig. 6 is summarized in Appendix 4, sorted by the occurrence of keywords.

The largest nodes are BIM and modular construction. This is not surprising since BIM and modular construction are key research topics in the construction industry. The figure also implies that many researchers focusing on RiC have been seeking synergies between BIM and RiC, as well as between modular construction and RiC. The modular construction research cluster is located at the top of Fig. 6 (in red), while the BIM related research cluster is to the left (in brown). Below and to the left of the BIM cluster is an radio-frequency identifiers (RFID) cluster (in blue)

Table 2
Top co-cited papers in RiC research.

Reference	Title	Source	co-citations
Bock, 2015 [31]	The future of construction automation: technological disruption and the upcoming ubiquity of robotics	Automation in Construction	19
Oesterreich and Teuteberg, 2016 [32]	Understanding the implications of digitisation and automation in the context of industry 4.0: a triangulation approach and elements of a research agenda for the construction industry	Computers in Industry	7
Song et al, 2006 [33]	Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects	Automation in Construction	7
Warszawski and Navon, 1998 [34]	Implementation of robotics is building: current status and future prospects	Journal of Construction Engineering and Management	6
Jaselskis, et al, 1995 [37]	Radio-frequency identification applications in construction industry	Journal of Construction Engineering and Management	5
Khoshnevis, 2004 [38]	Automated construction by contour crafting-related robotics and information technologies	Automation in Construction	5
Melenbrink et al, 2020 [39]	On-site autonomous construction robots: towards unsupervised building	Automation in Construction	5
Siebert and Teizer, 2014 [40]	Mobile 3d mapping for surveying earthwork projects using an unmanned aerial vehicle (UAV) system	Automation in Construction	5
Ulrich, 1995 [35]	The role of product architecture in the manufacturing firm	Research Policy	5
Wang, 2008 [41]	Enhancing construction quality inspection and management using RFID technology	Automation in Construction	5
Werfel et al, 2014 [36]	Designing collective behavior in a termite-inspired robot construction team	Science	5
Zhang et al, 2018 [42]	Large-scale 3D printing by a team of mobile robots	Automation in Construction	5

that includes several keywords such as material management, visualization, and knowledge management. There is also a research cluster in the bottom-middle of the figure (in green) that broadly focuses on management-related topics with keywords such as safety, productivity, monitoring, and performance evaluation. Positioned close to the management research cluster is a cluster (in yellow) with keywords related to artificial intelligence, such as machine learning, laser scanning, and point cloud. Finally, there is a maintenance-related research cluster to the far right of the figure (in purple) with keywords such as window cleaning and cleaning robot.

Fig. 6 presents a static pattern of RiC research clusters based on roughly twenty years of data, it does not show any changes in research trends over the past two decades. However, VOSviewer is also able to present the network of keyword co-occurrence overlayed with time series data as depicted in Fig. 7. Each node represents a corresponding keyword using different colors that indicate the average publication year. The more general keywords, such as construction automation/management and robotics, appear in publications whose average year of

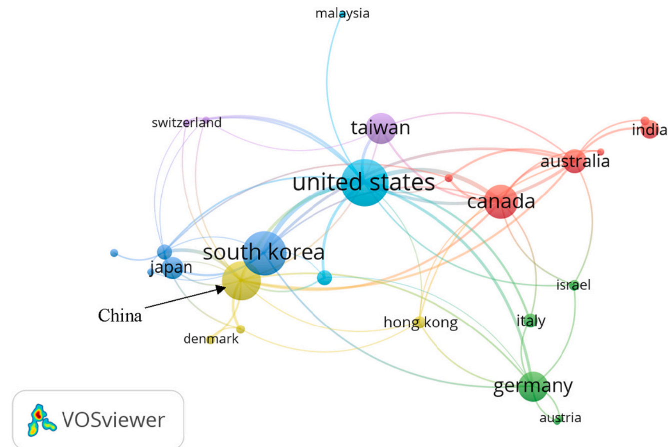

Fig. 5. Co-authorship network in the RiC research domain.

publication is around 2013 (close to the midpoint of the period covered in this analysis) reflecting that these keywords have generally been evenly used across the research period. Some keywords, such as RFID, monitoring, and performance evaluation, have an earlier average date as research areas that were prominent in the early days of RiC research. In comparison, keywords such as BIM, modular construction, and point cloud have a much later average publication date (around 2015) reflecting that these are relative new research areas. The newest keywords identified are machine learning, industry 4.0, and 3D printing, which are all emerging technologies that have seen huge developments in recent years. In addition, maintenance-related research in the RiC domain only appears in more recent studies. Overall, Fig. 7 can be helpful in visualizing the evolution of RiC research over time.

4. Qualitative discussions

4.1. Overview

Following on from the bibliometric analysis, a qualitative analysis is conducted to provide deeper insights into the RiC research field. In this section, the most representative RiC publications are first grouped and then discussed in terms of three dimensions: 1) *task*: the construction tasks completed using robotics; 2) *algorithm*: the algorithms developed for controlling the robots in construction; and 3) *collaboration*: the collaboration between multiple robots or between human and robots. Subsequently, the challenges to adopting robotics in the construction industry are identified and future research directions are proposed.

4.2. Tasks in RiC

In terms of the task dimension, the existing literature on robotic tasks in construction has been categorized into on-site operations, off-site manufacturing, and additive manufacturing. A detailed review of each sub-category is provided below.

4.2.1. On-site operations

Currently, many on-site operations in construction (e.g., material handling, bridge inspection, façade cleaning) require high energy levels and are dangerous for human workers. Many researchers are working on replacing manual labor with robotic technologies for some of the dangerous and repetitive on-site operations such as bricklaying, inspection, and cleaning [3]. Applying robotics to bricklaying has a relatively long history going back to the 1990s [46], and the tasks considered for robots include picking bricks, bonding materials, and the erection of brickwork. Recently, robotic bricklaying has achieved a high level of automation. For example, Dörfler et al. [47] built a double leaf dry-stacked brick wall using a fully automated mobile robot. Zandavali

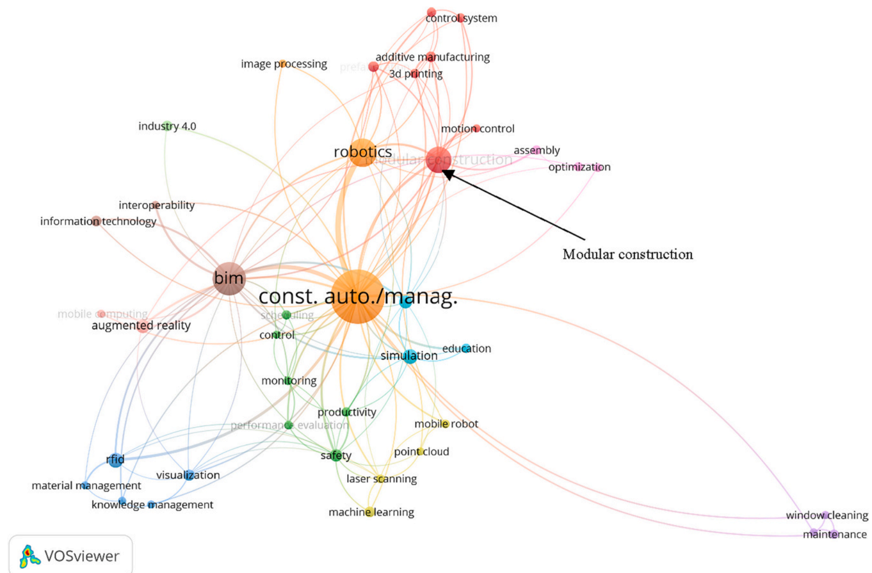

Fig. 6. Network of author keywords co-occurrence.

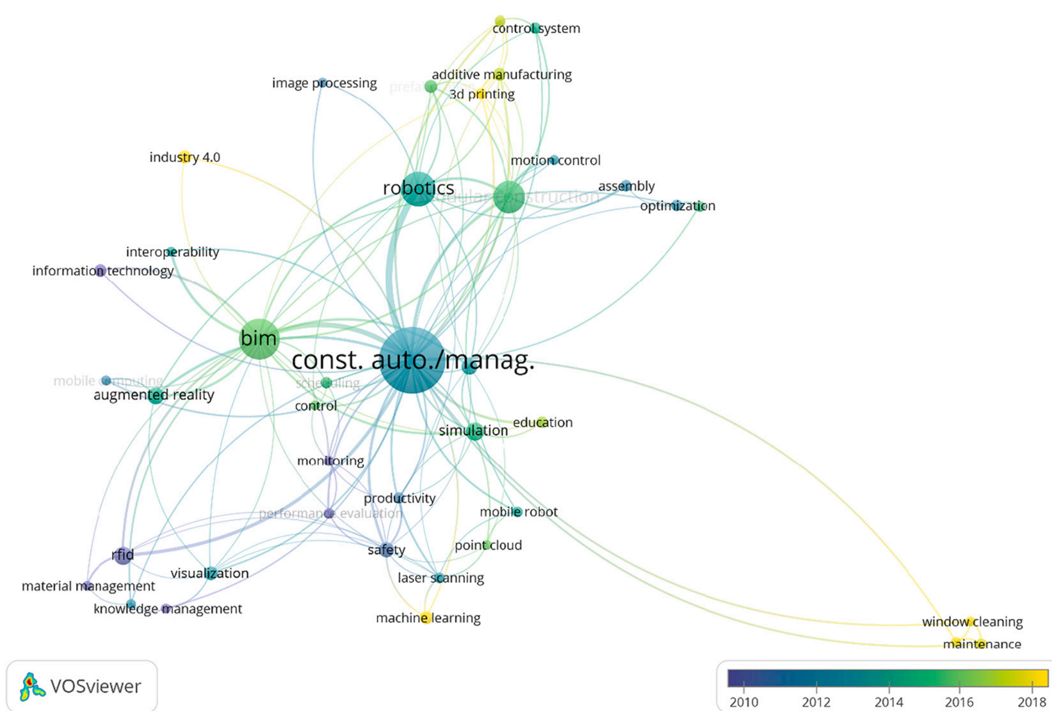

Fig. 7. Timeline-overlayed network of author keywords co-occurrence.

et al. [48] have integrated machine learning algorithms to automatically generate brick patterns for robotic assembly. Ding et al. [49] have proposed a BIM-based task-level planning method by adopting an vision-based 3D model for robotic bricklaying.

Inspecting the structural health of infrastructure such as bridges is an important task in built environment management and these tasks are difficult and tedious for workers. Recently, robots have been widely adopted for infrastructure inspection. For example, Murphy et al. [50] have developed a customized unmanned vehicle and two underwater robots for inspecting a rollover pass bridge. Further, Pham et al. [51] have developed a magnetic, wheeled robot for steel bridge inspection that can move along bridges with square or circular steel structures. Nguyen and La [52] have developed a climbing robot that can work on flat steel surfaces to inspect steel bridges. Robots can also be adopted for the inspection of façades, tunnels, roadways, and storage tanks. A more comprehensive review of robotic inspection of infrastructures can be found in [9].

Robotics has also been employed for cleaning purposes of high-rise buildings and seen as a way to improve the safety of the operation process. Traditionally, the cleaning of high-rise buildings is conducted by workers and presents risks for both workers and pedestrians. Mir-Nasiri et al. [53] have developed a portable autonomous robot for cleaning windows of high-rise buildings that is easy to manipulate. Kim et al. have developed a wall-cleaning robot equipped with dry and semi-dry wall-cleaning units that was found to be stable and achieve excellent cleaning performance in experiments. Beyond façade cleaning, Parrot et al. have developed a dry-cleaning robot equipped with a silicone rubber brush to clean solar panels in Thuwal, Saudi Arabia. In a different area, Walter et al. [54] have employed robotic technology to clean large-diameter sewers. These studies show that robotic technologies have reached a stage where they are ready for on-site construction operations. However, existing robotic applications in construction are developed for a single task and are difficult to deal with multiple tasks in a complex on-site environment.

4.2.2. Off-site manufacturing

A recent trend in the construction industry is off-site manufacturing, which refers to the manufacture and assembly of individual building components (e.g., precast concrete elements, steel structures, timber frames) in a factory environment prior to delivery to the construction site [55]. In such a controlled environment, robotics can help improve productivity, enhance safety, and reduce waste in off-site manufacturing since robots can undertake heavy shifting and working loads [56]. In concrete element production, robotics can be applied in cleaning and plotting, shuttering and de-shuttering, reinforcement production systems, insulation, concrete spreading, and cladding [10]. For instance, Garg and Kamat have developed virtual prototyping for the robotic prefabrication of rebar cages for concrete production in off-site manufacturing [57]. Reichenback and Kromoser [58] have introduced automation using robotics throughout concrete production in the construction industry.

Robotics can be adopted to assemble steel structures in off-site manufacturing, thereby replacing manual efforts. Liang et al. [59] have developed a robotic assembly system (RAS) that employs robot arms for the erection and assembly of steel structures in an off-site environment. The RAS involves four actions for assembling the steel structure: rotation, alignment, bolting, and unloading. Shi et al. [60] have proposed an assembly system for steel frames in an off-site factory that takes account of 3D manufacturability. In the system they developed, BIM models of steel frames serve as inputs and the intersection regions in an assembly line are detected. Next, the required manufacturing operations, such as fastening together with screws, are calculated. As such, potential collisions in the steel assembling process can be avoided and this improves safety in the off-site manufacturing.

Timber remains an important material for residential buildings in many countries (e.g., United States and Canada). Timber frames are relatively light, meaning that wooden components are easy to manipulate by robots, and considerable research has been conducted in this direction. For example, Villaneuva et al. [61] have designed and simulated an automated robotic cell for assembling cross-laminated timber panels. Hasan et al. [62] have developed a robotic fabrication system that employs a robot arm for nailing laminated timber in an off-site environment. They have shown that a robot arm can complete a range of manufacturing tasks with timber structures by incorporating multiple tools (e.g., gripper, vacuum, nail gun). Naboni et al. [63] have proposed a novel assembly procedure from design and simulation through to robotic assembly of reversible timber structures, and the results indicate that their proposed procedure could complete complex high-resolution assembly tasks for timber structures. Currently, highly automated robotics is being widely adopted in off-site manufacturing due to the well-controlled environment this approach provides. However, off-site fabrication still needs to distribute the assembled building components to the construction sites. In the future, setting up a robotic fabrication platform near the construction site can be a potential direction.

4.2.3. Additive manufacturing

In recent years, additive manufacturing (AM), also known as 3D printing, has grown rapidly in the field of RiC. This refers to creating 3D objects by depositing materials using a computer-controlled process [64]. Using AM, one is able to print construction components directly from BIM or CAD models without intermediate steps, which also allows optimized structural designs [7]. AM has already been used to 'print' entire structures such as offices, bicycle bridges, and houses [7]. In current practice, the equipment required for AM is commonly installed on robot arms to print construction components. Based on the construction materials adopted, AM applications can be categorized into three types: concrete, steel, and other materials.

In terms of concrete-related AM, Le et al. [65] have printed a concrete bench using high-performance fiber-reinforced fine-aggregate concrete without the need for formwork in the building process. Similarly, Carneau et al. [66] have 'printed' concrete cantilevers without needing to use temporary supports and this has reduced construction waste. Their study indicates that the stability of concrete AM products needs to be verified on the scale of the lace section, the layer, and the global structure. Meanwhile, Ducoulombier et al. [67] have adopted anisotropic concrete in printing construction structures, and a novel printing process (flow-based pultrusion) has been introduced. Currently, in terms of productivity, concrete AM lags conventional manufacturing. Here, Garcia et al. [68] compared the time and costs of manual construction versus robotic fabrication for building four different concrete walls. They concluded that the robotic fabrication method only achieved a higher productivity than the manual method for the fabrication of curved double-walls.

Turning to metal components, AM has been adopted in the construction sector to enable greater flexibility in the geometry of structural elements, reduce material consumption and wastage, and improve worker safety. The most common metal-related AM techniques include powder bed fusion (PBF), directed energy deposition (DED), sheet lamination, and electrochemical additive manufacturing (ECAM) [69]. The most popular AM technique with metal is wire and arc additive manufacturing (WAAM) [70] due to its relatively low cost and high deposition rate. Yuan et al. [71] have proposed a robotic fabrication method for producing metallic parts with overhanging structures using the multi-directional WAAM, which achieved high wire feed speed, high torch travel speed, and stable deposition positioning.

Besides concrete and steel, other materials such as polymers [72], ceramics [73], and tunable 3D-printed core materials [74] have been investigated for AM applications in construction. A review of the various materials adopted in AM can be found in [75]. AM can be adopted for both on-site and off-site construction environments, and is able to reduce construction waste and improve the mechanical properties of construction components. However, AM is facing challenges in construction sites including: 1) size limitation. AM is difficult to be applied for printing large building components; 2) lack of regulations. The AM is a relatively new technology in RiC and there lacking of regulations for quality control of AM; and 3) higher skill requirements. AM requires construction workers to have extra skills to manipulate the equipment.

4.3. Algorithms in RiC

This section discusses the algorithms developed for robotics in the construction industry. Based on the scenarios identified in the literature analysis, this section is focused on the introduction of state-of-the-art sensing algorithms and autonomy algorithms. Sensing refers to perceiving the environment, which include multiple sensing technologies including camera, RFID, and Laser scanner. Autonomy refers to the following steps after sensing to control the robots, which include positioning and path planning. Adopting robots in construction, sensing the environment, positioning the robots and other objects, and planning the working sequences contain most steps for controlling robots. Many studies have also considered the development of software that visualizes robotic operations in a virtual environment for training purposes in the construction industry and these are discussed in section 4.4.

4.3.1. Sensing algorithms

Sensing the environment is the fundamental step in positioning, mapping, and navigating robots in construction operations, and many sensors have been adopted for robotic sensing in construction such as cameras, RFID, and laser scanners [76]. Compared with other sensing methods, cameras have the advantages of relatively simple development and being less expensive, and have often been the preferred option for robotic sensing in recent years. For example, Wang et al. [77] have proposed a novel vision-based method by integrating Faster R-CNN to assist construction waste recycling robots to find nails and screws. Asadi et al. [78] have presented an integrated robotic system that navigates on construction sites based on the pixel wise semantic segmentation and Simultaneous Localization and Mapping (SLAM). Lin et al. [79] have developed a vision-based framework for bridge inspection using aerial robots that can automatically conduct visual data capture, 3D mapping, defect detection, analysis, and reporting. Their framework has been developed for 30 bridge inspection projects in the United States and Japan. Generally, the performance of vision-based sensing methods is sensitive to illumination changes at construction sites. Nevertheless, thanks to the rapid development of deep learning technologies, vision-based methods have achieved robust performance in sensing the environment surrounding construction projects.

RFID, a wireless non-contact technology based on exchanging information by electromagnetic signals, has been widely applied in the construction industry including in RiC applications. By placing different tags across a construction site and equipping a robot with a RFID antenna, the position of robots can be accurately calculated within the construction environment [80]. For example, Won et al. have proposed an integration method for analyzing RFID signals for construction resource localization, and have achieved an acceptable range of accuracy on construction sites [81]. Gunatilake et al. [82] have attached a RFID antenna to a robotic platform to inspect the internal environment of pipelines, and have achieved a positioning accuracy of 0.15 m. A negative aspect of this technology is that it requires manual effort to install the tags and provides only limited location information, and as such it is less convenient than other RiC sensing technologies.

Compared with vision-based and RFID-based methods, laser scanning methods using Lidar sensors can obtain highly precise 3D points in the construction environment. For example, Kim et al. have employed a laser scanning method to reconstruct the 3D environment for navigating mobile robots at construction sites, and have achieved better efficiency and accuracy than dynamic scanning would achieve. Vestartas and Weinand [83] have adopted laser scanning for sensing the timber frame fabrication process to automatically assemble wooden frames using industrial robot arms. However, laser sensors are much more expensive than other sensors (e.g., cameras and RFID). Given that each sensing method has its own limitations, many researchers are working on hybrid sensing solutions for robotics in construction (some examples can be found in [84–86]), and these have the potential to become a future direction in RiC. In addition, improving the speed and accuracy of the sensing methods is an important future work for RiC.

4.3.2. Autonomy algorithms

The development of autonomous robots for construction tasks such as site inspection and object manipulation is governed by navigation and mobility requirements, reflecting a need for precise positioning and path planning. Methods based on SLAM algorithms are widely used for the localization and mapping [87]. Mclaughlin et al. [88] used an unmanned ground vehicle (UGV) which incorporated red-green-blue (RGB) cameras, lidars, GPS, and IMU sensors to inspect a bridge for defects, and applied a two-step SLAM method to position the UGV for data collection. First, a lidar odometry and mapping algorithm (LOAM) [89] is applied for initial trajectory estimation using data extracted from lidar and IMU sensors. Following this, back-end optimization is implemented using the Georgia Tech Smoothing and Mapping library [90] to refine and complete the state trajectory. The state trajectory is used to produce a lidar map, and the position of the UGV and the map are expressed in the same frame. In another development, Gunatilake et al. [91] have used a sensor-based method that integrated a particle filter algorithm and Gaussian process data modeling to position robots inside underground water pipelines using RFID sensors. Their method achieved a precision of 0.15 m in the robot's location within a 6 m long pipe with a diameter of 600 mm.

Path planning algorithms provide collision-free paths between initial and final positions or determine optimal paths for a robot to visit multiple locations [92]. Asadi et al. [93] implemented a rapidly exploring random tree algorithm to accomplish point-to-point collision-free navigation for a brick grasping robot. Mantha et al. [94] proposed a combinational robot indoor path planning method to adapt to the constraints of minimum and maximum distances in robot path planning. Recently, some research works [88,95] have proposed robotic arm path planning for manipulating target objects. Industrial robotic arms are highly flexible and can be configured for complex construction tasks. In this approach, the motion plan is designed to reduce positioning errors caused by frequent robot base movement and avoid collisions. For example, Yang and Kang [96] have proposed a collision avoidance method for robotic arm path planning in modular home prefabrication by employing multiple level-of-detail colliders. In planning the movements of robot arms with multiple degrees of freedom, the environmental data are described in the form of a 3D point cloud, and a Sphere-Swept Bounding (SSB) method [97] is applied. In the SSB method, the obstacles are represented as points in point cloud set, and each link of the robot is covered by a coaxial capsule shape. The centerline of each link is defined as a sweeping line of a sphere in the capsule and is used to calculate the distance between the robot arm and the obstacle in collision-free path planning.

BIM has been widely adopted for use in robotic autonomy in the construction industry due to its ability to hold copious information on the built environment. For example, Kim et al. [98] have offered a novel BIM-integrated construction robot task planning and simulation system that has demonstrated the feasibility of using BIM for planning the operation of autonomous robots on construction projects. Karimi et al. [99] have also suggested an integrated system to leverage BIM for robot navigation in construction sites. Park et al. [100] have integrated the ultra-wideband technology of mobile robot navigation systems for indoor tracking in construction scenarios. Currently, BIM is mainly only adopted for position tracking applications in construction, and there is a need for more in-depth integration of BIM and RiC. Although existing autonomy studies have achieved relatively reliability, these studies still have difficulties dealing with flexible tasks in construction scenarios, and more advanced controlling methods should be explored in the future.

4.4. Collaborations in RiC

This subsection discusses research work on robotic collaborations in construction. In terms of the task dimension, the existing literature has been categorized into human-robotic collaborations and multi-robot collaborations. Detailed reviews of each sub-category are discussed below.

4.4.1. Human-robotic collaboration

Some research has looked into human-robotic collaboration (HRC) systems as a way to reduce or avoid injuries to human workers by allowing humans to work remotely off-site while controlling on-site robots [101–103]. These HRC systems usually apply both vision and sensor-based methods to link the motions of the human worker with those of the robot, with teleoperations being one of the most common applications. For example, Le et al. [102] created a smart observation system enabling workers to remotely control a tele-operated excavator. The system integrated a head mounted display, orientation sensors, three cameras, and a portable control station. The results of their experiment indicated that the proposed system reduced the operational time for digging by 12.5% and of levelling by 14% while also improving usability and ergonomics by 21%. The proposed system could be further improved by replacing the monocular camera with a stereo camera to provide a real sense of depth and any obstacles to the operator.

Kurien et al. [104] remotely linked the off-site motions of a human worker to an on-site robotic construction worker (RCW) in real-time with the aim of avoiding injuries to human workers. They created two systems for human worker and RCW collaboration. One system involved 3D body and hand position tracking to capture precise movements that include both the orientation and articulation of the entire body of a construction worker using RGB-D sensor-based detection and tracking methods. The other approach involved a real-time simulation system that connected an off-site human construction worker to a virtual RCW in Unity 3D [105]. A client-server software pipeline was developed to connect two systems of tracking and simulation to enable the tracked human hand and body data to be simultaneously transferred to the simulation platform. You et al. [106] used a similar method that integrated HMD, Unity 3D, cameras, and sensors to create an HRC system that linked human activity to a virtual robot in a 3D game engine to carry out masonry tasks. In this study, the human workers and the robots were placed to work in different areas: sometimes in the same work area and sometimes separated. Experimental results indicated that separating work areas increases the human workers' sense of task safety. In addition, creating a sense of safety at work increases the willingness of human workers to work with robots.

Other than remote control possibilities, some researchers have focused on the communication between human workers and robots in indoor building inspection. Considering the different capabilities and strengths of humans and robots, Wang et al. [95] created an interactive and immersive process-level digital twin (I2PL-DT) system to optimize the use of both humans and robots. In their system, the human worker is responsible for high-level planning and supervisory work, while the robot undertakes more specific activities such as path planning, workspace sensing, and monitoring. Turek et al. [107] indicated that the effectiveness of such cooperation highly depends on communication abilities since the human and robot perspectives on building elements differ significantly. Consequently, they proposed a method for mapping a formalized general BIM model to a functional robotic system model that could be easier understood by robots and facilitated communication between human and robots. Currently, most research of HRC is adopting human-friendly robots (e.g., Universal Robots) to ensure the safety. However, these robots cannot lift heavy components. Improving the collaboration safety of human and industrial robots (e.g., KUKA and ABB robots) will be the focus in the future HRC field.

4.4.2. Multi-robot collaboration

Communication capabilities are fundamental for effective environmental monitoring and exploration tasks performed by multi-robot systems [108]. In some multi-robot systems [108–110], researchers have created communication maps to optimize the measurement route for multiple robots. Im et al. [110] created an intelligent robot communication system using zigbee signals to locate robots and generate a communication map using Extented Kalman Filter (EKF) and Nearest Neighbors (*K*-NN) methods. The system is able to predict the possible area within which robots can move freely and avoid disconnecting with cooperating robots. Similarly, Li et al. [108] built a Gaussian process-based communication map with Wi-Fi signals and RGB-D cameras that can reduce the number of locations to be visited and optimize the routes of multiple robots in real-time.

Some complex infrastructure maintenance and inspection tasks require robots with different capabilities to accomplish the task collaboratively. Miura et al. [111] proposed a multi-robot system for tunnel inspection. The system consists of four robots: an investigation robot, a transfer robot, and two relay robots. The investigation robot was equipped with RGB and infrared cameras, various sensors (microphone, CO_2 and temperature sensors), lights, gas density measuring instrument, etc. The relay robots were equipped with RGB and infrared cameras, lights, and automatic cable reels. During the tunnel inspection, the transfer robot carried the investigation robot to the target location to carry out the inspection, and the relay robots followed the transfer robot while laying the cable. The experimental results show the feasibility of the proposed system for inspecting for surface deterioration, water leakage, and gas density.

There are multi-robot systems that include human-robot collaboration. For instance, to perform construction-related tasks and respond flexibly to unexpected situations, Nagatani et al. [112] proposed a human-controlled multi-robot approach. Their approach integrated multiple sensors, a teleoperation method, a self-organization method based on multistage emergence, and deep learning modules for environment assessment to evaluate environmental conditions (e.g., ground surfaces, obstacles, moisture content) with limited data collected from sensors to enable collaboration between multiple robots under human operation. Wallance et al. [113] created a virtual teleoperation (VT) framework such that an operator could control heterogeneous robots performing different construction tasks. The framework integrated a Unity interface, the Robot Operating System (ROS), and real-time DRC-Hubo robot operating systems to control two robots: a Spot quadruped robot from Boston Dynamic and the DRC-Hubo robot created by themselves. In the VT framework, the human operator controls both the DRC-Hubo and the Spot robots through a user interface in a virtual environment with an HTC VIVE headset and controllers, and the robots perform matching activities in the real environment. More specifically, the DCR-Hubo robot was used to manipulate the specific construction task and the Spot robot delivered items to a waypoint. Furthermore, the DCR-Hubo robot could be synchronously controlled by the operator, while the Spot robot could only be controlled asynchronously. Currently, multi-robot collaboration is still in the early stage in the research community. How to efficiently communicate, sense, and motion planning still remain challenges in RiC.

4.5. Discussion and future directions

By conducting a quantitative analysis and then providing qualitative discussions on the topics identified, the authors were able to highlight current challenges to adopting robotic technologies in the construction industry and corresponding research directions.

4.5.1. In-depth integration of BIM and robotics

As indicated in the bibliometric analysis, BIM was identified as one of the largest research clusters of the RiC literature, which proves the importance of integration of BIM and RiC. In the past two decades, BIM has been widely adopted in the construction industry as a valuable digital information management system that has helped both researchers and industrial practitioners in terms of decision-making, sustainable management, and cost-saving in projects [114]. Currently, BIM has been widely applied for robotic navigation [115], simulation [98], and multi-robot collaboration [116] on construction sites. However, the current integration of BIM and robotics is still at the task-level and there is a lack of research into how to deeply integrate BIM and robotics in an end-to-end manner.

Regarding that, the following research can be conducted to facilitate in-depth integration of BIM and robotics: 1) retrieval of building component information from BIM models; 2) generation of working sequences and motions for assembling individual building components; 3) visualization of working sequences of robots in a virtual environment; and 4) control real robots through virtual environment commands. Given that only a few construction professionals are able to program and control robots, the in-depth integration of BIM and robotics could help construction engineers adopt robotics in their projects. In this regard, developing integral solutions to link BIM and robotics could significantly promote robotic technologies in this industry. Yang et al. [117] have proposed a software package (RoBIM) to tackle this challenge. However, their research is still at the conceptualization stage, and more research effort is needed in this direction.

4.5.2. Near-site robotic fabrication

Near-site robotic fabrication refers to using a mobile and transportable robotic platform that can have several robotic devices installed, which is proposed as future direction because it can further reduce the delivery efforts compared with off-site construction. Currently, off-site (or modular) construction shifts most of the work to a controllable and usually indoor factory environment where many processes can be automated and carried out by robots. Off-site construction is an ideal scenario for robotic applications, and considerable research [118–120] has gone into robotic technologies for off-site construction. However, after off-site robotic fabrication, the building components need to be distributed to the construction sites, which is costly and time-consuming. As an alternative approach, the near-site robotic fabrication can be delivered close to the construction site to assemble building components and pass them directly to the site, which can significantly reduce distribution costs and time. Some researchers are working in this direction. For example, Wagner et al. [121] have developed a near-site robotic platform for timber assembly (TIM) and conducted a semi-industrial production case study to validate its feasibility. The development of near-site robotic fabrication is still in an early stage and more effort is required. To facilitate that, more research efforts can be conducted on mobile robot platform development and robotic working sequence design.

4.5.3. Deep reinforcement learning for flexible environment adaption

Understanding, decision-making, and planning are important to RiC considering the construction sites is an open, flexible, and complex environment. Deep reinforcement learning (DRL) has the potential to train construction robots to work in the job-sites and deal with the complex environment in the future. Existing robotic autonomy algorithms are not able to adapt to the unseen construction environment since these algorithms have only been validated in a laboratory environment [112]. For example, path planning has to predefine the possible locations in the map [94], and robot arms cannot automatically adjust to the environment geometry [95]. In future work, more open design systems and algorithms are needed to improve the environmental adaptability and flexibility of construction robots, which would improve their applicability in unknown construction environments and the flexibility of undefined work processes. DRL [122] refers to a machine training method based on rewarding desired behavior and/or punishing undesirable ones. Computer science studies [123–125] have indicated the DRL is able to teach robots to interact with the real-world environment and make appropriate decisions when dealing with unforeseen tasks. As such, DRL is a promising technology that could improve the future feasibility of construction robotics through adaption to flexible environments. To apply DRL in RiC, future research efforts should be conducted on real-time sensing of construction sites, efficient training of DRL algorithms with limited construction data, and applying DRL for various robotic tasks in construction.

4.5.4. High-level robot-to-robot collaboration

High-level robot-to-robot collaboration refers to multiple robots working at the same construction task without or with few manual manipulations, which will significantly improve the efficiency of robotics in construction in the future. Most current robotic cooperations are focusing on using robots in the same task, which are not sufficient for completing complex construction tasks [108]. For example, in Wallance et al.'s work [113], a human worker had to simultaneously control both an item-delivery robot and a manipulation robot carrying out different tasks to complete a construction function. This form of primary collaboration is relatively inefficient, increases the workload of human workers, and is inconvenient in use. Therefore, it will be beneficial if one could achieve high-level cooperation between robots with different dynamic tasks in different areas. For instance, a group of delivery robots could cooperate with robotic arms to complete a drywall installation task. High-level cooperation could be utilized in a wide range of construction tasks to improve overall automation. Moreover, it could also reduce the number of injuries and the workload of human workers. To achieve this high-level coordination, more efforts are requested in terms of multi-robot communication, smart sensing, and robot motion modeling.

5. Conclusions and limitations

This paper presents the findings of a literature review of recent advancements in the topic of RiC using a mixed-method approach that combines bibliometric analysis with qualitative discussion. In the bibliometric review, a publication cluster analysis was conducted to reveal the focal areas and links among publications in the RiC research field. Key indicators, such as publication versus citation, co-citation, and co-authorship have been plotted and described in detail to identify the most influential publication sources, authors, and collaborations among different areas. Following this, a research cluster analysis was conducted to reveal the key macro-level RiC research areas. Next, in a qualitative review, existing research topics in RiC have been categorized along three dimensions: task, algorithm, and collaboration. Under the task dimension, construction tasks that can be completed using robotics are discussed in terms of on-site manufacturing, off-site manufacturing, and additive manufacturing. Under the algorithm dimension, existing robotic algorithms related to sensing and autonomy have been analyzed. Following this, human-robotic and multi-robot collaborations have been summarized under the collaboration dimension. Finally, several future directions for relevant research are proposed: (1) an in-depth integration of BIM and robotics; (2) near-site robotic fabrication; (3) deep reinforcement learning for flexible environment adaption; and (4) high-level robot-to-robot collaboration.

The main contributions of the research are threefold: (1) the current publication situation regarding RiC is quantitatively presented and discussed on the macro-level; (2) key RiC research areas are identified and qualitatively discussed; and (3) potential future research directions for RiC are proposed and discussed. Overall, the paper presents the recent advancements in RiC research, creating a valuable overview for both the academic and industrial communities to understand the current situation and explore possible future innovative research directions and applications.

Nevertheless, the research has its limitations. First, the research has only considered publications in English, and it would be valuable to include publications in other languages in the future. Second, the proposed research directions reflect very much the opinions and areas of expertise of the authors. As such, there will inevitably be gaps and expert opinions could be sought to identify further worthwhile research directions. For example, the recent advancement of information technologies such as Industry 4.0, Internet-of-things, and Digital twin could have potential driving effects for RiC research, which requires more observations in the future and worth to be investigated.

Declaration of Competing 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.

Data availability

Data will be made available on request.

Appendix 1. Top co-cited sources in RiC research

Publication sources (ordered by number of citations)	Cluster	Links	Total link strength	Citations
Automation in Construction	3	20	409.23	961
Journal of Construction Engineering and Management	2	19	313.06	546
Journal of Computing in Civil Engineering	4	20	147.76	184
Advanced Engineering Informatics	3	16	81.77	94
Construction Management and Economics	2	14	79.02	93
Journal of management in Engineering	2	14	47.93	64
International Journal of Project Management	2	15	49.38	60
International Journal of Robotics Research	1	9	15.00	36
Computer-aided Civil and Infrastructure Engineering	3	13	29.78	35
Journal of Construction Engineering and Management	2	7	20.80	35
Building and Environment	2	10	21.40	29
Canadian Journal of Civil Engineering	2	13	27.50	29
IEEE Transactions on Pattern Analysis and Machine Intelligence	1	11	19.63	29
IEEE International Conference on Robotics and Automation	1	8	7.33	25
Journal of Information Technology in Construction	3	11	20.34	25
Science	1	6	11.33	25
Safety Science	3	10	17.51	23
Autonomous Robots	1	8	12.76	22
Nature	1	8	9.00	22
Engineering, Construction and Architectural Management	3	11	18.55	21
IEEE/ASME Transactions on Mechatronics	1	5	10.18	20

Appendix 2. Top co-cited authors in RiC research

Authors	Cluster	Links	Total link strength	Co-citations
Haas, C.T.	1	36	107.72	149
Bock, T.	5	33	81.60	117
Teizer, J.	1	36	82.80	112
Wang, X.	2	35	66.65	90
Sacks, R.	5	34	62.76	89
Al-Hussein, M.	4	34	57.47	77
Linner, T.	5	28	54.70	73
Moselhi, O.	4	30	45.28	72
Akinci, B.	1	30	60.31	71
Li, H.	2	35	49.74	69
Navon, R.	2	31	37.80	65
Pan, W.	5	22	38.98	62
Lee, S.	3	36	52.08	60
Kim, C.	1	33	48.57	59
Arashpour, M.	5	22	19.05	53
Caldas, C.H.	1	30	43.46	52
Kim, H.	3	35	43.42	52
Lee, J.	3	29	31.79	50
Balaguer, C.	2	30	25.21	49
Fischer, M.	3	34	35.12	49
Wang, J.	2	34	32.57	47
Golparvar-Fard, M.	1	31	34.81	44
Hong, D.	3	28	24.89	43
Hermann, U.	4	23	31.56	42
Hammad, A.	4	25	26.67	41
Khoshnevis, B.	2	23	19.08	40
Cho, Y.K.	1	31	29.53	39
Zhang, J.	2	32	21.89	39
Pena-Mora, F.	1	29	29.76	38
Wang, Y.	2	32	28.58	38
Heikkila, R.	3	11	7.00	37
Kamat, V.R.	2	34	30.25	37
Bosche, F.	1	28	33.63	36
Varghese, K.	4	29	28.95	36
Kim, J.	3	32	28.22	35
Kim, K.	3	24	22.65	35
Lu, M.	4	31	23.78	35

Appendix 3. Co-authorship regarding countries/regions

Countries/Regions	Cluster	Links	Total link strength	Documents	Citations	Normalized citations	Average publication Year	Average citations
United States	5	15	47	153	2004	267.74	2013	13.10
South Korea	3	9	19	130	574	91.39	2012	4.42
China	4	15	25	104	359	75.06	2015	3.45
Canada	1	10	21	84	374	67.52	2015	4.45
Taiwan	6	5	8	69	218	34.57	2011	3.16
Germany	2	9	11	68	546	91.52	2013	8.03
Australia	1	11	20	43	266	44.98	2015	6.19
Japan	3	3	4	39	639	44.18	2010	16.38
India	1	1	2	28	43	6.78	2013	1.54
Finland	5	4	5	20	98	19.55	2013	4.90
United Kingdom	3	10	12	20	234	46.35	2014	11.70
Italy	2	3	4	17	155	16.90	2013	9.12
Hong Kong	4	6	4	15	62	28.26	2018	4.13
Israel	2	4	4	11	40	8.75	2013	3.64
Poland	8	0	0	10	19	3.15	2016	1.90
Denmark	4	2	2	8	24	4.31	2013	3.00
Singapore	4	4	5	8	76	24.19	2016	9.50
Spain	1	1	1	8	191	17.79	2011	23.88
Iran	1	4	6	7	13	2.83	2017	1.86
South Africa	3	1	1	7	10	5.34	2019	1.43
Switzerland	6	4	4	7	138	37.47	2017	19.71
Brazil	1	2	2	6	0	0.00	2017	0.00
Sweden	3	3	1	6	46	4.78	2013	7.67
United Arab Emirates	6	5	6	6	104	31.60	2018	17.33
Austria	2	1	1	5	19	1.19	2012	3.80
Malaysia	5	1	1	5	31	5.28	2014	6.20
Netherlands	7	0	0	5	35	3.19	2010	7.00
Romania	2	1	1	5	1	0.16	2014	0.20

Appendix 4. Keywords co-occurrence

Author keywords	Links	Total link strength	Occurrences	Average publication year	Average citations
Construction Automation/Management	38	95	188	2013	6.99
BIM	21	42	76	2016	4.43
Robotics	14	36	54	2014	9.22
Modular Construction	13	22	49	2015	6.47
RFID	6	11	16	2010	16.00
Simulation	6	7	16	2015	3.50
Augmented Reality	5	9	14	2014	3.43
Project Planning	10	8	13	2013	3.85
Safety	12	11	11	2011	32.91
Visualization	8	5	9	2013	20.44
Additive Manufacturing	6	8	8	2017	34.13
Prefabrication	6	5	8	2016	7.13
Machine Learning	3	3	8	2018	1.88
Information Technology	2	4	8	2008	3.38
Industry 4.0	2	2	8	2020	2.25
3D Printing	7	6	7	2018	24.00
Control System	4	4	7	2014	0.29
Digital Fabrication	6	5	7	2017	24.71
Productivity	5	5	7	2011	18.57
Scheduling	5	3	7	2015	2.71
Maintenance	3	5	7	2017	0.29
Education	3	5	7	2017	2.00
Assembly	4	4	7	2012	13.00
Optimization	4	3	7	2012	1.14
Monitoring	7	5	6	2010	18.50
Performance Evaluation	3	4	6	2009	4.67
Laser Scanning	8	6	6	2013	28.83
Mobile Robot	4	4	6	2014	3.83
Risk Management	2	2	6	2015	3.67
Motion Control	3	4	5	2013	3.00
Control	4	3	5	2016	2.60
Knowledge Management	3	3	5	2008	5.60
Material Management	3	3	5	2010	5.00
Ontology	4	4	5	2012	3.40
Point Cloud	5	3	5	2016	4.40
Cleaning Robot	3	5	5	2018	0.40
Window Cleaning	3	5	5	2018	0.40
Image Processing	2	2	5	2012	3.40
Interoperability	2	5	5	2014	1.20
Mobile Computing	3	3	5	2012	5.00

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