Robotic Technologies in Concrete Building Construction: A Systematic Review

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Abstract –

Several researchers have worked in the field of implementing robotics technology in concrete building construction, after the first attempt in the 1980s in Japan. Various motivations such as the shrinking labor population, the aging of skilled workers, and the construction safety issues have promoted the development of such technologies. However, the future visionary on how construction robots can transform the concrete building construction sector is still not solid nor well structured.

What really needs to be changed? What types of construction activities can be taken by automated robotic technologies, as opposed to manpower or skilled worker? To answer these questions, the systematic review reported in this paper seeks to evaluate and synthesize empirical findings on the use of robotic technologies in concrete building construction.

A systematic search of Scopus, Web of Science, IEEE, and Engineering Village databases was conducted, and 48,200 documents were targeted. By applying the inclusion and exclusion criteria, 48,149 records were excluded, and the remaining 51 records were assessed for eligibility and included in the qualitative synthesis. The systematic review shows that researchers in the USA played a leading role on robotics in concrete building construction, followed by Germany and Switzerland. The robotics application and techniques have been largely used on-site and targeted low-rise buildings. The robotic technologies that have been popular in literature included 3D printers, and swarm robotics. Most of the papers have proposed a limited novel structural design, without introducing innovative construction material. Even though the direct and indirect construction activities related to formwork, steel reinforcement, and concreting can be replaced and thus eliminated, the horizontal RC elements still cannot be built on-site without supports. Moreover, rapid prototyping found to be the best robotic design for the purpose of building construction through utilizing manipulator robots.

Keywords –

Concrete buildings; Robotics in construction; Freeform construction; Future of construction.

1 Introduction

The fundamental principles in building construction have not yet substantially changed, since the Romans invented concrete about 100 BC [1]. Later, concrete is still considered globally as the primary material for construction. According to a recent report by the Cement Sustainability Initiative (CSI) [26], concrete is the second most consumed substance after water, with around 10 billion tonnes of concrete are manufactured globally in every year. Consequently, concrete has been the focus in several investigations into robotically fabricated, geometrically complex, non-standard loadbearing constructions [2].

The building construction industry has not been a favourable field for the application of robotic technologies, however, various motivations such as the shrinking labour population, the aging of skilled workers, and the construction safety issues have promoted the development of robotic construction systems [3]. The United Nations world population prospects in 2015 indicated that global population is expected to grow by 34% by 2050 compared to 2014, which will reach 6.5 billion people in 2050 or about two-thirds of the global population [4]. In accordance, the rising in population is expected to growth the necessity for new buildings.

Meanwhile, the building construction process has been characterized as simple and systematic; depending on formwork systems and skilled labour to build any type of concrete structural element [5]. The current construction methodologies used in structural concrete buildings are completely dependent on manual techniques that are slow, expensive, and non-coordinated [27]. Moreover, the main obstacles for the introduction of robotics within the building construction industry are the variability of the construction processes and the complex conditions of the construction environment [6].

Many building construction activities have the potential to be executed by implementing the robotic technologies techniques [7]. However, adapting new technologies necessitates several special properties of high payload, reliability, and wide workspace to be achieved [8]. In addition, many robots will work in the same task, in which path planning on site would be complicated [9]. As explained by Scott et al. (2011), human construction differs from construction by robots as it involves some sort of pre-defined high-level plan and in some regard is independent from the environment [10].

Several researchers have worked in the field of implementing robotic technologies in building construction, after the first attempt in the 1980s in Japan [2]. While some autonomous construction robots have been developed, they can only be applied to simple tasks to support human workers [9]. An example of such approaches is the Big-Canopy, which is the world's first automated construction system for building a precisely defined concrete structure in Japan [11]. Nevertheless, the degree of intelligence exhibited by commercially-available robots is still deemed very limited, as robots are currently deployed only in a small subset of possible applications with low level of localization accuracy [12, 31].

If robotic technologies could truly be implemented in construction, they would certainly have the potential to improve measures like its speed and efficiency, as well as enabling construction in settings where it is difficult or dangerous for humans to work such as working at heights, in extra-terrestrial environments and disaster areas [13, 32, 33]. In this context, this paper aims to review existing studies in this field, to investigate how the robotic technology can be implemented in the concrete building construction. To overcome the existing constraints and limitations, the ongoing research will examine construction activities with a potential to be executed by robotic technologies, functionality of the robots, and the interaction between humans and robots.

The remainder of the paper is structured as follows. Section 2 introduces the background of the research, followed by the methodology of using a systematic review. Section 4 and 5 detail the results and discussion. Finally, the paper concludes with the guidelines for future research.

2 Background of the study

2.1 Early attempts

Despite the recent advances in adoption of robotic technologies in the construction industry, the architectural processes which demand a high degree of geometric freedom remain largely labour intensive and manual [19]. This is due to the inherent difficulties in robotizing the current implementation of such processes coupled with the lack of alternate technologies [2].

In the last three decades some Japanese construction companies have attempted to remedy the shortage of skilled labour in building construction by resorting to automation [20]. Khoshnevis et al. (2006) categorized the current robotic technologies in concrete building construction in accordance to the Japanese companies. The first one uses single task robots that can replace simple labour activities at the construction sites. The second category consists of fully automated systems that can construct steel reinforced concrete buildings using prefabricated components [11].

So far, the application of robots is feasible only if it generates a value-adding effect. According to Hack et al. 2014, the centralised fully automated Japanese construction systems failed to do so, as they merely tried to automate the existing construction processes. They only focused on the elimination of human labour from the building site, without considering the complexity of the building process. Hence, Hack suggested that some innovated construction processes need to be developed first, to specifically address the strengths of robots to be applied where they actually outperformed humans and conventional construction [14].

2.2 Present attempts

The Chinese Huashang Tengda company in Beijing has recently claimed to 3D print an entire 400 m2 two story villa 'on-site' in 45 days uses a unique process allowing to print an 'entire house' in 'one go'. This is by erecting the frame of the house including steel reinforcements and plumbing pipes conventionally, and then ready-mix concrete extruded over the frame and around the rebars using a novel nozzle design and 3D printer [15].

The WinSun decoration design engineering company worked jointly with architectural and structural design companies such as Gensler, Thornton Tomasetti, and others to build an office building for the Dubai Future Foundation with a technique similar to contour crafting, in which wall elements are manufactured from extruded prismatic bodies [30]. One more technology known as WASP (World's Advanced Saving Project) has focused on using Additive

Manufacturing technologies to build "zero-mile homes" that utilize on-site materials to build houses in places where it is hard to find access to construction materials [16].

In despite of presently attempted, the current construction is in need for large scale 3D printers to build complex geometric shapes on projects where construction time, cost, and quality are the predominant and determining success criteria [17]. In accordance, a novel approach for 3DCP technology for on-site construction, named CONPrint3D, is currently being developed at the TU Dresden, Germany, which intends to bring 3DCP directly into the building sites [15]. In addition, Skanska is a construction company that recently has utilized advancements in the area of additive manufacturing by printing unique cladding for the Bevis Marks building in London [16].

2.3 Future visionary

A comparison by Helm et al. (2012) between the usages of robotic technologies in building site with other industries, revealed that the construction sector has been rather slow to adopt such innovative technologies with most tasks on a building site still carried out using manual methods [18]. As stated by Hwang, et al. (2005), the present state of automation and robotic technologies are not sufficient to economically replace skilled labour, thus suggested that the construction industry needs to think "out of the box" and seek alternatives to existing fabrication and assembly processes [19].

Howe at el. (2000) had a different view, when proposed to study the possible applications of robotic technologies to traditional methods because they are the most familiar to us, while the feasibility of automating the entire construction site would be dependent on need and would occur gradually. At the same time, Howe confirmed that there are many problems need to be overcome first in order to develop usable robotics in the building construction [20].

It has been furtherly explained by Choi et al. (2005) that in a field of construction work, the content of work and working material are frequently changeable, thus construction robot needs several special properties of high payload, safety, reliability, and a wide workspace [21]. Thus, a collaboration between conventional tools, humans and robots, and standard concrete pumps is required to transfer the actual structural mass, while the robot could unlock the inherent potential of concrete to take any desired shape by building complex formwork in high resolution [14].

The new paradigm brings a host of new topics into the forefront of robotics in construction research. These topics have been neglected in the past by researchers inspired by the old paradigm, and therefore there is a backlog of research problems to be solved. This systematic review has been performed to respond to this research gap, and by using its results to develop a comprehensive framework. The methodological approach of the systematic review is outlined in the next section.

3 Research methodology

To provide a robust investigation on the applications of robotic technologies in the concrete building construction, a systematic review approach was adopted. In comparison with a conventional literature review, a systematic review applies an explicit, rigorous, reproducible, and auditable methodology for evaluating and interpreting all available research relating to a particular research question, topic area, or phenomenon of interest [22].

A systematic review originates from the need to overcome the shortcomings of a single facet approach which is often adopted in a literature review, by representing the bigger picture by combining discrete pieces and synthetizing results in an organized way [23]. Additional benefits also include that researchers can summarize existing evidence about a phenomenon, identify gaps in current research, and provide grounds to position or support new ideas and hypotheses [24].

The review has been undertaken in distinct stages as shown in Figure 1, including the development of review protocol, the identification of inclusion and exclusion criteria, searching for relevant studies, critical appraisal, data extraction, and synthesis. In the rest of this section, we describe the detail of these stages and the methods used.

3.1 Protocol development

The protocol for the systematic review has been developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [28]. This protocol specified the research questions, search strategy, inclusion, exclusion and quality criteria, data extraction, and methods of synthesis.

3.2 Research question

The aim of the systematic review is to locate relevant existing studies based on the research question of 'What type of robotic technologies have been in use in the concrete building construction industry?', to report the evidence in a way that clear conclusions with regard to further research to be drawn [29]. For the purposes of this paper, the systematic review shall provide a theoretical basis for understanding to what extent the topic of robotic technologies is being addressed in concrete buildings construction.

3.3 Inclusion and exclusion criteria

Studies were excluded if their focus, or main focus, was not related to robotics in construction or if they did not present empirical data. Furthermore, the research question is concerned with concrete building, therefore, studies that focused on other building construction were excluded. Studies were eligible for inclusion in the review if they presented empirical data on robotics in concrete building construction and passed the minimum quality threshold (see Section 3.5). The systematic review included research studies published up to and including 2018. Only studies written in English, clearly describe its methodology, completed and concluded were included.

3.4 Data sources and search strategy

The search strategy included electronic databases. Of Scopus, Web of Science, IEEE, and Engineering Village. Figure 1 shows the systematic review process and the number of papers identified at each stage.

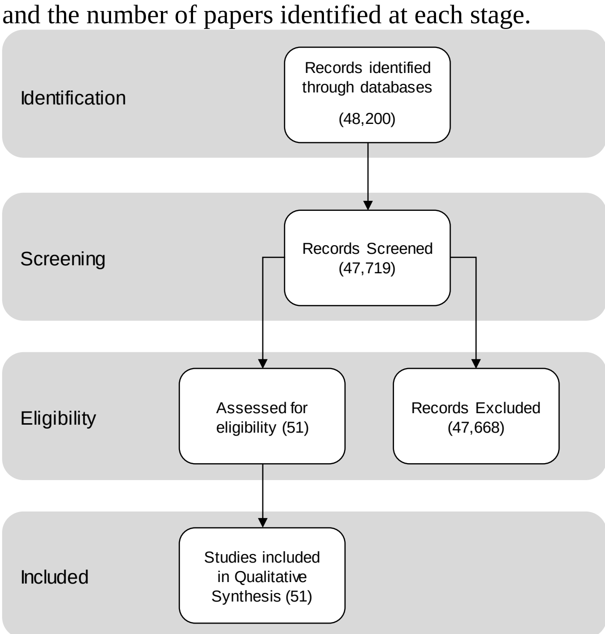

Figure 1. Flowchart of systematic review process. (PRISMA flow diagram [28])

In the identification stage, the titles, abstracts, and keywords of the articles in the included electronic databases and were searched using search term of (robot* AND construction)". These keywords are widely-known for their use in research articles. Excluded from the search were editorials, prefaces, article summaries, interviews, news, reviews, correspondence, discussions, comments, reader's letters and summaries of tutorials, workshops, panels, and poster sessions. This search strategy resulted in a total of 48,200 documents. Of total number of documents (n = 47,719), 1,020 were book sourced, 15,646 journals, and 31,053 were resulted from a conference proceeding source.

At screening stage, duplicates were removed as well as papers from undefined or trade publications resources. At this stage, 481 articles were excluded after removing duplicates as well as papers from undefined or trade publications resources. However, it was not always obvious whether a study was, indeed, an empirical one. Therefore, all studies that indicated some form of experience with robotics in construction were included. At eligibility stage, studies were excluded if their main focus was not robotics in on-site building construction. As a result, 51 primary studies were included for the detailed quality assessment.

3.5 Quality assessment

The methodological quality of the eligible selected studies was critically appraised using a set of screening questions adopted from the Critical Appraisal Skills Programme (CASP) [25]. A summary of the questions used to assess the quality of these studies is presented in Table **1**. The tool provides a guide for appraising qualitative research to consider if the results of the study are valid, what the results are, the benefits of the results, and the tool has been used in a range of reviews. Taken together, these questions provided a measure of the extent to which we could be confident that a particular study's findings could make a valuable contribution to the review. Each of the 9 questions was graded on scale of (YES = 1, NO = 0), and only question 1 was used as the basis for including or excluding a study.

Table 1. Quality appraisal questions

	Screening Questions
Q1	Research: Is the paper based on research
Q2	Aim: Was the aim of the research clear?
Q3	Method: Was the research methodology used appropriate?
Q4	Design: Did the study design address the aims of the research?
Q5	Data analysis: Was the data analysis sufficiently rigorous?
Q6	Findings: Are the findings clearly stated?
Q7	Gaps: Have gaps in the literature been clearly identified?
Q8	Acceptance: Can I accept these findings as true?
Q9	Value: Can I apply these findings to my own work?

The results of the quality assessment are shown in Figure **2**. Because only research papers were included in this review, all included studies were rated as yes on the first screening question, in addition, they all had a clear statement of the aims of the research as well as appropriate research methodology. While the number of negative answers was three for each criterion of research methodology, study design and findings acceptance. Furthermore, the data analysis did not seem sufficiently rigorous for four of the studies. The highest numbers of negative answers were 17, and 19 as it has been noticed that the findings were not well described, and gaps in the literature were often not identified.

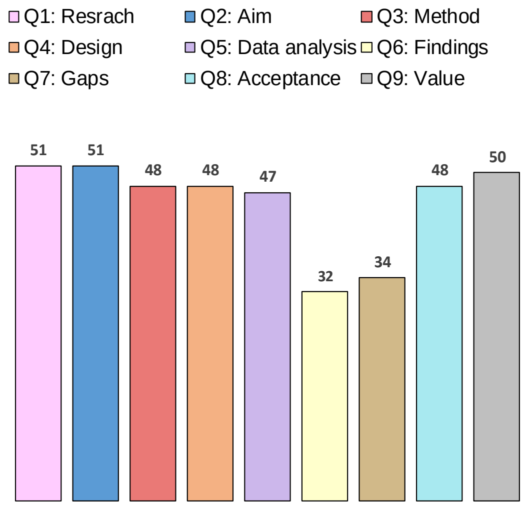

Figure 2. Quality appraisal summary results (out of total number of articles: 51)

3.6 Data extraction

During this stage, data was extracted from each of the 51 primary studies included in this systematic review according to a predefined extraction form (see Figure 3). This form enabled to record full details of the articles under review and to be specific about how each of them addressed the research question. All data from all primary studies were extracted by the authors in consensus meetings. The aims, settings, research methods descriptions, findings, and conclusions, as reported by the authors of the primary studies, were tabulated in Microsoft Excel.

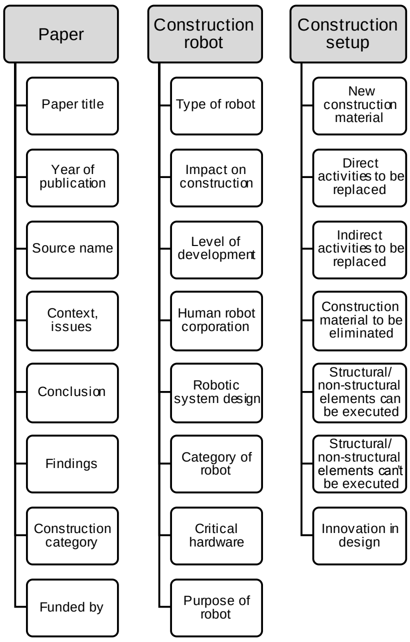

Figure 3. Data extraction

3.7 Peer assessment

The first two authors sat together and went through the titles of all studies that resulted from identification stage, to determine their relevance to the systematic review. At the eligibility stage, the abstracts were divided among the first two authors and the third author in such a way that each abstract was reviewed by two researchers independently of each other. All disagreements were resolved by discussion that included all three researchers, before proceeding to the final stage. Each of the 51 studies that remained was assessed independently by the authors, according to quality assessment procedure.

4 Results

4.1 Publishing framework

The chronological distribution of articles in Figure 4 indicated for a growing interest in performing research related to the subject. 6 papers have been published from 2000 to 2005 and 9 papers from 2006 to 2011. While the period from 2012 to 2018 accounted for the most published papers of 36 number. The analysis results demonstrate that there is a substantial increase in the number of literature during the last 6 years. This would indicate for a promising established research area in concrete building construction.

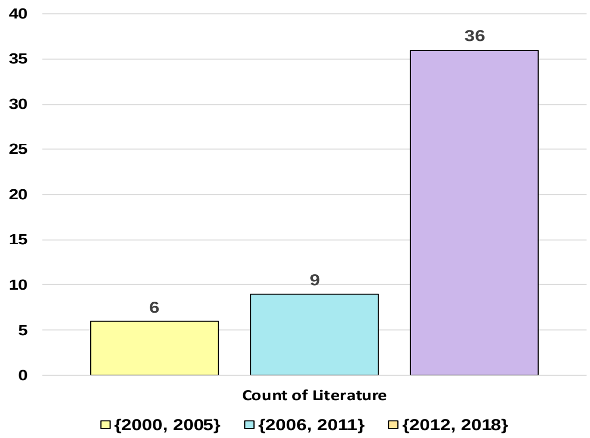

Figure 4. Chronological Distribution of publications (total number of articles: 51)

Furthermore, Figure 5 shows the number of publications according to the different country for each of the authors. When comparing the geographical distribution of the total number of 51 papers, USA and Germany are ahead of all others. However, by filtering out only the 23 articles of highly related studies to the review topic, research on the subject has been dominated by authors from USA, and France. While, focusing on the 4 extremely related studies revealed that authors from Switzerland are leading the topic.

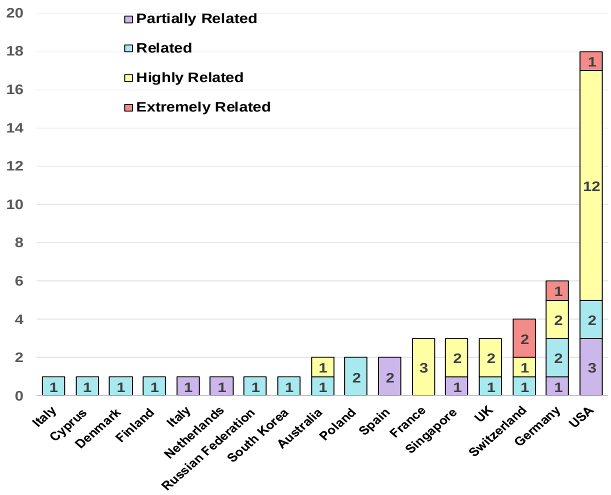

Figure 5. Geographical distribution of publications (total number of articles: 51)

4.2 Implementation on a construction site

The construction applications and techniques for the outcome are mainly on-site and related to the robotic technologies of 3D printers, automated building construction system, and swarm robotics construction system (see Figure 6). In context, 57% from the proposed technologies have targeted low rise building projects and 35% focused on low to medium rise buildings, while only 8% could target the medium to high rise building category. This could indicate that adapting most of the studies for the 3D printing technology, has resulted in a major limitation to target high rise building construction.

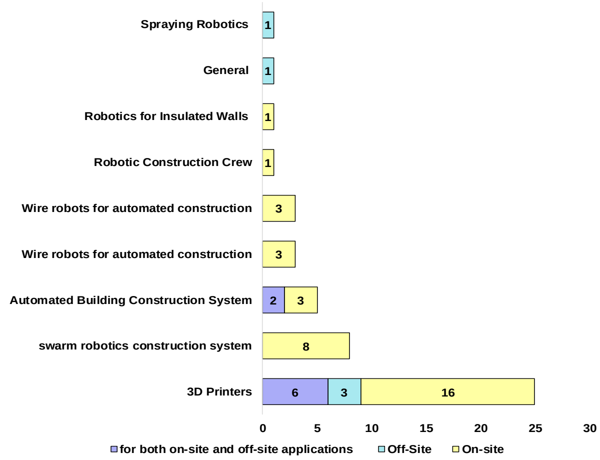

Figure 6. Construction robots' types & application (total number of articles: 51)

In parallel, Figure 7 shows that most of the researched robotic technologies were found to be either under development or conceptual. At the same time, their implementation in concrete building construction is challenging. Only 10% from the proposed topics were classified as developed technologies, and merely 8% could be implemented in a construction site.

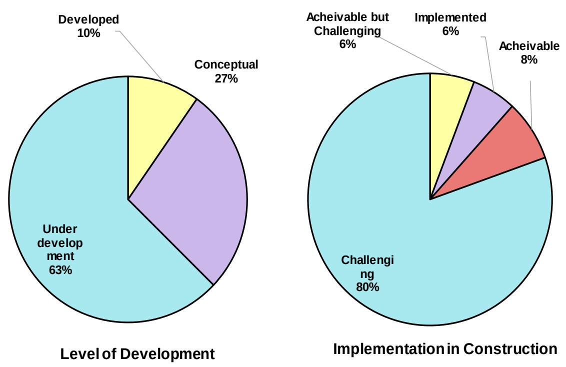

Figure 7. Robotics technologies level of development and implementation in construction

Concerning the reasons behind proposing such technologies, nearly 70% of the papers shared the same goal of enhancing the concrete building construction efficiency. While construction in space, besides proposing new construction technologies have attracted almost 20% from the authors. The remaining papers were interested in the construction in disaster or hazardous areas, as well as reducing the accident rate. (See Table 2).

Table 2. Purpose of the robotic technologies (total number of articles: 51)

Purpose of the robotic technology	Number of paper
Construction in disaster areas	1
Reducing high accident rate	2
Construction in a constrained/ hazardous environment	2
New construction technology	5
Construction in space	5
Greater efficiency	36

4.3 Innovation in construction material and structural design

As illustrated in Figure 8, 53 % of the papers proposed a limited novel structural design and 29% projected a complete novel design proposal, while the remaining 18% adopted the conventional structural design for the construction of concrete structures. Concerning the innovation in construction material, the researchers could not introduce novel material to the construction, however they have focused on finding alternatives to replace the conventional ready-mix concrete and steel reinforcement.

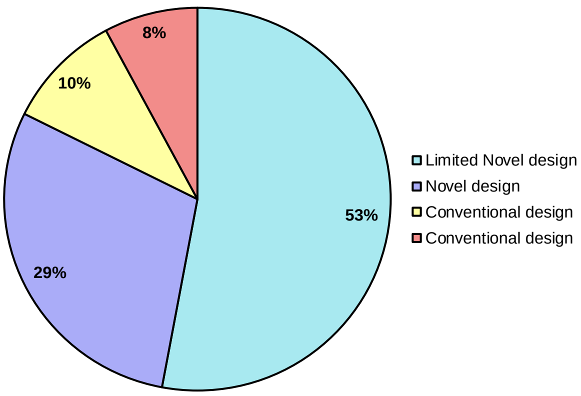

Figure 8. Innovation in structural design

As presented in Figure 9, 45% of the papers considered mesh wire as an alternative to reinforcement rebar, and around 79% from the total literature proposed polymer based material and cementitious material to replace the ordinary cement. While mortar mix, intelligent concrete blocks, and ultra-high-performance concrete found to be the new alternatives to conventional concrete mix.

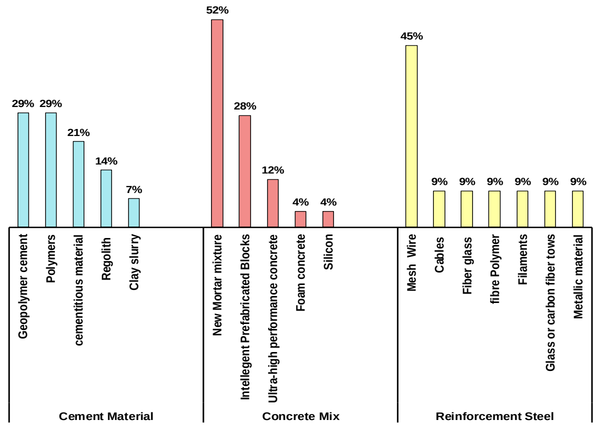

Figure 9. Alternative construction material

4.4 Impact on building construction activities

Formwork fixing and striking, steel rebar fixing, and concrete pouring and curing are the main direct construction activities could be replaced by the proposed robotic technologies. The major indirect construction activities that could be eliminated comprise ready-mix concrete delivery to site, formwork fabrication, steel rebar fabrication, and material handling by cranes and manually (see Figure 10). This would have a huge impact not only on the overall productivity of the construction activities, but also on the entire efficiency of the concrete building construction. The proposed construction technologies will not depend on plywood, formwork systems and scaffolding to build any concrete structural element.

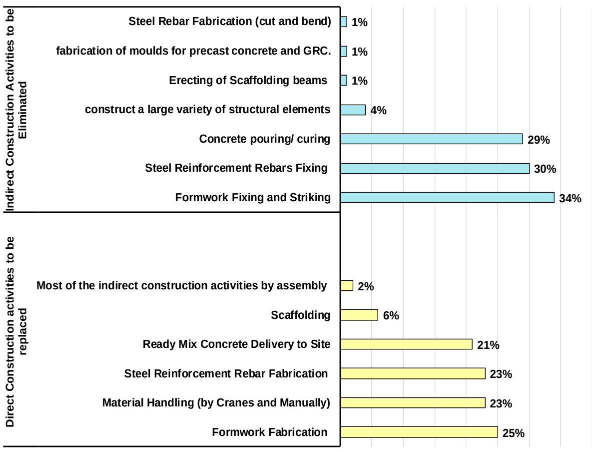

Figure 10. Impact on construction activities

Regarding the applicability of the construction robotics to build all the structural concrete elements, 93% of the literature claimed that their proposed technologies can build vertical RC elements on-site, while 4% suggested pre-casting and assembly, and only 3% proposed a full solution to construct all RC elements on-site for one story building. The same studies claimed to build vertical RC elements have shown incapability of their proposed technologies regarding the construction of horizontal RC elements on-site, unless they were temporary supported during the construction or pre-casted and assembled by cranes.

4.5 Construction robotic features

Different types of robotic systems have been adopted through the literature, however, rapid prototyping and self-assembly found to be the most appropriate systems for the purpose of concrete building construction (see Table 3). This outcome is in line with the results in 4.2 construction applications and techniques.

Table 3. Robotic system

Robotic system design/ programme	% of literature
VR-assisted virtual prototyping	2%
Multi-robot construction and assembly	2%
Automated assembly systems	2%
Generic, versatile mobile robotics system	4%
Cartesian motions	6%
Self-organized construction	8%
Controlled assembly	8%
Self-assembly	12%
Rapid prototyping	56%

In terms of the construction robotic category, 63% from the studies considered manipulator robots for their proposed technologies, and around 15% adopted the collective construction robot category (see Figure 11). This is in consonance with rapid prototyping and self-assembly systems, in addition to the results in 4.2. Furthermore, nozzle, manipulator arm, and multiple mobile robots were the most critical hardware components for such robotic categories.

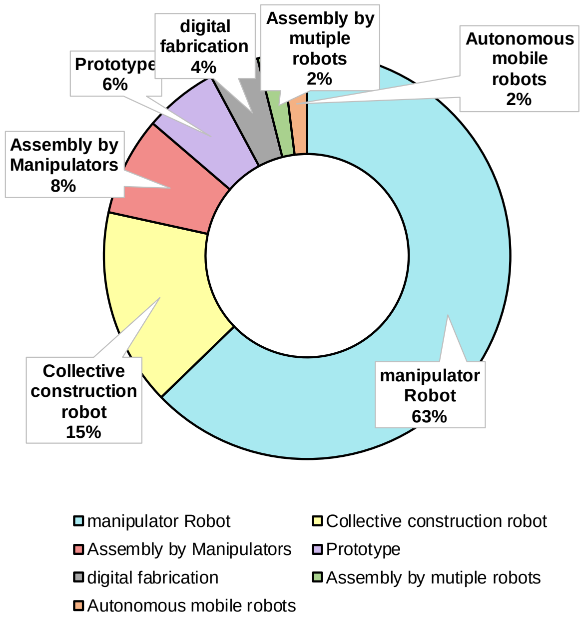

Figure 11. Category of construction robot

5 Discussion

Most of the present attempts to implement robotic technologies in concrete building construction were focusing on freeform construction for vertical RC elements, in the aim of improving the building construction efficiency and reducing the dependency on formwork.

The concrete building industry is currently in need for numerous researches to alter the conventional building process, by thinking out of the box in terms of innovating structural design and construction material. Moreover, lessons should be learned from the past attempts in the last three decades to robotize the building construction sector. Consequently, the future visionary is necessary for a systematic approach to increase efficiency in this type of research. An example for such visionary can be found in few innovative researches adapted the swarm intelligence for building construction by self-assembly.

Despite that the aim of this research is solely for concrete building construction, some other industries have attracted the researchers. Around 40% from the explored papers have been interested in building construction in extra-terrestrial environment. Their researches are mainly funded by the National Aeronautics and Space Administration (NASA), in addition to Kennedy Space Center Swamp Works and the Office of Naval Research in the USA, as well as the European Space Agency (ESA).

In this context, new research questions should concentrate on what could be altered within the construction process or the robotic technologies, to construct a complete building structure on-site. What type of concrete building structures should be targeted in the future researches, to overcome the present obstructions?

6 Conclusion

The review demonstrates that the research on robotic technologies in concrete building construction is still in its infancy, and thus is characterized to be under development and mostly challenging to be implemented. The literature all points that conventional methods for building construction proved to be inefficient, and the construction industry can innovate towards improved health and safety and time and cost savings.

The systematic review shows that the researchers in the USA played a lead role in researching robotics in concrete building construction, followed by Germany and Switzerland. The robotics application and techniques have been largely used on-site and targeted low-rise buildings. The robotic technologies that have been popular in literature included 3D printers, and swarm robotics. Most of the papers have proposed a limited novel structural design, without introducing novel construction material. Even though the direct and indirect construction activities related to formwork, steel reinforcement, and concreting can be replaced and thus eliminated, the horizontal RC elements still cannot be built on-site unless they were supported. Moreover, rapid prototyping found to be the best robotic design for the purpose of building construction through utilizing manipulator robots.

While the application of robotics in construction has limitations that need to be acknowledged, research for innovative robotic technologies to be adapted in the construction appears as an emergent approach. Collaboration in research across all the segmented disciplines such as architecture, engineering, building, computer science, would be an essential element for developing a related research area and also for deepening and widening research area dimensions and domain. Future research should also focus on the different types of barriers behind implementing the robotic technologies in the construction field.

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