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HUMAN-ROBOT INTERACTION IN CONSTRUCTION: A LITERATURE REVIEW
Automation in Construction

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ABSTRACT
This research presents a systematic review of the state-of-the-art research for interaction/ cooperation between humans and robots (HRI/HRC) in construction considering different types of robots. This paper represents, investigates, and further discusses the different domains of studies in terms of systems, metrics, and types of interactions and types of relative construction possibilities. The main goal of this research is to understand which type of relationship is studied in construction research and whether they have considered the interaction of humans and robots in construction. Also, it will identify the future of robotic construction and communication with humans in the research.

Keywords:*Construction, Robotics, Human interaction, Interoperability*

INTRODUCTION

Based on the Oxford Dictionary, construction is defined as gathering together different parts of the building and performing work to build a physical environment. So based on this definition, we are considering the interaction between humans and robots in construction activities. Consequently, there is no limit for the consideration of construction definition; either it should be the field of infrastructure (bridges, tunnels, etc.) or building construction. And we can apply the boundaries of this research in the whole domain of automation in construction.

Construction automation is one of the most critical research fields in recent decades, and it is followed by the application of automation technologies in different parts of construction (i.e. architecture, environmental engineering, civil engineering, etc.) even in prefabrication of various building materials components (Cousineau et al, 1998). The main aim of construction automation is to reduce the cost and time of performing a construction project with significant improvements in safety, corporation, and collaboration between humans and technology. The field of construction and building activities are prone to consider the robotic technologies as a part of the construction process (Parker, 2015).

In this research field, several researchers have worked on the topic of the interaction between robotics and humans. Recently after the first effort in Japan in the 1980s, there are different motivations for finding an interaction between humans and robots in construction. On one side, there is a demand for construction safety, quality assurance of challenging tasks, and shortage of the number of workers active in construction and on the other side introducing new technology related to robotics to the field of construction.

All the mentioned factors have motivated researchers to investigate the co-relation of humans and robots in construction. Besides, machines and robots are able to perform various difficult tasks whereas people are not able to perform these tasks because they are either unsafe or impossible to do in harsh hazardous environments. Furthermore, without using robots, humans are not able to perform difficult and complicated construction. Within this framework, there is a need to further contemplate the relation and interaction of humans and robots in the construction field.

Bearing in mind that since 1980, a significant portion of technology development in machinery and information has happened, different studies have been performed in automated construction elaboration, and in recent years there is a trend to further investigate the HRI (Human-Robot Interaction) and HRC (Human-Robot Cooperation) in the field of technology.

The primary aim of this research is to understand which type of relationship is studied in construction research. Also whether they have considered the interaction of humans and robots in the field of construction.

Therefore, this research tries to answer the following sub-questions parts:

i. What types of robotic applications are conceivable in construction?

ii. What are the different types of possible interactions between humans and robots in the construction environment?

iii. What is the preeminent and optimum model for the collaboration of humans and robots in construction?

iv. What kind of construction activities can be taken by interaction (or the cooperation) of humans and robots?

To answer the mentioned questions, a systematic review should be the best approach in order to understand to what extent this topic is being addressed in the recent research in construction and maintain a literature review.

LITERATURE REVIEW

It is necessary to understand the correlation between humans and robotics and besides follow up with this association in construction. Some researches (Parker, 2015b) defined the possible corporation between humans and robots in three main fields: manual assembly, hybrid assembly, and fully automated assembly. Based on these researches it is possible to consider all of the three different fields in the domain construction of robotics.

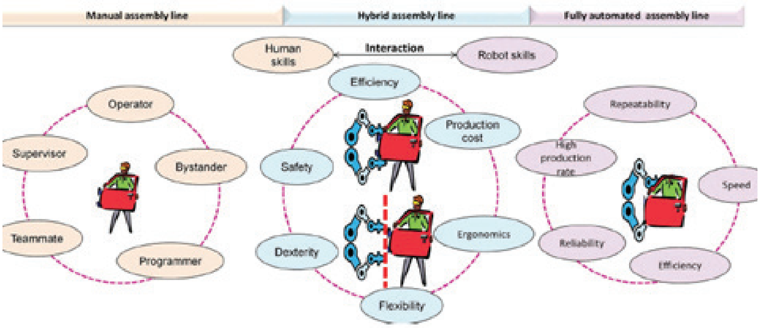

Figure 1. Possible ways of HRI/HRC

(Source: Parker, 2015b)

Based on this study, HRI is a promising aspect of achieving favourable production cost, an optimal combination of human and robot skills, increased efficiency, productivity and reduction in human stress and workload. On the other hand, although human-robot interaction is an advanced research area, the industrial robots are still not autonomous enough to allow interaction in such defined levels. In another research, a collaboration between human and robots are defined as "working jointly with others to perform shared goal in an internal endeavour" (Green et al, 2008), and it had defined three types of interaction between humans and robots: robot as a tool, guide hosting and assistant robots, and humanoid robots.

Table 1. Summary of the Most Critical Reviewed Paper in Human-robot Interaction (HRI) and Human-robot Cooperation (HRC) in Construction

Row	Research purpose	Method	findings	Ref
1	presents the development of a methodology for evaluating a robotized construction task	By examining and comparing various ways to share the work between robots and human operators and workers.	*economic benefits of human-robot collaboration	(Kahane et al, 2004)
2	Describe dialogue used among human to communicate and cooperate with robot agents	Performed peer-to-peer interaction joint actions are supported and the construction tasks agreed by both partners. (human and robot)	*Defining HRI models based on peer-to-peer human-human or human-robot joint action dialogues.	(Foster et al, 2006)

3	Performing risk analysis HRI. Identification of significant threat implementation of efficient protection	Using model-based safety analysis approach	*Facilitating interaction between human and robot by safety measures derived from risk analysis approach	(Fong et al, 2006)
4	Improvement in the automation system for curtain-wall installation	Define the control model in HCR according to the sort of contact conditions and using the adjustable impedance factors. Performing experiment to validate the model.	* Better handling heavy material in construction sites and installations with relatively less forces.	(Lee et al 2007)
5	Implementation and using cooperation bas control for mobile robots in the installation of curtain-walls.	Define control method, which contains HCR mode — required new hardware and software to compose robots' basic system.	*The new safer and more efficient model, HCR model. *Possibility of implementation of different construction materials	(Lee et al 2007)
6	Present unified treatments our human-robot interaction related problems	Using survey questionnaires	*Defining five types of human-robot interaction: teleoperation, mediated teleoperation, supervisory control, collaborative control, peer-to-peer collaboration. *The only human-robot cooperation:Human supervisory	(Goodrich et al, 2008)
7	Using augmented reality (AR) to investigate the possibility of human-robot collaboration in a team	Using AR augmented reality and human-robot collaboration system architecture as experience tools to testify possibility of simulation with an AR in HRI/HRC	* several advantages over using AR for stimulation of HRI and HRC *A multi-dimensional approach in developing the human-robot collaborated system would be the most effective System.	(Green et al 2008)
8	Introduces the prototype of improved multi-purpose field robots for construction	Implementation of a human-robot interface. Performed dynamic modelling of human-robot interaction	*Defining a two-phased HCR: installation of construction material by carrying materials to an installation site, the inserting materials in the proper position	(Lee et al, 2010)

9	Proposing new methodology for a heavy-duty glass glazing installation help of robots	Using experimental studies	*The corporation of human robots is more efficient in work time, performance and force interference. Possibility of combining this method with operation control and robot power	(Bock et al, 2011)
10	Experiencing rapid prototyping in recent robotic fabrication	Using mobile robots as the main tool for fabrication and construction, mainly with masonry bricks.	*Identifying the need to design a platform for human-robot interaction to optimize the corporation process.	(Helm et al 2012)
11	Future investigation application for mobile robots' units in construction and Interaction of human-robot interaction paradigm new construction Sites.	By combining the precision of the machine with the innate cognitive human skills, a simple but effective mobile fabrication system is tested for the building of algorithmically designed structures that would not be possible through conventional manual means. share control responsibilities between human and machine by 3D Scanning of Hand Movements	*a deeper understanding of the interpretation of human robots in construction within digitally controlled machines	(Helm et al, 2012)
12	Proposed installation methodology based on HRI installation of glazed window	Analytical comparison between three different installation methodology	*The glass installation work using intuitive manipulation device is more efficient while this method combines operator's control ability and the robot's power	(Gil et al, 2013)
13	Defining the metrics in human-robot interactions.	Using a systematic review of 29 papers in which the metric of human-robot interaction was introduced.	*Considering five main metrics of human-robot interaction: productivity, efficiency, reliability, safety, co-activity	(Murphy et al 2013)
14	Introduces a new method of human-robot cooperation	Using TRCI Robot as a test robot glazing installation	*Improvement in productivity *Improvement in safety *Reduction of working time *Reduction in danger *reduction the number of workers	(Lee et al, 2014)

15	Investigation of the system for human-robot collaboration for on table task	Performing experiments using PR2 Robotics research platform by using 5 action selection strategies: proactive, autonomous, reactive, human requested, and human comments	*simple bridge-building tasks with which people were interacting revolved around preferring to have proactive action selection interaction.	(Schulz et al, 2017)
16	Define a communication language and platform between human and robot in construction	Preposition of a theoretical model for human-robot communication management	*Defines basics for human-robot, Communication in construction	(Turek et al, 2017)
17	Introduces robot acceptances safety model	Use immersive virtual environment VR to test the safety by using masonry brick composition tasks.	*Improvement in safety level by separation the working environment of human and robots	(You et al, 2018)
18	To introduce tower construction as a new field for collaboration between human and robot (HRC)	Using tower-construction as a single human - single robot corporation. Using new experiments to investigate the corporation of robot with multiple human	*Introduction of a resource distribution task to collect data in HRC in order to designing human-robot interaction strategies	(Jung et al, 2018)
19	The Pictobot and human collaboration analysis	Considering human as an upper-level decision-maker for robot, and judgments and perception of workers becomes an upper-level planner for robot	*Having more reliance on skilled workers, improved productivity and decrease human exposure to harmful environments	(Asadi et al, 2018)

(Source: Author)

Japanese companies were the first to use automated construction and integrate robots in construction. With the help of a robot to mount single-glazed window robotic installation or constructing a steel-reinforced concrete building using prefabricated components (Khoshnevis et al, 2006). Although in comparison with the other industries, the construction sector has the lowest rate of using robots or automated technologies (Khoshnevis et al, 2006).

Automation constructions as a small part of a construction process framework mainly were included in the construction of buildings, tunnels, bridges, and infrastructures assembly or finishing interior and exterior materials and building concrete structures (Balaguer et al, 2008). Another research (Ardiny et al, 2015) classified three main tasks in robotic construction activities:

a) Activities based on gathering different types of building materials fabrication and finishing (such as bricklaying).

b) Joining and assembling rigid parts of the buildings and structures (such as welding different parts).

c) Forming process of manipulation of materials (city cutting disposition machinery and digging).

While based on (Khoshnevis et al, 2006) there are five different areas and a superior construction could be practical by using robots. In this paper, we have summarized related researches based on these five following applications:

Automated Construction of Vertically/ Horizontally Oriented Buildings

It includes the attempts of engineers to make the construction repetitive and frequent task, profession or practices automated. It originates from Japan where major contractors wanted to apply the potential of integrated robots as a supplementary of building construction (Bock, 2011). The single task construction robots were assistants of workers by performing frequent, repetitive, specific construction tasks (for example, digging, concrete levelling, concrete finishing, painting) or physical activities that were labour-intensive in a confined course (vertically or horizontally). The common feature of these kinds of robots is specification in performing a task, increasing the productivity in comparison with workers doing the task, increasing the quality of the results, reducing material consumption and saving in material usage (Saidi et al, 2016). Lack of integration in these types of single-task robots with parallel, upstream or downstream execution of work incurred their progress toward integrity in performing the construction works (Bock, 2015).

Housing Production

The advent of 3D printers facilitates manufacturing of complicated prototypes. It is denominated rapid prototyping (RP) but the scale of the printed products is limited because of restriction on the scale of the printers. Printing the entire building needs more advances in large-scale printers to perform. There has been fruitful progress in developing large scale 3D printers to reach the goal of printing the whole building (Amsterdam-based DUS architects and Qindoa Unique Technology) (Wu et al, 2016). A significant example is the mobile construction robot CyBe which is an arm-based system with the ability to fabricate a large-scale 3D print concrete structure in-situ (Dörfler et al, 2019).

In the construction sector the partial application of the robot is commonplace; for example, prefabricated components of the building may be constructed in an automated production line in a factory. Besides, some of the construction works can be performed on-site with the combination of the potential of the robust robots and the intellectual ability of humans. The industrial robot dimRob and similar in-situ fabricator is a good example of the implementation of the man-machine interaction paradigm (Helm et al, 2012; Giftthaler et al, 2017).

Novel Construction Markets Accessible through Automated/ Robotic Construction (Construction in Space, Sea and Deep Sea, Desert, Arctic areas, etc.)

The research revolves around using construction methods in severe or exceptional conditions is not unprecedented. Military and army sectors are the pioneers in this field. For example, ground-based forces are interested in applying robotics and autonomous systems (RAS) as assistants in construction. RAS help the military forces in performing partial or full of the work of construction (Ha et al, 2018).

Some attempts have been made by ETH scholars and researchers to use aerial robotic construction (ARC). Their ability and locomotion in the air can increase their capability in manoeuvring. The advantages of the mentioned system, such as obviating the need for scaffolding, having the ability to scalable make this topic interesting; however, its effectiveness in the architectural construction is an obscure concept (Gambao et al, 2006).

Various applications of robots in different construction contexts (such as space, sea, and deep sea, desert, arctic areas) make it in fact, a fresh, and appealing field of research.

Automated Building Servicing and Maintenance

Apart from the multitude of automated facilities and assistive robots that are available to help the elderly or people with disabilities (Gambao et al, 2006; Borangiu et al, 2012), there are several examples that indicate the application of robots in building servicing and maintenance. Although there is potential to introduce new applications, some of the current robotic services in the building industry already include cleaning facades, coating, and painting exterior walls, wall cleaning, and wall washing machines (Gambao et al, 2006).

Automated Deconstruction and Re-Customization

As the structure of a building have recyclable elements, controlled demolition of buildings or structure can be performed by robots. Since robots perform the construction precisely, they are capable of deconstructing accurately in order to reintroduce the removed structural elements to the fabrication system. There is an example of the mentioned process in Japan where an automated floor-by-floor deconstruction were done by robots. On the other hand, the old, decrepit elements can be substituted with the new, robust components based on the needs and requests of clients (Saidi et al, 2016).

METHODOLOGY

In this section, we are going to clarify the process of exclusion and inclusion of the research papers to this systematic literature review. The first step is the identification of the existing research in this domain. This report has covered the web of Science and Google Scholar databases in the search for documents that were related to this subject.

After conducting a holistic search in the web of Science, 8,494 journal papers were selected. By applying inclusion and exclusion filters, the number of articles came to 1049. Moreover, by performing final eligibility considering, removing duplicates, and applying a screening phase the direct contraction in construction environment the total number was 97 and directly related papers were discussed for further analysis.

The second step was screening and exclusion, the inclusion of the research papers. Therefore, different articles were excluded if their primary focus was out of the scope of HRI in construction. Furthermore, the research scope precisely focused on the

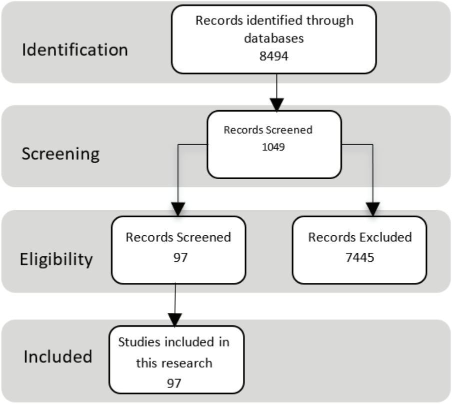

Figure 2. Inference Mechanism

(Source: Authors)

Therefore, all the considered papers have indicated some types of interaction between human and robots in the field of construction and have passed the eligibility of the screening stage, and the most important findings are represented in Table 1.

FINDINGS

A systematic review shows that the application of 3D printers and robots in construction are widely used in the USA, Switzerland, Japan, and Germany. There are different types of construction activities considered in the robotic field, such as indirect and direct activities related to structure, building and infrastructure, and on-site constructions. Among all, rapid prototyping is one of the best fields that is using more and more robotic implementation. The primary goal of HRI is advancement of manufacturing. While in this progression, the role of human is to be a supervisor of the tasks and this interaction in industrial environment construction robots is the dominant idea (Parker, 2015). Cooperative tasks are not always taken into consideration as a simulation phase or not widely used in HRI.

In this area, simulation for human-centred interaction should be one of the challenges. Planning and provision of low cost and easy to use tool for evaluation is another challenge. HRI and programming is the main area that warrants significant attention for researches, but there is still a big challenge in considering the complex system for a robot for perception and interaction in a way that makes a robot social and cognitive. That is the principal value of operation for communication in human environments.

Existing gaps in this field are as follows:

1. The first and most crucial challenge is to identify the best possible solution to produce decision-making between humans and robots in construction. There is a need to define complexity of tasks in construction, outline whether completion of this task is possible which results in supervisory of human over robots. Moreover, if there is a need for collaboration or supervisory what should be elements and limits for such cooperation for supervisory.
2. To give more autonomy to robots to perform construction works, there is a need to introduce sophisticated decision-making frameworks to be able to delegate tasks to robots in construction sites. Also, task planning and coordination as part of HRI/HRC research investigation is necessary.
3. There is absence of uncertainty and risk analysis in using robots in construction and managing related issues due to complexity of the performance in such automotive construction. The gap in research of uncertainty and risk analysis such as automation construction is clear.
4. Defining safety strategies should be one of the most important steps for future studies.
5. There is a gap in finding the distinction between fixed and mobile robot systems and interaction of each system with humans. Certainly, using mobile robot system in construction could give us great flexibility in performing contraction works, but lacking the framework in positioning for accurate systems or precision self-positioning of robots can cause a major problem in the interaction between humans and mobile robots in construction. Defining positioning and action in fixed orbits is easier than mobile robots therefore, in this field it is important to consider from the action-reaction side positioning of mobile robots. Human-robot collaboration requires a robotic system to understand spatial referencing.
6. As robots are pioneers in using technologies, creative ideas of using robots

in construction and human interaction should be expanded and the future of these technologies and consideration complexities need to have a fundamental platform to introduce the optimum solution for building robot corporations in each construction task. As an example, creative idea of flying robots should be one of the solutions.

7. There is barely any research in which the cooperation or interaction of a group of humans and robots is considered therefore there is room to consider teamwork construction with robots as a new field of human-robot interaction. Indeed, construction is teamwork and group activity; there are dynamic of different factors that could affect the interaction between humans and robots.
8. By studying robot integration in construction, it is clear that the total trend on the HRI is based on using the robot as a single based task performer for the construction activities. Take for instance cutting, fabrication, manipulation, and so forth. Although it should be considered as multi-task performing operator (or decision-maker) in construction activities and then consider the interaction of such robot with human.
9. The study of human-robot collaboration interaction is based on repetitive tasks in construction and are dynamic in performing repetitive tasks but are not considered in such study. Therefore, actions and reactions of robots' incorporation in dynamic test scenarios are still considered as a gap, and it needs to be investigated.
10. Implementation of safety issues and incorporation as well as the collaboration with robots in construction should be further analysed by considering all mentioned different types of construction scenarios for interaction between humans and robots.
11. The construction sector either needs to think out-of-the-box to implement more functions for robot application in the construction process, as stated by Helm et al (2012).
12. There is a great possibility of using augmented reality (AR) and virtual reality (VR) as two functional bases for simulation of human-robot interaction in construction.
13. In the area of interaction between humans and robots in construction we can consider different levels of autonomy supervisory of human cooperation or autonomy of robots. Therefore, in consideration of autonomous robots in construction it has never been studied in this field. Of course, such research should have critical challenges in terms of safety technology and multidisciplinary for the research.

14. Although there are multiple challenges facing this environment digital human modelling, these tools promise robustness and adaptability in HRI system and could be widely used in this domain (Parker 2015).

CONCLUSION

1049 scientific papers were analysed and the information is displayed chronologically in Table 1. The mentioned table shows how the field of research related to human-robot interaction has developed during the years. This table shows the summary of the most critical reviewed paper in human-robot interaction (HRI) and human-robot cooperation (HRC) in construction which helped the authors to categorize the gaps that have not been yet covered by scientific papers and recent research.

Chronological distribution of publications has shown that there is a growing trend since 2000 and there is a high number of publications in the last decade considering that last year had the highest number of publications in the past decade.

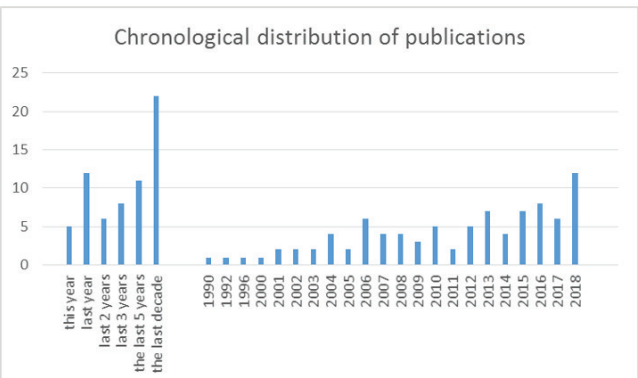

Figure 3. Chronological Distribution of Publications
(Source: Authors)

Based on the literature review, construction materials and installation of the construction materials is most important in the human-robot interaction with the most top proportion applications, and there is room to investigate further the multi-function robots, multipurpose robots and human-robot interaction in robotic fabrication.

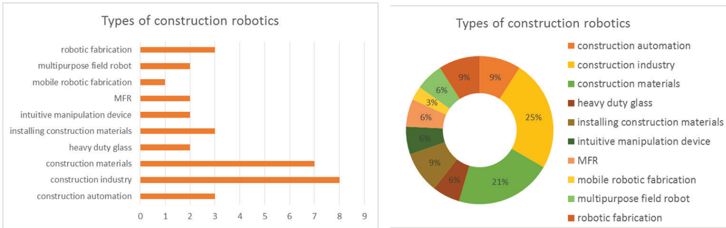

Figure 4. Types of Construction Robotics

(Source: Author)

The main purpose of automation is improving the corporation and quality between humans and robots, and it is vital to confirm high-quality construction more rapidly and decrease the level of a hazardous environment for human, and impossible tasks for humans are the most important aspects of HCR/HRI.

This review shows that the application of robots in construction is widely used in the installation and application of materials in construction projects. Robotic technologies are popular in construction publicly for various forms of installations, 3D printers, and mobile robots. These are involved with innovative construction of new material assembly. Besides, rapid construction and prototyping are the recent trends of study in the interaction of humans and robots in construction which can be proposed to researchers to follow.

Table 2. Research Percentage in Robotic Domain

Robotic domain	Research percentage
construction automation	6.3
construction industry	16.7
construction materials	14.6
heavy duty glass	4.2
installing construction materials	6.3
intuitive manipulation device	4.2
MFR	4.2
mobile robotic fabrication	2.1
multipurpose field robot	4.2
robotic fabrication	6.3

Source: Authors

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