Human-Robot Collaboration in the Construction Industry: A Mini-review

Ali Garshasbi, Jun Wang, Jingdao Chen, and Junfeng Ma

***Abstract*—This paper presents a mini-review of human-robot collaboration (HRC) in the construction industry, synthesizing key findings from the literature. The paper outlines the development of construction robotics, the current applications of HRC, the issues identified, and the factors affecting the adoption of HRC in construction. Furthermore, it discusses the future directions and opportunities for HRC in construction. This mini-review aims to provide some knowledge to advance the integration of HRC in construction.**

I. INTRODUCTION

The construction industry has long been seeking ways to make the construction process more efficient, sustainable, and safer in order to address challenges such as resource constraints, skilled labor shortages, and environmental issues. The use of robots in construction promises to be an ideal solution for improving productivity, quality, and safety in construction projects [1]. Human-robot collaboration (HRC) in construction provides an opportunity to boost the industry's effectiveness and competitiveness by capitalizing on the strengths of both human workers and robots. HRC in construction involves the interactive process where robots and labor cooperate in executing various construction tasks such as assembly, inspection, material handling, fabrication, repair, and maintenance. In this context, construction tasks can be carried out efficiently as robots complement and augment human capabilities [2].

The literature on HRC in the construction industry demonstrates that the collaboration between humans and robots has garnered significant attention due to its potential to enhance productivity, safety, and efficiency in construction projects [3-5]. A preliminary review conducted by [3] summarized the research objectives and environments, HRC methods applied, construction tasks and robots involved, technologies applied, and factors affecting the adoption of robotics in the industry. Reviewing these studies establishes a solid foundation for understanding the current state of HRC in the construction industry, its potential applications, and the factors that can influence its adoption and successful implementation. The adoption of HRC in the construction industry could enable experts to more efficiently address major issues such as safety hazards, labor shortages, and productivity levels, which have consistently put the industry at serious risk. By combining human skills, like decision-making and problem-solving, with robot abilities, such as precision, agility, and endurance, project outcomes can be optimized while mitigating safety risks [6]. There is also a critical need to understand the key factors affecting HRC adoption and its financial, social, legal, and technical implications, as well as the roles of various stakeholders in promoting and supporting HRC in the construction industry. This paper aims to provide a review of HRC in the construction industry, synthesizing key findings from recent literature. The objectives of this paper are to (i) summarize the development of construction robotics and their current applications; (ii) discuss the issues identified and the technical, safety, and human factors affecting the adoption of HRC in construction; and (iii) identify future trends and research directions to advance the integration of HRC in the construction industry.

Ali Garshasbi is with Mississippi State university, Starkville, MS 39759 USA (email: ag2875@msstate.edu).

Jun Wang is with Mississippi State University, Starkville, MS 39762 USA (corresponding author: 662-325-7185; e-mail: jwang@cee.msstate.edu).

Jingdao Chen is with Mississippi State university, Starkville, MS 39759 USA (email: chenjingdao@cse.msstate.edu).

Junfeng Ma is with Mississippi State university, Starkville, MS 39759 USA (email: ma@ise.msstate.edu)

II. SUMMARY OF RELEVANT LITERATURE

A systematic search of the relevant literature was carried out. The following keywords and their combinations were used in the search process, including “human-robot collaboration”, “human-robot interaction”, “construction”, “construction industry”, “robot”, “robotics”, “collaboration”, and “interaction”. The search was conducted on multiple publishers and websites, including ASCE, ELSEVIER, IEEE, SPRINGER, SCOPUS, Web of Science (WOS), Wiley Online Library, and Google Scholar, aiming for a thorough exploration of the available literature and ensuring the inclusion of the literature about HRC in construction.

After several rounds of search and the initial screening of abstracts, a total of 67 papers were identified as potentially relevant to the review study. Further, each of these papers was fully read and carefully reviewed with in-depth evaluation, and ultimately, 44 papers were selected for inclusion in the review study. Overall, the number of publications on this topic has surged in growth since 2020 (out of the 44 selected papers for this review, 28 were published in 2020 or later).

III. APPLICATIONS OF HRC IN CONSTRUCTION

This section explores various applications of HRC in the construction industry, highlighting the diverse ways robots can be integrated with human workers to enhance efficiency, safety, and productivity. The detailed categories discussed are (i) robots for building construction (with the most literature about this topic), (ii) construction inspection and monitoring, (iii) brainwave-driven HRC, and (iv) augmented reality workflows for HRC. The available literature discussing topics (ii) through (iv) is notably limited.

A. Robots for Building Construction

Studies have assessed the impact of HRC process on construction productivity, highlighting ways to optimize HRC for improved performance and occupational health & safety [7, 8]. The demand for applying collaborative industrial robots in construction to enhance productivity, safety, and efficiency has considerably increased. This type of robot has a great capability to replace or collaborate with human workers to do hazardous, time-consuming, or difficult construction tasks such as material handling, assembly, and inspection safely and efficiently [1, 5]. Also, the potential of haptic technology in five construction tasks - drywall installation, painting, bolting, welding, and pouring concrete, has been explored through a unique method [9]. However, to ensure a smooth and effective collaboration, the integration of robots into the construction teams seems to be essential [9]. In high-rise building construction, robot technology can significantly reduce safety risks and decrease labor costs associated with working at great heights. For example, construction robots for the outer walls of high-rise buildings can address safety concerns and improve overall efficiency [10]. These robots can also perform other functions, such as maintaining the buildings, window cleaning, and facade inspection, further demonstrating their versatility and potential in the construction industry.

B. Construction Inspection and Monitoring

The issue of inspection and monitoring in construction can be addressed by utilizing robots, which have the potential to reduce flaws and costs. A preliminary study conducted by [11] explored the use of quadruped robots in the construction industry as an alternative method for inspection and monitoring. These robots are capable of efficiently navigating through complex construction sites and accessing hard-to-reach areas for inspections.

C. Brainwave-driven HRC in Construction

Researchers have investigated the issue of brainwave-driven human-robot collaboration (HRC) in construction, utilizing electroencephalography (EEG) signals to control a robotic arm [2]. The proposed method offers the potential to improve efficiency and accuracy in collaborative tasks, as it encourages direct and intuitive communication between human workers and robots.

D. Augmented Reality Workflows for HRC

[12] investigated the implementation of an augmented reality (AR) workflow for HRC in timber prefabrication. The article proposed that AR technology can provide opportunities for construction workers and robots with interactive collaboration tools, which is more effective, and results in increased accuracy and reduced errors during the prefabrication process.

IV. Issues of HRC in Construction

This section delves into the various issues that arise with the incorporation of HRC in the construction industry, investigating the challenges and potential solutions under each category. The detailed categories discussed in this section are cost, safety concerns, legal and regulatory issues, and social acceptance. These categories highlight the financial, safety, legal, and social aspects of implementing construction robotics and their impact on the industry.

A. Cost

The adoption of construction robotics can elevate productivity and labor cost efficiency while decreasing materials waste. However, it can be influenced by economic factors such as high initial investment costs, uncertainty about the return on investment, and maintenance costs. Additionally, needed skilled operators can act as barriers to implementation [13]. Also, developing countries may have financial constraints to adopt robotics technologies in construction [14].

B. Safety Concerns

Safety has always been a significant consideration in human-robot interactions. To ensure the safety of working environments, potential hazards and risks must be considered and mitigated [15, 16]. Also, perceived safety and its impact on HRC can be enhanced through immersive virtual environments that allow workers to have enough knowledge about the technology before working with robots on-site [17]. For example, [18] proposed that VR-based training can increase self-efficacy, mental workload, and situational awareness when construction workers remote-operated a demolition robot in human-robot interaction.

C. Legal and Regulatory Issues

Incorporating robots in construction faces legal and regulatory challenges, including potential product liability litigation, privacy concerns, and unintentional operation of controls [19]. Governments can have a great effect on the promotion of advanced technologies like construction robots concerning R&D investments, offering incentive schemes and formulating regulations, and standards [20]. These challenges can be addressed by ergonomics studies to ensure compliance with standards, optimize workflows, and enhance productivity. Also, ensuring worker safety and risk assessment is vital to avoid potential legal issues [19].

D. Social Acceptance

People in different regions do not have equal knowledge of robotics and construction automation [21]. Stakeholders' concerns due to job displacement and the need for upskilling by robots can influence the future application of construction robots [20]. To have a successful implementation, [22] propose found that evaluating the perception of human-robot collaboration among construction project managers is essential. [5] think that social acceptance would be increased by addressing misconceptions, providing proper training, and demonstrating the potential benefits of robotics and automation in the construction industry.

V. Factors Affecting HRC in Construction

This section explores the various factors that influence the success of HRC in the construction industry, specifically focusing on technical, human, and organizational aspects. In this section, we will delve into the details of each category and discuss how they contribute to the effectiveness of HRC in construction projects.

A. Technical Factors

Robot capabilities and communication protocols are vital for effective collaboration [8]. Factors such as system complexity, robustness, and reliability of robots also can ensure the success of HRC in construction [23]. As technology advances, it is crucial to ensure that robots are compatible with existing construction systems and can adapt to changing environments, which can minimize the risk of project delays or failures.

B. Human Factors

The decisive factors including worker attitudes, trust, and communication with robots affect the collaboration process [5]. There is a need for adequate training and skill development for workers to adapt to new technologies and effectively collaborate with robots [18]. In order to facilitate smooth HRC, it is essential to address any concerns workers may have about job security and create an atmosphere where humans and robots can work synergistically to achieve project goals.

C. Organizational Factors

The adoption and integration of construction robotics and automation technology can be mainly affected by economic challenges, cost-benefit analysis, and regulatory requirements [13]. The extent of adoption of these technologies at the organizational level also is affected by the level of awareness about robotics and construction automation [21]. To promote the incorporation of HRC in construction, companies should invest in education and training, while government bodies should develop policies that incentivize the adoption of such technologies and address potential regulatory hurdles.

VI. Future Trends and Directions

In this section, we explore the forthcoming developments and trajectories in the realm of HRC within the construction sector. This section addresses three primary subtopics: (1) employing immersive technologies for HRC, (2) merging HRC with other cutting-edge technologies like IoT, AI, and 3D printing, and (3) formulating standards and best practices to govern HRC. These areas of focus examine the possibilities for improving efficiency and safety in construction while also considering the changing roles of construction workers as automation advances.

A. Immersive Technologies for HRC

A very promising trend is to apply immersive technologies (such as virtual reality (VR), augmented reality (AR), and mixed reality (MR)) for HRC, which already has been observed and identified from the existing literature [17, 24] and research projects, such as funded by NSF. However, very limited existing or completed work is available. These technologies can provide human with a more intuitive and interactive means of communicating and interacting with robotic systems. A very common application of this integration is for next-generation workforce training. [24] even opened the door of combining immersive technology with Digital Twin for HRC in construction.

B. Integration HRC with Other Emerging Technologies

Integration HRC with other emerging technologies such as IOT and 3D printing has been proposed as a promising research direction that could potentially enhance construction productivity and safety [8]. This interdisciplinary approach may also foster other innovation in the construction industry such as more efficient construction processes, new construction methods and advanced data-driven decision making.

C. Development of Standards and Best Practices for HRC

It is believed that future studies could research on the development of standards and best practices for implementing and integrating robotics within different construction activities [25]. Further studies should improve the understanding of human reaction to robotics collaboration, the nature of trust, task scheduling, robot design, methodologies in constructing human-robot teams, and other areas so that the appropriate standards and best practices can be developed accordingly [19].

VII. Conclusion

Human-robot collaboration in the construction industry could address safety hazards, labor shortages, and productivity challenges. HRC has been applied in various tasks such as assembly, inspection, material handling, fabrication, repair, and maintenance. However, factors such as cost, safety concerns, legal and regulatory issues, and social acceptance need to be addressed to facilitate successful implementation. Future research should focus on integrating HRC with other emerging technologies, developing standards and best practices, and exploring the transition of construction workers' roles. By fostering innovation and collaboration, the construction industry can achieve a sustainable balance between the strengths of human workers and robots, leading to increased efficiency, safety, and competitiveness.

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