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Research Review on Construction Robots in the Context of Intelligent Construction

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Abstract. The construction industry is currently facing challenges such as labor shortages and high operational risks, which significantly hinder the development of industry and affect overall productivity. These challenges highlight the urgent need for innovative solutions to improve efficiency and safety. The emergence of new technologies in intelligent construction, including construction robots, presents an opportunity for transformation and upgrading. In the context of intelligent construction, construction robots, as emerging intelligent devices in the construction field, are considered to enable "safer, more efficient, greener, and smarter" construction methods. This article first introduces the definition and classification of construction robots, analyzes the current state of research and development trends both domestically and internationally, then focuses on typical applications and case studies of construction robots in practice, and finally, based on international examples and technical principles, highlights the progress of human-robot collaboration and safety research, proposing future development directions. Construction Robots, Intelligent Construction, Human-Robot Collaboration, Construction Engineering.

Keywords: Construction Robots; Intelligent Construction; Human-Robot Collaboration; Civil engineering.

1. Introduction

The construction industry, as a pillar of urban economies, has long relied on labor-intensive production methods. The long-term dependence on substantial labor input has led to issues such as resource waste, environmental pollution, and low productivity. With the emergence of new urbanization and high-quality development demands, traditional inefficient models face significant challenges and must undergo technological innovation to achieve transformation and upgrading [1]. Construction robots, as products of the intersection of construction engineering and artificial intelligence, are seen as core elements and key drivers in the shift of industry towards intelligent and digital transformation [2].

The development of construction robots is constrained by various factors. On one hand, there is insufficient industrialization and standardization. It is recommended that product thinking be applied in design and promotion, advancing standardized and modular development, and creating corresponding norms and standards [3]. On the other hand, unlike manufacturing, the application environment of construction industry is highly variable, with large on-site construction errors, incomplete measurements, and high uncertainty, leading to robot malfunctions or reliance on human intervention [4]. Both domestic and international research on construction robots is primarily driven by academic institutions, but the focus has shifted from automating single construction tasks to integrating information technology to promote cross-domain development within the construction industry. Currently, most construction processes are still human-led, with only about 55% of construction companies beginning to experiment with construction robots [5].

The review indicates that construction robots encompass various task types, and together with new technologies such as the construction industrial internet and artificial intelligence, they form the intelligent construction system, laying the foundation for the industrialization of construction. At the same time, human-robot collaboration and safety issues have also received widespread attention. The review points out that construction robots are still in the development stage, and future technological breakthroughs and standardization are needed to promote large-scale applications, providing crucial support for intelligent construction. With policy support and technological advancements, construction robots are expected to play an increasingly important role in the era of intelligent construction.

2. Overview of Construction Robots

Construction robots refer to robotic systems used in civil engineering that automatically perform construction tasks based on computer programs or human instructions. In a broader sense, they encompass intelligent devices throughout the entire lifecycle of a building, while in a narrower sense, they refer specifically to automation equipment used on construction sites. These robots can replace humans in performing labor-intensive and repetitive tasks, playing a crucial role in the sustainable development of the construction industry [6]. Furthermore, based on application scenarios, construction robots can be classified into factory-based and site-based types. Depending on their level of intelligence, they can be categorized into remote-controlled, programmable automation, and high autonomy systems [8]. Research began in the late 1960s. Japan was the first to introduce robots into the construction field in the 1980s, with the SSR-I robot developed by Shimizu Corporation used for fireproof coating on steel structures [2]. Since then, various prototypes of construction robots have appeared worldwide, such as full-scenario mobile measurement robots, prefabricated production robots, and 3D printing robots. Many countries have promoted the integration of the robotics industry with the construction industry through measures such as optimizing industrial policies, supporting small and medium-sized enterprises, and forward-looking strategies, giving rise to new models and business types in the construction industry [7]. Researchers note that modern construction robots are continuously evolving with the integration of new technologies such as computer vision, BIM, and drones. Internationally, there is growing attention from companies and research institutions in the construction sector towards robotic technology. Wang et al. note that many renowned construction firms and robotics companies, such as Bouygues, Takenaka, and Sumitomo, are actively conducting research and experimental applications of construction robots. According to statistics, the global market for construction robots was approximately 100 million USD in 2022 and is expected to reach 242 million USD by 2030 [5].

3. Application of Construction Robots

In recent years, research on construction robots has been centered around various technological paths and construction scenarios. The academic community typically classifies construction robots into three categories: structural construction robots, interior construction robots, and new construction robots [8].

3.1. Structural Construction Robots

These robots are primarily used for stacking and forming structural components, including high-intensity processes such as bricklaying, concrete pouring, rebar tying, and floor leveling. Bricklaying robots have been commercialized internationally, such as the SAM100 in the U.S. and Hadrian X in Australia, which significantly improve masonry efficiency. However, challenges remain, such as reliance on human intervention, limited material compatibility, and issues with precision and path planning [9]. Concrete pouring robots typically rely on laser calibration for surface leveling. However, their autonomous navigation and intelligence are currently limited, and there is a need to develop more efficient positioning and control systems [8].

3.2. Interior Construction Robots

These robots are used for interior and exterior decoration tasks after a roof of building is completed, including wall plastering, polishing, interior and exterior painting, tile laying, and floor installation. They are typically designed to improve the quality and efficiency of decoration processes while reducing human injury. The common “6+3+1” degrees of freedom structure offers efficiency and quality advantages over traditional manual spraying, but further improvements in autonomy and work coverage are needed [10]. While indoor spraying robots have high precision, their environmental adaptability still needs improvement. Exterior wall spraying robots require higher stability, safety, and reliability, and their development needs to strengthen posture control and overall planning. Wall and floor grinding robots focus on construction precision and stability as core performance indicators. Their performance can be enhanced by optimizing algorithms and incorporating high-precision sensors [8].

3.3. New Construction Robots

This category includes 3D printing construction robots and on-site measurement robots. 3D printing construction robots, combined with additive manufacturing technology, can print structural components in a short time, reducing template and material waste, and enabling the creation of complex shapes that traditional methods cannot achieve. The development direction is moving towards lighter weight, greater intelligence, and lower costs [11]. Measurement robots use 3D laser scanning technology for on-site automated measurements but currently face challenges such as data loss, obstruction by personnel, and high costs [12]. In addition, various specialized robots for site logistics, prefabricated component installation, and safety inspections are actively being researched and tested.

4. Core Technologies of Construction Robots

4.1. System Composition

Construction robots typically consist of a mobility base (e.g., wheeled, tracked, or walking mechanisms), end-effectors (such as robotic arms), a perception system, and a central control and decision-making system. The mobility base provides movement capability, the end-effector performs specific construction tasks (such as grasping bricks or applying materials), the sensing and positioning modules are used for environmental awareness and navigation, and the central control system coordinates the operation of each component using pre-programmed algorithms [8].

4.2. Key Technologies

The implementation of construction robots relies on the integration of multidisciplinary technologies, including perception and recognition, motion control and execution, and human-robot interaction, enabling them to play a role in more complex construction activities [3].

4.2.1. Environmental Perception and Recognition

By employing various sensing methods, including LiDAR scanning, ultrasonic/infrared distance sensors, and sensors for force, pressure, and tactile feedback, robots are equipped with the ability to detect objects, identify defects, and conduct remote monitoring, thus acquiring environmental information from the construction site [3].

4.2.2. Motion Control and Task Planning

This involves the automatic control of robot behavior and responsive actions to changes in the external environment. The introduction of intelligent algorithms and digital models for trajectory planning of key components, such as the robot chassis and robotic arms, directly influences construction efficiency and quality [3].

4.2.3. Autonomous Decision-Making

Once equipped with artificial intelligence modules, robots can interpret motion control feedback data, reason, learn, and utilize patterns and knowledge from databases. This enables intelligent decision-making for optimal management and decision-making strategies for specific goals. With the global

AI industry expected to experience rapid growth over the next decade, increasing investment in the integration of AI with construction robots will have a revolutionary impact on productivity and industrial structure in intelligent construction [3].

4.2.4. Human-Robot Interaction and Collaboration

Robots use 5G, 6G, and IoT technologies to receive navigation routes sent from the cloud, allowing them to avoid obstacles and complete designated tasks. AR technology overlays digital construction information onto real-world scenes, helping operators monitor construction progress and quality more intuitively. IoT and scheduling systems can coordinate multiple robots with different functions, dynamically adjusting task allocation based on construction processes, reducing conflicts and delays, and improving overall construction efficiency [3].

5. Human-Robot Collaboration and Safety

Human-Robot Collaboration (HRC) is a key research direction in the context of construction robots, requiring robots to perceive human presence and intent and interact safely with humans [13]. The design of HRC systems includes three key aspects: the design of the collaborative robot itself, the perception-interaction mechanism, and the allocation and execution of collaborative tasks. Research reviews generally agree that collaborative robots should evolve towards bio-inspired structures, further enhancing perception and decision-making capabilities, and enabling more intelligent interactions. For example, ergonomic exoskeleton robots, developed for specific construction tasks, can reduce worker fatigue and improve endurance. Non-exoskeleton flexible collaborative robots, on the other hand, require lightweight designs and safety-oriented hardware and software to work alongside humans [14]. Additionally, digital twin technology has been proposed to create virtual collaborative environments for simulation training and remote monitoring, helping to improve training efficiency and scene adaptability, thus optimizing the design and scheduling of human-robot collaboration systems [15]. This "human-robot collaborative operation" model leverages the precision and efficiency of robots while combining the flexible judgment and operational capabilities of human workers. It is seen as the future development trend of construction sites, injecting new vitality into traditional construction industries [16]. However, the collaboration between humans and robots on construction sites also introduces new safety challenges. Therefore, ensuring safety during human-robot collaboration has become a major focus in both academia and engineering.

5.1. Collision Risk Prevention

Avoiding accidental collisions between robots and workers is the primary safety concern in human-robot collaboration. A common approach is to equip robots with non-contact environmental monitoring sensors, such as depth cameras and ultrasonic radar, to continuously detect the positions of nearby workers and obstacles. Flacco et al. proposed using Kinect depth cameras to capture 3D point clouds of the workspace of robots, calculating the distance between the robot and dynamic obstacles, such as nearby workers. They introduced a distance-based repulsion model into the control algorithm to adjust the motion trajectory of robots in real time, enabling smooth avoidance of collisions [17]. Liu et al. employed computer vision technology to estimate the intent behind workers' gestures and postures, allowing the robot to anticipate the worker's next action and adjust its movement to avoid conflicts, achieving a monitoring accuracy of 63.3% [18].

5.2. Path Planning

Effective task allocation and path planning can significantly reduce the risk of hazardous contact. Researchers suggest that robot motion trajectory planning should be coordinated with workers' operational processes to avoid potential interference in time-space regions. Wang et al. proposed constructing a robot navigation map based on a BIM model and optimizing the point selection strategy in the A* algorithm. By eliminating redundant turning points, they shortened computation time. Additionally, they applied the dynamic window approach for local obstacle avoidance, ensuring the planned path stays clear of obstacles and greatly improving avoidance efficiency. Experimental results show that this method reduced path computation time by over 50% and doubled the average distance between the robot and obstacles [19].

5.3. Force Feedback Regulation

When human-robot contact is inevitable, the robot must be capable of reducing impact and stopping quickly. Therefore, collaborative robots often use low-stiffness joint designs and force feedback control. When encountering abnormal resistance (e.g., contact with a worker), the torque sensors on the robotic arm detect the reaction force on the end effector. If the force exceeds a safety threshold, the robot immediately switches to compliance mode, increasing joint flexibility or triggering an emergency stop to prevent injury to personnel [14].

6. Conclusion

This study delves into the growing role of construction robots in intelligent construction, addressing both the current state and future prospects of these technologies. The findings highlight the significant potential of construction robots to improve the construction industry by automating labor-intensive tasks, improving safety, and increasing productivity. Key technologies such as artificial intelligence, machine learning, and advanced sensor systems have positioned construction robots as essential tools for overcoming challenges like labor shortages, safety risks, and inefficiencies. The research identifies several key areas where construction robots are already making an impact, including in structural tasks, interior construction, and specialized functions like 3D printing and measurement. These robots enhance efficiency through automation, reduce human error, and minimize environmental impact. However, the study also recognizes that there are considerable challenges, such as improving robot autonomy, adapting to dynamic environments, and achieving seamless integration with existing construction workflows.

One of the main contributions of this study is its comprehensive examination of current construction robot technologies, their applications, and the barriers to large-scale implementation. This includes a detailed analysis of the progress made in human-robot collaboration and safety, which are critical to ensuring successful deployment on construction sites. Additionally, the study offers valuable insights for future research, particularly in terms of overcoming the limitations in robot autonomy and increasing scalability to meet the demands of large-scale construction projects. However, this study has some limitations. While the review offers a broad understanding of the technologies involved, it primarily focuses on the technical aspects, with limited attention given to economic, legal, and social considerations. Furthermore, the study does not provide an in-depth analysis of long-term operational data from real-world construction sites, which would be crucial for evaluating the practical viability of construction robots in diverse environments.

In terms of future research, more field-based testing is necessary to understand the long-term economic and regulatory frameworks required for widespread adoption. Future studies should focus on enhancing the autonomous decision-making capabilities of robots, improving real-time adaptability in complex environments, and exploring the integration of construction robots with other emerging technologies such as IoT and digital twins.

In conclusion, while the adoption of construction robots presents substantial opportunities to transform the industry, achieving large-scale integration will require addressing both technological and practical challenges. The continued development of these systems promises to revolutionize construction, making it safer, more efficient, and more sustainable.

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