

Application and Prospects of Construction Robots in Building Construction

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Abstract. With the continuous advancement of technology and the development of the construction industry, construction robotics has emerged as an emerging building technology and has gradually attracted attention in the field of house construction. Consequently, the application of construction robotics in house construction has become a research hotspot in recent years. The purpose of this paper is to systematically summarize the current application status of construction robotics in intelligent construction in the house building sector. It discusses the development process, technological classification, and future trends of construction robotics in the field. Through a comprehensive analysis of existing literature and research findings, the advantages and challenges of construction robotics in improving construction efficiency, reducing labor risks, and enhancing construction quality are explored. Additionally, future directions and prospects for development are proposed. The conclusion indicates that there is vast potential for the application of construction robotics in house construction. By introducing robotics technology, construction efficiency can be significantly improved, construction costs can be reduced, labor demands can be decreased, and construction quality and safety can be enhanced. This paper serves as a reference for the construction industry and research institutions, promoting the further development and application of construction robotics in the field of house construction.

Keywords. Construction robotics, intelligent construction, robotics technology, house construction

1. Introduction

1.1. Background Introduction

The current construction industry remains labor-intensive, with many construction processes requiring manual operations by construction workers, and the quality of the projects heavily reliant on human experience. The entire construction process requires collaboration among multiple workers, leading to a high demand for labor in the construction sector. However, with the increasing aging population and diminishing demographic dividend in recent years, the construction industry is facing significant challenges such as high labor costs, high risk factors, and low production efficiency. Therefore, there is an urgent need for industrial upgrading in the construction sector to accelerate the high-quality development of automation and intelligence in construction, meeting the pressing demands for sustainable development in China's construction

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industry [1]. Currently, the technology of construction robotics is not yet stable and mature, especially in complex construction environments, where the performance and stability of robots still have certain limitations [2]. The robot's autonomous navigation and environmental perception capabilities still need improvement, and its flexibility and adaptability need further enhancement to meet the requirements of various construction scenarios. According to the plan of the Ministry of Industry and Information Technology of China, the installed base of industrial robots is expected to reach one million units by 2020, with a demand for 200,000 robot specialists, as shown in figure 1. The growth trends of various types of robots are illustrated in figure 2. This indicates that the future prospects of robotics are very promising.

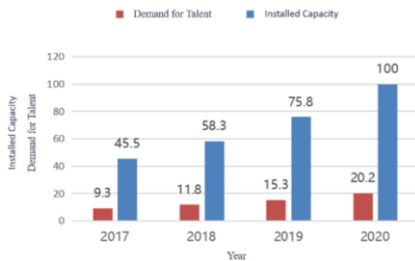


Figure 1. Industrial Robot Installations and Talent Demand from 2017 to 2020.

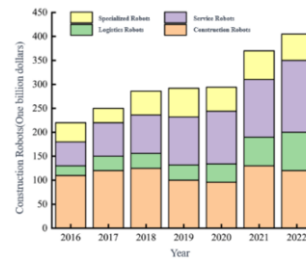


Figure 2. Growth Trend of Various Types of Robots.

1.2. Aims and Significance

The aim of this study is to conduct in-depth and comprehensive research and analysis on the application of construction robots in residential construction. Through a review of relevant literature and research findings from both domestic and international sources, the current status, technological characteristics, advantages, limitations, challenges, and future development trends of construction robots in the field of residential construction are explored. This research aims to provide valuable guidance and reference for promoting the application and innovation of construction robot technology. It is of significant importance to systematically summarize the research status, identify application advantages and issues, explore future development directions, and promote the application and innovation of technology. The study will offer crucial theoretical and practical support for the promotion and innovation of construction robot technology in the residential construction sector, facilitating the intelligent and efficient development of the construction industry.

2. The Development History of Construction Robotics

2.1. Early Applications of Robots in Construction

Early construction robots were primarily used for handling repetitive and labor-intensive tasks, such as transporting bricks, concrete, and sand. These early robots were typically fixed at specific workstations, performing single and repetitive actions. With the development of industrial automation technology, automated equipment like automatic mixing and pouring devices began to be applied in construction [3]. While

these automated devices may not be considered traditional robots, they represent the trend of construction moving towards automation. Developed countries, such as Europe and the United States, have long been engaged in researching various types of construction robots. However, due to factors like technology and cost, these devices were not widely adopted in practical applications. It was not until recent years, with the continuous maturation and improvement of relevant technologies, that these robots started transitioning from laboratory research to real-world applications, playing an increasingly significant role in the construction industry. Some representative examples include the bricklaying robot "SAM100" from the United States (Figure 3), the rebar-tying robot "Tybot" (Figure 4), and the "EffiBOT" developed by the French robotics company Effidence (Figure 5).



Figure 3. SAM100 Developed by Construction Robotics.



Figure 4. Tybot Developed by Advanced Construction Robotics.



Figure 5. "EffiBOT" Developed by Effidence.

2.2. The Emergence of Construction Robotics

Over the years, construction robotics has made significant progress, evolving from early experimental stages to more advanced capabilities. This progress can be attributed to the continuous development of computer technology and sensor technology, which have enabled construction robots to perform increasingly complex tasks. With the integration of reinforcement learning [4], construction robots have achieved functionalities such as autonomous navigation, obstacle avoidance, and path planning. The applications of construction robots have diversified, extending beyond traditional tasks of material handling and concrete pouring. Today, they are involved in various tasks, including welding, spraying, and inspection. The development of construction robots has transitioned from simple repetitive tasks to a diverse and intelligent range of capabilities, as depicted in figure 6. Through the journey of development, construction robotics has demonstrated its potential to revolutionize the construction industry. The adoption of cutting-edge technologies has allowed construction robots to tackle intricate tasks, improve productivity, and enhance safety on construction sites. As research and innovation in the field continue, construction robots are expected to play an even more crucial role in shaping the future of the construction industry.

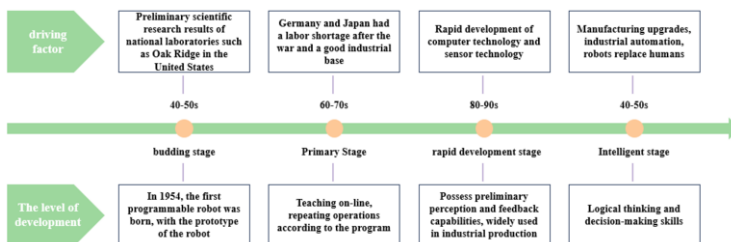


Figure 6. The development of construction robotics.

With the advancement of technology and increasing demands, construction robots are now appearing in a broader range of tasks and fields. Material handling robots, equipped with mechanical arms and sensors, can accurately grasp and move various shapes and weights of objects, replacing manual handling in construction sites. This reduces the burden on workers and improves work efficiency significantly. Another crucial application is drilling robots. Drilling is a common task in construction, but it often requires a substantial amount of labor and time. Nowadays, drilling robots can precisely perform drilling on building walls or floors based on predetermined coordinates and parameters. Built-in algorithms detect and correct the position and depth of drilling to ensure accuracy and quality. Moreover, modern construction robots are capable of handling more complex tasks, such as welding and assembly. Welding robots achieve high-quality welding results through precise motion control and sensor feedback. Assembly robots automatically identify and assemble components, such as doors, windows, wall panels, and pipes, according to predetermined assembly sequences and parameters. This improves construction efficiency and accuracy. The number of robots used in various industries is on the rise, and the construction industry is no exception. Construction robots have become a prominent presence in construction projects due to their ability to increase productivity, reduce labor costs, and enhance construction quality and safety. As technology continues to evolve, the deployment of construction robots is expected to increase further, driving the industry towards more intelligent and efficient construction practices.

2.3. The Development Trend of Construction Robots

The recent development trends of construction robots mainly focus on autonomy and intelligence, modularity and reconfigurability, safety and reliability, fault detection and self-healing, and data security and confidentiality. With the continuous advancement of technology, construction robots are bringing more efficient, intelligent, and environmentally friendly construction methods to the construction industry. The key development trends of construction robots are as follows:

2.3.1. Intelligent Autonomy and Flexible Collaboration

With the development of technologies such as artificial intelligence and machine learning, the autonomy and intelligence of construction robots have been continuously enhanced. They can now learn and adapt to perform various construction tasks and make decisions based on changes in the environment. In recent years, construction robots are no longer working in isolation but can collaborate with other robots and human workers. Through cooperation and information sharing, robots can better accomplish complex construction tasks, thereby improving work efficiency and quality [5].

2.3.2. Reconfigurable and Modular Operations

In recent years, modular design and reconfigurable technology have been applied to assembly-type robots. This means that robots can be reconfigured and assembled according to different task requirements to adapt to various construction environments and task demands. For example, the robot's mechanical arm can change its toolhead based on the operational needs to accommodate different types of construction tasks.

This modularity and reconfigurability provide robots with greater flexibility and adaptability [6].

2.3.3. Safety, Reliability, and Precision Efficiency

Construction robots are integrating more advanced technologies into their design and control to enhance safety and reliability, ensuring efficient, secure, and reliable operation on construction sites. They utilize technologies such as laser rangefinders, infrared sensors, and cameras with higher accuracy for real-time monitoring of the surrounding environment and obstacles. The robots have improved autonomous obstacle avoidance capabilities and are equipped with advanced remote monitoring and control systems, utilizing more intelligent machine learning techniques to continuously optimize their performance and enhance safety and reliability.

2.3.4. Fault Intelligent Diagnosis and Responsive Feedback

By incorporating advanced sensing technologies, automatic diagnostic algorithms, and data-driven preventive maintenance, the fault handling and self-recovery capabilities of robots are enhanced, ensuring the continuity and efficiency of construction operations. This enables construction robots to work more stably and reliably in complex and changing work environments. With an embedded self-healing system, the robot can automatically carry out repairs and restore normal operation when a fault occurs. Collecting a large amount of operational data and running status information allows for data analysis and mining, facilitating preventive maintenance to preemptively prevent faults. The robots possess automatic fault diagnosis capabilities, rapidly identifying the causes of faults based on their characteristics and data analysis, and providing corresponding solutions.

3. Technical Classification of Construction Robots

3.1. Autonomous Navigation Technology

Autonomous navigation includes three main components: localization, mapping, and path planning, as shown in figure 7. Autonomous navigation technology is a key technology for construction robots to achieve autonomous movement and positioning. Perception devices such as laser rangefinders, vision sensors, and ultrasonic sensors are used to perceive and model the surrounding environment, enabling autonomous navigation [7].

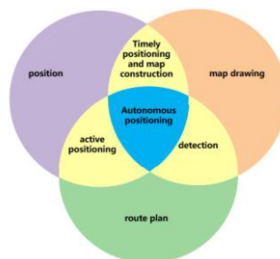


Figure 7. Autonomous Localization and Navigation Technology.

3.2. Robotic Arm Control Technology

Robotic arm control technology is a crucial aspect of building construction robots, enabling precise operations and flexible control. Common robotic arms and their characteristics are presented in table 1. Through the implementation of various sensors and control algorithms, robotic arms can achieve complex movements and posture adjustments to adapt to different construction tasks. For instance, robotic arms can be utilized for tasks such as concrete pouring, brick wall construction, and steel reinforcement welding. Currently, there are controllable flexible micro-robotic arms used in applications like surgical suturing and multi-degree-of-freedom mirror holding systems. Research in controllable flexible micro-robotic arms has explored biomimetic finger joint designs and optimized mechanical joint structures, as demonstrated in figure 8, to improve their motion capabilities.

Table 1. Common Robotic Arms and Their Function.

Mechanical Arm	Degrees of Freedom	Function
Cartesian Coordinate Robot Arm	-	Decoupled motion in each direction
Selective Compliance Assembly Robot Arm	-	Substitute for articulated robots
Articulated Robot Arm	6 or 7 degrees of freedom	Position control Orientation control
Parallel Robot Arm	3-DOF parallel mechanism	Position control
Stewart Platform	6-DOF parallel mechanism	Position control Orientation control

The stability of the robotic arm's end effector pose is crucial for ensuring accurate and precise control of the end tool or device during construction tasks, thereby achieving high-quality construction results. The stability of the robotic arm's end effector pose is demonstrated in figure 9. Force and visual sensors are installed at the end of the robotic arm to monitor the real-time position and orientation of the end effector tool. Feedback control technology adjusts the control signals of the robotic arm in real-time based on the sensor data to maintain the stability of the end effector pose. Safety protection devices are installed at the end of the robotic arm to immediately halt movement when encountering obstacles or abnormal situations, ensuring construction safety. Artificial intelligence techniques, such as deep learning and reinforcement learning, are used to enable the robotic arm to learn and optimize control strategies, enhancing the stability and precision of the end effector pose.

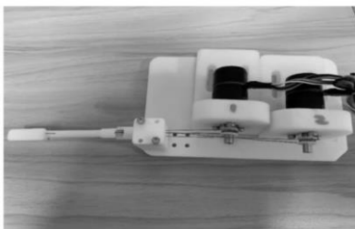


Figure 8. Validation of the functionality of a flexible micro-robotic arm.

Figure 9. End-effector pose stability display of the robotic arm.

3.3. Sensor Technology

Building construction robots rely on various sensors to obtain environmental information and work status. For example, laser rangefinders are used to measure the dimensions and shapes of buildings; cameras and visual sensors are used for target recognition and localization; force sensors are used to control the force applied by the robotic arm. Commonly used sensors for robots are shown in table 2. The development of sensor technology enhances the perception and feedback capabilities of construction robots, enabling real-time perception and monitoring of the surrounding environment and task execution process [8]. With the continuous development and innovation of sensor technology, the perception capabilities of building construction robots will continue to improve, bringing more convenience and progress to the construction industry.

Table 2. Commonly used sensors in robots.

Sensor Type	Detection Range	Accuracy	Function
Lida	>100m	high	Dynamic Obstacle Detection, Recognition, and Tracking Road Surface Detection, Localization, and Navigation, Environmental Modeling
Ultrasonic Sensor	2m-5m	high	Ultrasonic sensors measure the distance and position of target objects by emitting and receiving ultrasonic waves. They are used for distance measurement and obstacle detection.
Camera	50m	average	Computer vision is utilized to perceive the surrounding environment and objects, as well as to determine distances.
Millimeter-Wave Radar	250m	relatively High	Perceiving the operational status of vehicles over a large area, commonly used for adaptive navigation systems.

3.4. Data Processing, Decision-making, and Other Related Technologies

Building construction robots collect environmental data through sensors and transmit the data to a central control system or cloud platform for processing. Data processing and decision-making technologies are employed to analyze the perception data and make optimal decisions and actions. Simultaneously, data security and privacy protection are enhanced during data processing and decision-making to ensure that the robot's data is not accessed or used without authorization. Building construction robots also involve the application and research of other related technologies. For example, wireless communication technology is used for robot-to-robot collaboration and data transfer; virtual reality and augmented reality technologies are used to simulate and visualize construction scenes; human-computer interaction technology enhances robot operability and user-friendliness; nanotechnology improves robot flexibility and precision.

4. Application Prospects of Building Construction Robots

4.1. Concrete Construction

Concrete construction is a crucial part of building construction, and traditional processes involve labor-intensive operations, resulting in low construction efficiency and inconsistent quality. Building construction robots hold great potential and prospects for the future development of concrete construction applications. With continuous technological advancements and maturation of automation techniques, building construction robots are expected to play an increasingly significant role in concrete construction. This includes the following aspects:

4.1.1. Automatic Mixing and Conveying

Traditional concrete mixing and conveying rely on manual operations, which are labor-intensive and inefficient. Through the integration of artificial intelligence algorithms and building construction robots, automatic adjustment of mixing and conveying parameters based on real-time sensor data and predetermined concrete ratios can be achieved. For mixing process data, data analysis and predictive techniques are used to analyze and model historical concrete mixing and conveying data, thus predicting future construction demands and concrete ratios. This intelligent control over concrete mixing and conveying avoids resource wastage and construction delays. Natural language processing techniques enable voice or image interaction between operators and robots, streamlining the operational process and improving construction flexibility and efficiency. Machine learning technology enables continuous learning and optimization, gradually elevating the level of automation and precision in concrete mixing and conveying. Machine learning allows robots to autonomously choose the best mixing and conveying solutions for different construction scenarios and requirements.

4.1.2. Automatic Pouring and Leveling

Traditional concrete pouring and leveling require a considerable amount of manual labor and are prone to unevenness and irregularities. Building construction robots integrate machine vision technology to perceive and identify construction site conditions and obstacles using cameras and sensors. Real-time information is then used to adjust the pouring and leveling position and orientation as needed. Automatic path planning algorithms are applied to autonomously select the best construction path and motion trajectory, avoiding collisions and redundant movements, thus enhancing construction efficiency and accuracy. Machine learning techniques continually optimize pouring and leveling actions and speeds through learning and analysis of historical construction data, achieving process automation and intelligence, and improving construction stability and consistency. Control systems are adjusted in real-time based on sensor data and algorithm feedback, ensuring construction accuracy and quality, and promptly addressing any anomalies during construction. The extensive data collected during construction is analyzed and processed to extract valuable information and patterns, providing references for subsequent construction optimizations and decisions, and enabling continuous improvement and optimization of the construction process.

4.1.3. Automatic Curing and Treatment

After concrete construction is completed, certain curing and treatment work is required, which traditionally consumes significant manpower and time. Building construction robots equipped with temperature, humidity, and vibration sensors can monitor the structural status and performance of buildings in real-time, as well as cracks and damages during concrete curing. The robots automatically collect and analyze vast amounts of structural health data, maintenance history, and usage data, identifying potential issues and anomalies, and predicting the structure's lifespan and maintenance needs. Learning from historical data, robots construct maintenance models, anticipate future structural maintenance requirements, and formulate effective maintenance plans. Based on sensor data and machine learning models, robots autonomously decide on maintenance plans and plan maintenance paths. Building construction robots are moving towards increased intelligence and sophistication in concrete construction applications. With further technological innovation and application, building construction robots will become invaluable assistants in concrete construction, enhancing construction efficiency, improving construction quality, and promoting the advancement and development of the construction industry. However, safety and feasibility factors must be thoroughly considered, and comprehensive planning and assessment should be conducted during practical implementation.

4.2. Brick Wall Construction

Brick wall construction is a common task in building construction, and traditional methods involve manual work in brick transportation, laying, and plastering, resulting in significant labor intensity and time consumption. The application of building construction robots in brick wall construction holds the potential to improve construction efficiency and quality, reduce labor costs and risks, and propel the building construction industry towards a more intelligent, efficient, and sustainable direction.

4.2.1. Automatic Brick Handling

Traditional brick handling requires manual labor, leading to high work intensity and low efficiency. Building construction robots can achieve automatic brick handling through mechanisms such as robotic arms and conveyor belts, significantly increasing construction efficiency and reducing labor burdens. Based on vision sensors and cameras, machine vision technology is used for real-time recognition and perception of the positions, sizes, and shapes of bricks. Deep learning algorithms enable detection and identification of bricks, determining their positions and orientations. Simultaneously, the construction environment is monitored in real-time to dynamically adjust handling paths, ensuring high efficiency and safety during construction. Multiple robots can collaborate and integrate with the system to achieve highly automated brick handling and improve construction efficiency.

4.2.2. Automatic Laying and Positioning

Traditional bricklaying requires skilled bricklayers and is susceptible to inconsistent construction quality. Building construction robots, based on visual perception data and building design models, utilize navigation technology to accurately locate themselves

and the target positions for bricklaying. The robots precisely grip and transport bricks based on detected brick positions and orientations. Laser rangefinders, global positioning systems, and other precise positioning technologies determine the robots' positions and the target positions for brick wall construction. Smart decision-making algorithms and machine learning techniques enable intelligent decisions and optimization based on real-time construction data, enhancing construction efficiency and quality.

4.2.3. Automatic Plastering

After traditional brick wall construction is completed, plastering work is required, which typically consumes significant manpower and time. Building construction robots, equipped with machine vision technology, can recognize and perceive the unevenness, defects, and other conditions on the brick wall surface in real-time. Through deep learning algorithms, the robot inspects and identifies the areas and locations that require plastering, enabling precise plastering operations. Intelligent decision-making algorithms and machine learning techniques are utilized to make intelligent decisions and optimizations based on real-time construction data, ensuring the quality and efficiency of plastering. Simultaneously, the data during the plastering process is monitored in real-time, adjusting and corrections as needed to ensure that the plastering effect meets the required standards.

4.3. Reinforcement Welding

Reinforcement welding is an important process in construction. Traditional reinforcement welding typically requires manual operation by welders, which not only involves high labor intensity but also leads to welding errors. However, robots can automatically identify and position the reinforcement based on design requirements and reinforcement layout diagrams, and precisely weld them using welding equipment. This automated reinforcement welding can reduce the labor intensity and welding time for welders, while ensuring the quality and consistency of welds. As shown in figure 10, based on the study of the number of patent applications for welding robots from 1968 to 2019, the year 2019 reached a historical peak with 693 patent applications. It is foreseeable that with the development of artificial intelligence and related network technologies, the number of patents for crawling welding robots will show a rapid increase in the coming years.

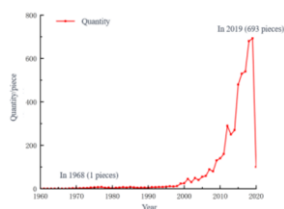


Figure 10. Global Patent Application Trend of Crawler Welding Robots.

4.3.1. Automatic Reinforcement Cutting

Traditional reinforcement cutting requires manual operation, and the accuracy and speed of cutting are limited by manual skills. However, construction robots, equipped

with machine vision technology, can perform real-time image recognition and detection of the reinforcement, determining the cutting positions and dimensions. The robot is also equipped with a laser cutting device, using laser technology for precise cutting of the reinforcement. Real-time monitoring of data during the cutting process enables adjustments and corrections as needed, ensuring the accuracy and consistency of cutting and making intelligent decisions and optimizations based on real-time construction data to ensure the quality and efficiency of cutting.

4.3.2. Reinforcement Welding Point Positioning

Reinforcement positioning is a critical step in ensuring welding accuracy. Traditional methods require manual measurement and positioning, which can lead to errors. Using high-resolution cameras and machine vision systems, robots can perform real-time recognition and positioning of the reinforcement welding points. This includes determining the position, shape, and angle of the welding points. Using laser scanning sensors, the robot achieves precise 3D scanning of the reinforcement welding points, thus achieving accurate positioning.

4.3.3. Automatic Welding

Traditional reinforcement welding requires skilled welders for operation, demanding high welding skills and knowledge of welding processes. However, construction robots, based on the detection results of welding points, autonomously plan welding paths, ensuring welding accuracy and efficiency. By applying artificial intelligence and digitalization technologies, construction robots can achieve automatic positioning and welding of reinforcement, enhancing construction efficiency and quality while reducing reliance on manual labor. Additionally, robots ensure the accuracy and consistency of welding.

4.4. Demolition, Cleanup, and Other Application Areas

Demolition of buildings and cleanup of construction sites are common tasks in the construction industry. However, these tasks often require extensive manual labor and involve hazardous operations. Building construction robots, based on machine vision systems, can real-time perceive the surrounding environment and recognize the structure, materials, and locations of buildings. Through deep learning algorithms, the robot can learn and identify different types of building structures and materials, enabling precise demolition and cleanup. Utilizing navigation systems, the robot can accurately locate the target areas for demolition and cleanup, and plan the most optimal paths and actions. Utilizing ultrasonic sensors, it can sense surrounding obstacles and hazardous zones, automatically avoiding them, and ensuring the safety of the construction process. Through human-machine interaction technology, workers can remotely monitor and control the dismantling and cleaning work of construction robots, enabling more flexible and convenient operations. By analyzing data and providing feedback, the process and results of dismantling and cleaning can be optimized. The application of construction robots will drive the construction industry towards intelligence, efficiency, and environmental friendliness, bringing more innovation and development to the construction sector. Construction robots play a significant role in many other scenarios. For example, they can be used for painting and spraying buildings to increase construction speed and coating quality. They can also be

employed in building decoration tasks, such as installing wallpapers, tiles, and decorative panels. Furthermore, robots can be utilized for building maintenance and upkeep, such as cleaning glass curtain walls and repairing exterior wall coatings.

5. Challenges of Construction Robots

5.1. Complex Construction Environments

Construction sites often face uncertainties such as weather changes, delays in material supply, and human resource availability, which can impact the work plan and efficiency of robots. In confined construction spaces, robots need to address precise positioning and operations within limited areas. Construction involves various processes like mixing, pouring, plastering, welding, etc., and robots need to enhance adaptability to different construction processes [9]. Construction robots must possess high levels of safety to avoid accidents and injuries. Handling diverse building materials like concrete, reinforcement bars, and bricks requires robots to have robust processing capabilities and adaptability. Construction robots face diverse and complex environments, necessitating high levels of intelligence, adaptability, and safety to tackle challenges and achieve efficient, accurate, and safe construction work.

5.2. Intelligent Control and Collaboration

Given the complexity of construction environments, construction methods also face challenges. Construction robots need to address intelligent control issues, perceive and understand the surrounding environment, make autonomous decisions, and plan the optimal construction path and sequence of actions to maximize construction efficiency and precision. Additionally, robots need to establish effective communication and coordination with other robots or personnel. In complex construction tasks, multiple robots work collaboratively to enhance construction efficiency and reduce construction time, facilitating efficient construction operations.

5.3. Technological Cost and Feasibility Challenges

The research, development, manufacturing, and maintenance costs of construction robots are relatively high. Advanced sensors, control systems, and artificial intelligence algorithms require significant investments, and the design and manufacturing process of robots demand substantial research and production costs. Furthermore, as technology continually updates and upgrades, the maintenance and upgrade expenses of robots also increase. Construction environments are complex and variable, and robots need high adaptability and flexibility to cater to different construction scenarios. However, current construction robots still have certain limitations in adaptability, as they can only be suitable for specific types of construction tasks, failing to meet diversified engineering requirements. Robot development necessitates integrating various technologies, such as mechanics, electronics, automatic control, and artificial intelligence, thus increasing technological difficulties and costs.

6. Future Development Trends of Construction Robots

6.1. Breakthrough in Key Technologies

The future development of construction robots will focus on breakthroughs in key technologies. For example, intelligent perception technology will enable robots to acquire real-time information about building structures, obstacles, and worker positions through high-precision sensors and perception systems. This information will be utilized for navigation, localization, obstacle avoidance planning, and task execution, enabling robots to intelligently adapt to different construction scenarios. Advanced mechanical arm control and motion technology, utilizing electric servo control, will achieve high-precision motion control and multi-degree-of-freedom operations. Artificial intelligence and machine learning techniques will continuously optimize robot behavior and decision-making through the analysis and learning of large construction datasets, enhancing autonomy and intelligence to adapt to various types and scales of construction projects.

6.2. Expansion of Potential Application Areas

The application areas of future construction robots will further expand beyond traditional tasks like bricklaying and concrete pouring. Robots will be used in other construction processes such as steel reinforcement binding, wall surface painting, and collaborative work with construction workers. Moreover, robots can be applied in special construction scenarios, such as high-altitude construction, tunnel construction, underwater construction, etc., to address challenges that traditional construction methods find difficult to overcome.

6.3. Human-Robot Collaboration and Intelligent Development

Human-robot collaboration technology will enable robots and workers to jointly complete complex construction tasks, harnessing human creativity and intelligence while achieving seamless cooperation between robots and humans. For instance, robots can handle tedious and high-risk operations while workers focus on complex and advanced tasks such as technical guidance and quality control. Additionally, robots will be capable of intelligently and autonomously adjusting and optimizing construction plans according to the construction environment and requirements.

The future development of construction robots is expected to make significant progress in breakthroughs in key technologies, the expansion of potential application areas, and the advancement of human-robot collaboration and intelligence. This will further enhance construction efficiency and quality, reduce human risks, enable better adaptation to complex construction environments, and drive the modernization and intelligent development of the construction industry, bringing more innovation and transformation to the construction sector.

7. Conclusion

7.1. Main Contributions of this Article

The main contribution of this article lies in a thorough exploration of the future development trends of construction robots. Firstly, it emphasizes the significance of key technologies in the development of robots and provides detailed discussions on critical areas such as perception, decision-making, and operations. Secondly, it expands the application areas of construction robots, covering both traditional and special construction tasks. Lastly, the article highlights the importance of human-robot collaboration and intelligent development in shaping the future of robots and proposes corresponding development directions. Through these contributions, this article offers important references and guidance for the future development of construction robots.

7.2. Prospects for Construction Robots

The prospects for construction robots are exceptionally promising. Firstly, with breakthroughs in key technologies, the performance of construction robots will be further enhanced, enabling them to adapt to more complex and diversified construction tasks. Secondly, with the expansion of potential application areas, construction robots will be able to operate in more construction scenarios, addressing challenges that traditional construction methods struggle to solve. Lastly, the development of human-robot collaboration and intelligence will promote close cooperation between robots and construction workers, leading to more efficient and safer construction processes. In the future, construction robots are expected to become a significant force in the construction industry, transforming traditional construction methods. Moreover, the development of construction robots will bring forth new employment opportunities and economic benefits, facilitating industrial upgrading and social progress.

In summary, construction robots possess vast potential and significant application value. The future development will require continuous technological innovation and interdisciplinary collaborations to drive the rapid advancement of the construction robot industry.

References

- [1] Xu Z, Song T, Guo S, et al. Robotics technologies aided for 3D printing in construction: a review. *Int. J. Adv. Manuf. Technol.* 2022;118: 3559–3574.
- [2] Diehl W, Quantmeyer F, Liu-Henke XB. Model-based development of algorithms for a battery-management system. *SSP 2015*; 220–221, pp. 401–6.
- [3] Cai, SY, Ma, ZL, Skibniewski MJ, et al. Construction automation and robotics for high-rise buildings: development priorities and key challenges. *Journal of Construction Engineering and Management.* 2020; 146(8): 4020096.1–4020096.15.
- [4] Juan Manuel Davila Delgado, Lukumon Oyedele. Robotics in construction: A critical review of the reinforcement learning and imitation learning paradigms. *Advanced Engineering Informatics.*
- [5] Tehrani MB, Cagri GO and Alwisy A. A Decision Support System for the Integration of Robotics in Offsite Construction. *Construction Research Congress.* 2022.
- [6] Tehrani MB, BuHamdan S & Alwisy A. Robotics in assembly-based industrialized construction: A narrative review and a look forward. *Int. J. Intell. Robot. Appl.* 2022.
- [7] J alas P, et al. Information modeling of an underground laboratory for the r&d of mining automation and tunnel construction robotics. *34th International Symposium on Automation and Robotics in Construction.* 2018.

- [8] Oke AE, Aliu J, Fadamiro P, Jamir Singh PS, Samsurijan MS and Yahaya M. Robotics and automation for sustainable construction: Microscoping the barriers to implementation. *Smart and Sustainable Built Environment*. 2023.
- [9] Sardroud, Javad Majrouhi, et al. Barriers analysis to effective implementation of bim in the construction industry. 35th International Symposium on Automation and Robotics in Construction (ISARC) 2018.