Application of Automation and Robotics Technology in High-Rise Building Construction: An Overview

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Abstract –

More and more high-rise buildings are being erected in extensively populated countries such as China nowadays with the requirement of higher living standards. However, on the one hand, with the development of aging society, the labor shortage has become a remarkable problem; on the other hand, the danger and difficulties in construction increase significantly with the height of the buildings. Thus, the application of automation and robotics technology is expected to ease such problems and concerns. Up to now, various methods and systems using automation and robotics technology have been proposed to be used in high-rise building construction. This paper summarizes the major advance on the application of automation and robotics technology in high-rise building construction through a literature survey and suggests directions of further research in this field. First of all, the research scope, the method and the results of the literature survey are presented. Then, based on the survey results, the relevant applications are summarized regarding the three parts of high-rise buildings, i.e., earth and foundation work, superstructure erection and façade installation. Finally, the future directions and opportunities mentioned in existing research are summarized and discussed. This paper provides a valuable aid in future research and application of automation and robotics technology for high-rise buildings.

Keywords –

Automation and robotics; High-rise building; Earth and foundation work; Superstructure erection; Façade installation

1 Introduction

Due to the demographic and economic developments, the number of the world's high-rise buildings is growing rapidly. The emergence of high-rise buildings mitigates the pressure of the growing population, but also requires a large quantity of labor force during the construction. Meanwhile, the number of young workers is decreasing at the construction site, due to the aging population in many countries in the world. What is more, the safety problems and the workers' psychological fear of the height are also remarkable challenges at the construction site of high-rise buildings. Obviously, both the predictable labor shortage and the life safety of the workers call for leveraging machines and robots to replace human labor in high-rise building construction.

The application of automation and robotics technology in the construction industry have been reviewed in several papers. Bock [1] suggested that conventional construction methodology had reached its limits, and outlined five aspects of future opportunities for construction automation: robot-oriented design, robotic industrialization, construction robots, site automation, and ambient robotics. Son et al. [2] analyzed the topics and contents of 1671 papers in International Symposium on Automation and Robotics in Construction (ISARC) proceedings from 1990 to 2008, to identify trends and future directions of automation and robotics technology in construction. Vähä et al. [3] surveyed on sensor technology and its potential use for construction automation and reviewed robotic applications in the main construction procedures. Taylor et al. [4] summarized the existing automated machinery and construction robots in Japan, and suggested that construction environments should be more structured and controlled to apply construction robots. Maas and van Gassel [5] discussed the development of automation and robotics technology and its influence on performance management, construction engineering, and construction management.

These papers have presented the application of automation and robotics technology in the construction industry as a whole, pointed out the key research areas and analyzed the current and ongoing research and development trends. However, there is a lack of a systematic review of the application of automation and robotics technology in high-rise building construction.

This paper summarizes the major advance on the application of automation and robotics technology in high-rise building construction through a literature survey and suggests directions of further research in this field. To this end, considering the characteristics, the paper focuses on three sub-phases of high-rise building construction: earth and foundation work, superstructure erection and façade construction. In Section 2, the research scope, the method and the results of the literature survey are presented. Then, by analyzing the survey results, Sections 3, 4 and 5 respectively present the application of automation and robotics technology in the construction of foundation, superstructure and façade, and Section 6 summarizes the future directions of automation and robotics technology for high-rise buildings. Finally, the paper is concluded in Section 7.

2 Research Scope and Literature Retrieval

The definition of the term "high-rise building" varies in different countries. For example, according to Chinese standards, a high-rise building refers to a residential buildings over ten stories or 28 m, or a nonresidential buildings over 24 m; in Japan, a high-rise building is over eight stories or 31 m; and in the U.S., it is over 24.6 m or seven stories. Besides, the high-rise buildings taller than 100 m are called "skyscrapers". In this paper, the high-rise building is not strictly defined, and it covers the definitions in different countries and includes the skyscrapers.

To implement a systematic literature review, a comprehensive search was conducted in the major databases, including Engineering Village, Scopus, ASCE, and Web of Science. The search keywords included "high-rise", "robot", "automation", "construction", "assembly", "installation", "machine", "equipment", etc. However, the publications in the form of editorials, books, discussions, or published before 2000 were excluded because they are considered to be of little value for the review. By reading the titles, abstracts and conclusions, we filtered out unrelated papers and finally obtained 50 papers. Particularly, we found the review on application of automation and robotics technology in the sub-phase of earth and foundation work is already comprehensive (which is further explained in Section 3), so we only included three latest review papers of earth and foundation work in this study. The distribution of the retrieved papers related to superstructure and façade (47 papers) is shown in Figure 1.

3 Application in Earth and Foundation Work

The earth and foundation work is an essential sub-phase for the construction of each type of buildings. It contains many repetitive operations and is also among the most dangerous work in building construction. Therefore, the research on the application of automation and robotics technology in earth and foundation work is one of the pioneers in the construction industry, and numerous papers have been published on this topic. Several reviews have been conducted in recent years to summarize the major studies comprehensively. To avoid repetitive work, this study only presents three latest reviews published in 2016 and 2017.

Naskoudakis et al. [6] reviewed 73 papers published from 2006 to 2015 about earthmoving equipment and divided them into seven main research themes, one of which is robotics and automation. Two sub-themes were then identified, i.e., unmanned construction, and real-time monitoring and detection. Azar and Kamat [7] provided a comprehensive review of the technical advances in earthmoving automation in both industry and academic community and discussed the limitations and future directions. They classified the studies of earthmoving equipment automation into four categories: equipment tracking and fleet management, safety management, equipment pose estimation and machine control, remote control and autonomous operation, among which the last one was identified as the most immature fields. Dadhich et al. [8] provided the background of the autonomous earthmoving, and presented a survey covering the key research topics and identified the knowledge gaps of automation of earthmoving machines, especially the operation of wheel loaders in a short loading cycle. In this review paper, the main knowledge gaps were identified as fragmented rock excavation, communication for remote operation, and operator experience during remote operation.

The major specific technologies included in automation and robotics technology and their applications mentioned in the above studies are identified and summarized in Table 1.

4 Application in Superstructure Erection

For the sub-phase of superstructure erection of high-rise buildings, the construction difficulty increases significantly as the building height grows, which mainly appears in three aspects, the low productivity and safety concerns due to the manual work in hazardous working environment, the vertical transportation of workers, materials and equipment, and assembly of heavy objects, especially for steel structures. Thus, the related studies are classified into three sub-themes corresponding to the three aspects: automated construction systems, automated lifting systems, and robot-based steel assembly systems. The following sub-sections will describe them respectively.

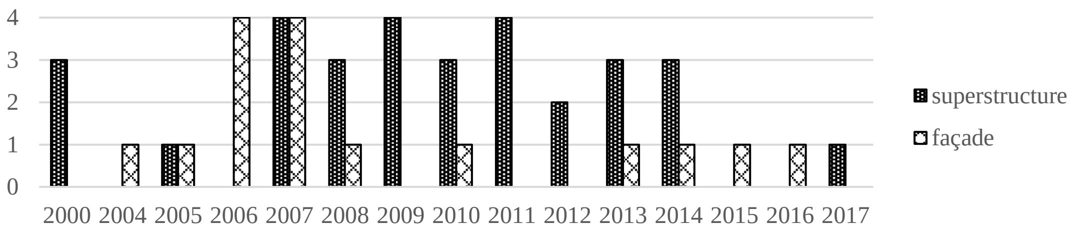

Figure 1. Distribution of the related papers of superstructure and façade

Table 1. Summary of the major specific technologies and their applications in the above studies

Application area		Function	Specific technology	Reference
Automated management	equipment management & progress monitoring	Localization	Radio-based technologies, such as GPS, RFID, and UWB; Vision-based technologies.	[6-8]
		Operation action recognition	Vision-based technologies.	[7]
	safety management	Accident warning	Vision-based technologies and 3D point cloud reconstruction.	[7]
Automated earthmoving operation	Remote operation	Human-machine interaction to improve the spatial and situational awareness of the operator	3D point cloud reconstruction; Augmented reality (AR); Haptic feedback joystick.	[6-8]
		Real-time information transfer	Wireless communication.	[8]
	Autonomous operation	Pose estimation of the end-effector	Radio-based technologies, such as GPS and UWB.	[7]
		Pile characterization for suitable excavation location and pose	Vision-based technologies; Laser-based technologies.	[8]
		Automatic control	AI & reinforcement learning.	[8]

4.1 Automated Construction Systems

Automated construction systems are designed to stabilize the construction process and improve the productivity of high-rise building construction by establishing a comfortable working environment which is suitable to employ the automated equipment and robots. In this study, seven related papers were identified.

Miyakawa et al. [9] proposed an automated building construction system (ABCS) for high-rise steel structures, which integrates three parts: 1) a synchronously climbing structure that encloses an all-weather working space, called "Super Construction Factory (SCF)"; 2) a parallel delivery system for material lifting; and 3) centralized management systems, for production management, equipment operation management and machine control. Based on ABCS, another system called "Big Canopy" was developed for prefabricated high-rise reinforced concrete buildings [10, 11], which adapts to the characteristics of reinforced concrete construction.

Compared with the conventional method, ABCS and Big Canopy successfully improved the working conditions and construction productivity. However, the equipment configuration of the SCF limits the versatility of automated construction systems. Moreover, the costs and weights are extremely high because of the combination of the robots, massive cranes and lifting systems [12, 13]. Therefore, Kang et al. [12] developed a robotic-crane based automatic construction system (RCA system) for steel structures of high-rise buildings, which comprises a construction factory (CF), a steel assembly system and a monitoring and control system. In RCA system, the tower crane was installed at the core of building so that the heavy lifting and robot systems are independent of the CF, which decreased the weight of the system and reduced the construction cost as well as provided a convenient working space. Kim et al. [13] developed several conceptual CF alternatives to improve the working environment, and evaluated them with the Computational Fluid Dynamics method. The evaluation procedure and results provided an economical approach to select the CF in high-rise building construction.

With the development of the automated construction system, assessment methods were proposed to measure the economic and construction efficiency. Kim et al. [14] developed a benefit/cost analysis process for the application of robot-based construction automation systems, which can measure the economic viability of the automated systems. Van Gassel [15] conducted a simulation of the construction process of a Dutch high-rise building, involving the use of an automated construction system. By comparing the simulation results and the real construction data, the paper verified the economic benefits of automated construction systems, and promoted the application of automated construction systems in the Netherlands.

4.2 Automated Lifting Systems

For high-rise buildings, the vertical transportation of workers, materials and equipment significantly influences the construction efficiency. Therefore, several studies have been conducted to improve the automation level of the vertical transportation equipment. Eight related papers are identified.

Kim et al. [16] proposed a table formwork lifting system integrated with construction hoists, which improves the productivity, cuts down the high initial cost and overcomes extra work for assembly and operation. Cho et al. [17] developed a hoist-mountable intelligent toolkit for the lift car. With this toolkit installed, an existing lift car can be converted to an intelligent one, which can utilize remote sensing and communication technologies to capture the information of material movement and manage it intelligently. Based on this toolkit, a concept of a smart robotic lift [18] is proposed, with functionalities of automatic loading/unloading operation and wireless communication.

Operation planning and optimization are major factors to determine the productivity of the automated lifting process. Sin et al. [19, 20] proposed an unmanned smart lifting system and devised an optimized operation algorithm for twin or multi-cage lifts, which can reduce work hours and traffic queues. Cho et al. [21] provided a simulation method of construction hoists to calculate the lifting cycle time according to lifting heights and loads, and to generate an optimal hoist operating plan. They also developed an optimal algorithm [22] for path planning of the multi-lifting operation in super-tall buildings. These algorithms and methods optimized the automatic control of the lifting system, and thus enhances the work efficiency of vertical delivery.

Operation monitoring is another important aspect, especially for the smart tower cranes. Lee et al. [23] proposed an automated lifting-path tracking system for a robotic tower crane, which used laser devices to measure the linear distance, and an encoder and an accelerometer to measure the horizontal and vertical angles. The system monitors the operation actions of the tower crane and is helpful in safety management and lifting path planning.

4.3 Robot-based Steel Assembly Systems

The robot-based steel assembly task in high-rise buildings can be divided into three aspects: alignment of the steel components and the bolting holes, transportation of the bolting robot, and bolting operation. Fourteen related papers are identified.

A research team from Korea University continuously studied on robot-based steel construction and proposed a robotic beam assembly system (RBA system) [24-26], which comprises three sub-systems: a robotic bolting device, a control system, and a robotic transport mechanism. The bolting device [27] consists of an end-effector for bolting operation, a robotic manipulator that places the end-effector in the bolting position, and a cabin as the control station. The robotic transport system [28] consists of a cross-wired lift and a rail sliding mechanism, respectively in charge of the vertical and horizontal transfer of the RBA system. Lee et al. [29] also proposed a robot-based steel beam assembly system with sub-systems of transportation and positioning. The transportation system combines a rail with a boom, and the positioning system comprises four wires-suspended motion control devices which can be teleoperated.

The steel components to be assembled are usually suspended from the tower cranes and have the problem of swinging, which affects the alignment operation. For easier and more precise alignment of the pendulum-like heavy objects, Jung et al. [30, 31] developed a robotic manipulator control algorithm to grip the steel components stably and efficiently. Bae et al. [32] designed an end-effector to fix the relative motion of the steel components and the end-effector itself. Mo et al. [33] developed a bolt-hole detection system with a 3D camera, which can estimate the location of a bolt-hole precisely and is robust in different illumination conditions.

To provide a safer and more convenient working environment for the human operators, Jung et al. [34] proposed a teleoperation system based on the RBA system. A control station is built outside the cabin, which comprises two joysticks, monitoring systems, and a controller for teleoperation. Liang et al. [35] developed a robotic assembly system for steel beam erection and assembly, which consists of four methods: rotation, alignment, bolting, and unloading. The system works autonomously without an operator in high places.

5 Application in Façade Installation

Façade installation is a common operation in high-rise building construction, which deals with heavy glass ceiling panels and exterior wall panels made of various materials. The operation locations are hazardous for workers to access and there is a high risk of injury and damaging the expensive panels in manual operations. In addition, the requirements of high-precision panel positioning and suitable weather condition further increase the difficulty. With these problems, façade installation robots and systems have been a hot research topic. A total of 16 related papers are identified.

The macro/micro motion-based robot is widely adopted in the proposed systems for both wall panel and glass ceiling installation. As shown in Figure 2, these robotic systems are usually combined with two relatively independent systems, respectively for macro and micro motion. The macro motion manipulator is usually a commercially available mini-excavator [36-40] or an aerial lift [36, 41, 42] to lift and move the panels, and the micro motion manipulator is usually a multi DOF robotic end-effector for precise handling of the panels. The installation is based on human-robot cooperative manipulation, which requires an intelligent manual robot controller to feedback the reaction forces from the environment. Compared with the manual operation, the robotic systems can improve the productivity and lower the safety risks at the construction site. Particularly, Cinkelj et al. [37] developed a closed-loop control system for the semi-automated façade assembly system by upgrading a commercial hydraulic telescopic handler. The closed-loop computer control significantly improves motion performance to meet the precision of façade installation and assures straight line motion of the end-effector.

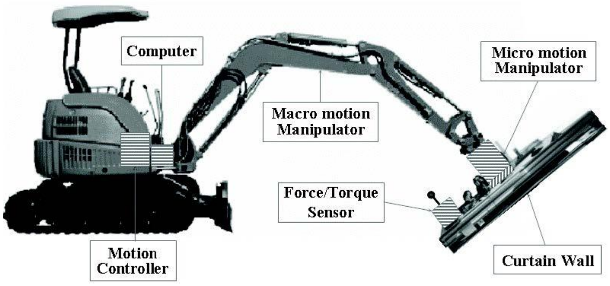

Figure 2. A typical macro/micro motion-based façade installation system [36]

Pan et al. [43] improved the conventional tower crane-based installation method and proposed a concept of a precast concrete panel installation system for high-rise buildings, which provides an integrated approach for panel loading, transportation, assembly and management. Van Gassel et al. [44] proposed a concept of a self-supporting robotic curtain wall system that integrates the assembly, disassembly and user functions of the curtain wall. Furtherly, they designed the mechanics and workflow of a self-assembling curtain wall system [45]. The stand of the system remains as part of the façade after installation, with the potential to serve in the following robot applications for disassembly or other user functions.

6 Discussion and Future Directions

As shown in Table 2 to Table 4, we summarized the major future directions and opportunities mentioned in the above-reviewed papers.

In the sub-phase of earth and foundation work, the current research is at the stage of semi-autonomous and tele-remote operation while the future work is towards fully autonomous operation. Therefore, the real-time communication, the situation awareness of the operator, the characterization of the geometry, and autonomous operation algorithms appear to be major problems. In addition, the technologies of Artificial Intelligence (AI) and machine learning are prospective to be adopted to deal with the various machines and materials and improve the automation level.

The automation and robotics technology application in the sub-phase of superstructure erection is divided into three sub-themes. First, the automated construction system was a versatile construction system when firstly proposed, while it has converted to several light-weight and independent systems, and the previous concept has evolved into "construction factory", which develops at the aim of providing a more desirable working environment for both workers and robots. Second, the automated lifting system should be combined with a ground-delivery system and a smart central control system to optimise the communication and operation planning. The radio-based technologies such as RFID are helpful in the lifting management. Finally, the robot-based steel assembly system is developing in the direction of teleoperation and autonomous operation, and the method of precise alignment of the wire-suspended swinging objects remains to be improved.

Table 2. Summary of the future directions (Sub-phase of earth and foundation work)

Future directions	Reference
Implementation of unmanned construction equipment and aircraft	[6-8]
Adoption of vision-based technology for monitoring	[7, 8]
Improvement of the situation awareness and reaction of the operator	[7]
Improvement of the real-time communication for remote operations and among the machines	[7, 8]
Adoption of AI and machine learning technology to support variations in machine and material	[7, 8]
Improvement of automatic pile shape and geometry classification with the technology of Simultaneous Localization and Mapping (SLAM)	[7, 8]
Development of autonomous loading algorithms and the method of fragmented rock loading	[7, 8]

Table 3. Summary of the future directions (Sub-phase of superstructure erection)

Future directions	Reference
1. Sub-theme: Automated construction system	
Simplification of the construction and dismantling of the temporary structure	[10, 11]
Improvement of the delivery efficiency	[10, 11]
Extension of the functions to be applicable for special-shaped building construction beside rectangular ones	[12]
Development of a light-weight system	[13]
Improvement of the simulation method	[13]
2. Sub-theme: Automated lifting system	
Implementation of RFID and USN technologies to improve the management	[17]
Optimization of the communication among the lifts, workers and the control system	[19, 20]
Improvement of the operation planning to adapt to various condition changes and lift unit changes	[22]
3. Sub-theme: Robot-based steel assembly system	
Extension of the functions to be applicable for special-shaped building construction beside rectangular ones	[24]
Development of complete robotic automation steel assembly system	[26]
Estimation and minimization of the shock of wire-suspended objects and development of robots that can absorb tremendous shock from heavy swinging objects	[30]
Improvement of the actuator for the alignment end-effector	[32]
Development of intuitionally joystick to improve operational performance	[34]
Adoption of AR and haptic technology to improve the working environment	[34]

The research on the sub-phase of automated façade installation is also on the way to teleoperation and autonomous operation to avoid human operators working in high places. Besides the remote operation techniques for human-robot cooperative manipulation, the development of algorithms and control strategies, and the implementation of related sensors will also improve the motion precision and installation performance. In addition, the façade installation robot can be adapted to other tasks involving lifting and carrying.

Although various technologies have been adopted in the application of automation and robotics technology in each construction sub-phase to deal with different problems, there are some basic equipment and operations.

Table 4. Summary of the future directions (Sub-phase of façade installation)

Future directions	Reference
Improvement of human-robot cooperative manipulation	[36]
Teleoperation based on force feedback	[36]
Development of software for integration of the handler into semi-automated façade assembly system	[37]
Implementation of inclinometers and ultrasonic sensors for automated leveling and distance measurement	[37]
Development for more application in other tasks involving lifting and carrying	[37]
Development of a mobile platform to replace the excavator for macro motion	[38]
Development of the control strategy and algorithms for human-robot cooperation	[36, 41]

Moreover, the steps of the automation process are also similar. For example, the five steps towards the autonomous operation of earthmoving machines [12], i.e., manual, in-sight teleoperation, tele-remote operation, assisted tele-remote operation, and fully autonomous, are also suitable in the development process of automation and robotics technology in other construction sub-phases. Therefore, the specific-task robots and automated systems are expected to learn from each other and may develop to handle more versatile tasks.

7 Conclusions

This paper summarized the application of automation and robotics technology in high-rise building construction from 50 papers published from 2000 to 2017 to provide a systematic review of the recent research and developments in this field from the perspective of three major construction sub-phases: earth and foundation work, superstructure erection, and façade installation. The paper also discussed future directions in each sub-phase in construction based on the literature.

This paper is expected to contribute to the knowledge body in that provides a valuable aid in future research and application of automation and robotics technology for high-rise buildings.

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