Analysis on the Implementation Mechanism of an Inspection Robot for Glass Curtain Walls in High-rise Buildings

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Abstract –

With a growing number of high-rise buildings, glass curtain walls are widely used. In the long-term service of such curtain walls, the safety problems arise, such as cracks and spontaneous breakages of glass. Therefore, they need regular inspections to prevent accidents. Current inspection work for glass curtain walls in high-rise buildings mostly depends on manpower and conventional tools such as ropes and gondolas, which exhibit poor performance and safety risks for the workers to operate in the high-elevation working environment. Thus, there is an urgent need for inspection robots to improve efficiency and reduce safety risks. As a preceding work for the development of an inspection robot for glass curtain walls, this paper investigates the existing publications of the robots for the façade works and analyzes the implementation mechanism of an inspection robot for glass curtain walls.

Keywords –

Inspection robot; High-rise building; Glass curtain wall; Work mechanism

1 Introduction

In recent years, the number of the world's high-rise buildings is growing rapidly. Glass curtain walls are widely used in high-rise buildings because they can enhance the appearance of the buildings by creating a beautiful façade, as well as allow the filtration of natural light into the building. For example, in 2018, the annual output of tempered glass in China was about 470 million square meters and more than 40% are used in glass curtain walls [1]. However, the wide usage of glass curtain walls also brings safety risks. The glass curtain wall system has the potential of failure, which may lead to falling of glass fragments. Since most high-rise buildings with glass curtain walls are located in downtown areas with large people and traffic flow, the accidents of glass falling would be devastating. Therefore, the glass curtain wall inspection of high-rise buildings is necessary.

The conventional method of glass curtain wall inspection in high-rise buildings mainly depends on manpower with ropes, gondolas and winch systems. However, it is costly and inefficient with safety risks for workers in high-elevations.

In a broader range, the interest in wall inspection of high-rise buildings is increasing in recent years and there have been studied exploring automatic methods to replace human workers to conduct the inspection work, such as developing inspection robots. These studies can be divided into two categories:

(1) Unmanned Aerial Vehicles (UAV) with visioning methods to detect visible cracks. For example, Liu et al. [2, 3] developed a bat-like inspection robot with abilities of flying and adhesion to save power and prolong the time of endurance. Bulgakov et al. [4] proposed control algorithms to stabilize the UAV for high quality captured images. However, photography by UAVs is not allowed in many cities around the world, which limits the applications of the research results based on UAVs.

(2) Wall climbing robots with visioning methods for wall inspection. For example, Muthukumaran and Ramachandraiah [5] developed a pneumatics based wall-climbing robot for façade inspection. The robots in this category have both technical feasibility and the potential of applications. However, there is only a small number of studies in this category and many of them deal with the bonding situation of the wall tiles rather than the quality of glass curtain walls. Besides, many studies only focused on the development of mechanical parts, without an in-depth analysis of the inspection method and the user demands.

Therefore, this paper aims to focus on the inspection robots based on wall climbing platforms and systematically analyze and summarize their implementation mechanisms for glass curtain wall inspection in high-rise buildings. The remainder of the paper is organized as follows. Section 2 introduces the method of this study. Section 3 proposes the requirements of an inspection robot for glass curtain walls based on an analysis of the glass curtain wall failure. Based on the requirements, Section 4 analyzes the implementation mechanisms according to the existing literature and discusses their features for the implementation of an inspection robot for glass curtain walls. Finally, the paper is concluded in Section 5.

2 Method

In this study, a literature review was conducted firstly in two aspects: (1) the essential information of the working environment of inspection robots and the knowledge of safety inspection of glass curtain walls. (2) the development of related robotic systems in both academic research and existing products in the market.

As the number of studies on wall climbing-based inspection robots is small, the literature retrieval in the second step was not limited to inspection robots but also expanded to other robots for façade works. First, since this study focuses on wall climbing-based inspection robots, the literature related to wall climbing robots also needs to be reviewed. Second, since wall-climbing robots can also be used for other façade maintenance works in high-rise buildings, particularly for façade cleaning and in most cases, the key technologies of a façade inspection (or cleaning) robot include climbing mechanisms and inspection mechanisms (or cleaning mechanisms) [6], hence the experience of façade cleaning robots can be a reference for inspection robots, so the literature of façade cleaning robots is also reviewed.

The literature retrieval was conducted in both Scopus and CNKI (China National Knowledge Infrastructure). The two databases were selected because Scopus covered a large range of literature in the field of construction robotics [6] and CNKI is the largest database of Chinese literature. The search keywords included “high-rise”, “robot*”, “curtain wall”, “façade”, “safety”, “inspection”, “climbing”, “maintenance”, and “cleaning” (in both English and Chinese). The asterisk (*) is a wildcard character that denotes a fuzzy search. Then a preliminary screening process was conducted successively to exclude the papers from irrelevant areas (e.g., biology, medicine, agriculture, etc.). By reading the titles, we successively filtered out unrelated papers and finally obtained 91 papers, including 71 ones about robot development and 20 ones about glass curtain wall inspection. Then we read the abstracts of each paper and selected the most related and important content for further reading.

Besides, we also referred to some Chinese national standards and industry standards for basic concepts of the glass curtain wall such as Terminology for Curtain Wall (GB/T 34327-2017), Standard for Testing of Engineering Quality of Glass Curtain Walls (JGJ/T 139-2001), and Test Method for the Defects of Glass – Photoelastic Scanning Method (GB/T 30020-2013).

The investigation of existing products in the market was also conducted by searching on the Internet with search engines including Google and Baidu. As a result, 15 products were found, which are all façade cleaning robots.

Both the analysis on the requirements and that on implementation mechanism are very much crucial for developing an inspection robot for glass curtain walls. Thus, the former is conducted based on the results of (1) because it needs our knowledge on both the related robotics and the inspection of the glass curtain wall. The latter is conducted based on the result of the former with the help of the results of (2) because it is a feasible way to build the implementation mechanism instead of building it from scratch.

Due to space limitation, this paper focuses on the following two points, i.e., requirement analysis of the inspection robot for glass curtain walls and analysis on its implementation mechanisms.

3 Requirement analysis of the inspection robot

3.1 Working environment of the inspection robot

The working environment of the inspection robot depends on the surface conditions of the glass curtain walls. A glass curtain wall system of a high-rise building consists of glass panels and a supporting system. The supporting systems are usually metal frames, such as aluminum frames and steel frames. According to the exposure of the supporting frames, the glass curtain wall systems can be categorized as exposed framing glass curtain wall, hidden framing glass curtain wall, and semi-exposed framing glass curtain wall, i.e., the horizontal/vertical frames are exposed and the frame in the other directions are hidden [7]. Besides, there are also other types of supporting systems, such as glass rib supporting curtain walls and point-supported glass curtain walls [7]. However, these supporting systems have no ledges at the external side of the curtain walls. For the climbing robots working on the façades of the buildings, the exposed frames are larger obstacles and the seams between glass panels are smaller ones, which need to be considered in the design of the climbing mechanisms.

In some cases, the façades of the buildings are not flat but curved. However, the glass panels are still flat but the panels are connected with small angles [8]. Therefore, in these cases, the climbing mechanism should be specially designed for the robot to cross from one panel to another.

3.2 Failure of glass curtain walls

The failure of the glass curtain walls on the high-rise buildings can be divided into two categories [9]: (1) Failure I is the partial failure of the aging components, including the spontaneous breakage of the glass under temperature stress or installation stress, the bonding failure because of the aging of the seals, the corrosion of metal fittings, etc. The most common one is the spontaneous breakage of the glass under temperature stress or installation stress. The characteristics of this failure type are as follows: the failure points cannot be easily found; the failure has a high probability to lead to accidents; the accidents caused by this type of failure will lead to serious damages and casualties without warning to people on the ground. (2) Failure II is the failure of the entire structure after large impacts from external forces such as typhoons, earthquakes, and fires. In these cases, one or more materials of the curtain wall reach their bearing capacity. This type of failure is caused by force majeure in a short time with great damage and low probability.

The prevention of accidents caused by Failure II depends on structural reliability, which is decided by design, construction and usage according to the standards. However, the prevention of accidents caused by Failure I depends on management and maintenance. In fact, most accidents of glass curtain walls were caused by Failure I. Therefore, this paper focuses on the inspect tasks on the detection of Failure I.

The spontaneous breakage of the glass (Failure I) can be explained as follows [1, 10]. Tempered glass for curtain walls has many internal defects, which are formed in production, processing, installation, and application. These defects will lead to stress concentrations. When these stress concentrations are combined with other environmental loads such as wind loads, vibration loads, and temperature loads, the local strength of the glass might exceed the capacity and the glass might break spontaneously. Although it is difficult to detect the defects, the stress concentrations can be detected with a specific instrument.

Some studies mentioned about using the visioning technology in inspection robots to detect visible cracks on the building façade [5, 11]. However, these studies are aimed at the cracks on other materials rather than glass panels. Actually, for the tempered glass, the spontaneous breakage happens before visible cracks are formed.

Therefore, the inspection robot needs the ability to detect the stress concentration of the glass panels.

3.3 Requirement analysis

Based on the above analysis and the usage scenarios of the inspection robot for glass curtain walls, the basic requirements include the following five points. Moreover, requirements 1-4 are for wall climbing and requirements 5-6 are for inspection.

1. Safe and reliable climbing mechanisms on the surface of the glass curtain wall. The climbing robot should attach to the glass panels safely with reliable protection methods. It should have the ability to move horizontally and vertically on the glass so that it can cover all the working areas.
2. Identification of the surrounding environment and obstacles. Multiple sensors and an intelligent control system are needed to identify the situation of the environment, especially the obstacles. Most obstacles are predictable ones such as the frames of the curtain wall, the information of which needs to be input preliminarily into the control system. Meanwhile, the control system also needs to consider the unpredictable obstacles that the robot might meet and the corresponding identification algorithms.
3. The ability to cross or avoid obstacles. After the detection of obstacles, the robots should have the corresponding methods to cross them safely and quickly. If there is an unpredictable obstacle that cannot be crossed, the robot should avoid it and record the situation and corresponding position.
4. Motion control. To realize the movement and cross the obstacles, motion control needs to be precise and instant to ensure safety. Besides, the sensors need to detect deviations and the control system needs to correct the motion direction.
5. Efficient inspection methods. Sensors are needed to identify the internal stress concentration of the glass panels.
6. The ability to record and export the inspection results. After the inspection on each panel of the curtain wall, the robot should record the results, especially the problems and the corresponding positions. When the inspection work is finished, the results need to be export to a computer.

4 Analysis on the implementation mechanisms of the inspection robot

The inspection robot should contain two parts, i.e., the climbing part and the inspection part. The most critical issue for developing it is to design the mechanism for each part.

4.1 Climbing mechanism

After reading the abstracts and important content of the 71 papers about robots of wall climbing, cleaning, and inspection in high-rise buildings, as well as the introduction materials of the 15 products of façade cleaning robots, we found the climbing mechanisms of façade cleaning robots are most valuable references to this study. The reasons are as follows: (1) as mentioned in Section 1, the number of papers on glass curtain wall inspection robots is small and many of them are based on UAVs or deal with wall tiles rather than glass panels; (2) although the research on wall-climbing robots proposed various mechanisms such as legged robots, biomimetic robots, and robots with dry adhesive materials on the footpads, they are still at the stage of laboratory prototype with low practicability.

Based on an analysis of the related robots for façade works, they can be divided into two categories, i.e., robots with and without built-in guide rails, which have different climbing mechanisms.

For robots with built-in guide rails, the climbing mechanism is based on the guide rails. For example, Lee et al. [12] proposed a robotic system for façade cleaning (Figure 1), which consists of a horizontal-moving robot (HMR) performing cleaning, a vertical-moving robot (VMR) for transporting the HMR to each floor, and a winch module to move the VMR to the target floor. Both the HMR and VMR are connected with the rails and move on the building façade by gliding along the rails. A communication network is built for information transmission among the robots and the monitors. The power source of the system is DC batteries installed on the robots.

For robots without built-in guide rails, the core mechanism of climbing mainly includes the techniques of adhesion to the wall and that of locomotion.

There are two most commonly used adhesion techniques that have the maturity to be implemented in on-site prototypes. One is using suction cups. As shown in Figure 2, the suction cups can not only provide adhesion but are also “feet” of the robot, which can be organized into several groups. The groups of suction cups can adhere to the glass and release alternatively and the released ones can retract and move on to the next position so that the robot can realize locomotion and cross the obstacles. Another method is using vacuum fans to extract the air to create a vacuum between the robot and the wall surface for adhesion, as shown in Figure 3.

Various types of locomotion were designed for climbing robots and the common ones implemented in on-site prototypes include footed/legged, wheeled, and cable-driven. The footed/legged robots usually use suction cups for adhesion as mentioned above. The wheeled and cable-driven ones can work with suction cups or vacuum fans for adhesion, as shown in Figure 3-5. For cable-driven robots, the cables can provide different functions. For example, in Figure 4, the robot can move in all directions based on the cables. In Figure 5, the robotic system consists of a robot and a rooftop gantry, which are connected with cables. In this system, the cables are only responsible for the vertical movement and the horizontal movement is realized by the rooftop gantry moving along the pre-installed tracks. The cables can also transfer data and provide power.

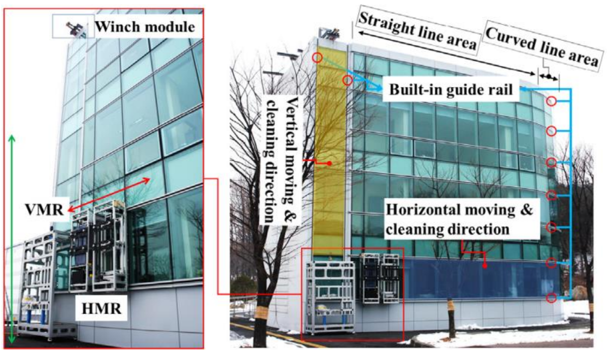

Figure 1. A robotic system with built-in guide rails [12]

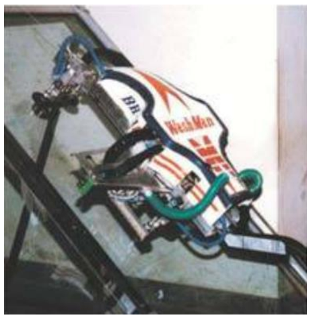

Figure 2. A robot with suction cups [13]

Figure 3. A wheeled robot with a vacuum fan [14]

Table 1 summarizes the climbing mechanisms mentioned above and compares their advantages and disadvantages. The guide rail-based robot has high efficiency because it can cover a large area and the motion path is very clear. It also has high safety and robustness because the connection between the robot and the guide rail is reliable. However, it is not versatile because it is based on the built-in guide rail of the building and its dimensions depend on the design of the building. The footed/legged robot with suction cups is flexible to cross obstacles by releasing and retracting the feet/legs alternatively. However, it needs a more complicated design of the gait and corresponding algorithms for movement. Wheeled and cable-driven robots with suction cups or vacuum fans are both easy to control and agile in movement but incapable of crossing large obstacles. The cable-driven robot has higher safety because the cables can protect the robot from falling once the adhesion fails. However, its versatility is limited by auxiliary tools such as pre-installed pulleys and rooftop gantry. Besides, it is difficult to deal with curved façades.

Figure 4. A cable-driven robot [15]

Figure 5. A robot with a rooftop gantry [16]

Table 1. Comparison of the basic climbing mechanisms

Climbing mechanism	Advantages	Disadvantages
Guide-rail based	High efficiency High safety and robustness	Limited versatility
Footed/legged with suction cups	Flexible to cross obstacles	Complicated design of gaits and moving algorithms
Wheeled with suction cups or vacuum fans	Easy to control Agile in movement	Hard to cross large obstacles
Cable-driven with suction cups or vacuum fans	Easy to control Agile in movement High safety	Hard to cross large obstacles Limited versatility

4.2 Inspection mechanism

According to the analysis in Section 3.2, the critical part of glass curtain wall inspection is the detection of stress concentrations.

The instrument to detect stress concentrations already exists and is named photoelastic scanner, as shown in Figure 6 [17]. In manual inspection, the photoelastic scanner is handheld and placed close to the surface of the glass. Then the photoelastic image of the glass will be transmitted to a computer through a wireless communication network. When a photoelastic scanner is placed close to the surface of the glass, it can take images based on the reflection of polarized light on the glass surface. Since the glass is a photoelastic material, which is isotropic in general but anisotropic at the positions of stress concentrations, the stress concentrations in the glass will result in spots in the image, which can be easily observed by people or identified by image processing [18]. Thus the photoelastic scanner can be implemented in inspection robots for glass curtain walls. A robotic device with a sensor for distance detection should be designed on the robot to move the photoelastic scanner and place it close to the glass surface for inspection.

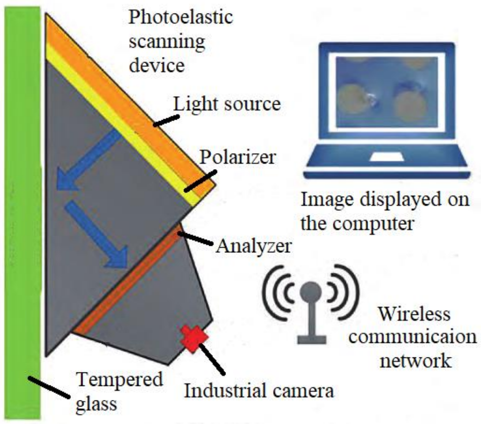

Figure 6. A photoelastic scanner for tempered glass inspection [17]

5 Conclusion

With a growing number of high-rise buildings, the glass curtain wall is widely used and its safety problem is concerned. To improve the safety and efficiency of glass curtain wall inspection, inspection robots are needed. As a preceding work of the robot development, this paper investigates the existing publications of the robots for the façade works. Based on the essential information above, six requirements of the inspection robot were proposed, in which four requirements are for wall climbing and the other two are for inspection. Then based on a literature review, the climbing mechanisms of a glass curtain wall inspection robot were summarized and compared. The inspection mechanism based on a photoelastic scanner and its potential to be implemented in the inspection robot were analyzed.

The results of this paper can be a valuable reference for further development of glass curtain wall inspection robots, as well as other robots for façade maintenance.

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