The Technological Development Analysis of Window-Cleaning Robots

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Abstract. With the acceleration of urbanization, the quantity of tall buildings is increasing. The problem of cleaning is becoming more serious than before, so some traditional methods are less likely to be useful. As a result, window cleaning has become an essential section of the maintenance of homes and commercial buildings. This paper will talk about the specific working principle, typical usage scenarios and analysis of improvements, analysis of typical cases and pros and cons. Through reading a lot of researches and magazines including Science and China Daily, the technology of window-cleaning robots is generally developing as the time goes. Due to this inclination, window-cleaning robots improve cleaning efficiency and quality which significantly solves the cleaning matter. At the same time, the tendency promotes the development of the smart home industry. In the future, with the development of Internet of Things technology, window-cleaning robots are expected to connect with other smart home devices to achieve more efficient home automation management.

Keywords: Cleaning problems, Developing technology, Home industry

1 Introduction

Traditional cleaning methods such as using a towel or splitting clean water, are not only inefficient but also dangerous. If a person needs to clean curved windows or shutters, the final cleaning effect is difficult to guarantee. However, in recent years, a kind of innovation named window-cleaning robots have gradually become popular, but what is little known is that it has developed for a quite long period. The cleaning efficiency of early versions of window-cleaning robots was far inferior to that of the current ones because they all included many limitations. For instance, unreasonable path planning led to missed part of cleaning and unstable adsorption force made them easy to fall off. Anyway, Because of the technical development, its structure, size, making material and so on are changed in order to achieve higher standards. Due to the desire for more sale quantity and profit, each of them spends much property on expediting window-cleaning robots to improve their quality. The applications of window-cleaning robots in two main domains of domestic use and high-rise building environments are presented and the corresponding technical requirements are summarized [1]. More and more redundant find that the working efficiency of them exceeds these of traditional solutions, so the demand of them booms to make them popular.

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So why we spend so much property researching it? It's not only for improving the cleaning efficiency, but also for improving living level and promoting the update of relevant industries. With the continuous development of technologies such as AI, smart homes have become a development trend of future life. As an important part of smart homes, the emergence of window-cleaning robots has further enriched the product lines of smart homes. By connecting to other smart devices, window-clean robots can realize functions such as remote control and scheduled cleaning. Users can control the robot's work anytime and anywhere through a mobile app. At the same time, users can set up scheduled cleaning tasks according to their habits, allowing the robot to finish cleaning automatically at the specified time. As a result, the window-cleaning robot noy only makes life more convenient, but also brings people a high level of living.

Apart from domestic homes, there is tremendous potential to implement autonomous cleaning robots to places such as schools, auditorium, shopping malls, etc [2]. Moreover, researching window-cleaning robots can promote the update of relevant industries. The researching, production and sales of window-cleaning robots involve robot technology, sensor technology, AI and material science. The rising of these fields promotes technological innovation and drives the growth of related industries. In manufacturing, producing window-cleaning robots requires a lot of parts and raw materials. This brings new market opportunities to parts suppliers and raw materials producers. In the service industry, professional people and organizations are needed for after- sales services and maintenance of window-cleaning robots, which gives a boost to the development of related service industries.

The paper will then carefully talk about four main aspects, which are separately principle and structural design, typical usage scenarios and analysis of improvements, analysis of typical cases and pros and cons. In the part of principle and structural design, the paper will talk about the general working principle including the whole body, cleaning system, adsorption system and intelligent control system. In the section of typical usage scenarios and analysis of improvements, the paper will analyse its cleaning effect in our families, business places and special scenarios. Although there is a development of window-cleaning robot technology, some apparent problems including insufficient adsorption stability and environmental adaptability appear and need to be solved. In the aspect of analysis of typical cases, combined to the cases of Jiashida Circular Window-Cleaning Robot, Ecovos Winbot W2S and personal experience, the real cleaning efficiency of window-cleaning robots can be demonstrated. About its pros and cons, the paper list two of them separately, in order to evaluate window- cleaning robots objectively.

2 Principle and structural design

2.1 General explanation of the working principle

Basically, these robots use advanced robot technology and AI to clean windows all by themselves. They're made to run on their own with using all kinds of built-in sensors. They have the ability to figure out the window's size, shape, and even how dirty it is.

Once they've got that, a computer system processes it and figures out the best path to clean efficiently.

To stay steady when moving up and down glass, these robots usually have two spinning rollers or rubber wheels that give enough friction and balance. Some models also have suction to stick better, especially when cleaning tall windows or ones with multiple panes. That way, they can move safely on all sorts of glass without slipping or falling.

When they're cleaning, the robot sprays the right amount of cleaning solution on the glass. Then, it uses soft rubber brushes, microfiber cloths, or both to wipe off dirt and smudges. Some models have spinning brushes or wiggling wipers to clean better and make sure there are no streaks. The fancier ones even have water tanks and drying systems, so they can finish the whole cleaning job without anyone having to step in.

Window cleaning robots are really handy for both homes and businesses. They're safer, easier, and save time compared to cleaning windows by hand. They're useful for hard-to-reach windows and tall buildings, where old-fashioned cleaning methods can be dangerous or take a lot of work. And as AI and robot tech keeps getting better, these devices are getting smarter, which can adapt to different places and keep cleaning well every time.

2.2 Body of the whole

Window-cleaning robots are mainly composed of a main control unit, a driving device, an adsorption device, detection sensors, a cleaning device, and other components.

Firstly, this paper will introduce the main control unit. It is the command center of the entire system, usually using a single-chip microcomputer as the core processor. It is responsible for receiving and processing sensor signals, controlling motor actions, and realizing functions such as the robot's movement.

Secondly, it is about the driving device. Generally composed of DC gear motors, it drives the robot to move on the glass surface through crawler belts. The design of the crawler belts or wheels ensures that the robot has good grip and stability on the glass surface.

The third one is detection sensor group. It includes micro switches, edge-sensing probes, etc. When the robot touches the window frame or other obstacles, the sensors will send signals to the main control unit, making the robot stop in time or change the direction of movement to prevent damage to equipment or accidents.

The fourth one is cleaning device. It usually includes a rotatable cleaning brush or a wiping cloth. Some window-cleaning robots are also equipped with a silicone scraper, which can scrape off water stains after cleaning. In addition, some robots are equipped with a water tank and a water spray device, which can spray water to moisten the glass during cleaning to improve the cleaning effect.

The last one is safety components. To prevent the robot from falling under abnormal circumstances, it is generally equipped with a safety buckle and a safety rope. Users can fix the safety rope in a firm position indoors when using it to ensure that the robot will not fall even if the adsorption fails. Structure of window-cleaning robot is shown in Fig.1.

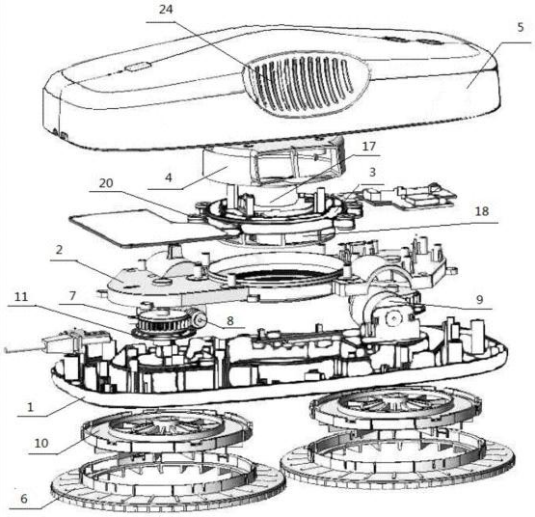

Fig. 1. Structure of window-cleaning robot [3]

Cleaning system. This part is what actually gets the window clean. It usually has a brush that spins around a cloth, it works to scrub off dirt and grime from the glass. A lot of window-cleaning robots also come with a soft silicone scraper. Once the brush or cloth has done its job, this scraper runs over the glass to wipe away any leftover water spots, so the window dries without streaks. What's more, some models have a small water tank and a little sprayer. When they're cleaning, they can squirt out a bit of water to dampen the glass first. This makes it easier for the brush or cloth to lift off tough dirt, so the window ends up looking even cleaner.

Adsorption system. The adsorption system of a window-cleaning robot is the key part that ensures it can stay steadily on the glass surface to work. It mainly achieves adsorption by creating a pressure difference. Here are two main methods which used in the absorption system.

Firstly, this paper will demonstrate the negative pressure suction cup adsorption. This is a widely used method. The system includes a small vacuum pump and several negative pressure suction cups. When the vacuum pump works, it pumps out the air between the suction cups and the glass, creating a partial vacuum. Using the pressure of the outside atmospheric pressure on the suction cups, the robot is firmly attached to the glass. The suction cups are usually made of wear-resistant and anti-aging rubber, which can better adapt to small unevenness on the glass surface, enhance sealing and ensure stable adsorption.

Another way is fan-type adsorption. Some robots use high-speed fans as the power for adsorption. When the fan runs, it quickly expels the air between the robot and the glass, making the internal pressure lower than the external pressure, thus creating a pressure difference and generating adsorption force. This method has a faster response

speed and has relatively lower requirements on the flatness of the glass surface. Even if the glass has slight bulges or scratches, it can still maintain a certain adsorption effect.

Intelligent control system. The smart control system of a window-cleaning robot is the core that enables it to clean on its own, plan paths, and work safely. It mainly combines hardware and software to perform functions like sensing the environment, making decisions, carrying out actions, and interacting with users.

The core control module is the main body of the system. It usually centers on a microprocessor, acting like the robot's "brain". It receives various signals, processes data, and sends instructions to modules like the driving and cleaning ones, making sure all parts work in order.

3 Typical usage scenarios and analysis of improvements

3.1 Typical usage scenarios

Nowadays, window-cleaning robots are used in all kinds of aspects in our daily lives, which help us clean the windows efficiently.

The first kind of scenarios is our families. It is suitable for cleaning windows in living rooms, bedrooms, balconies and other rooms, whether they are floor-to-ceiling windows or ordinary small windows. In addition, it can also be used to clean smooth surfaces such as wardrobes and large vanity mirrors, making household cleaning easier and saving user's time. Residents do not need to bear the risk of high-altitude operations. Some robots equipped with dual-turbine vacuum pumps can achieve a suction force of 80 Newtons, enabling them to stably adhere to high-rise glass [4].

The next one is about business places. It can be used to clean office building glass curtain walls, shopping mall display windows, hotel and restaurant windows, etc. It efficiently handles large-area glass cleaning tasks, improves the cleanliness and image of commercial places, and reduces the cost of manual cleaning at the same time. The AP3-P3 flexible tethered cleaning system developed by Wanshun Technology adopts Pliabot® flexible joint. It leaves no water marks after cleaning and has been used in commercial complexes of enterprises like China Resources and Vanke [5].

The last one I would talk about is some special scenarios. For example, the windows of vehicles like planes, trains and ships, as well as windows in special environments such as space stations. Window-cleaning robots can automatically adjust their cleaning paths and speeds according to different situations, completing cleaning tasks that are hard for humans to do. Jiashida robots, through dual-disk twisting cleaning technology, can clean both glass and window frames simultaneously. They have been applied in scenarios such as hospitals and schools. Equipped with over 250 sensors, they support real-time monitoring of disinfection needs [6].

3.2 Analysis of improvements

Anyway, there are also some disadvantages existing in window-cleaning robots, which are needed to adjust or improve.

The first problem is insufficient adsorption stability and environmental adaptability. some robots have poor compatibility with glass of varying thicknesses and frame materials like steels, which easily leads to side slipping. The Het C7 uses an imported Japanese DC brushless fan, providing a strong suction with a peak of 5500 Pascals [7]. It makes the machine generate stronger friction with the window surface during the climbing process, ensuring that even when navigating vertical glass panes, tilted surfaces, or transitions between different window sections. The robot maintains a secure and stable grip. This enhanced friction not only prevents unexpected shifts but also allows the robot to tackle steeper angles with confidence, which ensure consistent contact with the window throughout the entire cleaning cycle. As a result, the machine can operate more efficiently, cover the glass surface thoroughly without interruptions, and deliver a more reliable cleaning performance even in challenging climbing scenarios.

Also, the problem of treatment of stubborn stains is serious and needed to be solved. In scenarios involving complex window frames, the SLAM algorithm is prone to path repetition or omission, resulting in a coverage rate of only 85%. For stubborn stains like bird droppings and cement residues, the cleaning efficiency relying solely on mechanical friction is less than 50% [8]. Luckily, some improvements play a vital role on eliminating the matter. The Dreame C1 series is equipped with CornerClean™ cleaning technology [9]. This paper think it fixes the issue where those tricky corners and edges of windows are hard to get clean. With its adaptive rebound structure and corner brushes, the robot can reach into those tight spots that are usually missed, making sure even the corners and edges get properly cleaned instead of being left dirty.

The last problem of shortcomings in battery life and energy efficiency. Commercial robots rely on cable power supply, which limits their operating range. Their models generally have a battery capacity of less than 2000mAh, with a single charge only able to clean an area of 30 square meters [10]. Some big brands have improved this aspect to raise the quality of products. The Dreame C1 series builds a comprehensive safety protection system. Its maximum suction can reach 5500Pa, and combined with air leakage detection and pressure compensation technology [11]. As a result, it stays really securely stuck to the window. No matter if there's a little air leak or the surface isn't perfectly smooth, that tech kicks in to keep it from slipping or falling off. It just clings on tight the whole time it's working.

3.3 Analysis of typical cases

The first case is about Jiashida Circular Window-Cleaning Robot. It applies the principle of intelligence, enabling the robot to automatically adjust according to working conditions. To be specific, it will increase suction when slipping, and can perform targeted cleaning or increase cleaning frequency when encountering stubborn stains. At the same time, it has increased the adsorption force to 55 Newtons while reducing noise to 65 decibels, solving the industry-wide problem that greater suction leads to louder noise [12]. Due to the high efficiency of cleaning, it owns positive market performance. In 2024, the company sold 300,000 window-cleaning robots, and its products have been exported to 56 countries and regions including Germany, South Korea, Japan, and Russia.

The next case is about my experience of using a window-cleaning robot. I live on the 5th floor in a corner unit. My place has lots of windows, and they're pretty big. When it was time for the big spring cleaning, I tried to book several house cleaners, but none could come for various reasons. If l can clean the windows by myself, it didn't turn out well, and it was such a time-consuming hassle. Then, I saw someone post an ad on their WeChat Moments for renting window-cleaning robots—100 yuan a day, so I decided to rent one. After using the window-cleaning robot, I found it super easy to operate. The cleaning result was great, and it saved me a ton of time and energy. I thought this rental thing was both cost-effective and convenient.

The last case is about Ecovos Winbot W2S. The Ecovos Winbot W2S All-in-One Base Station model comes with a smart gap-rotating edge brush. It spots window corners and edges, then drops down to clean them thoroughly at a powerful 200 rotations per minute, tackling grime in those tricky spots. It also has a brand-new upgraded dual-direction, three-nozzle mist spray system [13]. This sprays ultra-fine mist to dissolve dirt ahead of time, so after cleaning, there's not a single water streak left. What's more, the robot packs a strong 8000Pa suction. It's got a design for the power cord and safety rope, plus a 5.2kg weight and 1000N downward suction [14]. And with multiple cleaning modes, it can handle all sorts of needs.

4 Pros and pons of window-cleaning robots

4.1 Pros

The first main advantage is high safety. For high-rise residents, manual window cleaning carries the risk of falling from heights. However, window-cleaning robots are firmly fixed on the glass surface by strong adsorption force. Some products are also equipped with safety ropes, emergency power supply for power outages, and other designs, which greatly reduce the possibility of accidents [15].

Another benefit is saving labor. There will be no need for people to climb up or scrub hard. Users just need to do some simple setup, like choosing a cleaning mode and the robot can work on its own [16]. It's especially good for citizens who don't have much strength, or for homes and places with lots of windows or big glass areas. This connectivity allows users to schedule cleaning sessions, monitor cleaning progress, and enhancing convenience and automation [17].

4.2 Cons

First of all, it has an apparent disadvantage of depending on the glass condition. It needs smooth, flat glass to work [18]. If the glass is cracked, or there are sticking-out frames, it might mess up the robot's movement and cleaning. So that maybe it won't even work at all.

Also, the noise problem is a kind of drawbacks. When it's working, the robot's motor and suction parts make some noise, usually around 50 to 70 decibels [19]. Most people can put up with that, but it might still bug folks who are sensitive to noise.

5 Conclusion

Humans are at this big turning point with robot tech, and one thing's clear. Robots aren't just gadgets anymore. They're teaming up with us to change where humanities headed. Whether it's on factory floors, in hospitals, deep under the ocean, or even on Mars, how they're getting better shows just how bad humans want to break through our limits.

But moving forward means people have got to be careful. Humans need rules that keep up with how independent robots are getting, making sure they help them out instead of taking over. When manufacturers design them, they need include all kinds of people's ideas. Otherwise, they might end up with robots that make unfairness even worse. And they've got to be good for the planet too, from using less energy to reusing parts. If not, they'll just end up draining our resources instead of helping protect them.

What comes next for robots isn't just about the wires and circuits. It's about the choices we make: caring more about understanding people than just getting things done fast. People should make sure everyone benefits instead of cutting corners, and working together instead of keeping ideas to themselves. As robots get smarter, humans need to get smarter too. Building a partnership where technology makes us more human, turning what if into what they make together. At the end of the day, the future of robots is really what the paper have expected.

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