Requirements of Glass Cleaning and development of Climbing Robot Systems*

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***Abstract* - Cleaning the outer walls of high-rise buildings is always dangerous and laborious work in mid-air. An alternative solution is to use walking-climbing robots which overcome the above-mentioned problems. Wall cleaning and maintenance of high-rise buildings is becoming one of the most appropriate fields for robotization due to its current low level of automation and lack of uniform building structure. In this paper, a family of sky cleaner robots for this difficult job which are totally actuated by pneumatic cylinders and sucked to the glass walls with vacuum suckers are presented. Firstly the basic functions for glass wall cleaning robot are summarized systemically. The individual robots' mechanical constructions and unique aspects are introduced in details. In the end a summary of the main special features of the three kinds of cleaning robots are given.**

Index Terms - glass wall cleaning robot; basic functions; mechanical constructions; unique aspects

I. INTRODUCTION

The last few years have witnessed a strong, renewed interest in climbing and walking robotic technologies. At the end of the 1990s several different prototype robots were developed for different types of applications in different areas [1] [2] [3]. In this paper the emphases for discussion is on the wall cleaning robot for high-rise buildings. There are a large number of high-rise buildings with curtain glass walls in modern cities. External cladding of buildings not only provides an attractive exterior appearance, but also increases their durability. These walls require constant cleaning which is presently typically carried out using a costly, permanent gondola system hanging from the roof of the building.

The benefits of developing glass wall cleaning robots include two aspects. Development and application of a kind of cleaning robotic system can free workers from this hazardous work and realize an automatic cleaning of high-rise buildings, furthermore improve the technological level and productivity of the service industry in the building maintenance. At the same time, the cleaning robotic system can be used on different buildings and save the expensive cost of investment for permanent gondola systems at the individual building.

II. CLIMBING ROBOTS IN LITERATURE

Recently various robots have been designed for wall cleaning and maintenance [4] [5]. Currently there are some different kinds of kinematics for motion on smooth vertical surfaces: multiple legs, sliding frame, wheeled and chain track vehicle. There are also four different principles of adhesion used by climbing robots: 1 vacuum suckers; 2 negative pressure; 3 propellers; 4 grasping grippers.

The robots with multiple-legs kinematics are too complex due to a lot of degrees of freedom. The kinds of robots which always use vacuum suckers and grasping grippers for attachment to the buildings do not meet the requirements of miniaturization and low complexity. Some climbing robots have been developed to move on complex wall surfaces. The famous robot ROMA [6] is a multifunctional self-supported climbing robot. It can travel into a complex metallic-based environment and self-support its locomotion system for 3D movements. Generally this kind of robots' construction and control is very complicated, and does not offer the high efficiency and simple operation required by a wall cleaning robot.

The robots with the wheeled and chain-track vehicle are usually portable. The adhesion used by this kind of robot is always negative pressure or propellers, so the robots can move continuously. One kind of robot has a pair of wheels actuated by electrical motors in its negative pressure chamber, so that it can move on the wall flexibly [7]. But it can only deal with plane walls without any obstacles. A new smart structure with two linked-track vehicles for a glass wall climbing robot was proposed in 2000 [8]. The robot's structure can be reconstructed so that it can move between the faces with a 0-90 degrees angle. Another climbing robot similar to the smart robot above in construction and actuation methods has also been developed in Japan [9]; however with a weight over 100 kg it is too heavy. Akira Nishi and Hiromori Miyagi developed a kind of wall-climbing robot using the propulsive force of propellers [10]. The robot is very light but the noise generated by propellers is too loud to use on glass walls. Even if the negative pressure chamber is not sensitive to a leakage of air, the negative pressure will not be enough for the safe

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and reliable attachment to the vertical surface when the robot crosses window frames.

A kind of pneumatic cleaning robot was developed for cleaning the embassy of Canada by a company in Japan [11], but it cannot walk sideways. Since 1996 the group at the Robotics Institute of BeiHang University has been developing a family of sky cleaner autonomous climbing robots with sliding frames for glass-wall cleaning.

III. BASIC FUNCTIONS PROVIDED BY CLEANING ROBOTS

A. *Study on the operation target*

It is essential to research the effects of working on glass walls since they are completely new operation targets for a climbing robot. The glass-curtain wall is a kind of external decoration structure made up of glass planks installed into metal components. There are four kinds of glass-curtain walls on high-rise buildings: exposed framing glass-curtain wall, semi-exposed framing glass-curtain wall, hidden framing glass- curtain wall and full glass-curtain wall.

Even in the case of glass walls with a kind of special curve, each piece of glass is also a plank with a regular shape. The regular shape of a single plank is suitable for cleaning. But there are always some window frames and seals between the glass planks which will become obstacles for cleaning. These boundaries of the planks destroy the consistency of the working areas and the robot will have to deal with all of them. From a global point of view, glass walls with a special curve shape are just because each glass is connected to the surrounding glasses at a small angle.

B. *Basic functions for the glass wall cleaning robot*

The basic functions of glass wall cleaning robots include 8 aspects.

1) Safe and reliable attachment to the glass surface: The climbing robot should be sucked to the glass wall safely and overcome its gravity. That is the first difference between a glass wall cleaning robot and an ordinary walking robot on the ground.

2) Movement spreading over all the working areas: The robots should have a function to move in both the up-down direction as well as the right-left direction to get to every point on the glass.

3) The ability of crossing window obstacles: In order to finish the cleaning work, the robots will have to face all obstacles and cross them safely and quickly.

4) Enough intelligence for the discrimination of a variety of obstacle situations: Multiple sensing and control systems are incorporated to handle uncertainties in the complex environment. Software should be dexterous enough to identify the various geometries of the wall and intelligent enough to autonomously reconstruct the environment.

5) Working autonomously with the corresponding effective treatment: Once the global task commands are entered by the user, the robot should keep itself attached to and move on the glass while accomplishing the cleaning tasks.

6) Motion control function: To meet the requirements of all kinds of movement functions, especially in crossing window obstacles, precise motion control is needed. The precise position control of the movement will begin immediately and automatically as soon as obstacles are detected on the surface.

7) Friendly Graphical User Interface (GUI): The controlling and monitoring of the robot is achieved through the GUI to allow an effective and user friendly operation of the robot. All information while working will be sent back and displayed on the GUI at the same time during the phase of the feedback. Some important information including the global environmental parameters and some important references for sensors will be passed to the controller on board.

8) Efficient cleaning: Efficient cleaning is the ultimate objective of cleaning robots. All functions above should serve this key point.

IV. OVERVIEW OF THE FAMILY OF SKY CLEANERS

A. *Advantages of the pneumatic system*

The family of the sky cleaner autonomous climbing robots for glass wall cleaning are totally actuated by pneumatic cylinders and attached to the glass wall with vacuum suckers. Pneumatic technology offers some advantages for application: low cost, cleanliness, and a readily available and cheap power source. The reasons for designing pneumatic cleaning robots lie in two points.

1. The climbing robot can be made lightweight and dexterous using the pneumatic actuators. The lightweight construction is one of the important specifications for devices working on high-rise buildings. Compared with a motor-driven linear-motion unit, a rodless cylinder with similar specifications is 2-3 times lighter (shown in TABLE I).

TABLE I
THE CONTRAST BETWEEN ELECTRICAL AND PNEUMATRC ACTUATORS

Items	Driven linear guidance units		
	Pneumatic		Electrical
	NORGREN	SMC	NEFF
Model	46140/400	MYC-400	WH50/400
F_{drive}(Kg)	75.0	75.0	67.0
M_X(NM)	39	19.6	16
M_Y(NM)	110	58.8	87
M_Z(NM)	110	19.6	50
Weight for linear unit(Kg)	4.9	8.9	6.16
Weight for actuator(Kg)[1]	<1.0	<1.0	6.0
Connectors (Kg)	0.5	0.5	0.5
Total weight G_{drive} (Kg)	6.4	10.4	12.66
power-to-weight ratio	11.72	7.21	5.29
Remark	1. Actuators for the pneumatic drive are valves and pipes; for the electrical drive those are motors and reducers.		

2. The movement driven by pneumatic actuators has the characteristic of passive compliance due to the compressibility of the air, thus makes the robot safer than being driven by motors under the situation of interacting with the brittle glass.

The sky cleaner robots can walk and do cleaning on the plane glass walls or some special curve glasses with a small angle. A hose for water, a trachea for pressured air, and cables for power and control signals are provided from the supporting vehicle on the ground. Even if the robots are very complex and intelligent, the suitable height for working is below 50 m because the weight of the hoses will be taken into account when robots working in the mid-air.

B. Sky cleaner 1

The group in BeiHang University designed the first kind of cleaning robot named sky cleaner 1 for cleaning the glass top of the Beijing West Railway Station in 1997 [12] (shown in Fig.3). The system consists of a robot also named washman at first, which is remotely operated and autonomously moves on glass walls to accomplish the cleaning work, and a support vehicle stationed on the ground providing electricity, air source and cleaning liquid for working. The lightweight robot can move on the surface of a slope up to 45 degrees in two perpendicular directions. Here the following unit for protection is no need because the robot is safe on the target surface while cleaning. The frame construction is adopted in the robot to satisfy the requirement of movement.

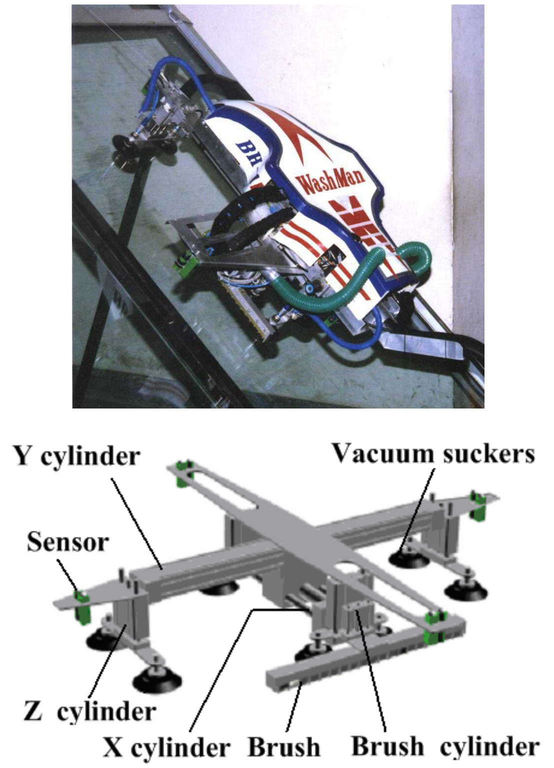

Fig. 1 An artistic impression and a real photograph of sky cleaner 1.

A real photograph of the robot and an artistic impression are shown in Fig.1. It can automatically detect obstacles and cross the glass panes. The main body consists two cross-connected rodless cylinders named X and Y cylinders. Connected at the ends of the X and Y cylinders are four short-stroke foot cylinders named Z cylinders, whose function is to lift or lower the vacuum suckers in the Z direction and support the body on the wall. Each group of vacuum suckers lay as the line distribution, so the robot needs precise position control when it moves on the surface in order not to touch any obstacles. Outside the Z cylinders there are also two brush cylinders connected to the ends of X cylinder, which lift and lower the brushes. The passive cleaning head (with brushes) is designed to be capable of supplying the detergent and collecting the drainage.

A PC is used as a console on the ground, and on-board controller includes PC104 and PLC. The PC104 computer is as the core controller and in charge of the global intelligent control such as planning, identifying the sensors inputs. PLC is the assistant controller that collects the internal switch sensor signals and actuates all the solenoid valves. The main specification features of the sky cleaner1 are shown in TABLE II.

Fig.2 shows the process of crossing an obstacle when robot moves from one glass to another in the right-left side. In this process the brush-sets are all in up-state and no touch with glasses.

(a) The robot is in home state, and the sensor detects the obstacle in the moving direction.

(b) The robot approaches the seals and begins the position control.

(c) The vacuum suckers connected to the Y cylinder are attached to the edge of one glass plank, the X cylinder moves from right to left.

(d) The vacuum suckers in the X direction are attached to the two glass planks, the Y cylinder is moving from right to left and the vacuum suckers connected to the Y cylinder will straddles the obstacle.

(e) The vacuum suckers connected to the Y cylinder are sucked to the two glass planks, the X cylinder is moving from right to left.

(f) The robot is now in home state again, and the process of crossing the obstacle is over.

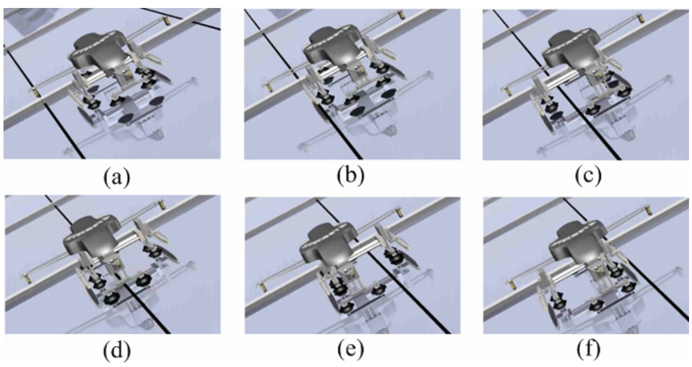

Fig. 2 The process of crossing an obstacle.

However, the first model has only limited dexterity and cannot work on a vertical wall. Because there is not a waist joint in the body, the robot is unable to correct the direction of motion. And the frequency for dealing with and crossing obstacles is very high so that the cleaning efficiency is only about 300 m^2/8 hours. Due to the above technical problems the robot will not really become a commercial product.

C. *Sky cleaner 2*

On the base of Sky cleaner 1, the aim of the following project is to develop a cost-effective, mobile and hassle-free robotic system for providing moving on vertical glass walls and a high quality cleaning on the surfaces of high-rise curtain walls in 1999 [13]. This project is based on the collaboration with the Centre for Intelligent Design, Automation & Manufacturing in City University of Hong Kong.

The sky cleaner 2 is designed to be compact and easy to transport. The robot is featured with 16 suction pads which can carry a payload of 45kg approximately including the body weight. Because of the special layout of the vacuum suckers, the robot can walk in all the directions freely without attention to the seals. A pair of pneumatic cylinders provides both vertical and horizontal motion. A specially designed waist joint, located at the centre of the robot (as shown in Fig. 3), gives a turning motion to the robot. For a turning action, the position pin cylinder is aired to release the locking pin, such that turning motions can be actuated by the waist turning cylinder. The waist joint is used for the correction of inclination during the robot's movement. A relatively small degree of rotation (1.6°) per step is turned in the present stage.

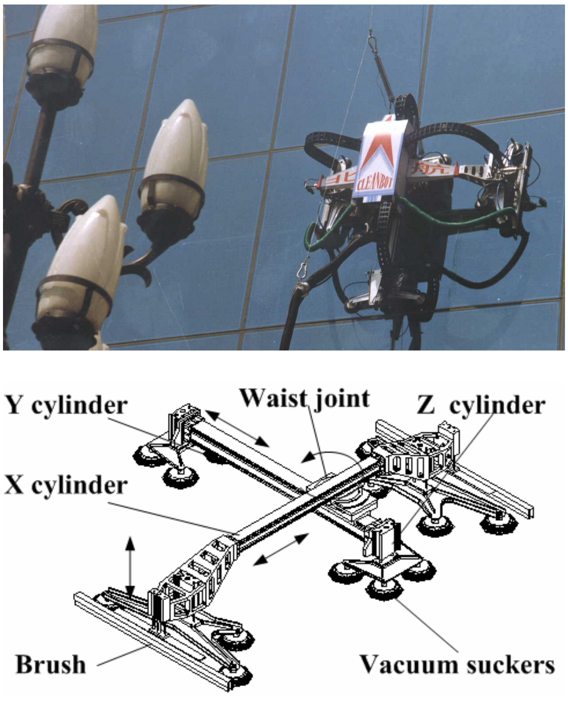

Fig. 3 An artistic impression and a real photograph of sky cleaner 2.

Only an on-board PLC executes a sequence of solenoid valves on/off actions to perform commands that are sent by the operator through the PC console. A PWM method associates with a mechanical braking mechanism to achieve better position accuracy for placing the suction pads as close as to the window frames when a sensory feedback signal has been detected by the sensors. The main specification features of the sky cleaner 2 are also shown in TABLE II.

The second robot is very portable and the cleaning efficiency is about 600 m^2/8 hours. But as considerable stress was laid on weight reduction, the construction stiffness is somewhat low so that there is a little distortion while cleaning and climbing. On the other hand, the function of the following unit on the top is simple and primary.

D. *Sky cleaner 3*

Sky cleaner 3 is a real product designed for cleaning the complicated curve of the Shanghai Science and Technology Museum (shown in Fig. 4) in 2001. The building top is 40 m from the ground. From the left to the right its height gradually decreases. The total surface area of the outer wall is about 5000 m^2. Due to the special arc shape, each glass is connected to its surrounding glasses at about a 2-degree angle.

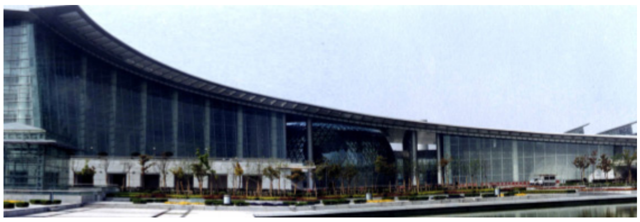

Fig. 4 Shanghai Science and Technology Museum.

The robotic system consists of three parts: 1) a following unit; 2) a supporting vehicle; 3) the cleaning robot (shown in Fig. 5) [14]. The robot is supported from above by cables from the following unit mounted on the top of the building. All following movements of the unit which protects against falling due to any type of failure are synchronized by the robot itself.

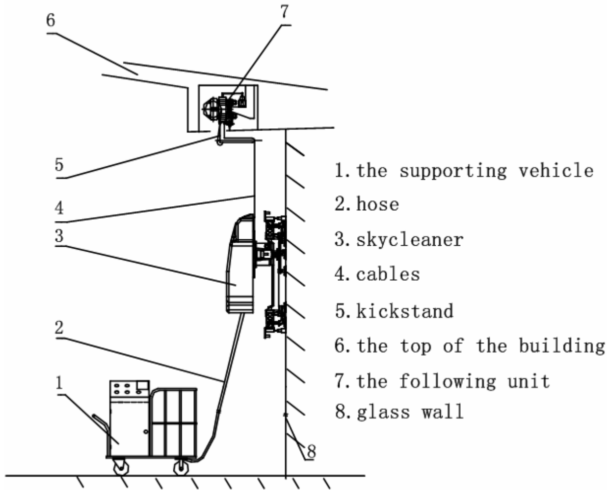

Fig. 5 The robotics system of sky cleaner 3.

The sky cleaner 3 is shown in Fig. 6. A turning waist joint actuated by a pendulum cylinder connects the X and Y cylinders. On opposite ends in the Y direction there are also four brush cylinders, which actuate the brushes up and down. An adaptive cleaning head is designed especially for effective, efficient and safe cleaning, equipped with a drainage collecting device. When the glass is being cleaned, the water is not allowed to drip down; it is firstly drawn off the glass wall through a vacuum pump on the robot. Then the water will flow down because of the gravity and be collected on the supporting vehicle on the ground. At last the drainage will be filtered, and then reused for cleaning. Some sensors that can detect the window obstacles are mounted on each end of the X and Y cylinders. The robot can both clean and walk on the glass walls automatically in the up-down direction as well as the right-left direction.

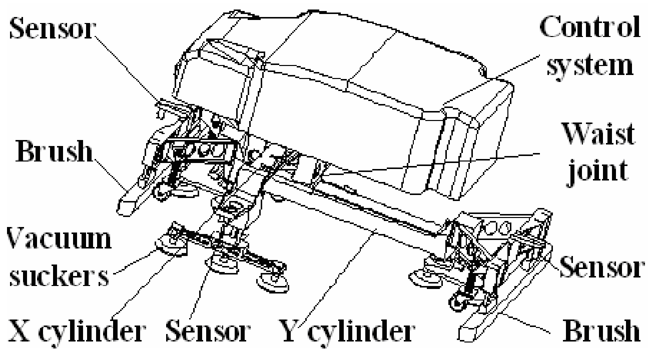

Fig. 6 The sky cleaner 3 prototype.

Because the glass walls of the Shanghai Science and Technology Museum have no window frames, there are some supporting wheels near the vacuum suckers in the X and Y directions, which have been added to the mechanical construction to increase the stiffness. In order to move from one column of glass to another in the right-left direction, a specially designed ankle joint gives a passive turning motion to the suckers. This joint is located between the connecting piece which joins the vacuum suckers with the Y cylinder and the plank beneath it to which 4 vacuum-suckers are attached.

A PLC is used for the robot control system, which can directly count the pulse signals from the encoder and directly drive the solenoid valves, relays and vacuum ejectors. FX2N-4AD which is added to the system can identify the sensor analog signals. The control and monitoring of the robot is achieved through the GUI to allow an effective and user friendly operation of the robot. The communication interface between the PLC and the controller of the following unit is designed to synchronizing the following movement of the cables. The sensors on the robot can be divided into external and internal sensors. The external sensors are responsible for collecting information about the operational environment. The internal sensors are to reflect the self-status of the robot. There are two kinds of external sensors on the robot: touchable sensors and ultrasonic analog sensors. For each active joint, there are limit switches to give the controller the position of the joint. On the joint where the accurate position is needed, the optical encoder is used. The vacuum sensors are used to monitor the vacuum condition of the suckers and provide information to determine whether the suction on the glass surface is stable. Fig. 7 shows the robot is working on the glass walls of this museum.

Fig. 7 Sky cleaner cleaning on the target glass wall.

V. CONCLUSION

This paper described the family of one kind of glass walls cleaning robots totally actuated by pneumatic cylinders. Firstly a summary on the basic functions for the glass wall cleaning robot is given. The robots has to keep to and move on the glass of arbitrary slope while accomplishing the cleaning tasks, they are portable, dexterous enough to adapt to the various geometries of the wall, intelligent enough to autonomously detect and cross the obstacles. The specification features of the sky cleaners are shown in TABLE II.

TABLE II

SPECIFICATION FEATURES OF THE SKY CLEANERS

Type / Capability	Sky Cleaner 1	Sky Cleaner 2	Sky Cleaner 3
Target character	Glass wall 0°-45°	Glass wall 0°-90°	Glass wall 0°-90°(with < 2° angle)
Efficiency(m^2/8 hours)	300	600	800-1000
Cross obstacles (mm^2): Height×Width	Window frame: 30×60	Window frame:30×60; Seal: -1×20	Window frame:10×60; Seal:-1×20
Weight (kg)	25	35	45
Body Mass(mm^3): Length×Width×Height	935×900×320	1220×1340×370	1136×736×377
Supporting unit	Supporting vehicle	Supporting vehicle and following unit	Supporting vehicle and following unit
Supply water(L/hour)	50(reused)	50(reused)	50(reused)
Operators	1	1-2	1-2

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