SERVICE ROBOTIC SYSTEMS FOR GLASS CURTAIN WALLS CLEANING ON THE HIGH-RISE BUILDINGS

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Abstract—The last decade has seen an increasing interest in developing and employing service robots for building maintenance. Cleaning the curtain walls of high-rise buildings is always very dangerous and strenuous. This paper describes three different kinds of cleaning robots developed by the authors cooperated with the researchers in Robotics Institute of BeiHang University. Sky Cleaner 3 for the glass curtain wall of Shanghai Science and Technology Museum, the auto-climbing robot for the spherical surface of the National Grand Theatre of China, and an automatic cleaning gondola for the windows of Beijing Hotel are introduced. The individual robots' mechanisms and unique characteristics are discussed in detail. The main special features of the three cleaning robots are given as a summary.

1. Introduction

At present there are a large number of high-rise buildings in modern cities. These curtain walls require constant cleaning which is presently carried out using a permanent gondola system hanging from the building roof [1]. Meanwhile, more and more buildings with complicated appearance have been emerging all over the world. Even skilled workers with safety ropes have difficulty climbing those buildings. Wall cleaning and maintenance of high-rise buildings is becoming one of the most appropriate fields for robotization because of current lack of uniform building's construction. The development of walking and climbing offers a novel alternative solution to the above-mentioned problems [2] [3] [4] [5]. Our eventual goal is to develop dexterity, intelligent cleaning robotic systems which can be used on different buildings and meet the requirements of real application. This paper describes three different kinds of cleaning robots developed by the authors. Sky Cleaner 3 for the glass curtain wall of Shanghai Science and Technology Museum, the auto-climbing robot for the spherical surface of the National Grand Theatre of China, and an automatic cleaning gondola for the windows of Beijing Hotel are introduced. The individual robots' mechanisms and unique characteristics are discussed in detail.

2. Overview of Sky Cleaner 3

2.1 The Sky Cleaner Robotics System

Since 1996 our group has been developing a family of sky cleaner autonomous climbing robots with sliding frames for glass-wall cleaning. The first model [6] has only limited dexterity and can not work on a vertical wall. The robot is unable to correct the direction of motion because it has no waist joint in the body. And the frequency for dealing with and crossing obstacles is very high so that the cleaning efficiency is only about 37.5 m^2/ hour. The second robot [7] is very portable and the cleaning efficiency is about 75 m^2/ hour. But as considerable stress was laid on weight reduction, the construction stiffness is very low so that there is a little distortion while the robot is cleaning and climbing.

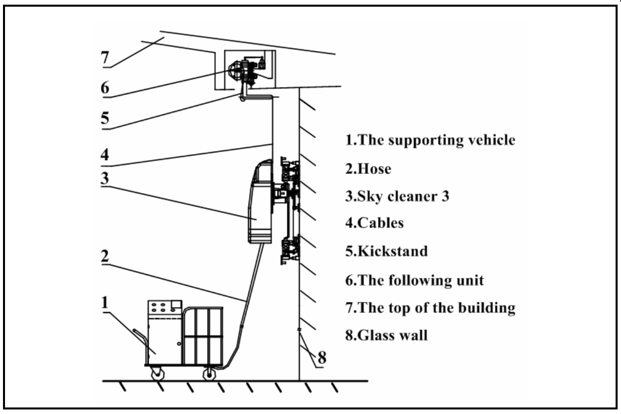


Figure 1 The robotics system of Sky Cleaner 3

Sky Cleaner 3 is a real product designed for cleaning the complicated curve of the Shanghai Science and Technology Museum [8]. The cleaning robot is supported above by cables from the following unit mounted on the top of the building, as shown in Figure 1. All following movements of the unit which protects against falling due to any type of malfunction are synchronized by the robot itself. A hose for water, a tube for pressurized air, cables for power and control signals are provided from the supporting vehicle on the ground, as shown in Figure 2.

Figure 2 Sky Cleaner 3 is cleaning the target

2.2 Mechanical construction

A novel and special movement mechanism actuated fully by pneumatic cylinders is developed to satisfy the lightweight and dexterity requirements (as shown in Figure 3). The robot features fourteen suction pads that can carry a payload of approximately 60 kg including the body weight. Two cross-connected rodless cylinders named X and Y compose the main body of the robot. A turning waist joint actuated by a pendulum cylinder connects the X and Y cylinders. For a turning action, the position-pin cylinder is aired to release the locking pin, so that turning motions can be actuated by the waist pendulum cylinder. At present the robot rotates to a relatively small degree (2°) per step.

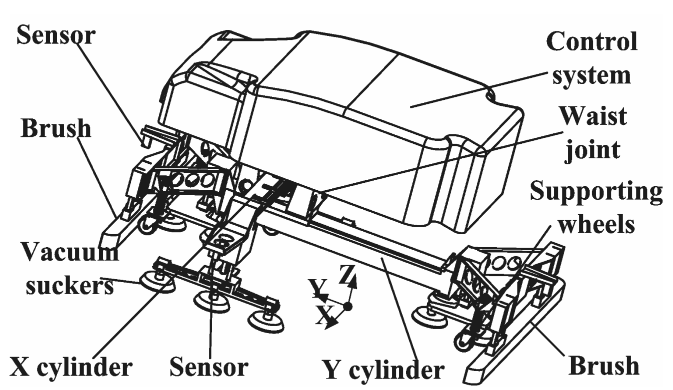


Figure 3 The mechanical drawing of the robot

At the ends of the X and Y cylinders are four connected short-stroke foot cylinders named Z, whose function is to lift or lower the vacuum suckers in the Z direction and support the body on the wall. 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 and safe cleaning, equipped with a drainage collecting device. When the glass is being cleaned, the water is firstly drawn off the glass wall through a vacuum pump. Then the water flows down because of the gravity and is collected on the supporting vehicle on the ground. At last the drainage will be filtered, and then reused for cleaning. The Sky Cleaner 3 can both clean and move on the glass walls automatically in the up-down direction as well as the right-left direction. Even if the robots are very intelligent, the suitable working height is below 50 m because the weight of the hoses has to be taken into account when the robot works in mid-air.

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 structure to increase the stiffness. In order to move from one column of glasses 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 pieces which joins the vacuum suckers with the Y cylinder and the plank beneath it to which 4 vacuum-suckers are attached.

2.3 Control system

The control system is shown in Figure 4. A programmable logic controller (PLC) which can directly count the pulse signals from the encoder and drive solenoid valves, relays and vacuum ejectors, is used for the control system because of its high stability and modularity. FX2N-4AD which is added to the system can identify the ultrasonic sensor signals and other analog sensors. The communication interface between the PLC and the controller of the following unit is designed to synchronize the following movement of the cables. There are two kinds of external sensors on the robot: touchable sensors and ultrasonic sensors which are responsible for collecting information about the operational environment. The internal sensors are to reflect the self-status of the robot. The waist sensor will send a signal to the controller once the inclination of the main body is about 2 degrees. There are limit switches to give the controller the position information 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 determine whether the suction on the glass surface is stable.

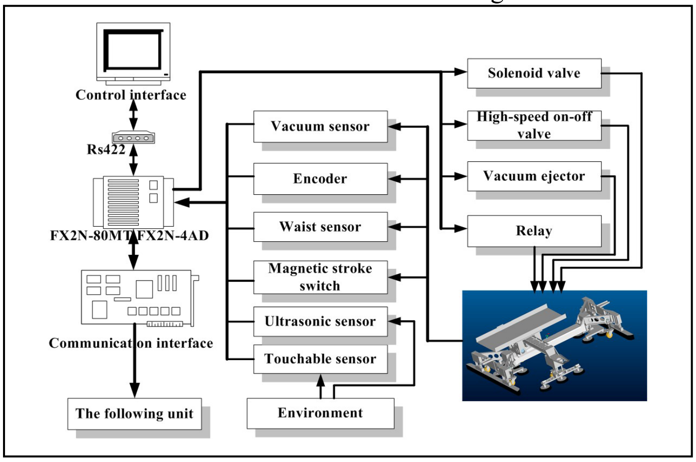


Figure 4 Control system

2.4 Cleaning path

Firstly in order to avoid passing over the same spot again and polluting the cleaned area, the cleaning path should lead from the building top to the ground. The robot generally moves along latitude or longitude, which is easy to realize. If the robot cleans the work target in the right-left direction, it has to cross two-degree-angle edges several times. But it can work and clean uninhibited in the vertical direction, because that way the glasses are considered as forming a plane. The robot begins to clean the glass wall from the upper left point, and then works its way down. It will move to another column when the first column of glass is finished cleaning.

3. The Auto-climbing robot for complicated curve surface

3.1 The auto-climbing Robot

Taking the National Grand Theater of China as the operation target, an auto-climbing robot was developed in 2004 [9]. The robot can autonomously climb and clean the covering outer walls with the shape of a half-ellipsoid. The height of the theater top is 54 m, the long axis and short axis of the ellipse on the ground are 212 m and 146 m respectively, as shown in Figure 5. The total surface of the outer walls is 36000 m^2, with 6000 m^2 of transparent glass walls, and 30000 m^2 of Titanium walls. Altogether the wall consists of 54 strips, with each strip bordering on the one's top. In order to achieve this half-ellipsoid, each plank is constructed at a different size and is connected to its surrounding planks at an angle. A track circling around the half-ellipsoid, which was originally designed for the needs of construction and maintenance, is mounted between every two strips.

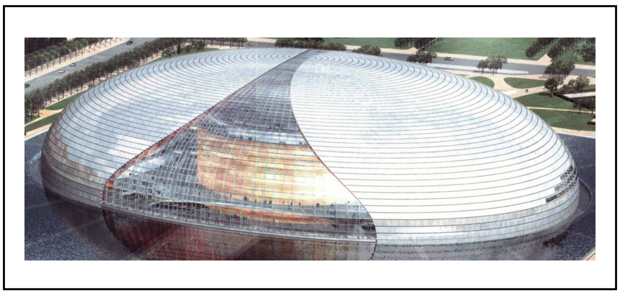


Figure 5 National Grand Theater of China

3.2 Mechanical construction

Based on the features of the construction mentioned above, an auto-climbing robot was designed, as shown in Figure 6. It will take the tracks on the wall as supports for climbing up and down between strips and moving sideways on one strip around the ellipsoid. The body consists of the climbing mechanism, the moving mechanism, two cleaning brushes and the supporting mechanisms. The size of the robot is 3 meters long, 1.5 meters wide and 0.4 meter high.

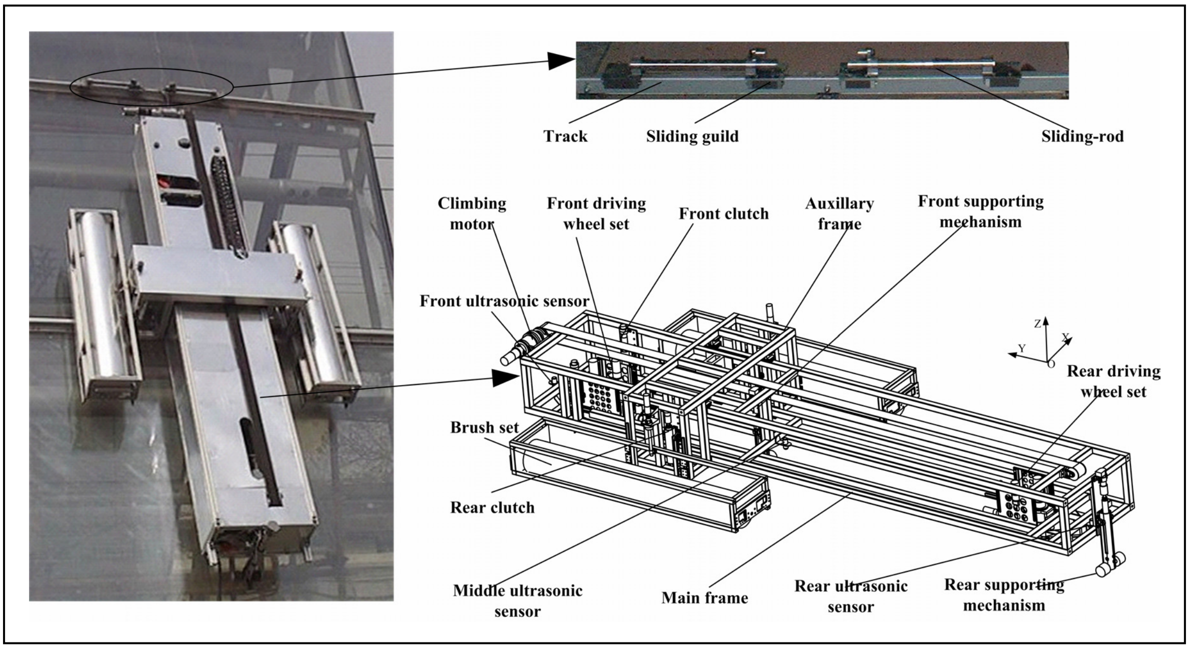


Figure 6 Mechanical construction of the robot

The degree of freedom of the robot is demonstrated in Figure 7. There are altogether 25 joints, out of which 17 joints are active and are actuated by respective DC motors. In this Figure, “P” means the linear movement joint and “R” means the rotating movement joint.

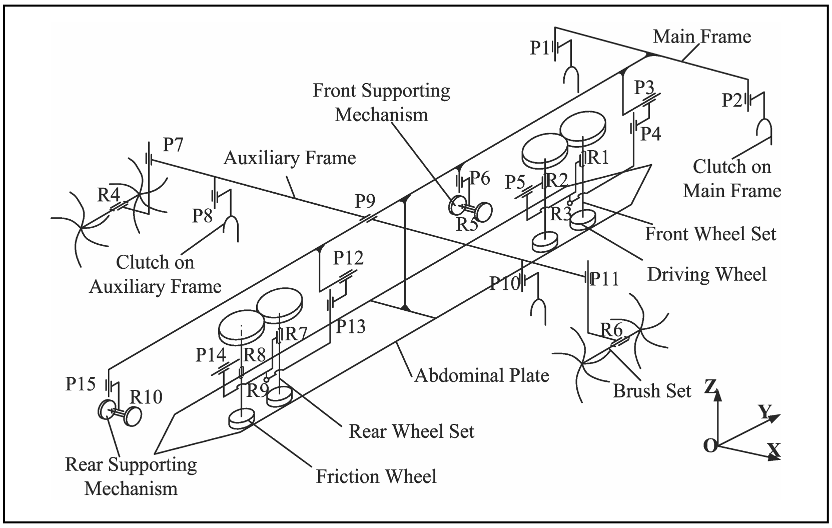


Figure 7 Degree of freedom

The main body of the robot consists of two frames: the main frame and the auxiliary frame. Other functional parts are all mounted on these two frames. The auxiliary frame sliding along the main frame is actuated by the DC motor and the belt, both of which are mounted on the top of the main frame. The auxiliary frame has a shape like an “n” encircling the main frame to ensure a safe and reliable movement (shown in Figure 8). A special slide bar made of polyethylene material is designed to create a sliding-mate between the two frames thus saving the weight of the linear guidance which is usually used to realize this kind of structure. When the robot is working on such a half-ellipsoid, obstacles and friction make it almost impossible to attach a safety cable to the robot from the theater top. As a result, a mechanical structure named abdominal plate was developed and designed to solve the safety problem. While a set of clutches hold the sliding-rod to avoid falling down, abdominal plates on the robot are inserted into the sliding-rod to avoid capsizing out of the wall.

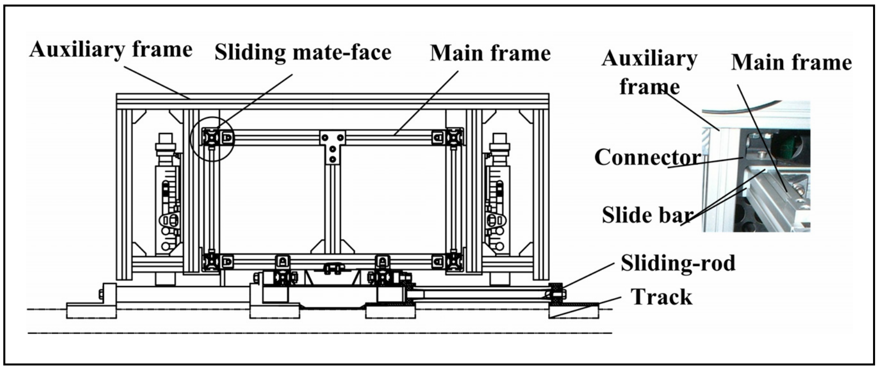


Figure 8 Sliding-mate between two frames

Two rotating brushes on the auxiliary frame can move up and down automatically and rotate for cleaning when the robot moves sideways along the tracks. Two pairs of clutches whose functions are grasping the sliding-rods are attached to the main frame and the auxiliary frame respectively. The sliding-rods can safely slide along the track but cannot be detached. They are designed to be the medium between the track and the robot in order to avoid the safety problem caused by the robot directly grasping the track. A DC motor is embedded in the mechanical clutch which allows for a very slight structure.

A front supporting mechanism and a rear supporting mechanism with the same structure as the clutches are used to adjust the robot's alignment with regard to the wall and support the body on the surface. There are two supporting wheels on the tip of the mechanism in order to increase the area of interaction and avoid damaging the plank surface. A front and a rear wheel sets are also installed on the axis of the main frame, which are used to provide the sideways driving force for the robot when they are clamped on the tracks. Three ultrasonic analog sensors are placed at the front, in the middle and at the rear respectively to detect the sliding-rod in the moving direction.

3.3 Control system

A distributed control system based on CAN bus is adopted to satisfy requirements, as shown in Figure. 9. The system is divided into 6 parts, five CAN bus control nodes and a remote controller. The PCM-9575 industrial PC (IPC) is the core part of the control system. It is a new EBX form factor 5.25" single board computer (SBC) with an onboard VIA Embedded low power Ezra 800 MHz. The VIA Eden processor uses advanced 0.13µ CMOS technology with 128KB L1 cache memory and 64KB L2 cache memory. This board can operate without a fan at temperatures up to 60° C and typically consumes fewer than 14 Watts while supporting numerous peripherals.

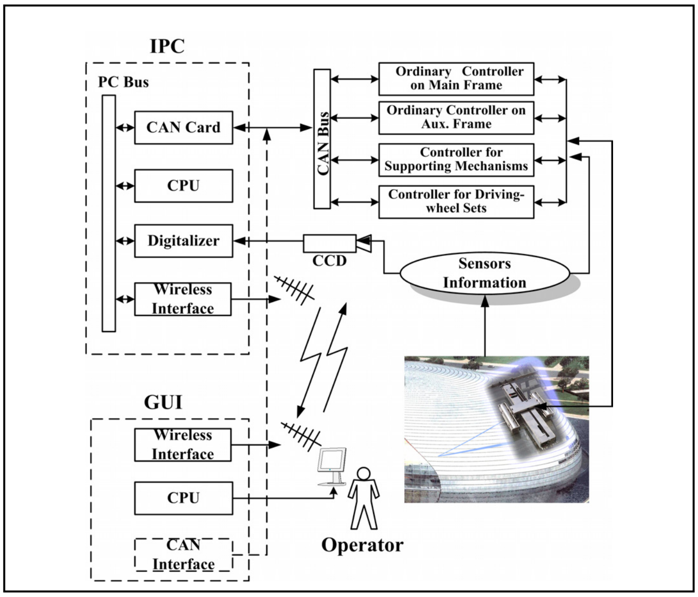
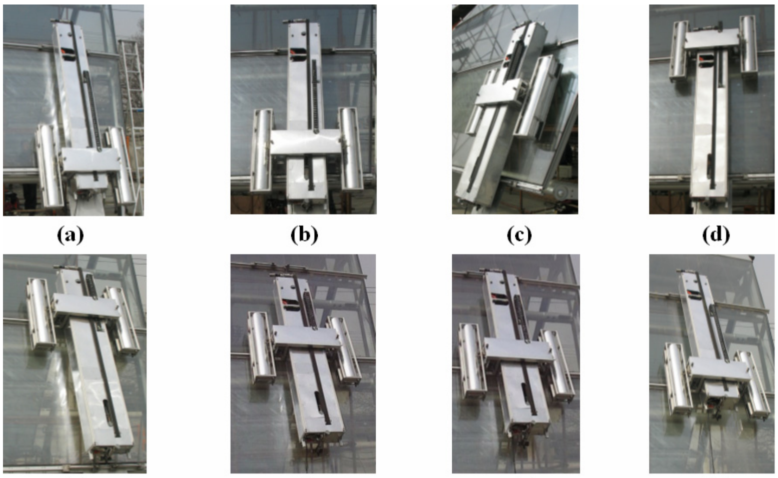


Figure 9 Control system

A PCM3680 card is used as a communication interface between the main node and the other CAN nodes. The PCM-9575 is a higher-level controller and does not take part in joint motion control. The responsibilities include receiving orders from the remote controller, planning operational processes, receiving feedback information from other nodes, and giving orders to other nodes. The other four lower-level nodes are responsible for receiving orders from IPC node and directly controlling respective joint motors.

The controlling and monitoring of the robot is achieved through the digitalized CCD camera and a wireless graphical user interface (GUI) which allows an effective and user friendly operation of the robot. It is important for the control system to realize precise position control when the robot moves vertically from one strip to another. On the other hand, some joints such as brushes and clutches only need ordinary on-off control. Two kinds of CAN nodes, both designed by us, which are mainly based on the P80C592 micro-chip are included in the control system in order to meet the requirements of functionality, extensibility and low cost. Each node is in charge of a special function in which all the related sensor signals are included. For example, the supporting mechanism node can directly count the pulse signals from the encoder, deal with the signals from the touchable sensors and other magnetic sensors, and directly drive the DC motors in the front and rear supporting mechanisms. In order to satisfy the requirement of extensibility, there are enough I/O resources on the control node, which make it easy to attach sensors and processing equipments. At the same time multiple process programming capability is guaranteed by the principle of CAN bus.

Figure 10 shows the process of climbing from one strip to the next on work target. The experimental results confirm the principle described above and the robot's ability to work on the spherical surface.



(a) **(b)** **(c)** **(d)**

(e) **(f)** **(g)** **(h)**

Figure 10 Real climbing experiment

4. Automatic Cleaning Gondola

4.1 Mechanical construction

An automatic gondola for cleaning glass windows was developed [10], which takes the Beijing Hotel in China as its operation target. The major challenge in designing this robotic system is the ability to overcome the high vertical jambs and horizontal bars on the surface and finish cleaning automatically. The bars around the windows are about 300 mm high, which is too high for a robot to cross. Furthermore a 700 mm-high brim is mounted between every two layers (Figure 11).

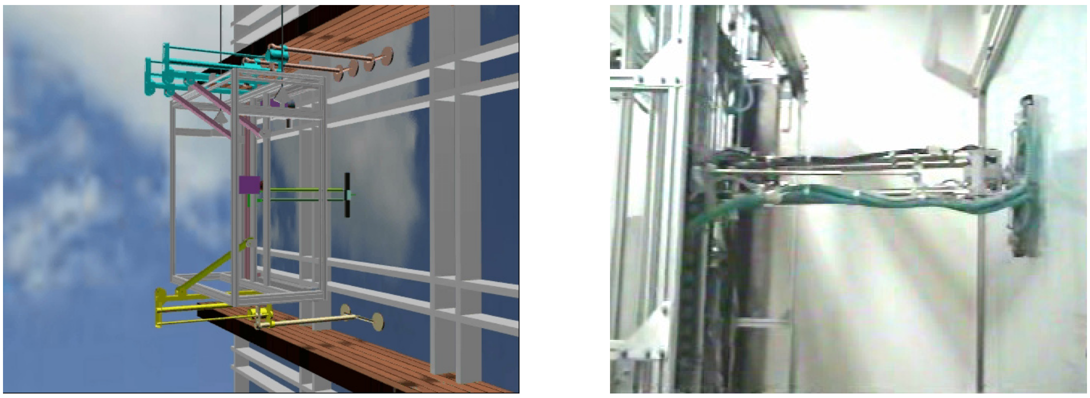


Figure 11 A model and a real photo of the robot

The robot is 2.9 meters high, 2.2 meters wide and 0.9 meters thick. The automatic cleaning gondola system can fulfill the work of attaching on the wall, cleaning the glass window, reclaiming, purifying and recycling the sewage. A remote control device and a wireless CCD camera are adopted for the robotic system which is pre-programmed to run in an autonomous and supervisory control mode.

The main specifications of the cleaning robotic system are summarized below.

1. High reliability, due to the simplified system and the reliability of the suspending sub-system.

2. Because of the unique adsorbing device, the robotic gondola can attach not only to glass, but also to a wall with tile, aluminium-boards.

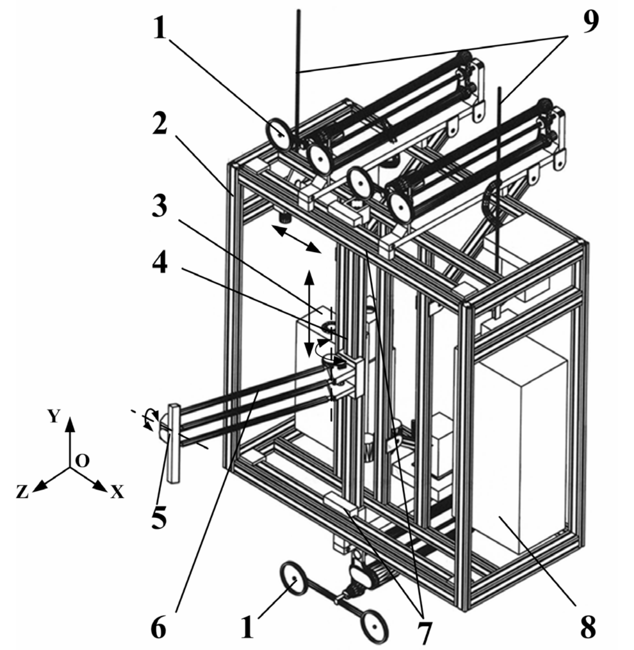
3. High cleaning efficiency and good quality, which are realized by using brushes, rubber scraper and glass detergent.

4. As it reclaims, purifies and recycles the sewage, the robot is water saving cleaning device.

5. Remote control mode, easy to use and low cost.

The robotic system includes a sub-system on the roof of the building which is used for suspending and hauling the robot to move vertically and horizontally, and the automatic gondola which is responsible for cleaning (Figure 12). The weight and payload of the robot are no longer limited by the suckers because its weight is completely supported by the cables.

The gondola consists of a main frame, attachment devices, a water-recycling device, a cleaning system, and a control system. The main frame serves as a carrier for all the other devices. The cleaning system is the core part of the robotic gondola and is developed to satisfy the dexterity cleaning requirements. Two parallel X linear guidance and a Y linear guidance compose the crossed cleaning mechanical frame. The Y linear guidance with a cleaning arm can move horizontally along the X linear guidance. The cleaning arm actuated by a pendulum joint can rotate to touch the window surfaces and accomplish the cleaning task. It can move vertically along the Y linear guidance itself. So the movement of this arm in vertical and horizontal directions is controlled by the X and Y linear guidance together. At the ends of the cleaning arm is an adaptive cleaning head. A turning joint like a wrist is mounted on the tip of the arm and connects the cleaning arm and the brush.



1. Adsorption modular; 2. Mechanical frame; 3. Water recycling device;
4. Y liner guidance; 5. Brush; 6. Cleaning arm;
7. X liner guidance; 8. Control system

Figure 12 Automatic cleaning gondola

Since there are a lot of high vertical jambs and horizontal bars on the outer walls of the Beijing Hotel, it is impossible to apply the normal principles of adhesion used by climbing robots directly. The robot cannot realize a continuous cleaning movement on the working target. As a result, three sets of adsorbing devices outstretching and returning automatically were developed and designed to solve the above-mentioned problem. Two sets are mounted on the top of the frame and the third one is at the bottom. During cleaning, the attachment devices are extruded out to touch the wall. Then the vacuum is generated by negative pressure which makes the absorption devices attach to the window surface well to avoid swaying in mid-air. Meanwhile the necessary contact pressure of the brushes on the outer surface is ensured during the cleaning process.

4.2 Control system

The alternating information and orders between the suspending sub-system and the gondola system are transferred by a couple of cables from the sub-system on the top of the building. And the cables also supply the gondola with power. The control of the cable winch on the sub-system is a part of the overall control system.

The control system on the gondola is based on IPC and master-slave structure, as shown in Figure 13. The hardware consists of a programmable multi-axis control card (PMAC), a PLC, a vision processing board and a GUI. The cleaning device is controlled by PMAC card respectively. Four AC motors in the cleaning device should act and be controlled together. Using PMAC, it is easy to realize a unique cleaning planning that mimics the human cleaning trajectory. The ability of PMAC greatly relieves the burden of the host [11]. Other joints such as absorption devices only need ordinary on-off signals and are controlled by PLC.

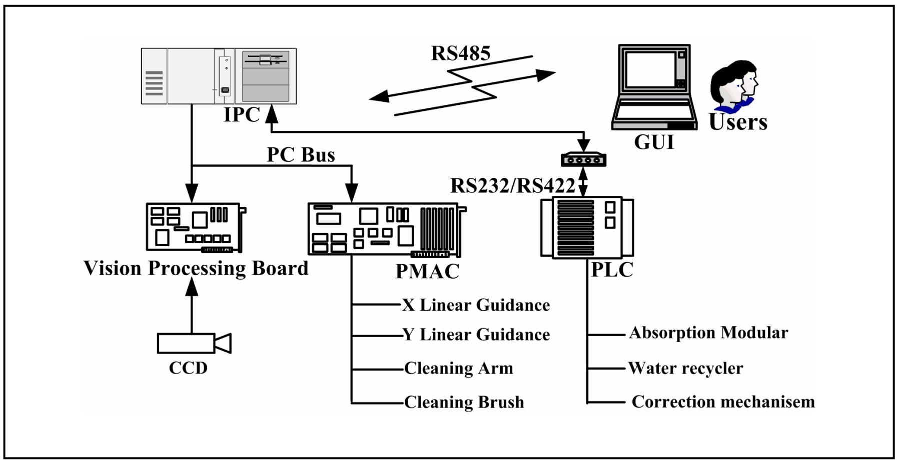


Figure 13 Control system

A kind of nonlinear prewitt named the sobel is used for detecting the window's edges which are the limitation of cleaning [12]. Based on this result of edge detection, the software will choose the starting point for cleaning automatically. The working process consists of moving in sideway, moving in vertical direction, absorption, orientation, cleaning and resuming home state. The water recycling is an independent part which will start automatically once the drainage water is enough to filtrate.

For our automatic gondola, a kind of mimicking cleaning trajectory is employed so that the efficiency and quality of the cleaning are guaranteed. The cleaning arm acts and moves like a human arm while the brush acts like a "hand" during the cleaning. The cleaning trajectory of the brush's center on a piece of window is shown in Figure 14. In this way, the time for reciprocating and orientation is saved. The efficiency of the cleaning is about 3.5m^2/minute, as shown in Figure 11 and 14, which is higher than other ordinary cleaning methods we have known.

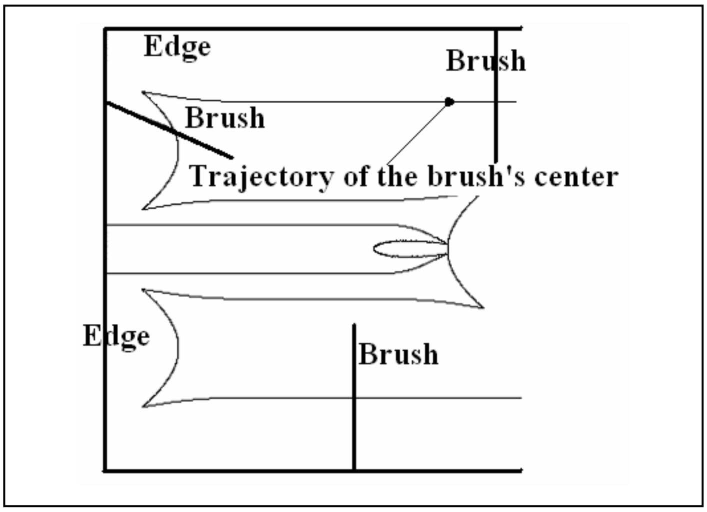


Figure 14 Trajectory of the mimic cleaning

5. Conclusion

This paper described three kinds of cleaning robots totally designed by our group from BeiHang University and University of Hamburg. The robots have to keep to and move on the arbitrarily sloped wall while accomplishing the cleaning tasks, they are dexterous enough to adapt to the various geometries of the wall, intelligent enough to autonomously detect and deal with the obstacles. The specification features of three robots are shown in TABLE I.

TABLE I Specifications of three robots

Character	Body Mass (kg)	Body Mass(mm^3): Length ×Width ×Height	Cleaning Efficiency (m^2/hour)
Sky Cleaner 3	45	1136×736×377	100-125
Auto-climbing	100	2800×1384×360	>100
Gondola	100	2900×2200×900	>150

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Brief curiculum vitae of authors

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