

# A Climbing Robot for Cleaning Glass Surface with Motion Planning and Visual Sensing

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## 1. Introduction

There exists increasing demand for the development of various service robots to relieve human beings from hazardous jobs, such as cleaning glass-surface of skyscrapers, fire rescue, and inspection of high pipes and walls (Balaguer et al., 2000; La Rosa et al., 2002;

Zhu et al., 2002). It shows our recently developed climbing robotic system aimed to clean glasses of high-rise buildings, using suction cups for adhering to the glass and a translation mechanism for moving. This robot can reach a maximum speed of 3 m/min and has the ability to cross cracks and obstacles less than 35mm in height and 80mm in width.

Utilizing a flexible waist, the robot can easily adjust its orientation. Motion planning of the service robot plays an important role to enable the robot to arrive in the target position and avoid or cross obstacles in the trajectory path. There are considerable approaches in the literature to address the motion planning problem of car-like or walking robots, such as Lamiroux and Laumond (2001), Boissonnat etc. (2000), Hasegawa etc. (2000), Chen et al. (1999), Hert and Lumelsky (1999), Egerstedt and Hu (2002), Mosemann and Wahl (2001), to name a few. All these algorithms are not suitable to our cleaning robot applications. This is because 1) the movement mechanism of the climbing robot uses translational suction cups, which is different from the other robots; and 2) the climbing robot works in a special environment, i.e., the glass wall, which is divided into many rectangle sections by horizontal and vertical window frames, and the robot must be able to cross the window frames to clean all sections. Because of these characteristics, there exists a demand for a unique motion planning scheme for the climbing robot application. Another key issue to the success of the climbing robot application lies in an effective sensing capability. To do the cleaning work on the glass surface, the cleaning robot must know when to begin or stop the cleaning job, how to control the orientation (or moving direction), and how to cross the window frame. Therefore, it is necessary to measure the robot orientation, the distance between the robot and the window frame, and the distance between the robot and the dirty spot to be cleaned. Some recent works on the sensing system of cleaning robots have been reported in the literature (Malis et al., 1999; Ma et al., 1999). Simoncelli et al. (2000) utilized the ultrasonic sonar for automatic localization.

Kurazume and Hirose (2000) proposed the so-called “cooperative positioning system” to repeat a searching process until the target position was reached. However, in a climbing robot on the glass surface, many traditional methodologies with laser and ultrasonic sensors etc. cannot be applicable to measure the distance between the robot and the window frame.

This is because that the height of the window frame is usually low and the light beam sent by the sensor is difficult to reach the frame unless the beam is exactly parallel to the glass surface. Due to inevitable installation errors, the sensors are usually hard to ensure that the light beam is parallel to the glass surface exactly. Cameras are often used for the robot's localization, visual servoing, and vision guidance. Malis et al. (2000) used two cameras for 2-D and 2-1/2-D visual servoing and proposed a multi-camera visual servoing method.

However, the use of a number of cameras may not be suitable to the climbing robot because

1), it is difficult to establish a big zone of intersection of points of view when using several cameras, and 2), using a number of cameras increases the load weight and thus affects the safety of the climbing robot. Based on eigenspace analysis, a single camera was used to locate the robot by orienting the camera in multiple directions from one position (Maeda et al., 1997). The drawback of this eigenspace method is that the measuring performance may vary as environment changes. In addition, the depth information is lost and the distance between the camera and the target object cannot be measured by traditional single camera.

This chapter presents our approaches to solving the above two challenging problems, motion planning and visual sensing, for a climbing glass-cleaning robot. Some works have been reported in Zhu et al. (2003) and Sun et al. (2004). The remainder of the chapter is organized as follows. In section 2, structure of the climbing robot is introduced. In section 3, motion planning of the robot on a multi-frame glass wall is presented. In section 4, a visual sensing system that is composed of an omnidirectional CCD camera and two laser diodes, is shown to enable the robot to measure its orientation and the distance between the robot and the window frame. Experiments are performed in section 5 to demonstrate the effectiveness of the proposed approach. Finally, conclusions of this work are given in section 6.

## **2. Structure of the Cleaning Robot**

The cleaning robotic system consists of a mobile climbing robot, a supporting vehicle, a compressor, and a computer. The climbing robot sticks on the glass surface to perform the cleaning job. The supporting vehicle supplies electrical power and cleaning liquid. The compressor acts as the air source. Through communication between the computer and the robot, the human operator can examine and control the operation of the robot.

The developed climbing robot has a length of 1220 mm, a width of 1340 mm, a height of 370mm, and a weight of 30 Kg. The body of the robot is mainly composed of two rodless cylinders perpendicular to each other. The stroke of the horizontal (X-) cylinder is 400mm, and that of the vertical (Y-) cylinder is 500mm. Actuating these two cylinders alternately, the robot moves in the X or Y direction. Four short Z-cylinders are installed at the two ends of each rodless cylinder. By stretching out or drawing back the piston beams of these four cylinders, the robot can move in the Z direction. At the intersection of two rodless cylinders, a rotational cylinder named the robot's waist is installed, by which the robot can rotate around the Z-pivot. Two

specially designed brushes, each composed of a squeegee and a sucking system, are fixed at the two ends of the horizontal cylinder. The squeegee cleans dirty spots on the glass surface using cleaning liquid provided by the supporting vehicle. The sucking system collects and returns the sewage to the supporting vehicle for recycling.

The robot employs suction pads for adhesion. Four suction pads, each with a diameter of 100mm, are installed on each foot of the robot. The total sixteen pads provide a suction force enough to withstand 15 Kg payload. The robot uses a translational mechanism for the movement. With the operating mode of sticking-moving-sticking, the robot can complete a series of motions including moving, rotation, and crossing obstacles. The rotation of the robot is controlled by adjusting rotation angles of the rotational cylinder. The robot can rotate 1.6 degrees per step around Z-pivot until reaching the desired posture.

The control system of the robot is based on a master and a slave computer. The master computer is located on the ground and manipulated by the human operator directly. The slave computer is embedded in the body of the robot. Using the feedback signal of sensors installed on the robot, the slave computer controls the movement and the posture of the robot to achieve automatic navigation on the glass surface. The master computer obtains the information and identifies the status of the robot by the visual sensing system together with the communication between the master and the slave computers with a RS422 link. In case of emergency, the human operator can directly control the robot according to the actual situation.

The movement of the robot is achieved by alternately sucking and releasing the suction cups installed on the horizontal and vertical rodless cylinders. The slave computer sends ON or OFF signals to connect or disconnect the vacuum generator with air source, resulting in sucking or releasing the corresponding suction cups. Vacuum meters measure the relative vacuum of the suction cups and check the safety of the robot. If the vacuum degree of the suction cups is less than -40 kPa, an alarm signal is sent to the master computer.

Fig. 3 illustrates the developed cleaning robot climbing on the commercial building of City Plaza in Hong Kong.

### **3. Motion Planning**

For simplicity, the robot moves horizontally and vertically to clean the whole glass surface in the motion planning. As an example, Fig. 4 illustrates a trajectory path of the robot within a rectangular glass section. The starting point is located in the up-right side of the glass section. The robot moves toward the left side horizontally while cleaning the glass surface.

When arriving at the boundary of the glass section, the robot moves down a distance  $l$  and then moves back to the right side horizontally. Note that the distance  $l$  is equal to the length  $lb$  of the brush cleaning path, and  $lb$  is determined by considering the size of the brush and the dimension of the glass section. Repeating the above procedures, the whole glass section can be cleaned. The ending position is located in the down side of the glass section. During cleaning the sewage may drop down and makes the downside glass surface dirty.

Therefore, the cleaning work should be performed from the upside to the downside.

### **3.1 Orientation Adjustment of the Robot**

When the climbing robot moves along the desired trajectory, the robot orientation is affected by various disturbances, especially by the gravitational force of the robot itself. To ensure a successful trajectory following, the robot must be able to adjust its orientation automatically.

The orientation of the robot is measured by the visual sensor installed on the robot, relative to the window frame. Two laser diodes send two laser lights to the window frame so that an image of the frame can be acquired. The orientation of the robot relative to the window frame can be calculated by analyzing and comparing the image coordinates of two laser points. The technical details of this measurement are given in the next section.

Based on the orientation measured by the visual sensor, the controller actuates the rotational cylinder to adjust the orientation of the robot. The orientation is adjusted by the sticking-releasing- sticking mode, as shown in Fig. 5. Firstly, the suction cups installed on the vertical cylinder are released (see Fig. 5 (1)). Secondly, the rotational cylinder is actuated to rotate the vertical cylinder (see Fig. 5 (2)). Then, the suction cups on the vertical cylinder are sucked, and meanwhile, the suction cups on the horizontal cylinder are released (see Fig. 5(3)). Finally, the rotational cylinder is actuated again to rotate the horizontal cylinder (see Fig. 5 (4)).

### **3.2 Crossing the Window Frame**

The window frames separate the whole glass wall into several sections, as shown in Fig. 6.

After cleaning one section, the robot must be able to cross the vertical or horizontal window frame to enter another section. The two major steps for the robot to cross the window frame are:

- 1) Measuring the distance between the robot and the window frame

The distance between the robot and the window frame, denoted by  $d$  as seen in Fig. 6, is an important factor to evaluate the position of the robot in each section. When this distance is close to zero, the robot prepares to cross the window frame. The visual sensor is employed to measure the distance between the robot and the window frame. According to the theory of triangulation, one laser diode is needed to measure the distance. The distance is measured by analysis and calculation of the pixel coordinate of the laser point, based on the position and posture of the CCD camera relative to the laser diode, which will be shown in the next section.

- 2) Crossing the window frame

After measuring the distance between the robot and the window frame, the robot plans its motion to cross the frame. Four ultrasonic sensors are installed to help the robot to detect whether the suction cups have crossed the window frame, as shown in Fig. 7, where  $D$  ( $=300\text{mm}$ ) denotes the distance between the ultrasonic sensor and the boundary of suction cups. When the ultrasonic sensor is crossing the window frame,

the ultrasonic sensor measures the height of its position relative to the surface of the window frame. After the ultrasonic sensor crosses the window frame, the height measured by the ultrasonic sensor is the one relative to the glass surface. Since the height measurements in the two cases are different, the robot knows whether the ultrasonic sensor has crossed the window frame.

When the ultrasonic sensor lies in the window frame, the robot also knows when the suction cups will follow the ultrasonic sensor to cross the window frame after moving a distance  $D$ .

## 4. Visual Sensing

The visual sensing hardware system consists of an oriented CCD camera with the model number Sony EVI-D30 (J), two laser diodes, and a capture card. Two laser diodes, fixed on

the camera as "eyes" of the sensing system, send two laser lights to find the window frame and generate two laser marks. The distances between the reference points and the window frame, and the orientation of the robot relative to the window frame, can be determined by analyzing image pixel coordinates  $u$  and  $v$  of two laser points in the image plane.

### 4.1 Position Measurement

The theory of triangulation will be utilized in the measurement. Fig. 8 (left view) illustrates how the robot position is measured by the visual sensing system. The launching point of the laser diode is represented by  $L$ . Point  $L1$  is the laser mark on the window frame. Point  $L2$  is the corresponding point of  $L1$  in the image plane, where  $I$  denotes the center of the image.

Treating the focal point of the camera as the origin, denoted by  $F$ , a base coordinate frame represented by  $F-xbyzbz$  is established, where  $x_b$  coordinate axis is parallel to the glass surface and perpendicular to the window frame,  $y_b$  coordinate axis is parallel to both the window frame and the glass surface, and  $z_b$  coordinate axis is perpendicular to the glass surface ( $x_b-y_b$  plane), as shown in Fig. 8. Using  $F$  as the same origin, another coordinate frame named camera coordinate frame, represented by  $F-xyz$ , is also established, where  $x$  axis is parallel to line  $I-F$  that is the main light pivot of the camera,  $y$  axis is the same as  $y_b$  axis of the base coordinate frame, and  $z$  axis is perpendicular to the  $x-y$  plane. Denote  $[x_0, y_0, z_0]^T$ ,  $[x, y, z]^T$  and  $[x, y, z]^T$  as coordinates of the points  $L$ ,  $L1$  and  $L2$ , respectively. Denote  $u$  and  $v$  as coordinates in pixel in the image plane, and  $u_0$  and  $v_0$  as the pixel coordinates of the central point  $I$ .

### 4.2 Orientation Measurement

Fig. 9 (front view) illustrates a measurement of the robot orientation using the visual sensing system, where two laser diodes are needed. Points  $A$  and  $B$  are launching points of laser diodes 1 and 2, respectively. Points  $A1$  and  $B1$  are the corresponding laser marks in the window frame.  $\gamma_1$  and  $\gamma_2$  are the pan angles of laser diodes 1 and 2 relative to the camera.

## 5. Experiments

The robot was tested in cleaning a glass wall of the academic building at the City University of Hong Kong, as shown in Fig. 10. The robot operation includes: 1) adjusting the orientation by rotating the waist, 2) cleaning the glass wall with brush, and 3) crossing the window frame from one glass section to another section. The successful demonstrations show that the climbing robot can clean the glass wall automatically and effectively.

When the robot cleans the glass wall, detection of the orientation is important for the robot to move along the desired trajectory, and measurement of the distance between the robot and the window frame is also important to infer the robot to cross the window frame. A series of experiments were performed to evaluate the effectiveness of the visual sensing system in measuring the robot's orientation and the distance between the robot and the window frame.

### 5.1 Measurement of the Robot Position

Firstly, the visual sensing system was calibrated by acquiring images and analyzing  $u$  or  $v$  coordinates of the laser points when the robot was at different calibration positions on the glass surface. With the least square fitting, the distance between the robot and the window frame could be developed from the calibration as a function of  $u$  coordinate of the left laser point  $u_L$  (pixel) and the tilt angle of the camera  $\alpha$  (degree).

The distance functions in  $v$  coordinate of the two laser points were also developed. After comparison, we found that the distance measurement with  $u$  coordinate was more accurate than with  $v$  coordinate in this experiment. Figs. 11 (a) and (b) illustrate the relationships described in equations (13) and (14), respectively.

In the following experiments, equation (13) was used to measure the position of the robot on the glass surface. Experimental results of the relationship between the measurement error and the distance measured is shown in Fig. 12, where the squared points denote the measurement errors with different distances, and the solid line denotes a trend of the measurement errors as the distance increases. When the camera pans 90 degrees anticlockwise, the distance between the robot and the left window frame can be measured.

When the camera pans 90 degrees clockwise, the distance between the robot and the right window frame can be measured. To solve the error accumulative problem of the measured distance, the visual sensor needs to be reset after several measurements. Note that the camera distortion may affect the measurement of  $d$ . It is seen from Fig. 12 that the measurement error is small (i.e.,  $< 10$  mm) when the distance is not large (i.e.,  $< 1000$  mm). In case of large distance, the camera distortion correction should be considered.

### 5.2 Measurement of the Robot Orientation

The visual sensing system was further calibrated to find the relationship between the robot's orientation and the  $u$  coordinates of the left and the right laser points in the

image.

### **5.3 Measurement of the Location of the Dirty Spot**

The pattern recognition technique was used to find out the dirty spot to be cleaned and then to obtain the image of the laser mark. Equation (14) was used to measure the distance between the robot and the dirty spot. Based on the measured distance and the pan angle of the camera, the location of the dirty spot can be known.

## **6. Conclusions**

This chapter presents an application of a climbing robot for the glass cleaning service. The robot is constructed by two rodless cylinders and a rotation cylinder. The robot can adjust its orientation to maintain in the desired trajectory path. After finishing the cleaning work in one section of the glass wall, the robot can cross the window frame to enter another section.

A visual sensing system, which is composed of an omnidirectional CCD camera and two laser diodes, is applied to measure the robot's position and orientation on the glass wall. Experiments demonstrate that with the assistance of the proposed motion planning and visual sensing technologies, the climbing robot can perform cleaning work on the glass wall effectively. Future work will be toward developing more efficient motion control system and reducing size/weight of the climbing robot.

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