Journal of Intelligent and Robotic Systems **35:** 427–444, 2002.

Development of a Tracked Climbing Robot

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(Received: 9 August 2001; in final form: 11 February 2002)

Abstract. This paper describes a climbing robot, using chain-track as the locomotive mechanism and suction cups as the adhesion method. The main structure, sensors, and the vision-based motion control system of the robot are described in the paper. The robot can turn in a limited range by adjusting the steering wheel and twisting the chain. The turning gait is discussed and relations between turning angles of the chain node, the front wheel, and the frame of the robot are formulated. Forces applied to the robot are analyzed in order to obtain a safety condition that prevents the robot from slipping and falling. An experiment is conducted to measure the safety factor of suction cups and determine the payload capacity of the robot.

Key words: climbing robot, chain-track, suction cup, turning gait, safety analysis.

1. Introduction

The prospect of climbing robots is coveted because they can take the place of humans to carry out hazardous and maintenance jobs, such as cleaning glass-surface of skyscrapers, fire rescue, and inspection of high pipes and wall, which are usually dangerous for human beings. Due to the ability to relieve human beings from these hazardous work, more and more people are interested in developing various service climbing robots in recent years. The adhesion methods used for climbing robots are divided into three categories: magnetic equipment, thrust force, and vacuum pad. The magnetic adhesion is suitable for ferromagnetic surface (Grieco et al., 1998). The thrust force, adopted with propeller (Nishi et al., 1990), can help robots avoid obstacles in movement, but its unsatisfied stability hinders this method from being used extensively. The vacuum pad, as the most commonly used adhesion method for the time being, can be used in even platforms such as glass, wall, ceramics and so on (Pack et al., 1997; Bahr et al., 1996; Nagakubo and Hirose, 1994; Luk et al., 1991, 1996; Nishi et al., 1986; Wang et al., 1999). The movement mechanism of climbing robots can be divided into walking (legged) mechanism, crawling mechanism, translation mechanism, and track mechanism. Robots with two (Pack et al., 1997; Bahr et al., 1996), four (Nagakubo and Hirose, 1994; Luk et al., 1991), six (Grieco et al., 1998), and eight (Luk et al., 1996) legs have been developed. The advantage of legged climbing robots is that they can move over

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rough surface and have a good obstacle-avoiding ability. However, the control system of the legged climbing robot is complicated because of using harmonic gait control. Meanwhile, the moving speed is low due to the discontinuous movement. Robots with the crawling mechanism move continuously and the speed can be subsequently improved greatly (Nishi et al., 1986; Wang et al., 1999). However, this kind of robot cannot handle cracks or obstacles, and the payload capacity is small. Our previous climbing robot, named Cleanbot I, which was developed for cleaning glasses of high-rise buildings (Tso et al., 2000), employed the translation mechanism. Its control strategy and process are not complicated due to the easy movement mode of sticking-moving-sticking. The disadvantage lies in the large size that hinders it from being used in narrow space. The movement of Cleanbot I is also discontinuous, and the speed is low too.

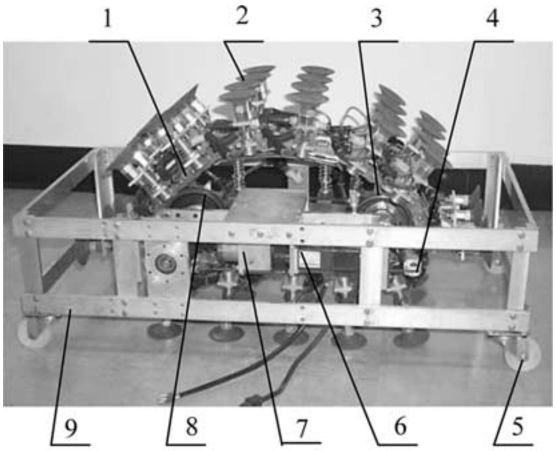
A new kind of climbing robot with the track mechanism, named Cleanbot II, has been recently developed by us. Using a chain-track, Cleanbot II can achieve continuous movement virtually. Suction cups (with the number of fifty-two) are used for adhesion purpose. With flexible structures, Cleanbot II can climb over an obstacle with a height less than 6 mm and track a circular path. This paper addresses certain important issues in developing Cleanbot II. Firstly, the structure design of the robot is described, which is followed by the vision-based motion control system. Then the turning gait is discussed. Finally, the safety measure and experimental results are analyzed.

2. Structure Design of Cleanbot II

Cleanbot II has been developed to move smoothly on horizontal, vertical, sloping, and overhead glass surfaces. The robot has a length of 720 mm, a width of 370 mm, a height of 390 mm, and a weight of 22 kg. The main structure is shown in Figure 1.

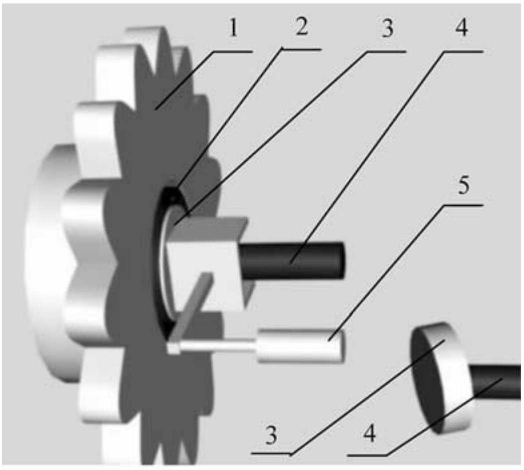
The robot employs a flexible chain-track as the locomotion mechanism. Compared with climbing robots with legged and translation mechanism, the chain-track robot can move more continuously, and hence the climbing speed can be improved subsequently. The maximum speed of Cleanbot I is 2–3 m/min, while the maximum speed of Cleanbot II can reach 8–10 m/min. The robot turns by twisting the chain, where the flexibility of the chain plays an important role.

Two wheels, both with diameters of 122 mm, are used to support the chain-track. The back one is used to drive the robot's movement, and the front one is used to steer the movement direction. The back wheel is connected with an AC motor by a harmonic drive with a reduction ratio of 126 : 1. The AC motor is with the model number MR-J2S-A (MITSUBISHI), selected for its small size, light weight, and satisfied power capacity (100 W). The front wheel is oriented by a double acting hydraulic cylinder. The turning angle of the front wheel is controlled by adjusting the pushing distance of the piston beam of the cylinder. The corresponding structure of turning the front wheel is illustrated in Figure 2, where shaft 1 is connected with shaft 2 by a joint (invisible) with which shaft 1 and the front wheel can rotate,



1. Chain-track 2. Suction cup
3. Front Wheel (steering wheel)
4. Cylinder 5. Castor Wheel
6. Servo Motor 7. Harmonic Drive
8. Back Wheel (driving wheel) 9. Frame

Figure 1. Main structure of Cleanbot II.



1. Front wheel 2. Bearing
3. Shaft 1 : fixed with front wheel
4. Shaft 2 : fixed with frame
5. Cylinder

Figure 2. Structure of turning the front wheel.

controlled by the steering cylinder. When the front wheel is aligned with the back wheel, the robot moves straightly. When the front wheel is turned by the cylinder, the robot changes its movement direction. In Cleanbot II, each chain node can be

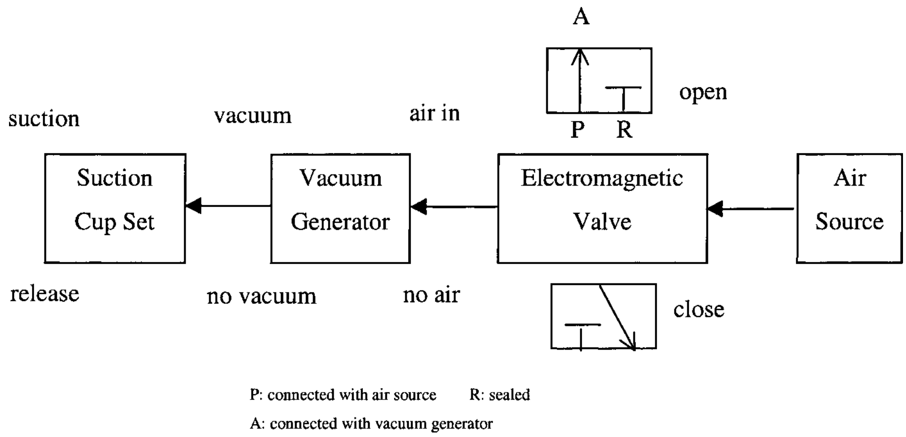


Figure 3. Connecting figure of pneumatic units.

twisted by 2.4 degrees, and the robot can track a circular path with radius of nearly 600 mm.

Amongst three adhesion methods, the magnet adhesion is a grasping device specially designed for the ferromagnetic surface, the thrust force is not satisfied in stability, while the vacuum pad is more suitable to climbing robots on the glass surface. Some climbing robots employ a big single cover, but these robots have a small payload capacity and cannot take heavy instruments to do service jobs. In Cleanbot II, the adhesion equipment utilizes thirteen suction cup sets fixed with the chain. Each set consists of four suction cups, and the diameter of each cup is 55 mm. The robot has a satisfied payload capacity of nearly 20 kg. Thirteen electromagnetic valves are used to control suction cup sets (suction/release). When a suction cup set comes into contact with the glass, the corresponding electromagnetic valve is open, which results in the connection of this suction cup set to the corresponding vacuum generator to suck the glass. When a suction cup set leaves the glass, the valve is closed and the suction cup set is released from suction. Figure 3 illustrates how the air source, the electromagnetic valves, the vacuum generators, and the suction cup sets are connected. At any moment, there are at least four sets sucking the glass surface so that an enough suction force is supplied to prevent the robot from falling, even if some leakage occurs in certain suction cups.

Since each valve is connected with the air resource, there exists the twisting problem caused by air pipes when the valves rotate with the chain. This problem can be solved by using a rotatable joint. One point of this joint is connected with the air source, and the other point is connected with valves by air pipes. This structure is similar to a parachute, illustrated in Figure 4. There is a spring around each rod which supports the corresponding suction cup set, as illustrated in Figure 5. The installation of springs helps robot move over an obstacle with a height less than 6 mm.

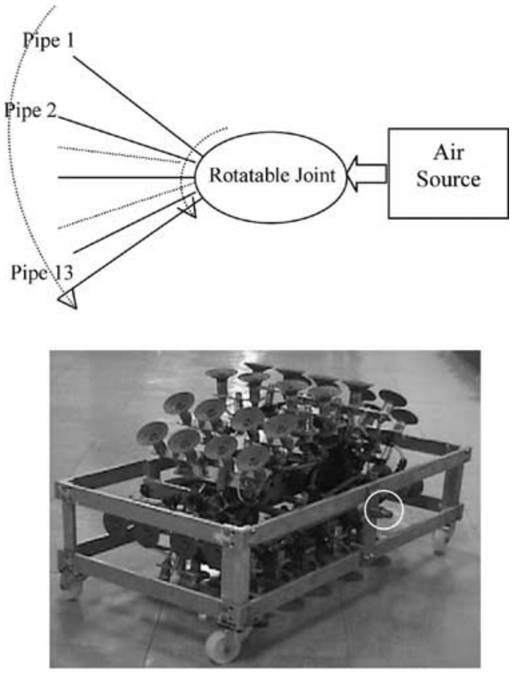


Figure 4. Illustration of the rotatable joint and air pipes.

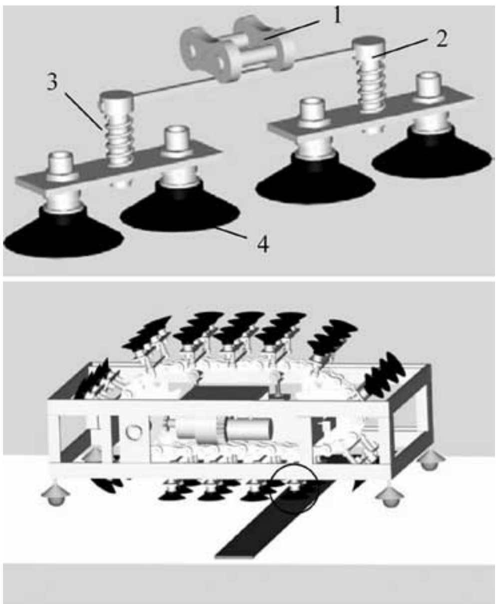


Figure 5. Obstacle-avoidance structure.

As shown in Figure 1, there are four castors to prevent the robot from leaning and increase the robot's stability.

3. Vision-Based Motion Control System of Cleanbot II

The control system is based on master and slave computers. The master computer is located on the ground and can be manipulated by the operator directly. The slave computer is embedded in the body of the robot. A control strategy is written into the slave CPU. Using the feedback signal of sensors installed on the robot, the movement and the posture of the robot can be controlled by the slave CPU, so that the robot can navigate on the glass-surface automatically. The master CPU obtains the information and identifies the status of the robot using the vision sensor or the communication between the master and the slave computers with a RS422 link. In case of the emergency, the operator (master CPU) can directly control the robot based on the actual situation. Figure 6 illustrates the proposed vision-based control system of Cleanbot II.

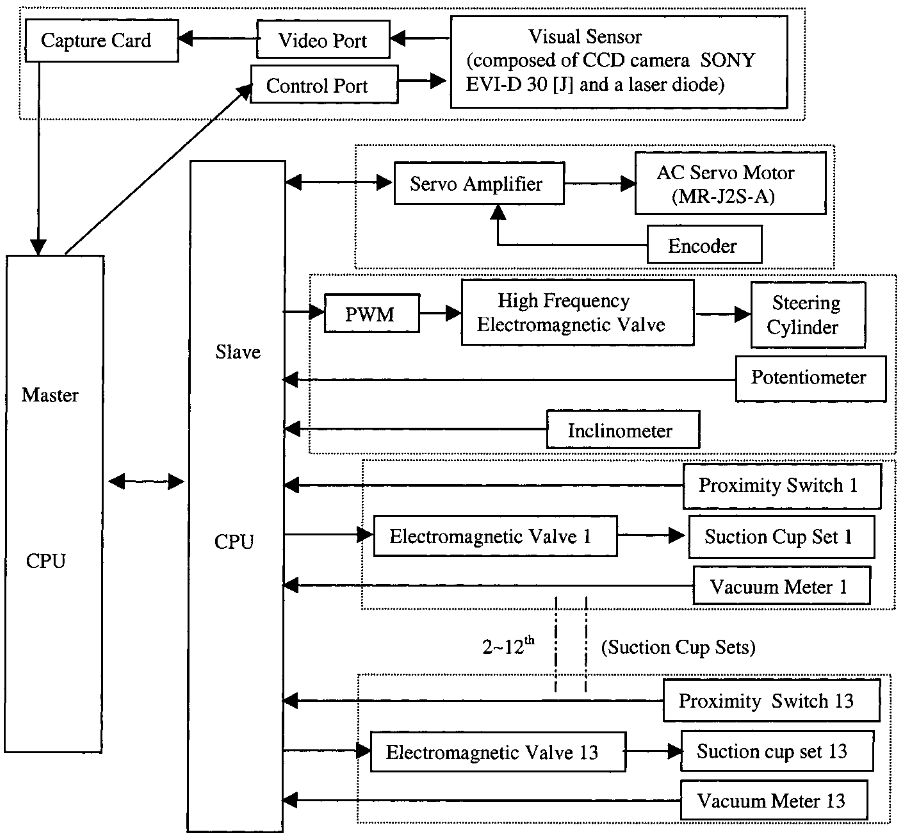


Figure 6. Vision-based motion control system of Cleanbot II

In Cleanbot II, the employed sensors and control modules are described in the following:

1. Vision system. The CCD camera SONY EVI-D30 (J) is used, whose posture with the pan angle (−100–100 degree) and the tilt angle (−25–25 degree) is controlled by the operator. With a capture card, the camera sends the video signal that can be displayed on the screen so that the operator watches the situation on the glass surface around the robot. At the same time, the camera with the assistance of a laser diode is used as a visual sensor to measure the distance between the robot and the glass frame. The laser diode, fixed with the lens of the camera, sends a concentrated laser light to the widow frame to generate a laser mark. The posture of the visual sensor can be adjusted to make sure that the laser light arrives at the window frame. According to the triangle measure theory, the distance between the camera and the window frame can be determined by analyzing pixel coordinates of the laser points in the image, on the basis of the relative position and posture between the camera and the laser diode.

2. Control of the robot configuration. The operator sends the desired speed signal to adjust the rotation speed of the motor and obtains the pulses from the encoder. The motive speed and the distance of the robot are obtained based on the number of pulses and the time consumed. The rotation angle of the front wheel depends on the pushing distance of the piston beam in the steering cylinder, as seen in Figure 2. This cylinder is connected with a high-frequency (HF) valve controlled by pulse-width-modulation (PWM). A potentiometer measures the rotation angle of the front wheel with respect to the frame of the robot. When the signal is ON, the HF valve is open, and the piston of the steering cylinder moves. When the front wheel achieves the desired angle, the signal is OFF, and the movement of the cylinder piston stops. An inclinometer is used to measure the attitude or the pan angle of the robot. Since the torsion and the gravity affect the movement of the robot especially when the robot turns or moves horizontally, the robot may deviate from the desired trajectory. The front steering wheel is controlled by a PID controller. Through tuning PID control gains, the motion error can be minimized.

3. Suction cup sets. Thirteen proximity switches are fixed with chain nodes and suction cups sets. When a suction cup set comes into contact with the glass surface, the corresponding proximity switch is vertical to the glass surface and sends a signal to the controller to open the corresponding electromagnetic valve, so that this suction cup set sucks the glass. When the suction cup set leaves the glass surface, the switch is not vertical to the surface and the suction cup set stops sucking. The vacuum meters measure the relative vacuum of the suction cups and check the safety of the robot. If the vacuum degree of the suction cup sets is less than −40 kPa, an alarm signal is sent to the operator.

In summary, with the above modules, the robot can climb over the glass surface successfully. In case that the robot climbs straightly and is far away from the window frame, the maximum speed can reach 5–10 m/min. In case that the robot turns or moves closely to the window frame, the speed reduces to be 1–3 m/min.

4. Turning Gait

Turning of the robot is an important ability required. The developed Cleanbot II robot can turn on a domestic window-pane, which has typically a length of 1.5 m and a width of 1.5 m. When the robot turns, the turning angle of the front wheel is different from that of the front chain node and the frame of the robot. Figure 7 shows the turning gait of the robot with steps from a to h. As can be seen in Figure 7, the thick line denotes the supporting rod by which the suction cup set is connected with the chain, the thin line denotes the chain, and the dotted line denotes the frame of the robot. The large circle denotes the suction cup, and the small one denotes the joint of each chain node.

Although the chain is flexible, it may be damaged if it is twisted too excessively. In Cleanbot II, each chain node can be twisted by 2.4 degrees, and the body of the robot turns as the chain nodes are twisted one after the other. The frame of the robot is connected with the front and the back wheels through two spherical joints.

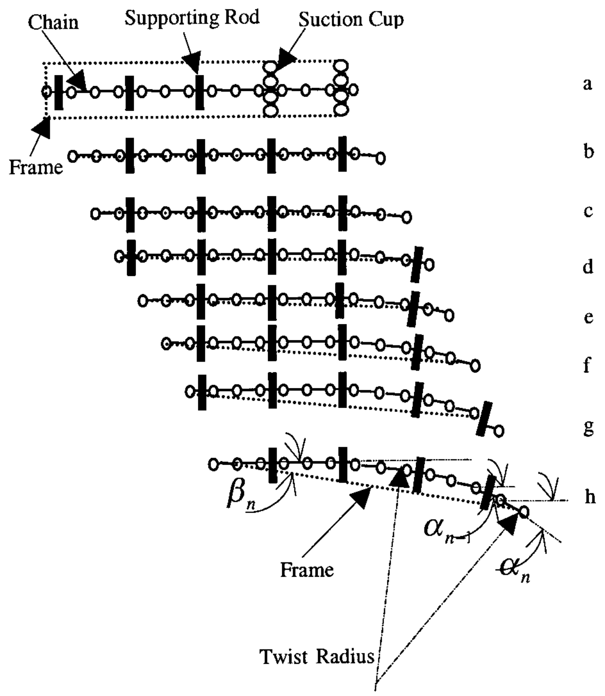


Figure 7. Turning gait of Cleanbot II.

Since the distance between the front and the back wheels approximately equals the length of thirteen node separation of the chain, at the thirteenth step, the back wheel arrives at the position of the first turning chain node and begins to turn. From this step onward, the back wheel follows the turning chain nodes to move forward step by step. The back wheel and the front turning chain node then turn the same degrees (2.4) per step, so that the body of the robot keeps the same posture in turning. In other words, from the thirteenth step, the frame of the robot turns 2.4 degrees per step, while the turning angle of the front wheel remains constant. There are close relations amongst the turning angles of the front wheel, the front chain node, and the frame. The turning angle of the nth chain node is represented by

$$\alpha_n = 2.4n. \tag{1}$$

For the step $n \leqslant 12$,

$$L \sin \beta_n = l(\sin \alpha_1 + \sin \alpha_2 + \cdots + \sin \alpha_{n-1}) + \frac{l}{2} \sin \alpha_n, \tag{2}$$

$$\beta_n = \arcsin \left[\frac{l}{L}(\sin \alpha_1 + \sin \alpha_2 + \cdots + \sin \alpha_{n-1}) + \frac{l}{2L} \sin \alpha_n \right], \tag{3}$$

where l denotes the length of each chain section, L denotes the distance between the front and the back wheel, and β_n denotes the turning angle of the frame at the nth step.

For the step $n > 12$,

$$\beta_{n+1} = \beta_n + 2.4. \tag{4}$$

At the first step, the front wheel turns 2.4 degrees, namely, $\gamma_1 = 2.4$.

For the step $n > 2$,

$$\alpha_n = \beta_{n-1} + \gamma_n, \tag{5}$$

where γ_n denotes the turning angle of the front wheel at the nth step. Thus, $\gamma_n = \alpha_n - \beta_{n-1}$.

The turning angles of the chain node, the frame, and the front wheel can be calculated based on (1) and (3)–(5). In Figure 7, step b illustrates that the first chain node turns 2.4 degrees, when the front wheel turns 2.4 degrees and the frame turns 0.18 degrees. Step c illustrates that the second chain node turns 4.8 degrees, when the front wheel turns 4.62 degrees and the frame turns 0.55 degrees. Step h illustrates that the seventh chain node turns 16.8 degrees, when the front wheel turns 12.94 degrees and the frame turns 5.13 degrees. Figure 8 shows turning angles of the front node, the frame, and the front wheel at each step. When the front wheel turns certain angles step by step, as shown in Figure 8, the chain nodes turns 2.4 degree one by one, and the robot tracks a circular path with radius of 600 mm. Turning of Cleanbot II is illustrated in Figure 9.

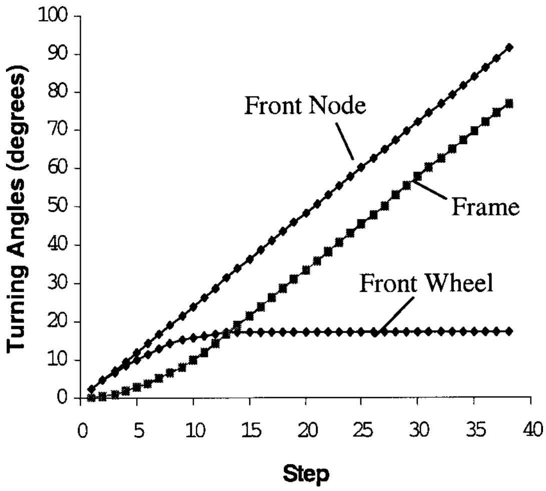


Figure 8. Turning angles of the front wheel, the front node, and the frame.

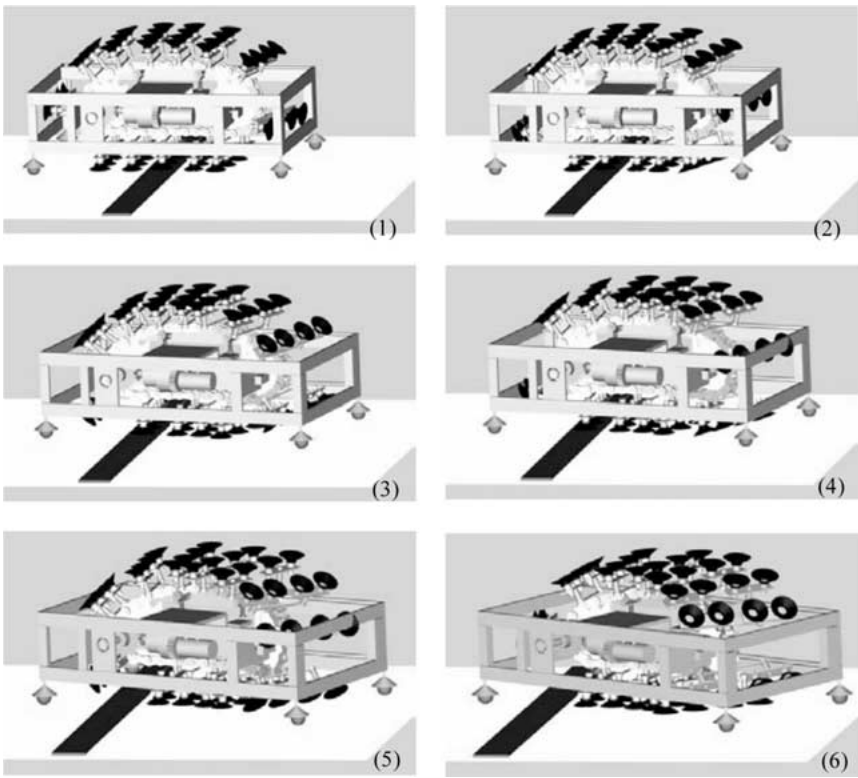


Figure 9. Illustration of turning of Cleanbot II.

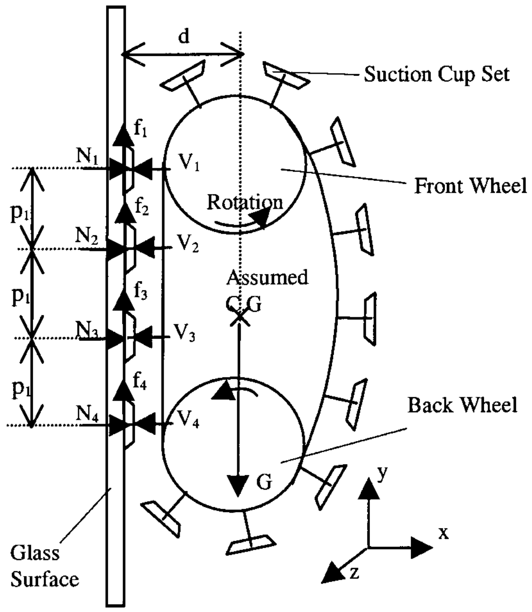


Figure 10. Forces applied to Cleanbot II when it sticks to the glass surface vertically.

5. Safety Analysis

The robot needs to carry special equipment for the service work. If the load of the equipment is too heavy, the robot may not be able to stick to the glass surface and fall from the work platform. Therefore, the loading capacity is an important issue for safety consideration.

5.1. THEORETICAL ANALYSIS OF THE LOADING CAPACITY

In order to investigate the loading capacity of Cleanbot II, forces applied to the robot must be analyzed. Figure 10 illustrates forces applied to Cleanbot II, when the robot sticks to the glass-surface vertically by suction cups. In Figure 10, the symbols are defined as follows:

N_i reaction force acting on the ith suction cup set, $i = 1, \dots, 4$,

V_i force acting on the ith suction cup set due to vacuum pressure, $i = 1, \dots, 4$,

f_i friction acting on the ith suction cup set, $i = 1, \dots, 4$,

G gravitational force of the robot and the additional load on the robot,

p_1 distance between two suction cup sets,

d distance between the center of gravity of the robot load combination and glass surface.

Ignoring forces acting on the free castor wheels, the force balance in the x-direction is represented by

$$\sum_{i=1}^{4} (N_i - V_i) = 0. \tag{6}$$

Assuming that vacuums of all suction cups are the same, the force acting on each suction cup set produced by the vacuum pressure is

$$V = V_i = sv, \tag{7}$$

where s denotes the suction area of each suction cup set, and v denotes the vacuum degree.

The force balance in the y-direction is represented by

$$G - \sum_{i=1}^{4} f_i = 0. \tag{8}$$

The moment balance around z-axis is

$$\sum_{i=1}^{4} (N_i - V_i)(i-1)p_1 = Gd. \tag{9}$$

Two dangerous circumstances may occur when the robot climbs over the glass-surface. One is slipping from the surface, and the other is falling from the surface due to detachment of the upper cups. There are certain constraints to determine forces N_i for the safety concern. We assume that forces acting on the first and the fourth suction cup sets in the x-direction form a force couple, and so do forces on the second and third suction cup sets. We also assume that forces acting on the first and the second suction cup sets are approximately the same. All assumptions can be expressed by the following equations:

$$N_1 - V_1 = -(N_4 - V_4), \tag{10}$$

$$N_2 - V_2 = -(N_3 - V_3), \tag{11}$$

$$N_1 - V_1 = N_2 - V_2. \tag{12}$$

Solving (6) and (9)–(12), the following equations can be obtained:

$$N_1 = V - \frac{Gd}{4p_1}, \tag{13}$$

$$N_2 = V - \frac{Gd}{4p_1}, \tag{14}$$

$$N_3 = V + \frac{Gd}{4p_1}, \tag{15}$$

$$N_4 = V + \frac{Gd}{4p_1}. \tag{16}$$

To prevent the robot from slipping off the glass surface, the following condition must be satisfied

$$G \leqslant F_f = N\mu, \tag{17}$$

where μ denotes the frictional coefficient, and N denotes the reaction force at the contact surface, which satisfies

$$N = \sum_{i=1}^{4} N_i. \tag{18}$$

Considering (6), we have

$$N = \sum_{i=1}^{4} V_i = 4V. \tag{19}$$

Substituting (19) into (17) yields the following equation

$$G \leqslant 4\mu V. \tag{20}$$

To prevent the robot from falling off the glass, the following condition must be satisfied

$$N_i \geqslant 0, \quad i = 1, \dots, 4. \tag{21}$$

Then, we have

$$G \leqslant \frac{4Vp_1}{d}. \tag{22}$$

From (20) and (22), the condition to prevent the robot from falling and slipping, when the robot sticks to the glass surface vertically, is given by

$$G \leqslant \min(f_{v1}, f_{v2}), \tag{23}$$

where $f_{v1} = 4\mu V$ and $f_{v2} = 4Vp_1/d$.

In a similar manner, the condition to prevent the robot from falling and slipping, when the robot sticks to the glass surface horizontally, can be obtained as follows

$$G \leqslant \min(f_{h1}, f_{h2}), \tag{24}$$

where $f_{h1} = 4\mu V$, representing the maximum weight of the robot system without slipping off the glass surface, and $f_{h2} = 4Vp_2/d$, representing the maximum weight of the robot system without falling from the glass surface, in which p_2 denotes the distance between every two adjacent suction cups within the same suction cup set.

When the robot turns, the condition to avoid falling and slipping is given by

$$G \leqslant \min(f_{t1}, f_{t2}), \tag{25}$$

where

$$f_{t1} = 4\mu V \quad \text{and} \quad f_{t2} \leqslant \frac{4Vp_1p_2}{d\sqrt{p_1^2 + p_2^2}}$$

representing the maximum weights of the robot system without slipping and falling, respectively.

From (23)–(25), we conclude that the distance between the gravity center of the robot system and the glass surface, denoted by d, is an important safety factor for a climbing service robot. The longer the distance, the more likely it is to fall. Therefore, in the direction vertical to the glass surface, the location of the installing service equipment, such as cleaning systems and assistance equipment etc., should be considered accordingly. The payload should be placed as close to the bottom surface as possible to reduce the torsion caused by the gravitational force. On the platform parallel to the glass surface, the location of the payload is an important factor to affect the allocation of forces executed to the suction cup system. The gravity center of the payload is suggested to be close to the central position of the robot. This makes the forces applied to the suction system symmetrical and thus equally allocates the effect of the torsion and the gravity to each couple of suction cups. Otherwise, some suction cups may be executed larger forces than the others, and are more likely to detach from the glass surface.

The dimensions of Cleanbot II are $p_1 = 78$ mm, $p_2 = 76$ mm, and $d = 180$ mm. The typical frictional coefficient between the glass and the suction cup is $\mu < 0.3$. As a result,

$$f_{v1} < f_{v2}, \tag{26}$$

$$f_{h1} < f_{h2}, \tag{27}$$

$$f_{t1} < f_{t2}. \tag{28}$$

It is seen from (26)–(28) that the maximum weight of the robot system without slipping is less than that without falling. This implies that slipping may happen to Cleanbot II robot prior to falling off the surface. Therefore, the safety condition of (23)–(25) becomes

$$G \leqslant 4\mu V \tag{29}$$

which can also be expressed as

$$G \leqslant \frac{V_{\text{total}}}{\lambda}, \tag{30}$$

where $V_{\text{total}} = 4V$, representing the total suction force acting on the robot by the suction cups, and $\lambda = 1/\mu$, is defined as the 'safety measure' of suction cups.

5.2. EXPERIMENT

An experiment was carried out to evaluate the safety measure of Cleanbot II and the loading capacity of the suction cup system with respect to the glass-surface.

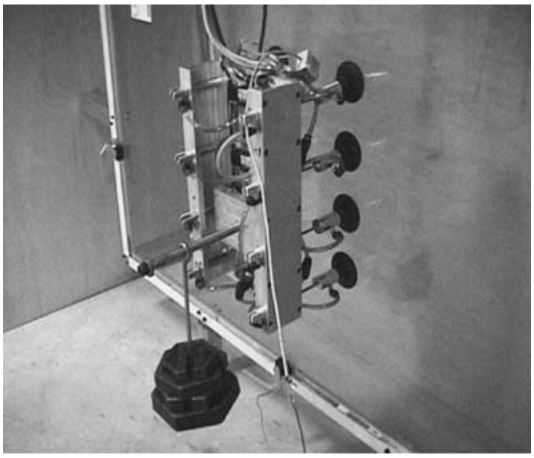


Figure 11. Experimental setup to measure the loading capacity.

Table I. Safety loading test results

Vacuum value (−kPa)	25	31	40
Max allowable provision (kg)	12.3	14.1	15.0
Falling/Slipping	Slipping	Slipping	Slipping
Vacuum value (−kPa)	51	67	82
Max allowable provision (kg)	18.0	18.7	19.5
Falling/Slipping	Slipping	Slipping	Slipping

Figure 11 shows the experimental setup. Electromagnetic valves are used to control suction cups. Vacuum generators produce various vacuum negative pressure. The vacuum value, measured by a vacuum meter, is adjusted progressively from −25 to −82 kPa. As the absolute value of the vacuum's pressure increases, the load that the robot can stand increases. If the load is too heavy to be held by the suction cups, the experimental platform drops down from the glass. Table I illustrates the safe loading test results. It is observed from the experiment that the common hazard caused by the excessive loading is slipping off rather than falling from the glass surface.

The relationship between the suction force and the safe loading capacity is shown in Figure 12. It is seen that doubling the suction force from −25 kPa to −50 kPa results in about 46% increment in the safe loading, and doubling the force from −40 kPa to −80 kPa results in about 27% increment. Hence, it is more cost-effective to produce a lighter-weight robotic system.

From (30), the safety measure of the suction cups is

$$\lambda = \frac{V_{\text{total}}}{G_{\max}}, \tag{31}$$

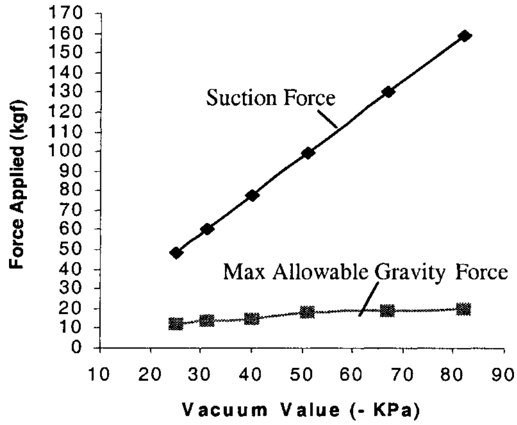


Figure 12. Suction force and max allowable gravity force.

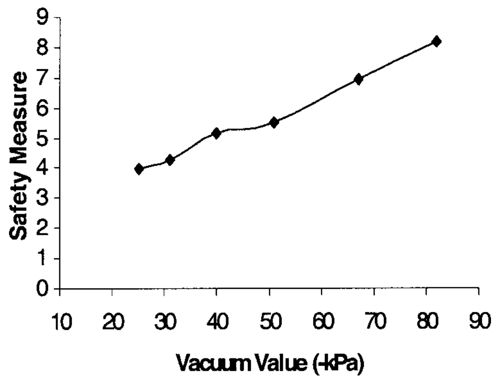


Figure 13. Safety measure of suction cups.

where $G_{\max}$ denotes the maximum weight of the robot system without slipping and falling.

Figure 13 illustrates the safety measure with different vacuum values. As the absolute value of vacuum's pressure increases, the safety measure increases. When the vacuum value reaches -82 kPa, the safety measure is nearly 8.

Once the loading capacity of the robot is determined, it is advisable to establish the allowable payload based on the accepted safety measure (8 in this case). The robot payload capacity can then be obtained using the following equation

$$G_p = \frac{V_{\text{total}}}{\lambda} - G_r, \tag{32}$$

where G_r denotes the weight of the robot itself.

In Cleanbot II, at any moment there are at least 16 suction cups sticking on the glass-surface. The vacuum applied to suction cups is -80 kPa. According to (32), the robot can carry up to 26.5 kg. It is safe for the robot to carry a cleaning equipment up to 26.5 kg.

6. Conclusions

This paper describes a tracked climbing robot with vacuum suction cups supplying adhesion forces to make the robot stick to the glass surface. The main structure, the actuation, and the vision-based motion control system of the robot are introduced. The robot has a length of 720 mm, a width of 370 mm, a height of 390 mm, and a mass of 22 kg. With a steering cylinder, the robot can track a circular path by twisting the flexible chain. The turning gait of the robot has been discussed, and the relations amongst turning angles of the chain node, the front wheel, and the frame have been formulated. Safety analysis has been performed to obtain conditions that prevent the robot from slipping and falling off the platform surface. The safety measure of suction cups is important for the payload capacity of the robot. The experiment shows that the safety measure of the developed Cleanbot II should be set at 8 or a higher value. Cleanbot II can carry a cleaning mechanism with the mass of 25 kg.

Acknowledgements

The work described in this paper was partially supported by a grant from the Research Grants Council of the Hong Kong Special Adminstrative Region, China [Project No. cityu 1085/01E], and a grant from City University of Hong Kong (Project No. 7100211).

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