Development of a Climbing Robot with Vacuum Attachment Cups


*Titu Maiorescu* University, str. Dâmbovnicului, nr. 22, 040441 Bucharest, Romania, E-mail: apostolescucatalin@yahoo.com

**Mechatronics and Precision Mechanics Department, "Politehnica" University of Bucharest, Spl. Independentei 313, 060042 Bucharest, Romania

Abstract

The problem of a wall-climbing robot is holding on the wall. There are many factors, which effect in holding, all forces, robot movement and mechanical design. In this paper an autonomous mobile robot, which moves on horizontal and vertical surfaces using an electro-pneumatically vacuum cups attachment system is presented. The original robot construction, developed as a cleaning robot, includes two triangular platforms that provide a light weight. The system modelling and simulation were performed by means of SolidWorks – Cosmos Motion software package. The robot driving is ensured by a command system developed using LabView software facilities.

Keywords

Mechatronics concept, climbing robot, cleaning, vacuum fixing, electro-pneumatic actuation.

Introduction

By its nature, the theoretical and experimental research in the field of robotics has an interdisciplinary character specific to the mechatronics concept through which mechanics, electronics and informatics are sinergically integrated.

Wall-climbing robots are helpful systems for various applications on vertical surfaces. Wall cleaning for buildings is one of the areas which is expected to obtain a strong benefit from these robots. The most common attachment principle is the vacuum adhesion [1]-[3], where the robot carries an onboard pump to create a vacuum inside the cups, which are pressed against the wall. This system enables the robots to adhere on any type of material, with low energy consumption. The vacuum adhesion is suitable for usage on smooth surfaces, because the roughness can influence a leakage loss in the vacuum chamber such as suction cup.

The mobile robots endowed with platforms and legs with cups are widely spread in practical applications due to high relative forces of locomotion, mobility and good suspension. The disadvantage of increased overall size less disturbs in applications of cleaning and inspection of large vitrified surfaces covering the buildings [4].

A new generation of cleaning robots based on all-pneumatic technology is on study [5].

The objective of this research was to develop a robot of small sizes and reduced weight for window cleaning. The novelty of the approach consists of the robot capability to move on vertical surfaces, which involves basic studies enlarging the horizon of knowledge related to: displacement cinematic structures, robot leg anchoring solutions, actuating solutions, as well as control system of such robots.

Climbing robot construction

The autonomous robot, which is the subject of a vast research work [6], is shown in two positions in Figure 1: robot placed on a horizontal surface (a) and robot placed on a vertical surface (b).

As shown, the fixing system consists of six suction cups, three for each of the two triangular platforms through which the cinematic operating scheme ensures horizontal or vertical movement of the robot.

Platform 5, that is the nearest to the support surface, will be referred to as the interior platform and the other platform 2 will be the exterior platform. For the interior platform are used the suction cups 4 and for the exterior platform - suction cups 1.

Other components are the followings: motor-reduction gear 3 for controlling linear motion of the platforms, electro valves 6 and 11 for controlling vacuum in suction cups, vacuum micro pump 7, motor-reduction gear 8 for controlling rotation motion of the platforms, motor-reduction gear 9 for controlling motion of suction cups of the interior platform, motor-reduction gear 10 for controlling motion of suction cups of the

To obtain an autonomous robot, the electric actuation of all degrees of freedom was chosen, as well as for the depressurization of the cups. An original driving system was introduced for the moving of robot legs. The system uses screw mechanisms synchronized by a toothed belt transmission. The developed system for the relative translation of the platforms contains a ball guide way of reduced size and good guiding accuracy. The use of a rack mechanism allows a compact and fast actuation. The rotation of the robot is achieved by modifying

![Figure 1: 3D Model of the robot placed on horizontal surface (a) and vertical surface (b)](image)

extrior platform.
the relative angular position of the two platforms.

The cinematic scheme of the robot is presented in Figure 2: 1, 9 - vacuum cups; 2, 8 - screw mechanisms; 3 - exterior platform (PLE); 4, 6 - toothed driving belts; 5 - shaft; 7 - interior platform (PLI); 10 - guiding part; 11 - rolling guide way; 13 - rack; 14 - gear; $M_1R_1$, $M_2R_2$, $M_3R_3$, $M_4R_4$ - motor-reduction gears; $m_1$ - raising and lowering of PLI legs; $m_2$ - raising and lowering of PLE legs; $m_3$ - orienting rotation; $m_4$ - translation between platforms.

![Figure 2: Cinematic scheme of robot](image)

The pneumatic diagram used for reducing the pressure inside the cups of the robot legs, in order to ensure the contact force when vacuumed suction cups adhere on the surface to be cleaned, is presented in Figure 3: $PV$ - vacuum micro pump (NMP 015 B – KNF Neuberger); $Ac$ - tank; $EM1$, $EM2$ - electromagnets for the electro valve operating; $V1$, $V2$, $V3$ - suction cups for the interior platform; $V4$, $V5$, $V6$ - suction cups for the exterior platform; $D$ - depression; $A$ - atmospheric pressure.

![Figure 3: Pneumatic diagram](image)

Although the robot attaches itself to the glass surface vacuum suction cups, a significant miniaturization was achieved. The overall sizes of the robot, 350 x 350 x 220 mm, prove that degree of miniaturization is optimal, also presenting a high quality of autonomous movement.

The main parameters of the robot (Figure 4) are:
- triangular platform side length $L = 247$ mm, corresponding to a stroke $S$ of about $100...110$ mm;
- full cycle for a translation step: $200...220$ mm;
- maximum angle of relative rotation between platforms: $30^\circ$;
- duration of a cycle: $8$s;
- depression $\Delta p = 0.57$ bar;
- diameter of the vacuum cups (ESS 50 – FESTO type): $50$ mm;
- normal detachment force: $86$ N;
- lateral detachment force: $110$ N;
- cup raising and lowering speed: approx. $6$mm/s.
An important part of the research concerned with the robot fixing on the vacuum cups. In order to establish their bearing capacity, the cups were subjected to external (normal, lateral and combined) loads. Tests were performed for different depressions. The influence of the different supporting (cleaned) materials was also studied, as well as the behaviour of the cup in presence of different liquids on the surface.

Force determinations with $\Delta p = 0.57$ bar using the pump NMP 015 B from the robot were performed, Figure 5. The results are useful for supporting simulation on the robot legs. The characteristic in this case, for glass surfaces, is shown in Figure 6.

Regarding the force determinations on wet surfaces, the characteristic shape is maintaining, but with some differences of the values. The cup behaviour at wetting with water diminishes a little the performance, because water is eliminated during the connection on the surface, in the contact zone of the cup. An enhanced reduction of the force can be observed at wetting with detergent, which persists partially after connecting.

The maximum detachment force values for the conditions from above, at different depressions, are given in Figure 7. A more substantial reduction of cup capacity, only for wetting with detergent (of about 6 %), was found.
Figure 6: Cup behaviour on glass for different conditions: 
- **FSt06** – dry surface,
- **FstUd06** – wet surface with water,
- **FstDet** – wet surface with detergent for window washing

Figure 7: Cup detachment force from glass for different conditions: 
- **Fd** – dry surface,
- **FdUd** – wet surface with water,
- **FdDet** – wet surface with detergent for window washing

**Modelling and simulation of the robot displacement relative to the cups**

As the robot functions are in a sequential mode, the simulations can be performed separately for translations and rotations [7]. Simulations are obtained with Cosmos Motion program attached to SolidWorks software. The robot displacement relative to the cups is the displacement of one platform related to the other platform on whose cups the robot fixing was made. The simulation results are similar for both PLE and PLI because the movable masses are similar. A parabolic variation was imposed for the acceleration. The numerical values for simulation are the followings: 
- $n_{max} = 4280$ rot/min (maximum rotation speed of the motor),
- $v_{max} = 5$ mm/s (maximum translation speed),
- $a_{max} = 20$ mm/s$^2$ (maximum acceleration),
- $t_{ac} = 0.19$ s (acceleration time),
- $t_{reg} = 1.22$ s (displacement time with constant speed), and
- $t_{tot} = 2 \cdot t_{ac} + t_{reg} = 1.6$ s (periodic time of the full movement). Figures 8, 9, and 10 present the simulation results for acceleration, velocity, and displacement. From Figure 10, the stroke $\Delta S = 20$ mm was checked.

The variation of the instantaneous power during the robot translation relative to the cups results from Figure 11. The maximum value of the instantaneous power can be consequently computed: $P_{r, i} = 0.56$ W. Considering the losses at the motor level, the necessary power at the exit of the driving motor was determined as equal to $P_{M, tr c} = 4.49$ W. This is ensured by that one of 6.5 W of the chosen motor. The results of all simulations
have been used in dimensioning and choosing of the driving motor-reduction gears $M_1R_1 \ldots M_4R_4$ (MAXON type). They were validated by experimental data, performed on the actual experimental model of autonomous mobile robot.

Figure 8.: Acceleration variation during the robot translation relative to the cups

![Figure 8](image1.png)

Figure 9: Velocity variation during the robot translation relative to the cups

![Figure 9](image2.png)

Figure 10: Displacement variation during the robot translation relative to the cups

![Figure 10](image3.png)
Control of the robot

The robot can be controlled with a data acquisition board 7344 National Instruments and LabView programming or with microcontrollers. The microcontroller BS2 (Parallax) is used, easy to program but with a number of limitations concerning the control of motor speeds.

Using a data acquisition board allows introducing home switches for each of four servo axes in order to find the reference position. For axis 1 (robot translation) and axis 4 (orienting rotation), home switches are mounted between the limiting micro switches. For axes 2 and 3, representing cup translations for PLE and PLI, respectively, micro switches are used only as stroke limit. The reference position is found with the help of a photoelectric system, as shown in Figure 12. The system consists of a light stop 6 fixed on the mobile plate 4 whose displacement s gives the position of the cups. The light stop moves between the sides of the photoelectric sensor 2 (of type OPB 916).

Figure 11: Instantaneous power variation during the robot translation relative to the cups

Figure 12: Photoelectric system used in order to establish the reference position of axes 2 and 3. 1 – corner support; 2 – photoelectric sensor; 3 – rod for movement obstruction; 4 – plate attached to the mobile rod; 5 – mobile rod; 6 – light stop; 7 – microswitch.

Figure 13 presents the scheme of the photoelectric system used to determine the reference position. When the light stop reaches the optical axis of the sensor, the state of its output changes. The emitter diode is supplied through the resistor R_a for current limitation. A power amplifier OPB916 is connected at the circuit
output. The suppressor diode $D_s$ protects the transistor during its disconnection. Connection to the data acquisition board is made through the NO contact of the relay $Rel$.

![circuit_diagram](image_url)

Figure 13: Scheme of the photoelectric circuit

The LabVIEW software program that allows founding the home switch is shown in Figure 14. The activation of limit switches is also needed during the search. After the reference is found, the position counter is reset. The program is applied for each of four axes of the acquisition board.

![labview_program](image_url)

Figure 14: LabVIEW program for founding the home switch: 1 – maximum speed load; 2 – acceleration load; 3 – deceleration load; 4 – elements of curve S (kinematics without jerk); 5 – home switch use; 6 – while type cycle; 7 – reading of search state; 8 – delay producing; 9 – position counter reset; 10 – sequential cycle with two sequences; 11 – search settings; 12 – reading of different interrupt situations; 13 – end cycle condition; possible errors indication of possible errors

The programs consists of two sequences introduced by the cycle 10. The first one searches the reference position and the second resets the position counter (subVI 9).

The subVI 1 loads the maximum search speed and performs axis selection. The subVIs 2 and 3 load the maximum acceleration and deceleration. The subVI 4 defines the movement kinematics (S curve of the speed). A while type cycle is introduced. The subVI 7 reads the state of the search. The subVI 12 seize various interruption cases. The subVI 13 stops the cycle.

In order to clean glass surfaces, the robot must cover the whole window area, paying especial attention to corners. The main control program of the robot controls the travel on the vitrified surface by horizontal and vertical movements, as well as by rotations that allow changing the direction. An ultrasonic PING sensor (Parallax) was introduced as decision element for changing the direction and stopping. The sensor is mounted on the PLI platform using the corner 3 and the jointed holder 2, as shown in Figure 15.
Figure 15: The ultrasonic sensor mounted on the interior platform: 1 – sensor; 2 – sensor holder; 3 – corner; 4 – interior platform PLI of the robot.

Figure 16 presents a sequential cycle of travel. The cycle consists of the following sequences:
0. sequential translation from left to right. This sequence ends at the appearance of the signal (given by the sensor S) of proximity of the rim from right side;
1. clockwise rotation with 90°;
2. lowering with a step;
3. clockwise rotation with 90°;
4. sequential translation from right to left. This sequence ends at the appearance of the signal (given by the sensor) of proximity of the rim from left side;
5. counterclockwise rotation with 90°;
6. lowering with a step;
7. counterclockwise rotation with 90°.

Figure 16: Travel cycle of the robot.

The robot covers the whole window area by repeating the travel cycle. The robot stops if the sensor S sends the signal of proximity of the bottom rim of the vitrified surface.
The block diagram of the program is shown in Figure 17.

Figure 17: Block diagram of main control program of the robot: 1 - setting port 1 as output; 2 - setting port 2 as input; 3 - initialization of local variable; 4 - boolean local variable; 5 – while cycle of the travel program; 6 – travel stop; 7 – first order while cycles; 8 – sequences of the first order cycles; 9 – sequences of the first order cycles

The program uses the ports 1 and 2 of the acquisition board. The port 1 is used as program output, sending the commands towards the electro valves. The port 2 is used as input, receiving the signal from the sensor $S$. The control 3 initializes the boolean local variable as “False”. The variable changes its state to “True” during vertical displacement. The signal from the sensor $S$ is used also for stopping the horizontal translation sequences.

Conclusions

Some aspects regarding design and control of a prototype of climbing autonomous robot with vacuum attachment cups, for cleaning operations on vitrified surfaces, are presented. An optimal degree of miniaturization, and at the same time, a high quality of autonomous movement is ensured. The modelling and simulation of the robot functioning certifies that its performances are comparable to similar solutions conceived worldwide.

References


