Design and Control Aspects of a Climbing Robot with Vacuum Cups Attachment System

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Abstract: The paper presents some design and control aspects of an autonomous mobile robot, which moves on horizontal and vertical surfaces using an electro-pneumatically vacuum cups attachment system. 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 control is obtained with the motion data acquisition board 7344 from National Instruments and LabView programming support.

Keywords: climbing robot, cleaning, vacuum cups, pneumatics, robot design, mechatronics concept.

1. INTRODUCTION

The objective of this research was to develop a robot of small sizes and reduced weight for window cleaning.

A prototype of such a robot has been achieved, e.g. Miyake T. et al. (2006). Its dimensions are approximately 300 x 300 x 100 mm and the weight is of about 3 kg. The prototyped robot consists of two independently driven wheels and an active suction cup. The control system that includes a movement direction controller using an accelerometer and a traveling distance controller using a rotary encoder and edge sensors was installed for autonomous operation.

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, e.g. Sun D.et al. (2007).

The robot system consists of the cleaning mobile robot, the supporting vehicle, a compressor and computers (master - slave). The master one is placed on the supporting vehicle. The slave part controls the position and the movement of the robot for an autonomous navigation. Systems of viewing and ultrasonic sensors equip the robot.

A new generation of cleaning robots based on all-pneumatic technology is on study, e.g. Belforte G. et al. (2005).

Three main fields as motion, cleaning and drying are taken in consideration. Referring to motion, a new design using pneumatic cylinders as structural elements was tested. Implementation of a control made with digital valves has permitted to reduce costs, decrease setup times and obtain a unit, which can be easily reconfigured for various applications. The developed vacuum cups allow the unit to stick itself on surfaces even if dirty or wet.

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.

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.

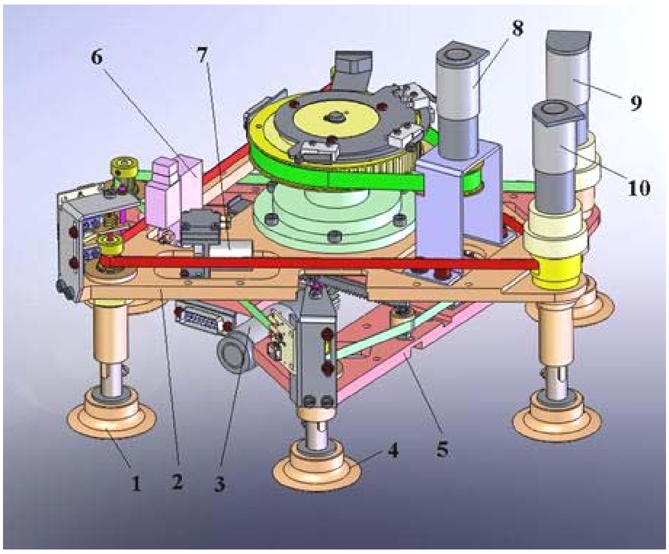
2. ASPECTS OF ROBOT DESIGN AND CONTROL

The autonomous robot, which is the subject of a vast research work, Apostolescu, T.C. (2010), is shown in two positions in Fig. 1: robot placed on a horizontal surface (fig. 1a) and robot placed on a vertical surface (fig. 1b).

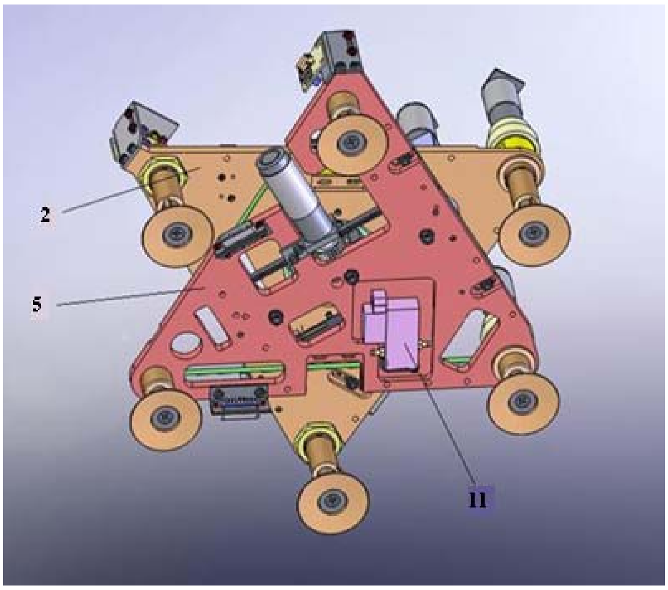
As shown, the fixing system consists of six suction cups, three for each of the two triangular platforms through which the cinematic operating scheme ensures horizontal or vertical movement of the robot.

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 of Fig. 1 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 exterior platform.



a)



b)

Fig. 1. 3D Model in SolidWorks of the robot placed on: an horizontal surface (a) and a vertical surface (b).

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 the relative angular position of the two platforms.

The cinematic scheme of the robot is presented in Fig. 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.

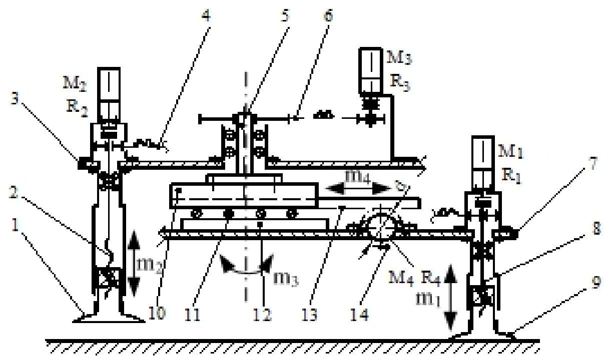


Fig. 2. Cinematic scheme of robot.

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.

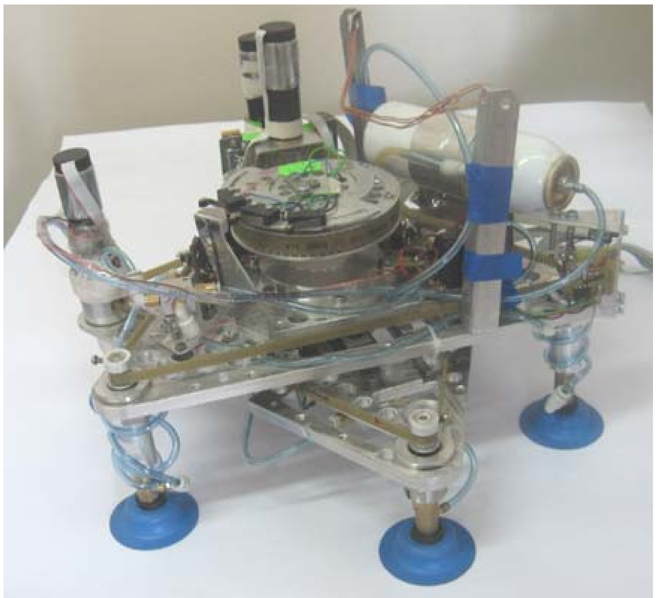


Fig. 3. Photo of the autonomous mobile robot used for cleaning operations.

The main parameters of the robot (Fig. 3) 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: 30º;
- duration of a cycle: 8s;
- depression Δp = 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. 6mm/s.

2.1 Pneumatic diagram used to ensure vacuum adhesion

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 Fig. 4: *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.

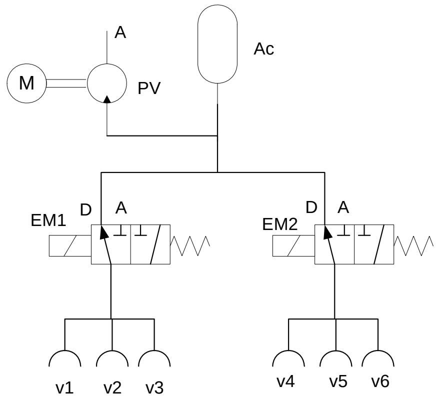


Fig. 4. Pneumatic diagram.

2.2 Cup behaviour under external force

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 Δp = 0.57 bar using the pump NMP 015 B from the robot were performed, Fig. 5. The results are useful for supporting simulation on the robot legs. The characteristic in this case, for glass surfaces, is shown in Fig. 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 Fig. 7. A more substantial reduction of cup capacity, only for wetting with detergent (of about 6 %), was found.

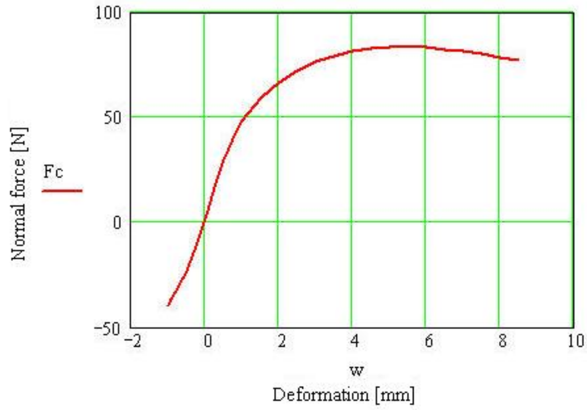


Fig. 5. Cup characteristic for Δp = 0.57 bar.

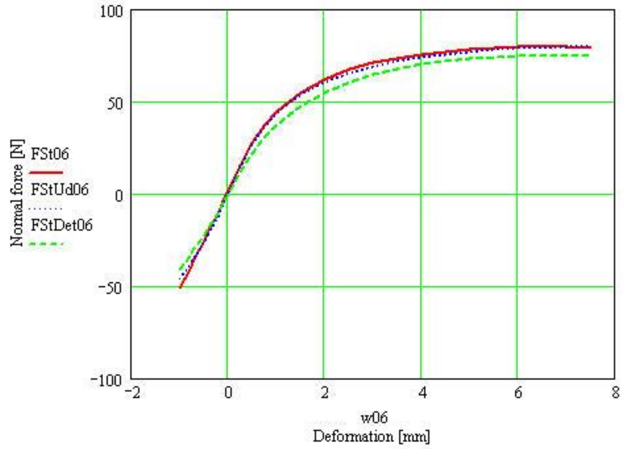


Fig. 6. Cup behaviour on glass for different conditions: *FSt06* – dry surface, *FstUd06* – wet surface with water, *FstDet* – wet surface with detergent for window washing.

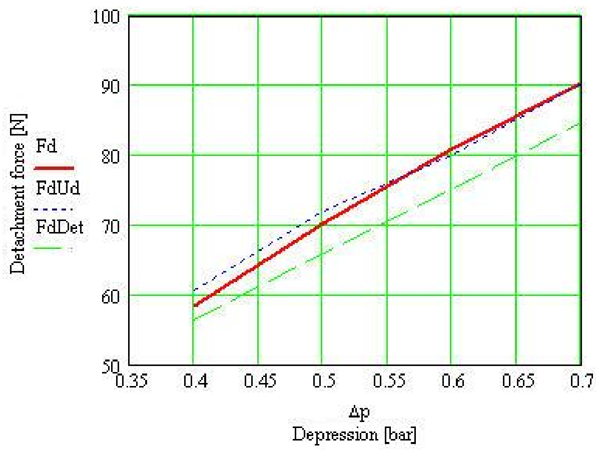


Fig. 7. Cup detachment force from glass for different conditions: *Fd* – dry surface, *FdUd* – wet surface with water, *FdDet* – wet surface with detergent for window washing.

2.3 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, Alexandrescu, N. et al. (2010). 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: $n_{M\ max}$ = 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 $t_{tot} = 2\ t_{ac} + t_{reg}$ = 1,6 s (periodic time of the full movement).

Figures 8, 9, and 10 present the simulation results for acceleration, velocity, and displacement. From Fig. 10, the stroke ΔS = 20 mm was checked.

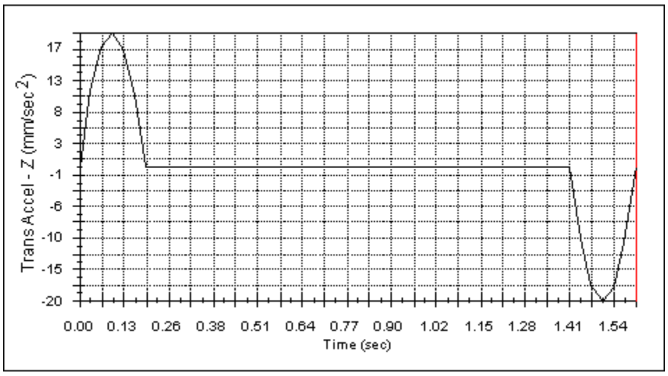


Fig. 8. Acceleration variation during the robot translation relative to the cups.

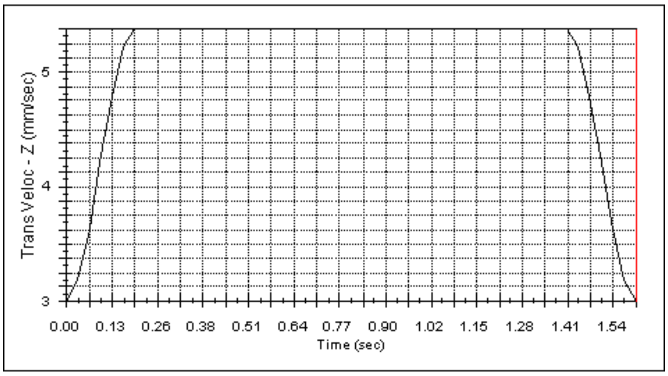


Fig. 9. Velocity variation during the robot translation relative to the cups.

The variation of the instantaneous power during the robot translation relative to the cups results from Fig. 11. The maximum value of the instantaneous power can be consequently computed: $P_{tr\ c}$ = 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 $M_1R_1 \dots M_4R_4$ (MAXON type). They were validated by experimental data, performed on the actual experimental model of autonomous mobile robot.

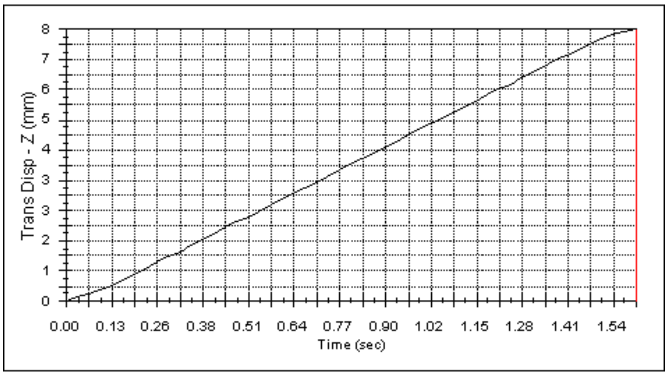


Fig. 10. Displacement variation during the robot translation relative to the cups.

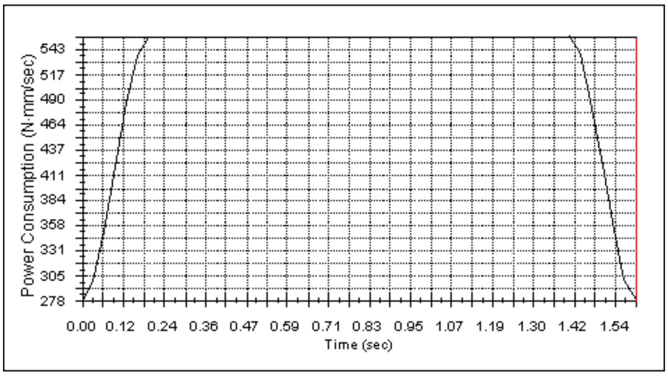


Fig. 11. Instantaneous power variation during the robot translation relative to the cups.

2.4 Precision of axial positioning of the cups

The actual positioning of robot relative to the vertical supporting surface is given both the cup deformation and the errors that appear:

- errors of the mechanisms for cup actuating (cinematic errors, clearances, deformations of different elements, whose sum is of 0.075 mm);
- errors of the actuating system.

As concerns the motor driving, it can be made by means of a data acquisition board with connections to a PC or, using a simplified system – as in case of a microcontroller, with stroke limiting micro switches. By taking advantage of the controlling board on axes (for example, 7344 National Instruments), the encoders (increment angular transducers) that equip the motor-reduction gears can be used. The control system needs a “home” transducer in order to create a reference position. In a practical way, an adjustable photoelectric sensor is inserted inside of the cinematic chain of cup stroke. The start-stop commands are performed numbering the impulses given by the encoders and comparing them with the programmed values from PC. The errors of this type of command are due to the error of evaluating the “home” position and encoder error. Considering ε_{home} = 0.05 mm, ε_{cmd1} = 0.1 mm results (the influence of encoder error is negligible).

For simplified version with microcontroller, errors of position adjustment and of switching appear. ε_{cmd2} = 0.15 mm results in this case. The control system using micro switches at stroke ends, simpler and easer to be adapted to the command through microcontroller, is less precise, but much more efficient.

Summarizing all the errors from above, the error of axial positioning of the cups for one platform, ε_{c1} = 0.225 mm is obtained. For both platforms, the total error is ε_c = 0.450 mm. It was found that the total error of axial positioning of the cups does not exceed 0.5 mm. This error is easy to be compensated within the stroke of 5 mm, which the actuating systems of both platforms ensure for all the cups.

2.5 Control program of the robot

The program has used LabView software, which can be easily correlated with data acquisition board from National Instruments. The board allows introduction the switches of reference position (home switch) for each of four servo axes. Axis 1 (robot translation) and axis 4 (orienting rotation) are endowed with micro switches of reference position, practically placed between the limiting micro switches. For axes 2 and 3, which represent cup translations for PLE and PLI, respectively, micro switches are used only as stroke limit. Scheme of the photoelectric system used to determine the reference position is given in Fig. 12.

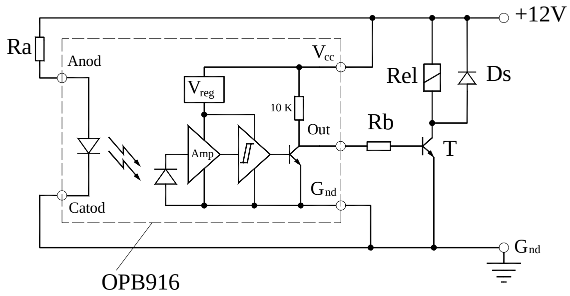


Fig. 12. Scheme of photoelectric circuit.

LabView program for founding “home switch” is shown in Fig. 13: 1 – maximum speed download; 2 – acceleration download; 3 – deceleration download; 4 – elements of curve S (kinematics without acceleration jump); 5 – using of “home switch”; 6 – cycle of “while” type; 7 – reading of search state; 8 – delay producing; 9 – reset at “0” of the position counter; 10 – sequential cycle with two sequences; 11 – search settings; 12 – reading of different stop situations; 13 – condition of cycle end; possible errors indicating. The program is applied for each of four axes of the acquisition board.

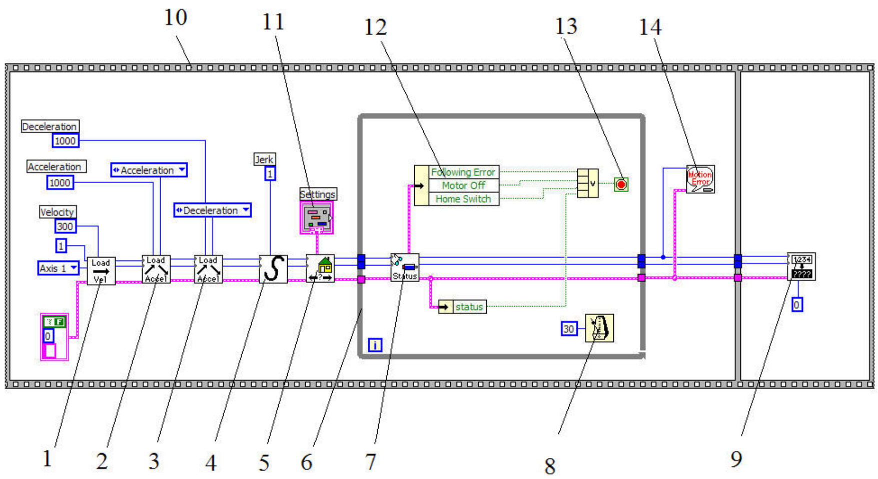


Fig. 13. Program for founding “home switch”.

The main control program of the robot allows travelling on the vitrified surface by horizontal and vertical movements, as well as by rotations of changing the direction. An ultrasonic sensor was introduced as decision element for changing the direction and stopping. A sequential cycle of travel, with starting from point I (Fig. 14) consists of the following subcycles:

0. sequential translation from left to right. This subcycle ends at the appearance of the signal (given by the sensor S) of proximity of the rim from right side;
1. clockwise rotation with 90º;
2. lowering with a step;
3. clockwise rotation with 90º;
4. sequential translation from right to left. This subcycle ends at the appearance of the signal (given by the sensor) of proximity of the rim from left side;
5. counterclockwise rotation with 90º;
6. lowering with a step;
7. counterclockwise rotation with 90º.

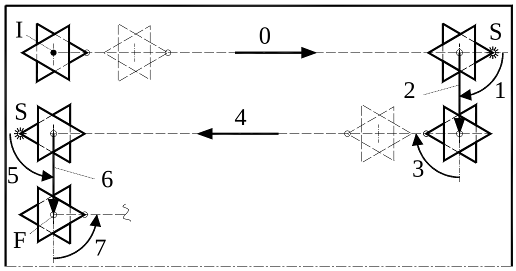


Fig. 14. Travel cycle of the robot.

The surface covering is performed by repeating the travel cycle. Stopping the robot displacement is made if in subcycle 6 the sensor S gives the signal of proximity of the rim from bottom side of the vitrified surface. The block diagram of the program is shown in Fig 15: 1 - setting port 1 as output; 2 - setting port 2 as input; 3 - initialization of local variable; 4 - local variable “Boolean”; 5 - cycle “while” of travel program; 6 - stop travel program; 7 - cycles “while” of first order included in subcycles; 8 - sequential cycles of the subcycles (first order); 9 - sequential cycles of second order.

The program uses the ports 1 and 2 of the acquisition board. The port 1 is used as output from program, taking the commands towards the electro valves. The port 2 is used as input, taking the signal from the sensor S. The program contains a cycle “while” 5, which allows repeating of travel program as the conditions of signal from the sensor and of vertical displacement do not meet simultaneously. Initialization of local variable “Boolean” 4 is made at the value “False” from the control 3. The variable changes its state in “True” in the subcycles of vertical displacement. The signal from the sensor S is used also for stopping the subcycles “while” of the horizontal translations.

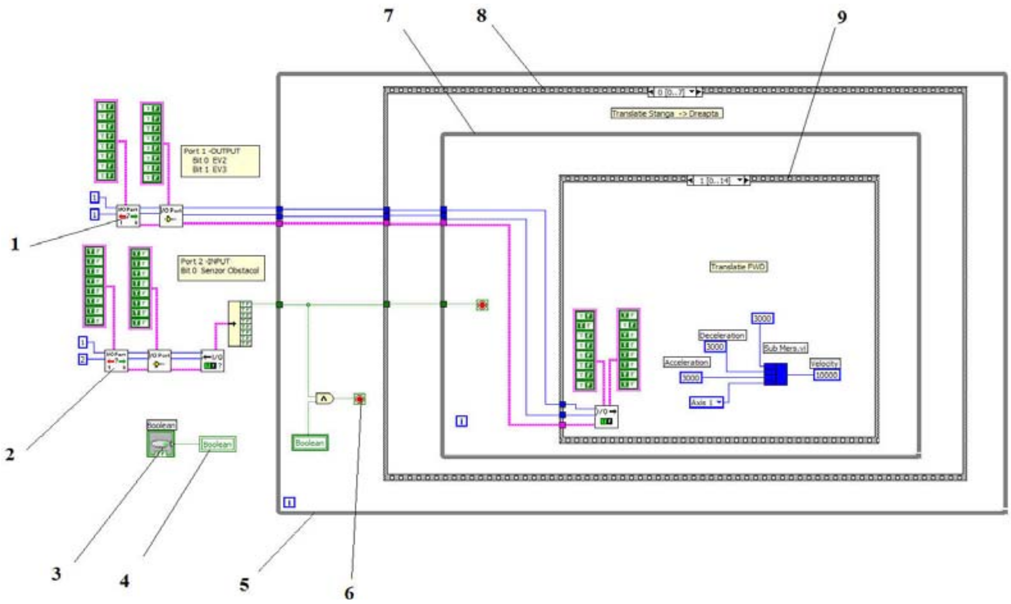


Fig. 15. Block diagram of main control program of the robot.

3. 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. Further activities will be carried on to improve control using microcontrollers as well as strategy to work around obstacles by using multiple ultrasonic sensors. It will also consider the introduction of video systems for surface inspection and creating a database of motion strategy.

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