STUDY ON VACUUM ATTACHMENT CUPS FOR A ROBOT WITH VERTICAL DISPLACEMENT

Tudor Catalin APOSTOLESCU[1], Nicolae ALEXANDRESCU[2], Constantin UDREA[3], Lucian BOGATU[4], Georgeta IONASCU[5]

În lucrare este prezentat un studiu al sistemului de fixare sub acțiunea vidului, materializat prin ventuze de prindere cu vid, pentru un robot cu deplasare verticală.

Forța normală, în general şi forța de desprindere, în particular sunt măsurate şi comparate în cazul fixării ventuzelor pe suprafețe de sticlă, aluminiu lustruit şi textolit, în stare uscată şi umedă (cu apă şi detergent pentru spălarea geamurilor). Rezultatele sunt prezentate şi comentate, demonstrând fezabilitatea soluției de fixare aleasă.

In this paper a study of vacuum–based adhesion system using vacuum attachment suction cups, for a robot with vertical displacement is presented.

Generally, the normal force and particularly, the detachment force, when vacuumed suction cups adheres on glass, polished aluminium and textolite surfaces, are measured and compared - dry and wet conditions (a water and detergent solution for window cleaning is used). Results are presented and discussed to show the feasibility of the chosen adhesion solution.

Keywords: mobile robotics, vacuum, suction cup, cleaning robot

1. Introduction

Wall-climbing robots are helpful systems for various applications on vertical surfaces. Wall cleaning for buildings is one of the areas in which to obtain a strong benefit from these robots is expected.

The most common attachment principle is the vacuum adhesion [1]-[4], where the robot carries an onboard pump to create a vacuum inside the cups,

[1] Assist., Dept. of Information Science and Technology, University "Titu Maiorescu" of Bucharest, ROMANIA, e-mail: apostolescucatalin@yahoo.com
[2] Prof., Dept. of Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, ROMANIA
[3] Lecturer, Dept. of Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, ROMANIA
[4] Lecturer, Dept. of Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, ROMANIA
[5] Prof., Dept. of Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, ROMANIA

which are pressed against the wall. This system enables the robots to adhere on any type of material, with low energy consumption. But vacuum adhesion is suitable for usage on smooth surfaces, because the roughness can lead to a leakage in the vacuum chamber such as suction cup.

In this paper, the force in the normal direction when a suction cup adheres on glass, polished aluminium and textolite surfaces, is measured and compared for dry and respectively wet conditions. A computer simulation of the suction cup stress state depending on the vacuum level and preliminary experimental results necessary for the normal force determinations are also presented.

2. Suction cup coupling to the supporting surface

Suction cups used for the developed robot [5] are of ESS50-FESTO type (with an outer diameter of 50 mm). In order to make a model of the robot supported by suction cups, an analysis of different functional states for a suction cup in correlation with the depression applied, Δp and the effect of a working force on the supporting leg is necessary.

In Fig. 1, the cup without external force is represented.

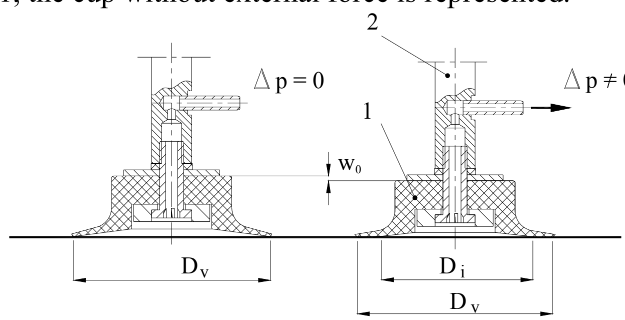


Fig. 1. Suction cup not connected (a) and connected (b) to a vacuum pump:
1 - suction cup, 2 - nut-suction cup support.

The cup and the leg weight were neglected. An approaching displacement w_0 of the cup relative to the attachment surface caused by its elastic deformation is observed ($D_i < D_v$, $D_v = 50$ mm).

Experimentally, for $\Delta p = 0.6$ bar, we get $w_0 = 1.95$ mm.

A computer simulation using FEM was performed, with Cosmos Works program attached to Solid Works software. The stress state is shown in fig. 2. It is observed that the equivalent stress (von Mises) does not exceed $9.83 \cdot 10^5$ Pa.

3. Cup behaviour when loaded with an external force

To make a modelling of the robot supported by suction cups an experimental determination of the suction cup's characteristics is necessary, that is the connection between external force F and displacement w. Both the force and the displacement are referred to the fixing surface of the cup in the robot leg.

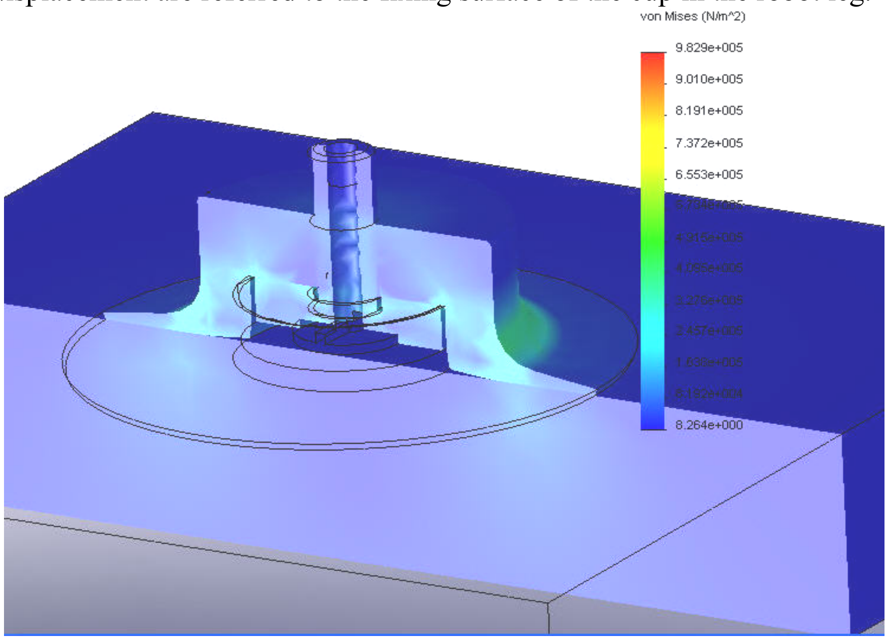
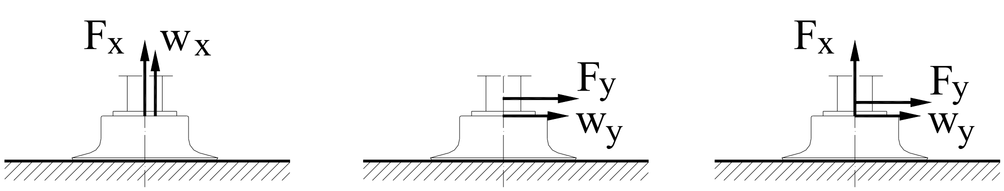


Fig. 2. Stress state in the suction cup for Δp = 0.6 bar, without external force.

Determinations was made for three situations, as follows:

a) the usual case of a force normal to the supporting surface, $F_x - w_x$ (Fig. 3a);
b) loading with a lateral force, $F_y - w_y$ (Fig. 3b);
c) combined loading with F_x and $F_y - w_y$ (Fig. 3c);



a) b) c)

Fig. 3. Types of determinations: loading with normal force F_x (a), lateral force F_y (b) and combined forces F_x, F_y (c).

For cases b) and c) - loading with a lateral force F_y, the main effect is the lateral displacement w_y, therefore determinations for w_x were not made.

An experimental setup, Fig. 4, was conceived to obtain the depression; a VAD-M5 FESTO ejector [6] is used.

The characteristics of depression, Δp and of consumed compressed air flow, q_n depending on the supply pressure, p are shown in fig. 5.

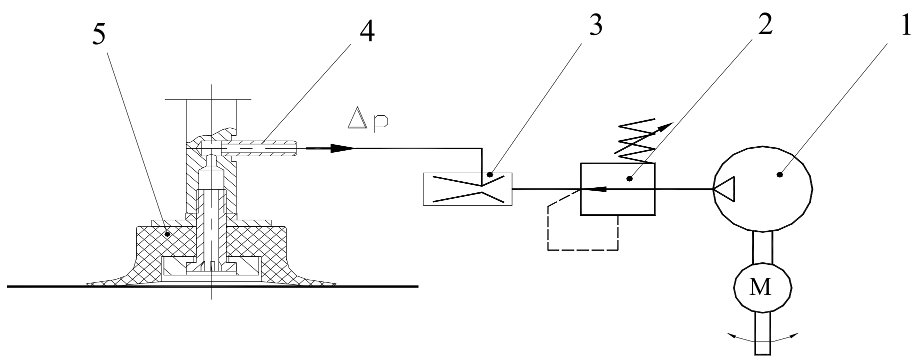
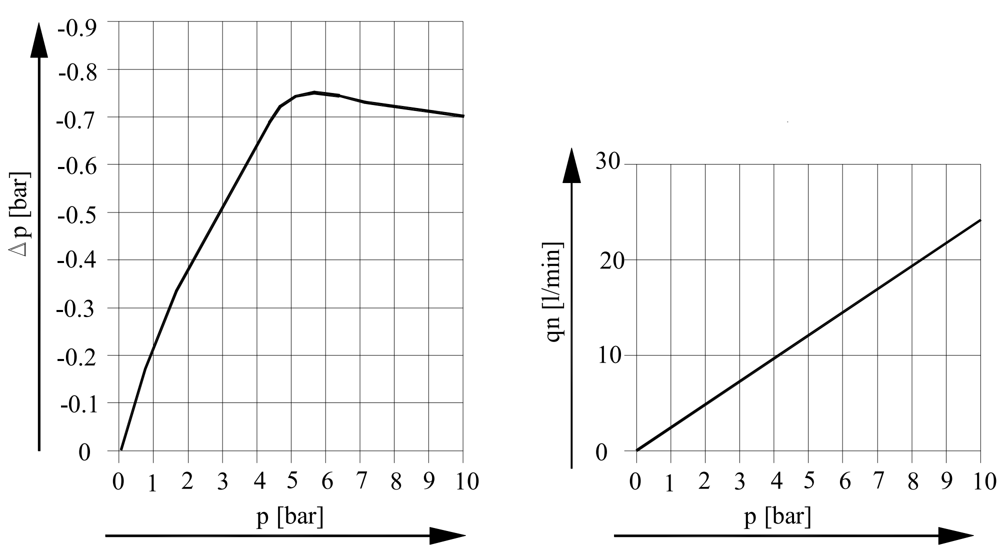


Fig. 4. Experimental setup to obtain the depression during the general determinations: 1 - compressor, 2 - pressure-regulating device, 3 - ejector, 4 - piping, 5 - suction cup.



a) b)

Fig. 5. Characteristics of the ejector VAD-M5 FESTO: depression Δp (a), consumed compressed air flow q_n (b) vs. supply pressure, p.

The general experimental determinations are made for depressions Δp = 0.4; 0.5; 0.6 and 0.7 bar, which ensure the practical working range of different vacuum systems. For the developed robot, the depression is ensured by the micro pump NMP 015 B.

The value of depression measured experimentally is Δp = 0.57 bar. The determinations for normal force were made by connection to this micro pump.

4. Determination of the normal force

4.1. The testing equipment and experimental conditions

The general experiments for normal force were made by means of the testing stand of IMADA, Fig. 6. The checked vacuum suction cup 5 is fixed by the rod 7 (equivalent to the robot leg) to the dynamometer 3. The part 6 (cup working surface), against which the cup is pressed, is fixed with screws on the testing stand table 8. The force values are shown on the measuring head display and can be transmitted to the computer 1. The displacement in the vertical direction is obtained with the hand wheel 9. The displacement reading is made at the electronic “vernier” 4 moving relative to the incremental rule 2.

Fig. 6. Testing stand of IMADA used to determine the cup characteristic for normal force.

In order to cover a wide area of applications, the determinations were performed on different materials with various average roughnesses, R_a: glass ($R_a = 0.02$ µm), polished aluminium ($R_a = 0.59$ µm) and textolite ($R_a = 1.1$ µm).

The roughness was measured using the rough meter Mitutoyo system Surftest SJ 201P. Different functional conditions were generated: tests in dry working condition and, also, tests on surfaces with water and detergent solution for window cleaning.

4.2. Results and discussions

In Fig. 7, the experimental results regarding dependence between normal force and deformation, for the glass surface case in dry condition, are plotted varying with different depressions, Δp. The force values are considered positive for the pulling up trend (cup detachment) and, conventionally, negative for the approaching trend (compression) relative to the supporting surface. The tests in both directions of the force are necessary to study the robot leg positioning during its sustaining on vertical surfaces.

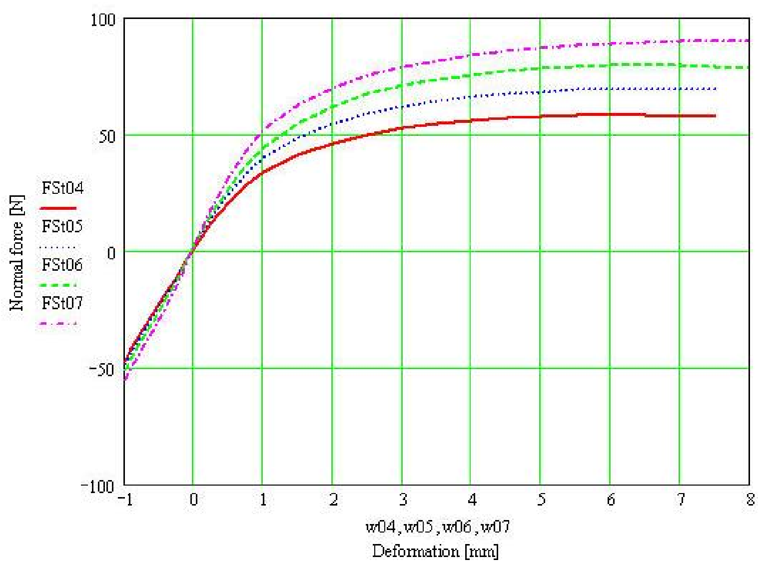


Fig. 7. The cup characteristics on glas, in dry working condition: FSt04 (Δp = 0.4 bar), FSt05 (Δp = 0.5 bar), FSt06 (Δp = 0.6 bar), FSt07 (Δp = 0.7 bar).

The global rigidity of the attachment on a cup:

$$c = \frac{\partial F}{\partial(\Delta w)} \tag{1}$$

In Fig. 8, the cup characteristic for Δp = 0.6 bar is deduced. The main working range I shows a positive rigidity. For the zone of maximum sustaining force, a null global rigidity is obtained. The detachment takes place after a short zone II of "flowing" with negative rigidity. The theoretical explanation of such behaviour can be made considering the forces which appear to equalize the load F:

$$F = F_v + F_p - F_c \, . \tag{2}$$

The following notations were used: F_v – the elastic force due to the cup rigidity, F_p – the force developed by the system of pressures, F_c – the contact force between the cup and the sustained part.

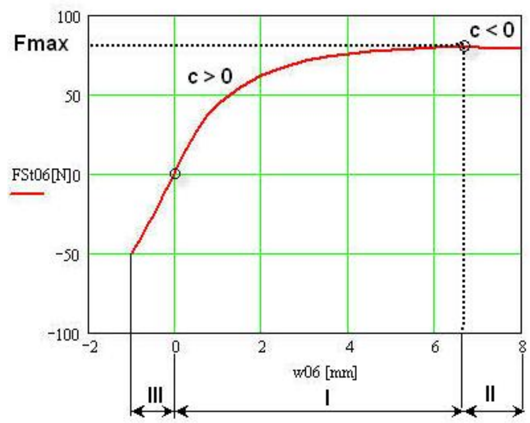


Fig. 8. The global characteristic of the suction cup, illustrated for Δp = 0.6 bar: I - zone with positive rigidity, II - zone with negative rigidity, III - testing at "compression" with $F < 0$ ($w < 0$).

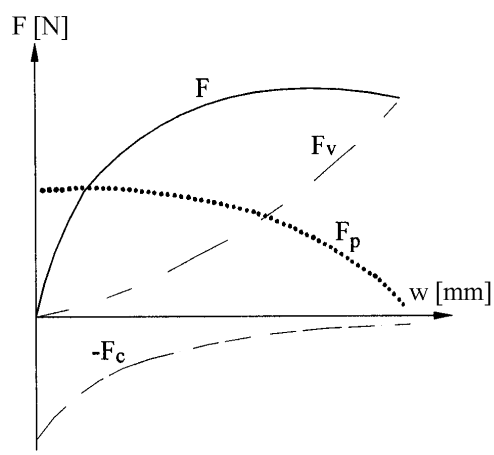


Fig. 9. Forces appearing in the case of cup detachment trend: F - external force, F_v - deformation force of the cup, F_p - force due to the pressures, F_c - contact force with the part.

In Fig. 9, the graphical representation of these forces varying with the displacement w is given. The force F_v has a variation of increased rigidity, similar to the membranes.

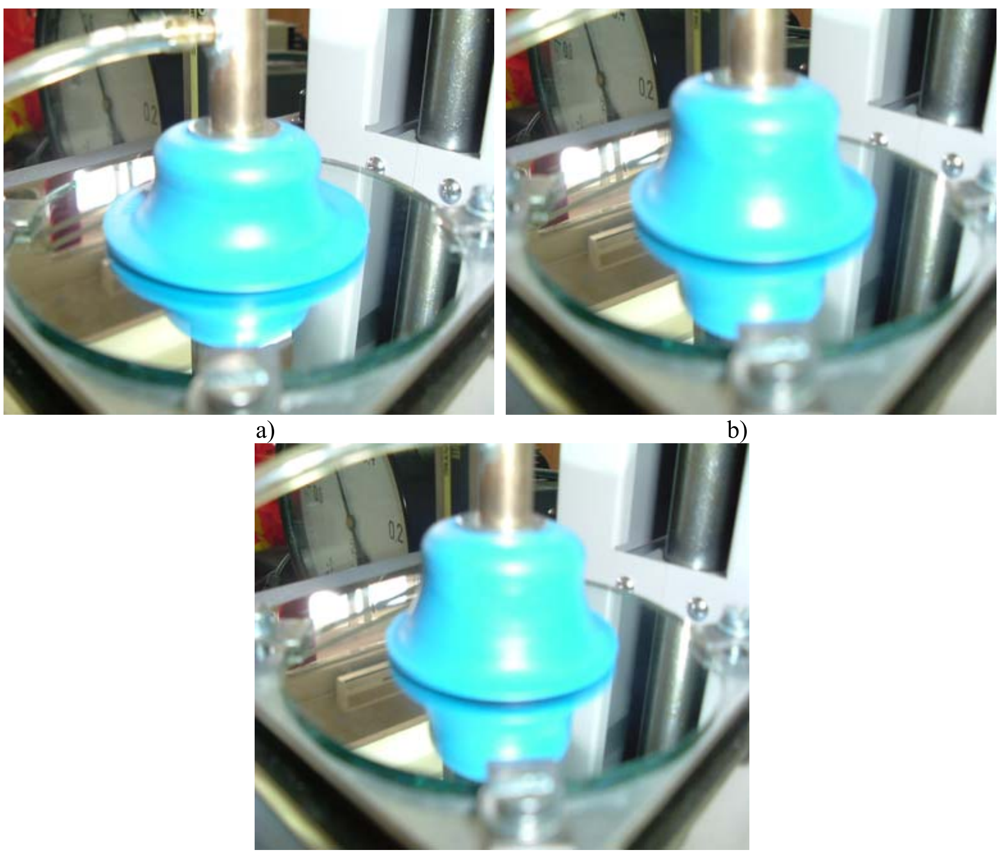
In the zone III of the compression tests (Fig. 8), the rigidity is almost constant, caused by the reduced range of deformation ($w > -1$ mm).

Cup diameters vary with the load, Fig. 10. In table 1, the values of these diameters for Δp = 0.6 bar, are given. The diameter D_i was determined by visualization on a transparent part.

Table 1

Contact diameters of the cup at different deformations, Δp = 0.6 bar

w_{06} [mm]	0	1	2	3	4	5	6	7	8
D_i [mm]	39	39.6	39.6	39.7	40	40.7	41.5	41.7	41.9
D_v [mm]	50	50	49,9	49.5	48.9	48	47	45.7	44.3



a) b)

c)

Fig. 10. Modification of shape and external diameter of the cup contact surface for Δp = 0.6 bar, at various deformations: w = 1 mm (a), w = 6 mm (b), w = 8 mm (c).

For the same deformation, the force is proportional with the depression Δp, due to the proportional variation of its components. In Fig. 11, the force variation (F_1, F_2 and F_3) extracted in the case of deformations w of 1, 2 and 3 mm is represented. The maximum detachment force varying with the depression Δp is shown in Fig. 12. Here too, the dependence on Δp is linear.

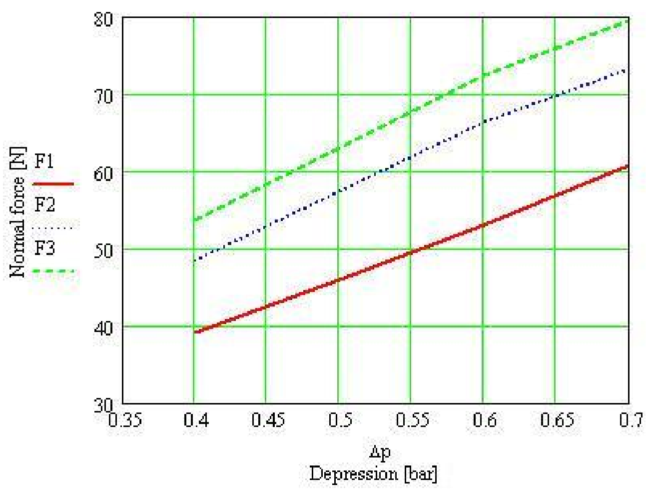


Fig. 11. Force variation with depression Δp, at the same deformation: *F1* (w = 1 mm), *F2* (w = 2 mm), *F3* (w = 3 mm).

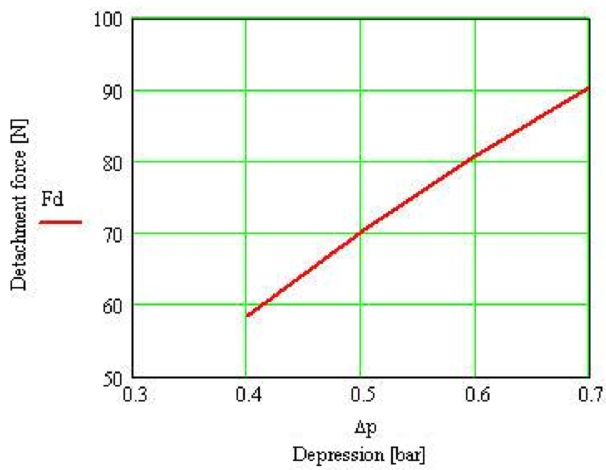


Fig. 12. Detachment force variation with the applied depression.

Regarding the force determinations on other materials, a similar load variation with deformation was observed for all three materials: glass, aluminium and textolite. In Fig. 13, the three characteristics for Δp = 0.6 bar are illustrated.

The differences between characteristics are relative low. At small deformations, glass and textolite have almost the same behaviour, the roughness influence being low for $R_a < 1$ μm. The suction cups used on aluminium allow for a smaller load. In the zone of compression the characteristics are very close, only influenced by the rigidity of the cup.

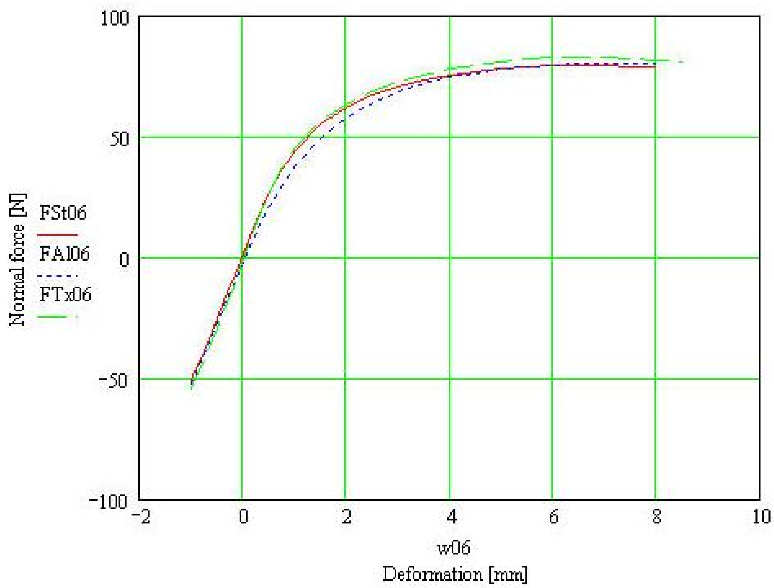


Fig. 13. Cup behaviour on different materials at Δp = 0.6 bar: *FSt06* (glass), *FAl06* (aluminium), *FTx06* (textolite).

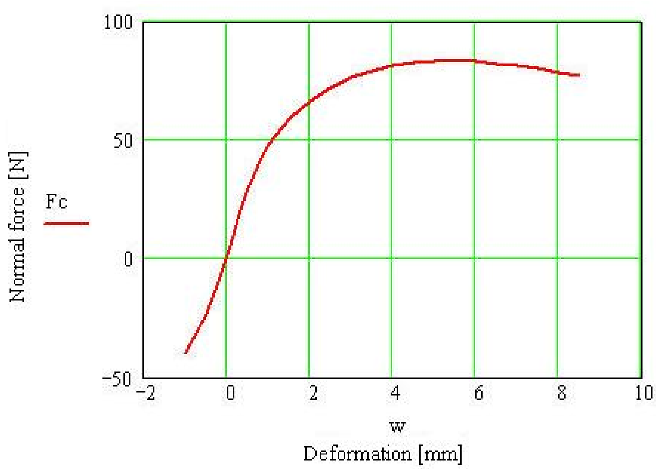


Fig. 14. Cup characteristic for Δp = 0.57 bar obtained with the vacuum pump from the robot.

Force determinations with Δp = 0.57 bar using the pump NMP 015 B from the robot were performed, Fig. 14. The results are useful for supporting simulation on the robot legs. In Fig. 15, the characteristic in this case is shown.

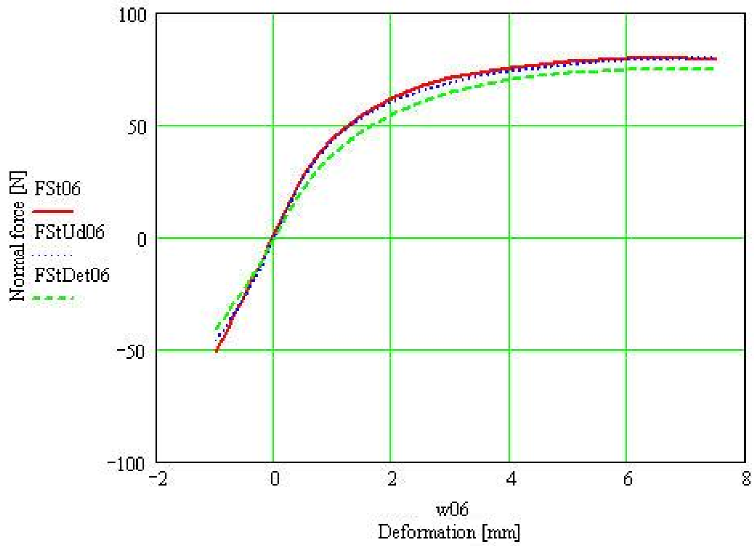


Fig. 15. Cup behaviour on glass for different conditions: *FSt06* (dry surface), *FstUd06* (wet surface with water), *FstDet* (wet surface with detergent for window cleaning).

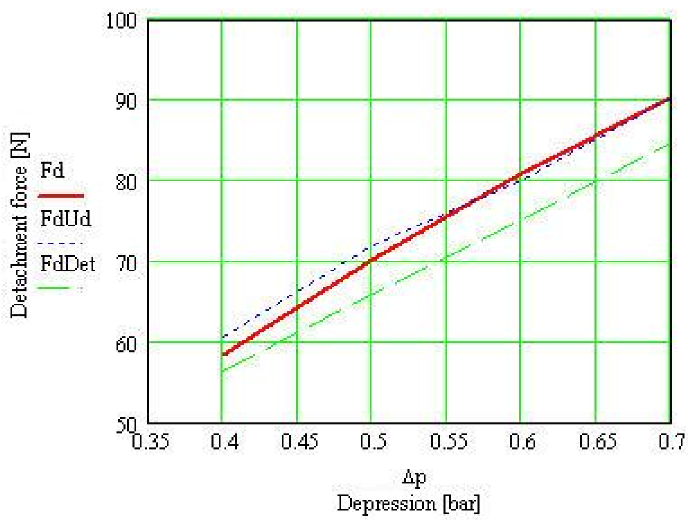


Fig. 16. Cup detachment force from glass for different conditions: *Fd* (dry surface), *FdUd* (wet surface with water), *FdDet* (wet surface with detergent for window cleaning).

Regarding the force determinations on wet surfaces, the characteristic shape is similar, but with some differences of the values. For example, in Fig. 15, the cup characteristics on glass for dry, wet condition with water and wet condition with detergent are presented. The cup behaviour with water diminishes a little the performances, 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 above, at different depressions, are given in Fig. 16. A more substantial reduction of cup capacity, only for wetting with detergent (of about 6 %), is found.

5. Usage of suction cup fixing system for an experimental model of an autonomous mobile robot

The autonomous robot, which is the subject of research paper [5], is shown in two positions: robot placed on an horizontal surface (Fig. 17a) and robot placed on a vertical surface (Fig. 17b).

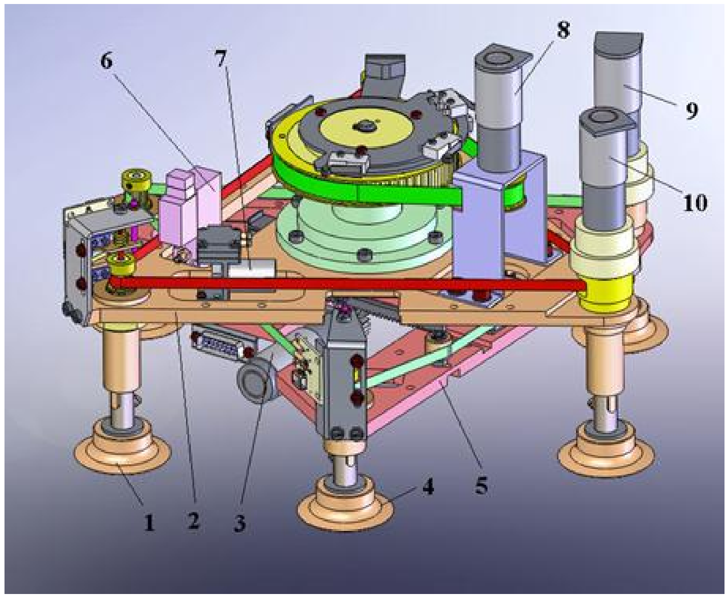
As shown, the fixing system consists of six suction cups – as studied in the present paper, three for each of the two triangular platforms through which the kinematic operating scheme ensures horizontal or vertical movement of the robot.

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

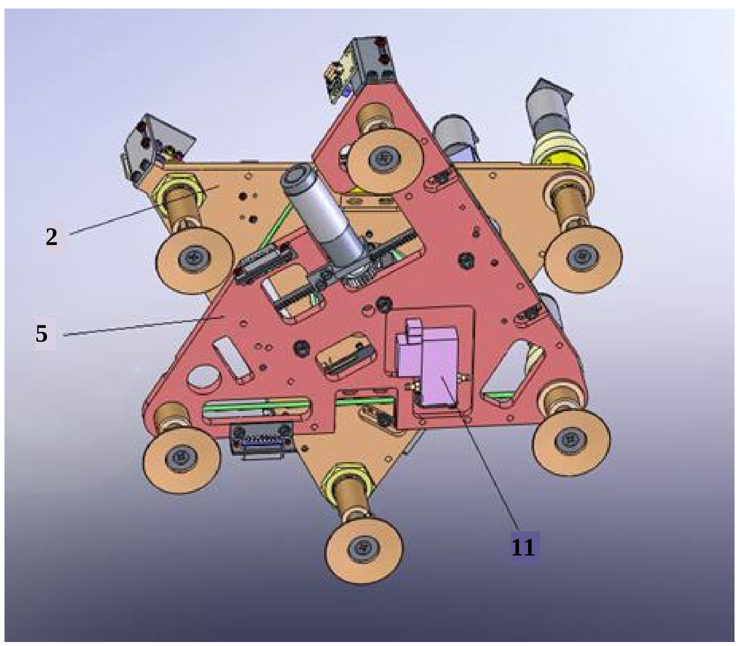
Other components of Fig. 17 are the following: motor-reduction gear 3 for controlling linear motion of the platforms, electro valves 6 and 11 for controlling vacuum in suction cups, vacuum micro pump 7, motor-reduction gear 8 for controlling rotation motion of the platforms, motor-reduction gear 9 for controlling motion of suction cups of the interior platform, motor-reduction gear 10 for controlling motion of suction cups of the exterior platform.

6. Conclusions

This paper reports a part of the results of basic characteristics of vacuum suction cups, representing the adhesion solution for a mobile robot with vertical displacement. The cup behaviour during loading with an external force in normal direction, applied on glass, polished aluminium and textolite, was studied. The force determinations were performed and compared for dry and respectively wet conditions. These results, combined with the ones referring to loading with a lateral force and combined (normal and lateral) forces, are useful for modelling and simulating the robot legs positioning during its sustaining on vertical surfaces.



a)



b)

Fig. 17. 3D Model of the robot placed on: an horizontal surface (a) and a vertical surface (b).

REFERENCES

[1] *F. Cepolina, R. Michelini, R. Razzol and M. Zoppi,* "Gecko, a Climbing Robot for Wall Cleaning", 1 st Int. Workshop on Advances in service Robotics ASER03, March 13-15, Bardolino, Italia, 2003, http://www.dimec.unige.it/PMAR/

[2] *D.P. Tocut, C. Tripe-Vidican and A. Tripe-Vidican,* "Vacuum Robot for Cleaning the Glass Frontage of the Buildings", in Annals of the Oradea University, Fascicle of Management and Technological Engineering, Volume VII (XVII), 2008, pp. 1118-1125

[3] *T. Miyake, H. Ishihara and M. Yoshimura,* "Basic Studies on Wet Adhesion System for Wall Climbing Robots", in Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Diego, CA, USA, Oct.29-Nov.2, 2007, pp. 1920-1925

[4] *Fr. Novotny and M. Horak,* "Computer Modelling of Suction Cups Used for Window Cleaning Robot and Automatic Handling of Glass Sheets", in MM Science Journal, June, 2009, pp. 113-116

[5] *T. C. Apostolescu, N. Alexandrescu, C. Udrea and D. Duminica,* "Original Solution for an Autonomous Mobile Robot with Vertical Displacement", in Bulletin of the Polytechnic Institute of Iasi, Fascicle 3, Volume LIV (LVIII), Section Machine Construction, 2008, pp. 87-92

[6] *** Festo Catalog – Vacuum generators VAD/VAK, Festo AG & Co KG, 2008/09.