

Development and Analysis of Robotic Sliding Suction Cup System for Wall Climbing Applications

G. Muthukumar* and Uppu Ramachandraiah

Department of Electronics and Instrumentation Engineering, Hindustan Institute of Science and Technology, Chennai – 603103, Tamil Nadu, India; gmkumar@hindustanuniv.ac.in, uppur@hindustanuniv.ac.in

Abstract

Background/Objectives: The wall climbing robots normally uses suction cups for adhering to the wall surface. The conventional suction cup system using common suction generator suffers from the failure of centralized suction motor. The practically realized climbing robots with on board suction generator are limited with single suction chamber due to load and power limitations. **Methods/Statistical analysis:** In the proposed work, the climbing robot is realized with two on board suction motors to cater two chambers. Each suction motor is integrated with a suction cup with suitable skirting. A drive system with flat rubber wheels enables the robot to move on smooth surfaces. The design concept of dual suction cup enables safe mobility through adaptive control and ensures the robot functions even any one suction generator fails or encounters higher leakage. This arrangement provides the required negative pressure for cup individually to adhere to the wall. An adaptive control scheme is developed and implemented by interactively controlling the suction cups negative pressure by varying the speed of the corresponding suction motor. This paper also discusses about its basic mathematical analysis, the simulation of the model and the prototype wall climbing robot. **Findings:** The simulation of the robot is performed using Matlab Simulink Software and also realized with hardware components using an embedded controller, pressure sensors and drive motors. It is observed through simulation that by varying the speed of the suction motor, the negative pressure in the suction cup system can be controlled. The simulation result for the complete holding of the suction cup system considering the frictional forces is found to be -70.25 kPa. The sliding and drop off negative pressure levels by allowing a minimum suction leakage percentage is found by performing simulation. These pressure level values are compared with the experimental suction cup system and found to be closer. **Application/Improvements:** The developed climbing robot can be deployed for various inspection tasks of concrete walls, high rise buildings, steel structures etc., The payload capacity of the robot can be still improved by optimizing the pressure levels in the chambers.

Keywords: Negative Suction, PID Control, Sliding Suction Cup, Smooth Surfaces, Wall Climbing Robot

1. Introduction

The wall climbing robot systems mainly functions using adhesion principle mechanism. For climbing on vertical surfaces, the adhesion force between robot and surface has to be sufficient enough and also relatively higher traction force should be generated for ensuring the mobility of the robot. Salient features of the robot to be designed are two on-board suction generator integrated with suction cup

and skirting, efficient traction system for safe mobility. One of the most challenging tasks is to develop a proper adhesion mechanism to ensure that the robot system sticks to wall surfaces reliably without sacrificing mobility.

2. Literature Survey

The vertical wall climbing robots can be classified by the adhesion system¹. For climbing smooth surfaces, vacuum

*Author for correspondence

system driven by rubber wheels is more suitable due to simple mechanical design and continuous fast movement. Active or passive generation of adhesion force finds application as per requirement. Active generation of adhesion force requires continuous operation of a suction generator, but a passive generation of adhesion force does not require a continuous energy need. The CLAUS robot is an example of passive generation of adhesion force². Passive suction cups do not consume additional energy to keep adhesion. However, the robot could not move up the wall well and fell down often³. Active suction cups by using external vacuum generator is also developed using flexible tubes which provides required adhesion force for holding on the wall. Active suction cups using vacuum pump installed on the robot is also realized by continuously operating the vacuum pump. A “V-ROBO SYSTEM” is a remotely controlled robot system with a suction-adhering and self-propelled mechanism which maintains constant negative pressure even if leakage exists. The robot using negative force to stick to the wall is achieved using sliding suction cups, with the suction created by centrifugal pumps driven by high speed air motors. The force pushes the robot towards the wall till the suction cup becomes attached to the wall⁵. A wall climbing robot with vortex vacuum technique and adhesion by means of a single sliding suction cup with vacuum created by a propeller is developed to provide fast motion on all types of surfaces (e.g. brick, concrete, glass, etc.). The robot can operate for about 30 minutes. It is supplied by two sets of Li-Po rechargeable batteries and it can carry a 1 kg payload. A wheeled locomotion system enables fast motion and the robot can climb on nearly any kind of vertical wall surface in an urban environment⁶. Xiao Qi Chen et al., used Bernoulli's principle to get non-contact adhesion⁷. It has advantages of high force/weight ratio (as high as 5), low cost, ubiquitous mobility under different surface conditions, and modularity but it is not capable to handle higher payload. Jizhong Xiao et al., used vacuum based wheel drag system technology with good payload capacity, good stability but it requires more power since friction involved is more⁸. B.L. Luka et al, used vacuum suction based sliding frame walking mechanism technology which can step over small obstacles and good payload capacity but it is slow and doesn't have 3D transition⁹. Samuel G Maggio developed remote-controlled devices that can scale virtually any vertical or inverted surface, and, because they are operated safely from the ground, humans are not exposed to dangerous heights or to dangerous chemical or toxin environs. By

this way, the International Climbing Machines (ICM) can climb walls, tanks, ships, building structures, dams, towers, etc. by using rolling seal and vacuum adhesion to surfaces.

3. Robotic System

The Robotic Sliding Suction cup system (RoSS II) is a climbing robot that uses sliding suction cup technique and capable to climb on vertical smooth surfaces, will overcome minimal (~1 mm) surface irregularities such as rivet heads, welds etc. The experimental model with a payload of 3 Kg is developed. The developed robot travels at 0.6 meters/min. The outline of work is primarily focused on deriving the dynamical equations contributing for the mathematical system design of the dual suction cup system. The amount of suction force and corresponding negative suction pressure required by each suction cup for holding the robot on vertical surface is computed theoretically and compared with experimental simulation of suction cup system. The study of dynamics of the suction inside each of the suction cup is required for analyzing the proper suction variables to withstand in any situations in such a way to adhere to the surface with the required holding force.

3.1 Suction Cup System

The Suction cups are normally used in the climbing robots for adhering to the surface. The suction cups with the necessary negative pressure sticks to the surface firmly. The conventional suction cup system employs centralized negative pressure system provided by a common suction generator (suction motor). This may provide negative suction pressure to suction cup used for the movement of the climbing robot. The drawback observed is the probability of single point failure if the centralized suction motor fails and also suffers from requirement of high power. The proposed suction cup system is developed to overcome the drawbacks of the existing systems. In the proposed model each suction cup is coupled with a suction motor by which the required suction pressure for each cup is generated by its own. The climbing robot is realized with two suction cups and a drive system. The robot moves using suction drag principle (active sliding technique). For mathematical analysis two suction cup systems is considered as shown in Figure 1. The suction cup is selected with an outer diameter of 50 mm. The different functional states for a suction cup in correlation with speed of the suction

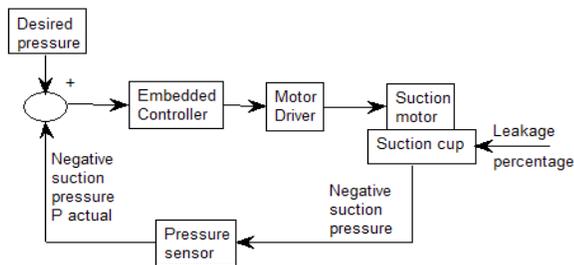


Figure 1. Graph of suction motor speed and time.

motor is analyzed mathematically to calculate the effect of a working force of the suction cup required to rigidly hold to the surface. V_m, V_c, V_s represents the volume of the corresponding segments of the suction cup respectively.

3.1.1 Governing equations for the RoSS climbing Robot

N_{c1}, N_{c2} – Reaction forces exerted by the cups, N_{w1}, N_{w2} – Reaction forces exerted by the drive wheels f_{c1}, f_{c2} – Frictional forces between the cup and the wall, f_{w1}, f_{w2} – Frictional forces between the wheel and the wall, W – Weight of the robot, L_1 – Position of the cup 2 from the bottom edge, L_2 – Spacing between the wheels and the cup 2, L_3 – Spacing between the wheels and the cup 1, L_4 – Position of the cup 1 from the top edge, h – Distance from the wall to the centre of gravity, F_c – Suction force of the suction cup, μ – Static frictional coefficient, Because of the symmetry in the drive system¹⁰, $N_{w1} = N_{w2} = N_w$

Figure 1 represents the Force balance diagram and considering the Force balance,

$$\text{X axis: } N_{c1} + N_{c2} + N_{w1} + N_{w2} = F_{c1} + F_{c2} + 2F_w \quad (1)$$

$$\text{Y axis: } f_{c1} + f_{c2} + f_{w1} + f_{w2} = W = mg \quad (2)$$

Moment around the Point A:

Case 1: Suction cup is in holding condition

$$Wh = (L_1 + L_2 + L_3)(F_{c1} - N_{c1}) - [(L_1 + L_2)(N_{w1} + N_{w2})] + L_1(F_{c2} - N_{c2}) \quad (3)$$

Case 2: Suction cup is in moving condition

$$\left. \begin{aligned} f_{c1} &\leq \mu N_{c1} \\ f_{c2} &\leq \mu N_{c2} \\ f_{w1} &\leq \mu N_{w1} \\ f_{w2} &\leq \mu N_{w2} \end{aligned} \right\} \quad (4)$$

Case 3: Suction cup is in falling condition i.e., zero reaction forces applied to the suction cups can be obtained from (1), (2) and (4) as

$$f_{c1} + f_{c2} + f_{w1} + f_{w2} \leq \mu(N_{c1} + N_{c2} + N_{w1} + N_{w2}) \quad (5)$$

$$W \leq \mu(F_{c1} + F_{c2} + 2F_w) \quad (6)$$

As the system is about to fall the reaction force at the cup tends to zero i.e., $N_{c1} = 0, N_{c2} = 0$ and

so also is F_w i.e., $F_w = 0$.

Hence (1) and (3) will simplify to (7) and (8) respectively

$$(N_{w1} + N_{w2}) = F_{c1} + F_{c2} \Rightarrow 2N_w = F_{c1} + F_{c2} \quad (7)$$

$$Wh = (L_1 + L_2 + L_3)F_{c1} - [(L_1 + L_2)(2N_w)] + L_1(F_{c2}) \Rightarrow$$

$$Wh = (L_1 + L_2 + L_3)F_{c1} - 2(L_1 + L_2)N_w + L_1(F_{c2}) \quad (8)$$

Using (7) and (8),

$$Wh = L_3F_{c1} - L_2F_{c2} \Rightarrow F_{c1} = \frac{Wh + L_2F_{c2}}{L_3} \Rightarrow F_{c2} = \frac{-Wh + L_3F_{c1}}{L_2} \quad (9)$$

This shows that when the mass (= W/g) of these system increases the holding force required also increases, as can be anticipated.

3.1.1.1 Theoretical Force Calculation

Mass, $m = 3Kg$, Length between cup and wheel, $L_2 = 120mm$ and $L_3 = 120mm$, Height, $h = 110mm$, Gravity, $9.81m/s^2$, $\mu = 0.3$, Safety factor, $S = 2$

Substituting the above values in (6), (9) and assuming the system is stationary, $F_w = 0$ and $F_{c2} = 0$

$$F_{c1} = (W/\mu) = 98.1N \text{ (considering the frictional force)}$$

$$F_{c1} = (Wh/L_3) = 26.97N \text{ (Without considering the frictional force)}$$

Table 1. Force and Pressure values of the two suction cups. (without considering frictional forces)

	Suction cup1 Force F_{C1} (N)	Suction cup2 Force F_{C2} (N)	suction cup1 Pressure P_{c1} (Kpa)	Suction cup 2 Pressure P_{c2} (Kpa)
(1)	26.97	(worst case)	13.760	0
(2)	40.46	13.485	20.642	6.880
(3)	47.20	20.23	24.081	10.321
(4)	50.57	23.60	25.80	12.04
(5)	52.25	25.28	26.658	12.897
(6)	53.10	26.125	27.09	13.329

By considering suction cup diameter as 50mm and Area of the suction cup to be $A = 1.96 \times 10^{-3} \text{ m}^2$. The Active sliding suction cup can be achieved with this value of $F_{c1} = 53.10 \text{ N}$ (without frictional force) and $F_{c2} = 26.125 \text{ N}$ (Without frictional force) and the corresponding suction pressure of $P_{c1} = -27.09 \text{ Kpa}$ and $P_{c2} = -13.329 \text{ Kpa}$ respectively. By considering the safety factor, $S = 2$, the minimum suction pressure required will be -54.18 Kpa and -26.65 Kpa respectively to tightly hold the robot on the surface/wall without sliding.

Table 2. Force and Pressure values of the two suction cups. (considering frictional forces)

	Suction cup1 Force F_{c1} (N)	Suction cup2 Force F_{c2} (N)	suction cup1 Pressure P_{c1} (Kpa)	suction cup 2 Pressure P_{c2} (Kpa)
(1)	98.1	(worst case)	50.05	0
(2)	49.05	49.05	25.02	25.02
(3)	73.57	24.525	37.53	12.510
(4)	61.32	36.78	31.28	18.76

The Active sliding suction cup can be achieved with this value of $F_{c1} = 61.32 \text{ N}$ (with frictional force) and $F_{c2} = 36.78 \text{ N}$ (with frictional force) and the corresponding suction pressure of $P_{c1} = -31.28 \text{ Kpa}$ and $P_{c2} = -18.76 \text{ Kpa}$ respectively. By considering the safety factor, $S = 2$, the minimum suction pressure required will be -62.56 Kpa and -37.52 Kpa respectively to tightly hold the robot on the surface/wall without sliding.

3.2 Drive System

The drive system consists of single wheel units, driven by 7 kgf torque square gear motor, steerable presently with one degree of freedom. The drive unit is positioned in between the two suction cups for a balanced operation and imparts a speed of 0.6 meters /min.

4. Embedded Control System

The closed-loop control of the negative pressure sliding suction cup system is implemented with Atmega micro-controller 328. The pressure sensor, drive motor, suction motor and High Definition Camera is connected through this microcontroller. A dedicated control algorithm is

programmed to maintain the required negative pressure inside the suction cup to adhere with the wall and also functions to maintain the mobility of the climbing robot. The feedback from the pressure sensors is used to maintain the negative pressure by varying the speed of the suction motor through specified motor drivers. The control scheme is explained in Figure 2. The pressure sensor data and the Inspection HD Camera data is also transmitted wirelessly to the remote computer for data logging and analysis. The complete embedded system is shown in Figure 3.

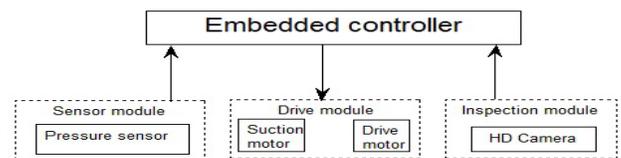


Figure 2. Negative suction pressure controller – basic control loop.

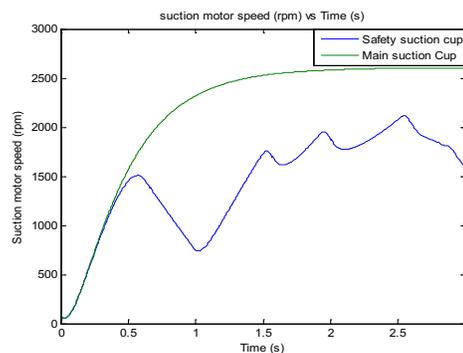


Figure 3. Block diagram of RoSS – Robotic System using Sliding suction cup.

5. RoSS II Suction Pressure Control

5.1 Matlab Simulation

The Simulink design for interacting system using two suction cup chambers is shown in Figure 4 and Figure 5. Several blocks are used to design the overall Simulink model including the DC motor with driver block, Suction pump, interacting block and scope to monitor the Suction pressure. Each suction cup chamber has its own DC motor with driver connected to a controller. These

suction cup chambers are there by connected to the interacting block for controlling the required negative suction pressure for holding the WCR in vertical position without falling down.

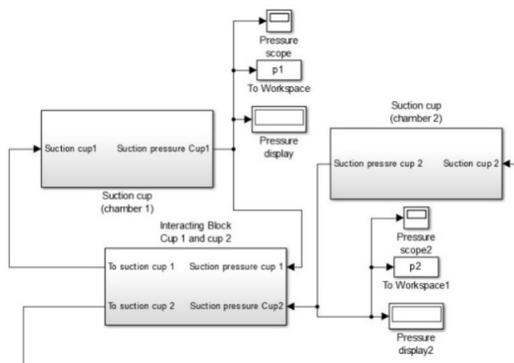


Figure 4. Simulink of Interacting suction cup system.

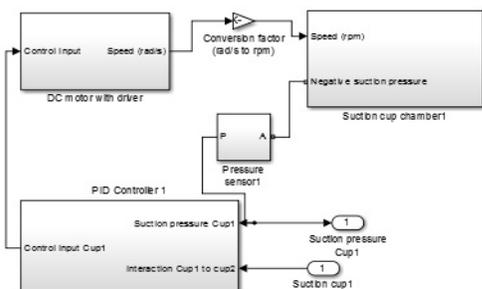


Figure 5. Simulink of suction cup chamber.

The RoSS suction pressure control is achieved through controlling the Speed of the DC Motor with PID controller by comparing the Suction pressure of chamber 1 and chamber 2. The interacting block takes the suction pressure as input and compares the suction pressure of chamber 1 and chamber 2 with desired set pressure. The output of the interacting block is given to the PID controller of suction chamber 1 and suction chamber 2. The proportional-integral-derivative controller is a closed loop feedback mechanism controller which eventually controls the speed of the DC motor of two suction chambers. The PID controller continuously calculates the error value as per the difference between the actual pressure and the desired pressure. The controller attempts to minimize the error and finally controls the DC motor speed.

The controller provides the desired speed to regulate the air flow and thereby achieving the suction pressure.

$$V_{sm}(t) = K_{sc} \Delta P_{sc}(t) + K_{sc} \cdot \frac{\Delta t}{T} \cdot \sum_{T=1}^i \frac{\Delta P_{sc}(T) - \Delta P_{sc}(T-1)}{2} + K_{sc} \cdot \frac{T_{sc}}{\Delta t} (P_{sc}^{act}(t) - P_{sc}^{act}(t-1))$$

The above equation gives the PID controller functions using the portions of proportional, integral and derivative constants where

$V_{sm}(t)$ is the Speed of the suction motor, $K_{sc} \Delta P_{sc}(t)$ is the function of proportional constant K_p of suction cup pressure.

$K_{sc} \cdot \frac{\Delta t}{T} \cdot \sum_{T=1}^i \frac{\Delta P_{sc}(T) - \Delta P_{sc}(T-1)}{2}$ is the function of Integral constant (K_i) of suction cup pressure.

$K_{sc} \cdot \frac{T_{sc}}{\Delta t} (P_{sc}^{act}(t) - P_{sc}^{act}(t-1))$ is the function of derivative constant (K_d) of suction cup pressure.

The tuning of PID controller is studied through the simulation results observed in Simulink model. The simulation parameters for PID controller is set to the constants as follows

$$K_p = 1, K_i = 0 \text{ and } K_d = 0$$

The simulation results is achieved for two suction cup system with interacting controller module. The observed results of simulink model is shown in Figure 6 and Figure 7.

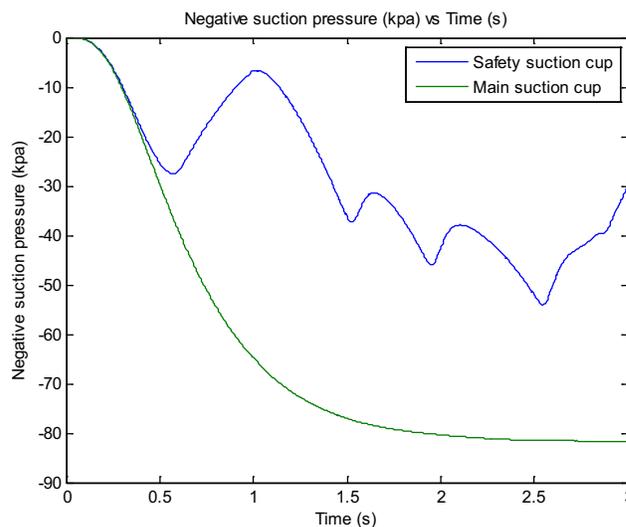


Figure 6. Graph of suction motor speed and Time

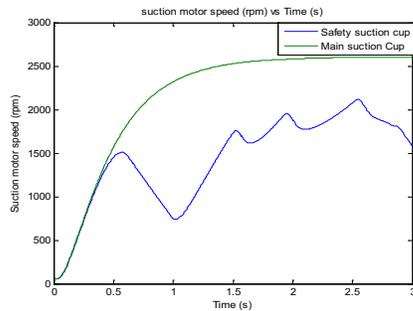


Figure 7. Graph of suction pressure. and time.

6. Experimental Results

RoSSII is tested in real time smooth surface environment with two suction cups. Each suction cup has its own suction motor to provide necessary negative adhesion pressure. Figure 6 represents the graph between suction motor speed and suction pressure generated by the suction cup of suction chamber 1 and suction chamber 2. This Figure 7 shows the relation between the main suction cup of chamber 1 and the safety suction cup of chamber 2. This investigation is carried out to find the adherence characteristics of the suction cup to the smooth surface and helps to find the holding capacity of the robot by comparing and maintaining the required suction pressure in suction cup chamber 1.

The main objective of the proposed robot is to develop a climbing robot which can adhere to the smooth wall surface and also able to move without falling at any instance. It is also observed that by maintaining the suction pressure of chamber 1 to be much higher than the suction pressure of chamber 2, achieves the amount of necessary adhesion pressure to hold and slide the WCR. This simulation result is compared with the experimental data. The experimental analysis is carried out with the RoSS prototype shown in Figure 8.

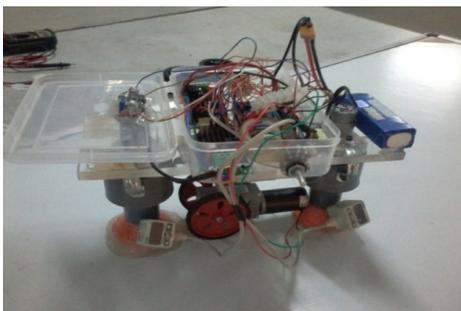


Figure 8. Experimental prototype of RoSS – climbing robot.

From the simulink analysis, it is observed that the required suction pressure in the chamber is controlled with the main suction chamber to overcome the leakage affected by the second cup. The simulink model delivers the pressure of $-70.25KPa$ and upto $-36.4\ddot{u}$ for main suction cup and safety suction cup, whereas the mathematical design achieves the pressure of approximately $-31.28Kpa$ for the suction cup1 and $-18.76Kpa$ for the suction cup 2 with controller for the design of 3 kg of mass. The simulink design concludes that the maximum of 5% of leakage is allowed to stick on the wall firmly. It is also observed in simulation that by continuously monitoring the suction pressure in each cup and setting the controller and the comparator block with desired pressure, the overleakage can be neglected and thereby WCR moves in vertical position without falling down at any instant.

7. Conclusion

In this paper, the design of RoSS climbing robot which is capable of moving vertically on a smooth surface wall is attempted. The preliminary results examined conclude that a sliding suction cup technique can be used for climbing the smooth vertical wall structures. It is also observed that higher complexity is to be addressed to reduce the slip of the motor over the smooth surface. The implemented control algorithm is able to provide a maximum speed of 0.6 metre/min. The time delay introduced by the controller to realize the target speed of the suction motor has to be reduced for improving the performance of the robot for safe mobility. The future work will be to tune the control algorithm for efficient operation and also to reduce the height of the system to increase the adhesion force and allow calculated suction leakage enabling the climbing robot to climb faster. The contact area of the wheels of the drive motor also will be studied for reducing the slip to improve the climbing speed.

8. References

1. Albitar H, Dandan K, Ananiev A, Kalaykov I. Underwater robotics: Surface cleaning techniques, adhesion and locomotion systems. International Journal of Advanced Robotic Systems. 2016.
2. Available from: http://www.inf.uos.de/techinf/demo_robots.html#claus
3. Yoshida Y, Shugen. Design of a Wall-Climbing Robot with Passive Suction Cups. 2010.

4. Available from: http://www.urakami.co.jp/img/pdf/vrobo_brochure_en.pdf
5. COMM European commission: CORDIS: Projects & results service: Final report summary - RIMINI (development of new and novel low cost robot inspection methods for in-service inspection of nuclear installation). 2016 Jul 5. Available from: http://cordis.europa.eu/result/rcn/52080_en.html
6. Moldable robotics and NDT automation. 2016. Available from: <http://robotics.umng.edu.co>
7. Balaguer C, Gimenez A, Abderrahim CM. ROMA robots for inspection of steel based infrastructures. *Industrial Robot: An International Journal*. 2002; 29(3):246-51. doi:10.1108/01439910210425540
8. Wagner M, Chen X, Nayerloo M, Wang W, Chase JG. A novel wall climbing robot based on Bernoulli effect. *IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications*; 2008. doi:10.1109/mesa.2008.4735656
9. Xiao J, Sadegh A. City-climber: A new generation wall-climbing Robots. *International Journal of City University*. 2007.
10. Luk B, Collie A, Cooke DS, Chen S. Walking and climbing service robots for safety inspection of nuclear reactor pressure vessels. *Measurement and Control*. 2006; 39(2):43-7. doi:10.1177/002029400603900201
11. Ikeda K, Nozaki T. Fundamental study on a wall-climbing robot. *5th International Symposium on Robotics in Construction*; Tokyo, Japan. 1988.