A wall climbing robot with vacuum caterpillar wheel system operated by mechanical valve

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Abstract: **This paper describes a new concept of the robot that can climb on vertical planes. The engineering design problem of the main structure is presented and the experimental results (climbing speed, payload) regarding a new mechanism of climbing on the vertical wall are discussed. The continuous locomotive motion of the robot is realized by using a series chain of two caterpillar wheels on which 24 suction pads are installed. While each caterpillar wheel rotates on the vertical plane, the suction pads are activated in sequence based on the sequential opening by specially designed mechanical valves. The detail mechanism and design feature of the vacuum caterpillar wheel including mechanical valve are described in this paper. The overall size of the robot is around 460 mm in width and length and 200 mm in height. Its mass is slightly over 14 kg. The maximum climbing speed is about 15 m/min and the static payload is about 23 kg. The main mechanical structure of the robot consists of driving motors, vacuum caterpillar wheel system, vacuum pump, wireless control module and battery. The performance of the robot is controlled remotely and verified on the vertical wall. Finally, an optimization experiment to maximize vacuum pressure and minimize the fluctuation of vacuum pressure of suction pads using Taguchi methodology is presented.**

Keywords: **climbing robot, vacuum caterpillar wheel, suction pad, Taguchi method**

I. INTRODUCTION

Climbing robots have been researched and developed all over the world for the main purpose of cleaning outer walls of multi-storied buildings, painting large vessels and inspecting problems in storage tanks. Most climbing robots developed up to now, climb the wall using legged mechanisms or translation mechanisms. Despite the fact that these climbing robots are capable of climbing uneven surfaces, their climbing speeds are comparatively low due to their discontinuous moving methods. [4][5]

A Cleanbot II, developed by City University of Hongkong, which uses track mechanism, stands unique among climbing robots. Using a chain-track on which 52 suction pads are installed, this robot can move continuously, hence its speed is relatively high. This robot uses solenoid valves to control the vacuum supply into suction pads. But this robot has a length of 720 mm, a width of 370 mm, a height of 390 mm, and a weight of 22 kg, even if a power supply and the source of vacuum supply are not included in the robot. Furthermore, the maximum speed is 8 m/min at most in spite of using track mechanism. [1]

In this research, a robot which is able to climb a vertical wall with continuous motion is developed based on engineering design. [3] Mechanical valves installed on the robot to control vacuum supply into suction pads contributed the improvement in climbing speed. It is a self-contained robot in which vacuum pump and power supply are integrated.

The first part of this paper introduces the mechanical system and climbing mechanism of the robot. In the second part, static analysis to calculate required vacuum force enabling the robot to attach to the wall safely is described. Finally, an optimization experiment to maximize vacuum pressure and minimize the fluctuation of vacuum pressure of suction pads using Taguchi methodology is presented.

II. STRUCTURAL DESCRIPTION OF THE ROBOT

A. *Overall structure of the robot*

Generally, this robot consists of vacuum caterpillar wheel and main body including vacuum pump and power supply. Especially, vacuum caterpillar wheel is composed of caterpillar wheel on which 24-suction pads are installed, mechanical valves opening and closing vacuum air flow, grooved guide-rail which guides the movement of suction pads according to the rotation of the wheel and controls the operation of mechanical valves, and rotary joint preventing pneumatic tubes from twisting by wheel rotation. The overall size of the robot is around 460 mm in width and length and 200 mm in height. Its mass is slightly over 14 kg. Fig.1 shows the overall structure of the robot. The caterpillar wheel is made up of timing belt and pulley. 12 suction pads which are assembled with mechanical valves are installed on each timing belt. The rear axis of the wheel is connected to a BLDC motor (Faulhaber, 200W) with a gear reduction ratio of 111:1. Each suction pad is 60 mm in diameter and it can lift the load of 14kg at the pressure of 400mbar (-60kPa). In case of vacuum pump (KNF, N838_DC) which supplies vacuum pressure for each suction pad, its maximum vacuum pressure is about -90 mbar and maximum flow rate is about 32 L/min.

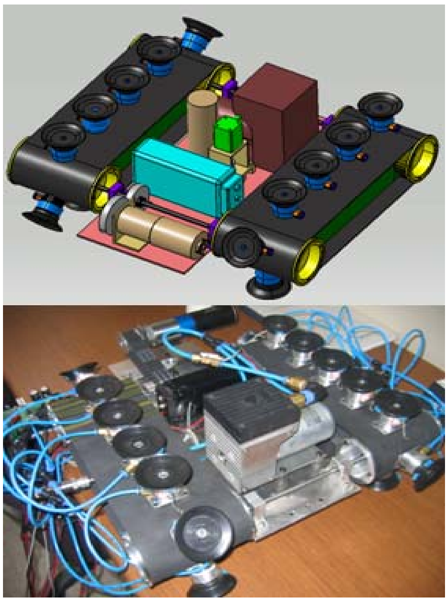

Fig. 1. Overall feature of the robot.

B. *Working mechanism of caterpillar wheel system*

The caterpillar wheel system consists of 12 suction pad & mechanical valve assemblies (SPMV), two guides, one cam profile, one timing belt, and two pulleys. The assemblies and timing belt are bolted together. They move according to the rotation of caterpillar wheel. The mechanical valve as shown in Fig.2 is choked at the beginning by the force of a spring and then opened when a ball bearing located on top of the valve is pushed down. At this time, there is a free flow between vacuum pump and suction pads. It makes the robot attach to the wall. On/off operation of the mechanical valve is controlled by following the cam profile having a grooved rail which pushes up the ball bearing of the valve and is connected with axis of the caterpillar wheel. When the suction pad is in a position of approaching the wall, the grooved rail pushes up the ball bearing and then the suction pad attaches to the wall. This cam profile shown in Fig.3 also guides the smooth movement of suction pads according to the rotation of the wheel. This mechanism enables the robot to climb the wall with fast and continuous motion.

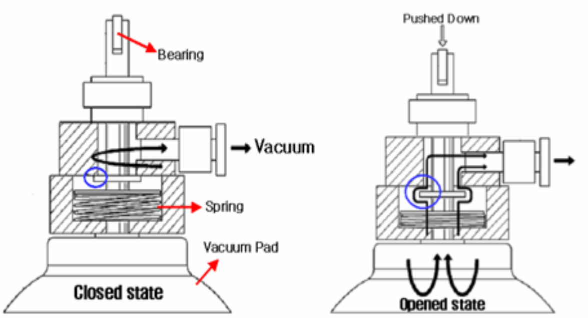

Fig. 2. Working principle of mechanical valve.

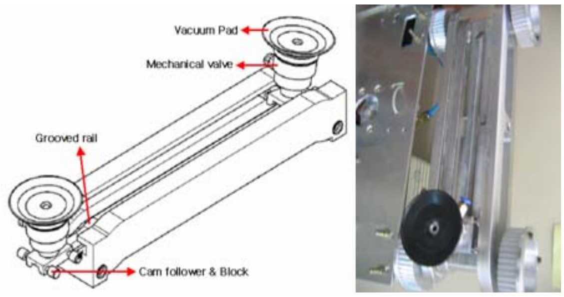

Fig. 3. Feature of cam profile.

III. ANALYSIS OF VACUUM FORCE AND VACUUM PRESSURE

A. *Analysis of the required vacuum force*

The required vacuum force of the robot should be guaranteed for stable climbing without falling or slipping. Fig.4 shows the forces applied to the robot, when the robot attaches to the vertical wall (steel plate). Each symbol is defined as follows:

V : Vacuum force acting on each suction pad
N_{vi} : Normal reaction force acting on each suction pad
W : Weight of the robot
D : Distance between two neighboring suction pad
H : Distance from wall to the center of gravity of the robot
μ : Coefficient of friction

Fig.4 shows a free body diagram of the robot and it gives four equations from force and moment equilibrium. Among them, the force equilibrium in the x-direction is

$$\sum_{i=1}^{3} N_i - 3V = 0 \tag{1}$$

The force equilibrium in the y-direction is

$$\mu \sum_{i=1}^{3} N_i - W = 0 \tag{2}$$

In the z-direction, the moment equilibrium which bases point O is

$$HW + D(N_2 - V) + 2D(N_1 - V) = 0 \tag{3}$$

Besides the three equations, one more equation can be obtained by assuming that the robot is considered as a rigid body and the values of reaction forces acting on suction pads are in linear relation each other. Therefore, it is represented by

$$N_2 = \frac{N_1 + N_3}{2} \tag{4}$$

Firstly, to prevent the robot to fall, the reaction force value should be positive.

$$N_i \geq 0 \tag{5}$$

Then, the smallest reaction force, N_1 can be obtained by solving (1) – (4) and (5) can be applied as follows:

$$N_1 = V - \frac{WH}{2D} \geq 0 \tag{6}$$

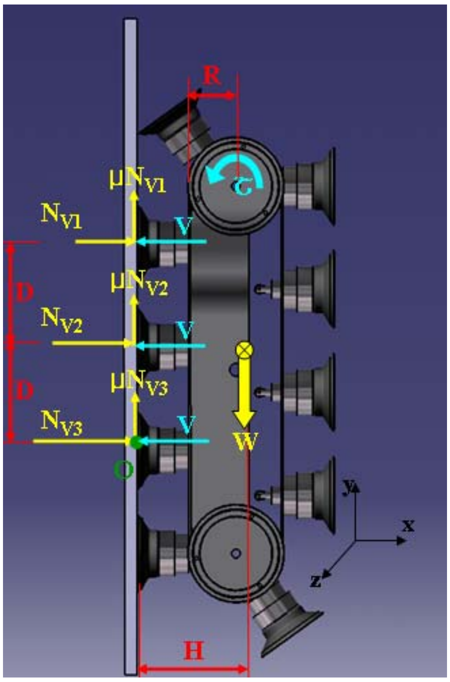

Fig. 4. Forces applied to the robot.

From (6), decreasing H or increasing D decreases the vacuum force required.

Secondly, to prevent the robot to slip, the friction force should exceed the gravitational force.

$$\mu\sum_{i=1}^{3} N_i - W \geq 0 \tag{7}$$

Substituting (1) into (7) yields the following result.

$$V \geq \frac{W}{3\mu} \tag{8}$$

Clearly, if the vacuum force satisfies both (6) and (8), the robot will not fall and slip. In case of the robot, the real dimensions are W = 14 kg, D = 65mm, H = 80mm and μ = 0.35 (between steel wall and suction pad). By substituting these values into (6), the required vacuum force not to fall is given as 84.38 N. In the same way, the required vacuum force not to slip is given as 130.34 N. The calculated value above is the required vacuum force of 2 suction pads. Therefore, the required vacuum force per each pad not to slip and fall is 65.17 N. Since the vacuum force of the suction pad used in the robot is about 137.2 N at the pressure of 400mbar, it guarantees a safety factor of 2.12.

B. A characteristic of the vacuum pressure of the robot system

In this robot, 24 SPMV are connected directly with vacuum pump. Therefore, there should not be any leakage from suction pad and vacuum pressure in the vacuum pump should exceed the required vacuum force in order to withstand the weight of the robot. Besides, a reservoir tank is not installed on this robot for low weight and miniaturization. Hence, the fluctuation of pressure occurs by periodic addition of volume in the mechanical valve and suction pad according to wheel rotation. This fluctuation may interrupt stable climbing of the robot.

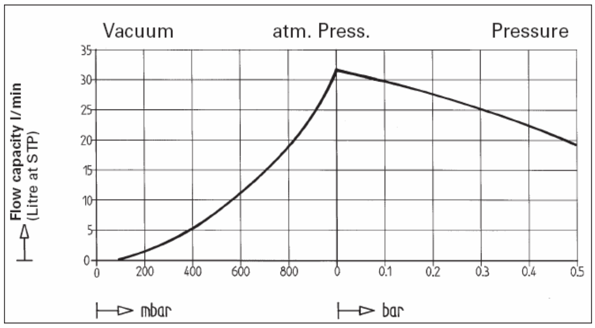

Fig. 5. Performance graph of pump.

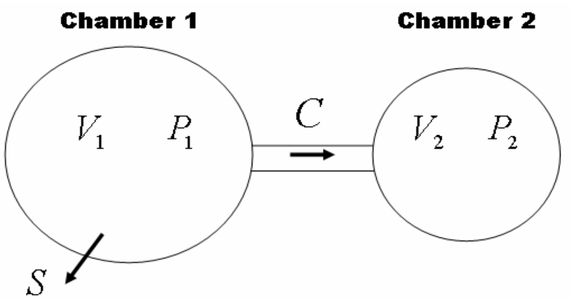

Fig. 6. Model of air flow.

Fig.5 shows a performance curve of the vacuum pump. The volume flow rate (pumping speed) of the pump depends on the pressure. Fig.7 is a transient graph which shows the relationship between the pressure and time when a regular volume is added to the working vacuum pump periodically. For this simulation, basically, the following equations are applied. [6]

$$Q = PS = P(dV/dt) \tag{9}$$

where Q is gas throughput defined as the product of the pumping speed S, and the inlet pressure P, of the pipe. From Fig.6 which describes a simplified model for simulation, the throughput can be considered as

$$Q = C(P_1 - P_2) \tag{10}$$

where C is the conductance which depends on the kind of flow and the geometry of the pipe.

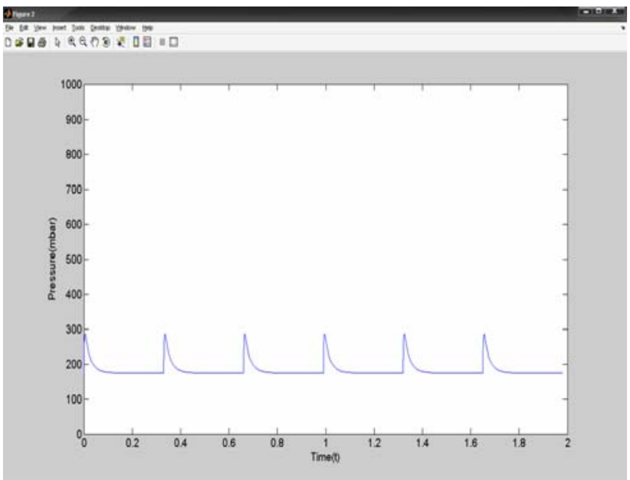

Fig. 7. Expected tendency of pressure change.

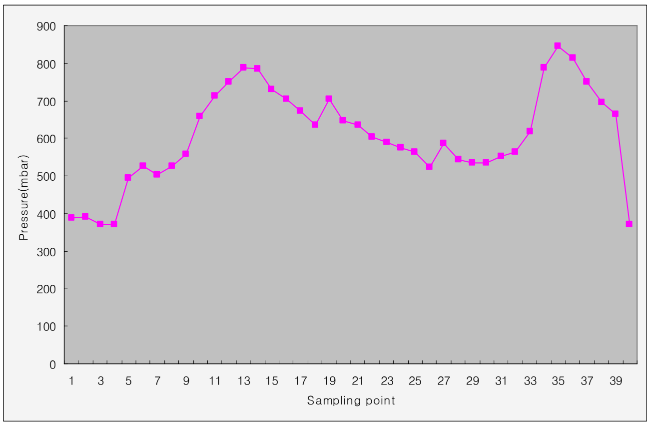

Fig. 8. Preliminary experimental result.

When there is only exhaust at a chamber1, then the throughput balance equation based on (9) and (10) can be written as follows:

$$V_1 \frac{dP_1}{dt} = -SP_1 - C(P_1 - P_2) \quad (11)$$

$$V_2 \frac{dP_2}{dt} = C(P_1 - P_2) \quad (12)$$

The combined volume of the 6 SPMV which are already attached to the wall is selected as V_1 and the volume of 2 SPMV which are to attach to the wall is selected as V_2. The fact that pump pressure fluctuates with time when a regular volume is added periodically to working vacuum pump is proved through this simplified simulation. This simulation is just to grasp the tendency of the pressure and the real value will be more critical, because the shape of pipe, the effect of orifice, and a minute leakage which determine the value of the conductance are not considered. In fact, the preliminary experiment showed more critical results like Fig.8.
An experiment to improve this problem is discussed in the next part of this paper.

IV. Optimization Experiment of Vacuum Pressure Using Taguchi Method

The most frequently used approach to design an experiment is a full factorial experiment. But, in case of many factors, this approach is time-consuming. Taguchi's methodology makes use of an experimental process for finding an optimal design. In this method, all factors affecting the performance quality can be classified into two types: control factors and noise factors. The former being most important in determining the quality of product characteristics, can be determined by the experimenter and are easily controllable. The main issue is to find the control factors and determine their appropriate levels. For the robot system used in this experiment, typical control factors include a diameter of pneumatic tube, a configuration of the cam profile, and the number of air tunnels inside the valve. The others, on the other hand, are undesired parameters that are difficult and impossible to control, such as climbing speed in case of this experiment.[2] The process of performing a Taguchi method follows a number of these steps:

(1) Determine the objectives of the experiment and define the quality characteristic
(2) Identify the control factors and the noise factors affecting the objectives
(3) Identify the levels of each factor
(4) Design an appropriate orthogonal array
(5) Conduct the experiments
(6) Analyze the effect of each factor and determine the optimal levels
(7) Undertake a confirmatory run of the experiment

A. Determining the objectives and defining quality characteristic

From the preliminary experiment on vacuum pressure of the robot, the tendency of vacuum pressure change was not uniform and more critical than the expectation. When the robot wheels rotate, the fluctuation of pressure is caused by periodically added volume of SPMV to vacuum pump. In order to obtain best climbing performance, maximizing the vacuum pressure and also minimizing the fluctuation of pressure are determined as the objectives. As a quality characteristic, a smaller-the-better characteristic in which the desired goal is to obtain a measure of zero is applied to this experiment. Therefore, the value would be the sum of the fluctuation of pressure and the reciprocal of the vacuum pressure.

$$Y = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{(P_i)^2}$$
$$\Rightarrow \left(\frac{1}{P_1}+\frac{1}{P_2}+\cdots\frac{1}{P_n}\right)^2 + \left[\left(\frac{1}{P_1}-\frac{1}{P_2}\right)^2+\left(\frac{1}{P_1}-\frac{1}{P_3}\right)^2+\cdots+\left(\frac{1}{P_n}-\frac{1}{P_{n-1}}\right)^2\right] \quad (13)$$

where n means the number of pressure data.

B. Selecting the control factors and noise factors

The objective of this experiment focuses on maximizing vacuum pressure and minimizing the fluctuation of the pressure. Eventually, timing of valve opening and air flow may have a significant impact on the pressure change. Therefore, the following control factors whose values can be set and maintained are chosen in this experiment: the diameter of pneumatic tube, the configuration of the cam profile, and the number of air tunnels inside the valve. In case of the number of levels, three levels for each control factor are determined for fine tuning the experiment. The factors and the levels are shown in Fig.9 and Table I. The climbing speed, on the contrary, is selected as a noise factor because the speed is not controllable and has a desirable or undesirable effect on the vacuum pressure. The number of levels of the noise factor is fixed at two levels which have a lower speed and upper speed for ensuring robustness.

TABLE I

CONTROL FACTORS AND NOISE FACTORS

Factor	Control factor			Noise factor
Item	Diameter of pneumatic tube (A)	Number of air tunnel of valve (B)	Configuration of cam profile (C)	Climbing speed
Level1	8 mm	0 (5.13 mm^2)	47°	11.7 m/min
Level2	6 mm	1 (10.03 mm^2)	55.8°	5.2 m/min
Level3	4 mm	2 (14.98 mm^2)	40°	

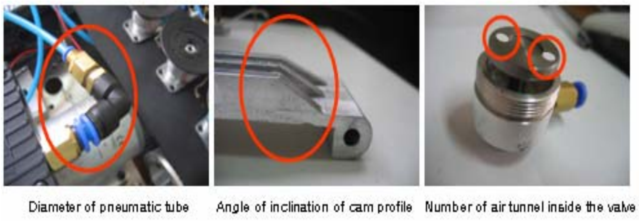

Fig. 9. Feature of control factors.

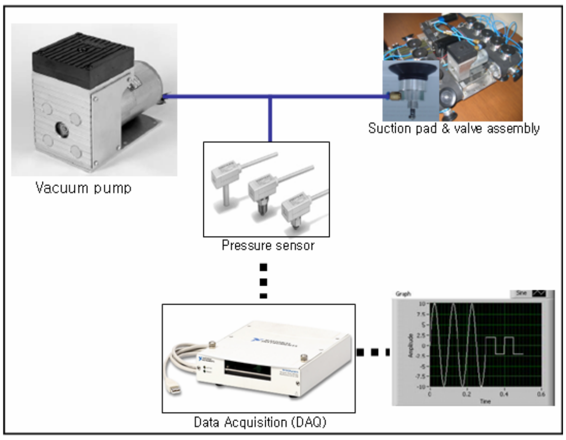

Fig.10. Schematic of the experimental set-up.

C. *Designing an orthogonal array*

An orthogonal array is the basis for designing an experiment using Taguchi methodology. Unlike a full factorial experiment, the experiment based on an orthogonal array is very efficient. $L_9(3^4)$ which is the most commonly used 3^n array is selected because the number of control factor is three and each level is three. In this experiment, 27(3^3) experiments are needed using full factorial experiment. On the contrary, only 9 experiments are carried out using the orthogonal array.

D. *The experiments and analysis*

Fig.10 shows the experimental set-up. A pressure sensor (SMC, PSE510) is connected with a SPMV. The experiment is conducted replacing each control factor and level shown in Table I according to the orthogonal array L9. Since the quality characteristic of this experiment is the smaller-the-better characteristic, the equation for calculating S/N ratio of this formulation is as follows:

$$S / N_{smaller-the-better} = -10\log\left(\frac{1}{k}\sum_{j=1}^{k} Y_{ij}^2\right) \qquad (14)$$

where $k = 1,2$ means the level of noise factors and $i = 1,2,\cdots 9$ presents the number of experiment based on the orthogonal array. Therefore, the total number of experiment comes to 18 including noise factors.

Table II presents the result of the experiment. S/N ratios for each experimental trial can be obtained by (14). To produce the most desired results, it is necessary to identify control factors that have strong effect on the pressure. Since the effect of each control factor is same with the difference between the average S/N ratio for each level, it can be presented by calculating the average experimental result for each level of control factor.

TABLE II

EXPERIMENTAL DATA

	Control factor			Output Y		S/N Ratio(dB)
	A	B	C	High speed	Low speed	
1	1	1	1	4.15	3.16	-11.33
2	1	2	2	5.03	3.61	-12.82
3	1	3	3	5.82	5.74	-15.24
4	2	1	2	3.64	2.71	-10.12
5	2	2	3	5.53	2.99	-12.96
6	2	3	1	5.77	4.72	-14.44
7	3	1	3	4.30	4.60	-12.97
8	3	2	1	7.41	5.89	-16.52
9	3	3	2	4.90	4.32	-13.29

For example, -13.13 dB can be obtained by averaging the values of S/N ratios which come under level 1 of the control factor A. These results are shown in response table (Table III). The difference between the extreme values informs how strong the control factor has impact on the quality characteristic. From Table III, B has most strong influence and A has weakest influence on the value of S/N ratio.

Thus, the combination of B1, C2, and A2 is recommended to get high S/N ratio. Based on the selected levels of the strong effects, a estimate of the predicted response can be computed. The calculations are based on the overall average experimental value defined as $\overline{T}$.

$$\overline{T} = \frac{1}{9}\sum_{i=1}^{9}(S / N)_i = -13.30 \qquad (15)$$

Finally, prediction equation $\hat{\mu}$, defined as predicted S/N ratio based on the selected levels of the strong effects can be written as (16).

$$\hat{\mu} = \overline{T} + (\overline{A2} - \overline{T}) + (\overline{B1} - \overline{T}) + (\overline{C2} - \overline{T}) = -9.46 \quad (16)$$

TABLE III

THE RESPONSE TABLE (SIGNIFICANT FACTORS IN BOLD)

Level\Control factor	A	B	C
1	-13.13	**-11.47**	-14.09
2	**-12.51**	-14.1	**-12.08**
3	-14.26	-14.32	-13.72
Difference	1.75	2.85	2.02

From the results, the recommended setting can be implemented because the actual results are close to the predicted results. Fig.11 shows the improved result of vacuum pressure using optimized factors. The total mean value of vacuum pressure increased by 23.3% (143mbar) and the deviation value between maximum pressure and minimum pressure decreased by 44% (208 mbar) when the climbing speed is 11.7 m/min. In case of 5.3m/min, vacuum pressure increased by 35% (205 mbar) and the deviation value decreased by 12.7% (57mbar).

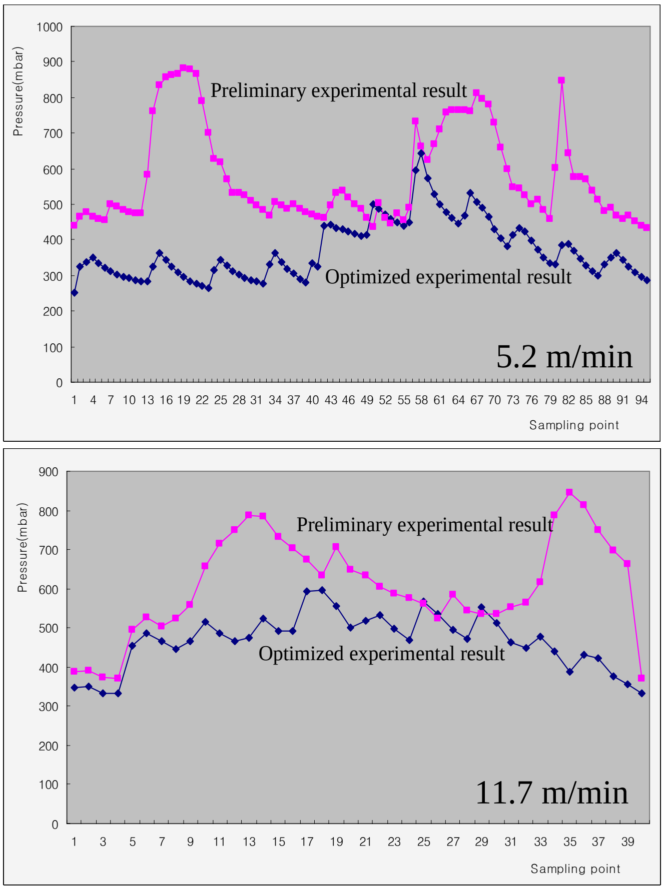

Fig. 11. The optimized results of vacuum pressure.

V. CONCLUSION

This paper introduces the developed climbing robot that climbs a vertical wall with continuous motion using a vacuum caterpillar wheel system operated by a mechanical valve. The linear climbing speed of the robot reaches 15m/min. It is a self-contained robot in which vacuum pump and power supply are integrated. The mechanical system and climbing mechanism were described. By optimization experiment using Taguchi methodology to maximize vacuum pressure and minimize the fluctuation of vacuum pressure of suction pads, the control factors having influence on climbing performance have been optimized.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Jian Zhu, Dong Sun, and Shiu-Kit Tso, *Development of a Tracked Climbing Robot*, Journal of Intelligent and Robotic Systems 35: 427-444, 2002.

[2] Glen Stuart Peace, *Taguchi Methods : A hands-on approach to quality engineering*, Addison-Wesley Publishing Company, 1995.

[3] G. Pahl, W. Beitz, *Engineering Design*, Springer-Verlag, 1997.

[4] Shigeo Hirose, Akihiko Nagakubo, *Walking and Running of the Quadruped Wall-Climbing Robot*, Proc. IEEE Int. Conf. on Robotics and Automation, pp.1005-1012, 1994.

[5] N. Elkmann, D. Kunst, T. Krueger, M. Lucke, T. Bohme, T. Felsch, and T. Sturze, *SIRIUSc – Façade Cleaning Robot for a High-rise Building in Munich, Germany*, In Int. Conf. CLAWAR 04, pp. 1033-1040, 2004.

[6] A. Roth, Vacuum technology, North-Holland, 3rd edition, 1990.