Proceedings of the 2007 IEEE/RSJ International
Conference on Intelligent Robots and Systems
San Diego, CA, USA, Oct 29 - Nov 2, 2007

Basic Studies on Wet Adhesion System for Wall Climbing Robots

Tohru Miyake, *Student Member, IEEE,* Hidenori Ishihara, *Member, IEEE and* Motoi Yoshimura

Abstract— **This paper reports a vacuum-based wet adhesion system for wall climbing robots. In this adhesion system, a suction cup adheres on a wet surface. The problems addressed are an adherability on a rough surface, which is comes from the seal action of a liquid, and low friction between suction cup and adhered rough and smooth surfaces which is comes form lubricating action of a liquid. Generally, it is difficult that a vacuumed suction cup adheres on rough surface such concrete plate and hardly slidable. In this paper, the adhesion force and friction when a suction cup adheres on smooth glass plate and concrete plate are measured and compared wet condition with dry condition. The experiment result showed that a viscosity is important at the sealing performance of adhesion on rough surface. The silicon oil of a viscosity of 5000cSt allows a suction cup to adhere on concrete surface. In this condition it comes up to the adhesion force when a suction cup adheres on smooth glass with dry condition.**

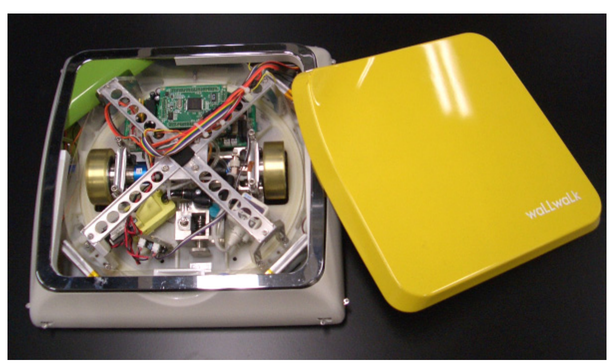
I. Introduction

WALL climbing mechanisms are helpful systems for the various applications on the vertical surface. Building maintenance is one of the most effective applications of wall climbing robot. Recently, we can recognize tall buildings downtown, and such buildings contain the walls with many pieces of glasses. Maintenance including inspections and repairs are important for keeping the conditions of building and for increasing its life time. A wall climbing robot is expected as the automatic maintenance system instead of human's work.

Various wall climbing mechanisms have been reported in the world. These wall climbing robots are categorized by the principle of adhesion and locomotion mechanisms: wheels, crawlers and legged walk. Here, the prior development are categorized by adhere principles. Wall climbing robots using magnetic adhesion have been developed [1]-[4] and some robots have come into practical use. The magnetic adhesion needs no energy for adhere and is available on the rough surface. But this adhesion principle is available on magnetic materials. Nishi et al. have developed the wall climbing robot using impelling force by single and multi impeller [5]. This principle is prospective on the nonmagnetic materials and rugged surfaces, but there are problems on feasibility: e.g. position and attitude controllability in the outdoor environments, impeller's noise and energy efficiency. The most major adhesion principle is the vacuum adhesion[6]-[26]. This system enables to the robots adhere on magnetic and nonmagnetic materials by simple mechanisms. This principle helps low energy consumption. But vacuum adhesion is not suitable for using on rough surface, hence the roughness makes a leak of air at the vacuum chamber such as suction cup. In order to apply vacuum adhesion for adhesion on rough surface, larger capacity of vacuum source is required.

Part of the authors developed the wall climbing robots for window cleaning, "WallWalker", which consist of a suction cup and two driving wheels as shown in Figure 1, Figure 2. This robot moves on all over the glass window by the

(a) A scene of WallWalker working on the window in the living room



(b) The detail of WallWalker

Fig. 1 The developed window cleaning robot

Manuscript received April 9, 2007. This work was supported in part by The Prototype Development Support Enterprise, Next-Generation Robot Commercialization Project, The New Energy and Industrial Technology Development Organization (NEDO) under Grant 04001529-0 and in part by Okayama Prefecture Industrial Promotion Foundation under Grant 2006-405.

Tohru Miyake is with the Graduate school of Engineering, Kawagwa University, 2217-20, Hayashi-cho, Takamatsu-shi, Kagawa, 761-0396 Japan and also with Miraikikai Inc. (e-mail: miyake@miraikikai.jp).

Hidenori Ishihara is with the Graduate school of Engineering, Kawagwa University (e-mail: ishihara@eng.kagawa-u.ac.jp).

Motoi Yoshimura is with the Faculty of Engineering, Kagawa University.

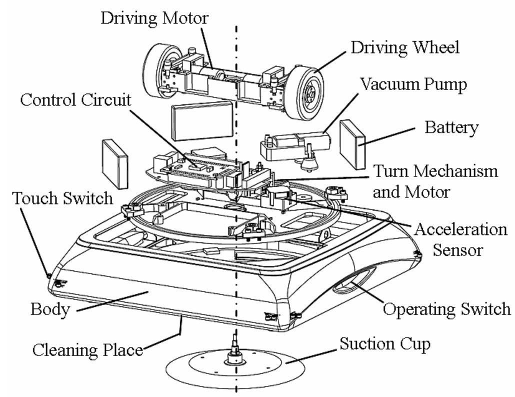


Fig. 2 Mechanism of small-size window cleaning robot. The top cover is removed for explanation

Table 1 Specifications of prototype

Motors	Wheel driving: DC servo motors x 2, Turn mechanism: DC motor x 1
Vacuum pump	Pressure: Maxmum -33.3 kPa, Flow volume: 2.5 l/min
Continuous work time	Approx. 1 hour
Power source	Li-Polymer Batteries, Actuators:14.4 V, Controller: 7.2 V
Dimensions (W x D x H)	Approx. 0.3 X 0.3 X 0.1 m^3
Weight	Approx. 3 kg

autonomous control system. The specifications are listed in Table 1.

This paper reports the effectiveness of wet adhesion system by the basic experiments. The authors aim at improvement of the mobility by the progress of adhering performance which is composed of seal capability and triboperformance between the seal and adhered surface. The seal capability decides degree of sealing on various roughnesses. The high performance seal makes a contribution to realize the wall climbing robot which can move on rough surface. In addition the capability of vacuum pump will also be minimized by the improvement of seal performance. As the result, the robot has

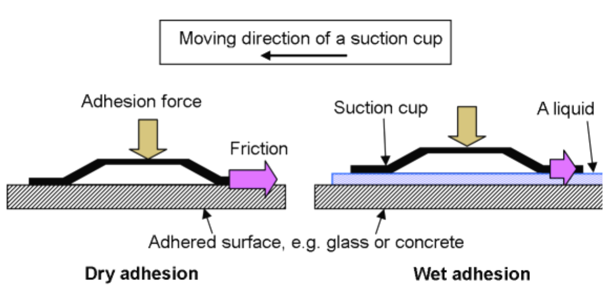
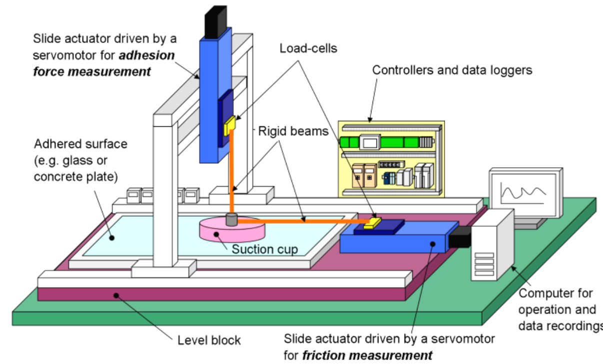
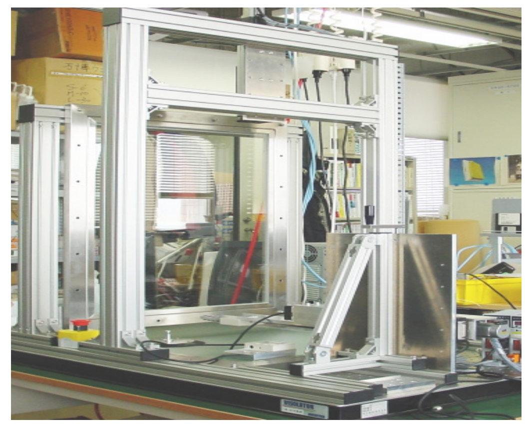


Fig. 3 The mechanism of vacuum-based wet adhesion system



(a) Schematic diagram



(b) A photograph of apparatus aspect

Fig. 4 Experimental setups of adhesion characteristics measurements

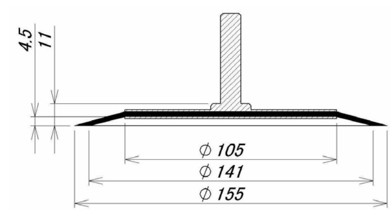


Fig. 5 Tested suction cup with experimental jigs

the potential of miniaturization and getting high moving velocity and larger payload by weight saving of vacuum system. Furthermore, the decreasing of friction coefficient on the suction cup helps the saving of loss energy. It is of benefit to long same capability of actuators compared to time per charge.

II. Principles of Wet Adhesion System

In wet adhesion system, a liquid is applied between the projecting ridge of the suction cup and adhered surface as shown in Figure 3. This system has two aims. First one is to keep the friction between a rubber seal of a suction cup and adhered surface low for steady and efficient mobility of the wall climbing robot. Second one is to improve the seal performance of the suction cp to avoid miss adhesion. In this case, the liquid is expected to woks as the filler for the small gap. As the lubricant methods, solid lubricant such as polytetrafluoroethylene (PTFE) and molybdenum disulfide (MoS_2) are generally used for lubrication of rubbers. But friction coefficients of solid lubricants are about higher than that of fluid lubricant.

The advantages of wet adhesion system are:

1) Low friction between suction cup and adhered surface by fluid lubrication;
2) Improvement of the seal performance of suction cup;
3) Wear free on of solid lubricant.

The issues on wet adhesion system are:

1) The supply and resumption mechanism are required;
2) The lubricant which does not soil a wall should be selected;
3) The menthols for preventing an attaching of lubricant to the driving wheels of wall climbing robot are required.

This paper focuses on aiming at the adhesion force on rough surface under low coefficient by the wet adhesion.

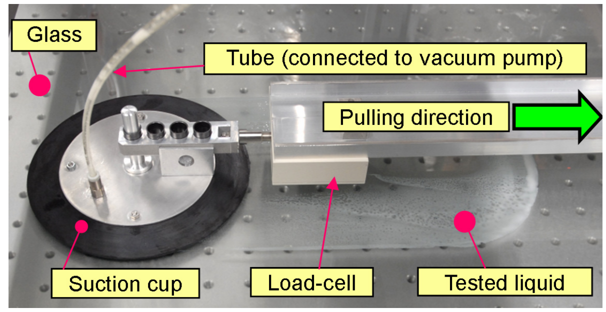
III. Experiments

In this paper, the frictions and the adhesion force when a suction cup adheres on a surface in various conditions are reported. First, the effectiveness of wet adhesion system was confirmed by the basic experiments concerning the differences between dry and wet adhesions. Next, the experiments using several different liquids for lubrication indicate performance by the differences in viscosity of lubricant.

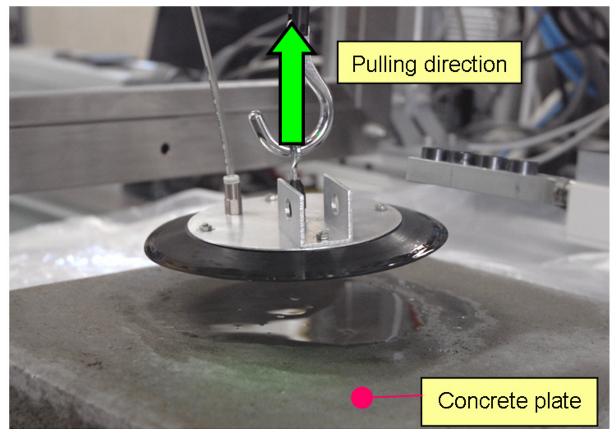
The suction cup shown in figure 4 is used in all experiments of this paper. This suction cup made of rubber substitute of which shore hardness is approximately 60 degrees. An air in the suction cup is vacuumed up by using downsized diaphragm vacuum pump of which maximum vacuum pressure is -26.7kPa and maximum flow volume is 1.5L/min. A vacuum pressure in the suction cup is made adjustment by needle valve. This valve works for changing the volume of the inlet flow from outside of the suction cup to vacuum pump. A vacuum pressure in the suction cup is measured by digital pressure sensor.

A. Experimental setup

Figure 4 shows the experimental setup for the tests of wet adhesion system. This apparatus was built for measurement of adhesion force and friction between suction cups and adhered surfaces. Two of slide actuators which driven by servomotor are installed into this system to pull the suction cup adhering on the test surface. The actuator for the experiment of friction is placed in parallel with adhered surfaces. The actuator for the experiment of adhesion is fixed with adhered surfaces at right angle. On this apparatus, adhesion force and friction are measured by load-cells which are installed on each moving part of slide actuator rigidly.



(a) Experiment on measurement of the friction



(b) Experiment on measurement of the adhesion force

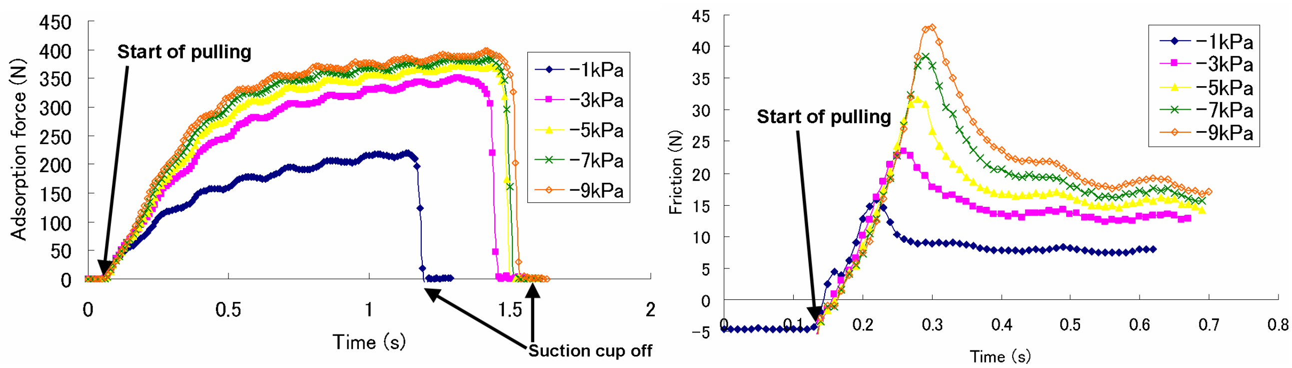
Fig. 6 The aspects of adhesion characteristics measurement

Either of load-cells is connected to the suction cup by steal rods solidly. The choice of load-cell depends on the target of experiment, adhesion force measurement or friction measurement. The velocity and moving distance of actuators are set by an operator. The force data measured by load-cells are recoded by data-logger and saved to computer. Every measurement was done 5 times under the same condition in series and the averages of them were plotted in the graph. The sampling frequency of force measurement in every experiment was set at 100 [Hz].

B. Experiments of basic characteristics with dry condition

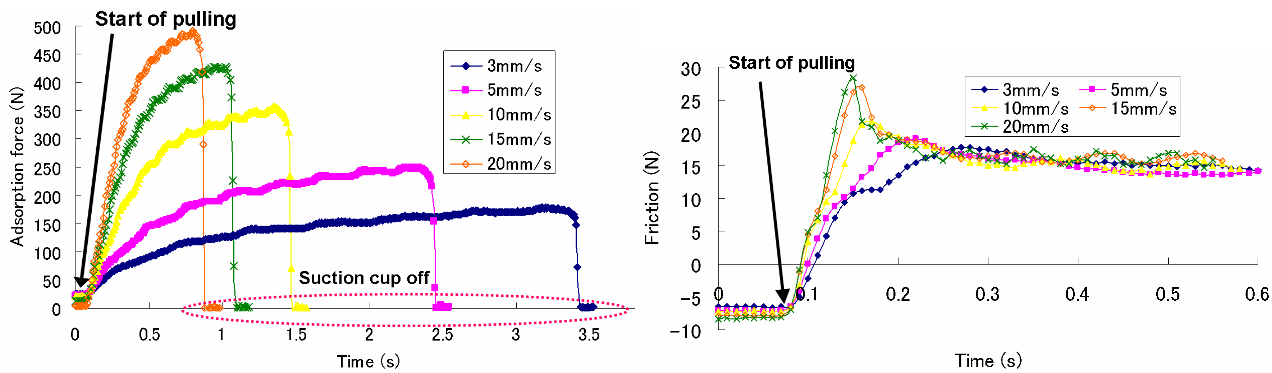
First, adhesion force and friction of dry adhesion on the glass were examined. The characteristics measured under two kinds of conditions are reported. One is pressure dependence of adhesion characteristics. Another is pull speed dependence of adhesion characteristics. In each condition, the suction cup was pulled at a velocity of 10 [mm/s] and the suction cup was moved a distance of 200 [mm] at friction measurement and moved a distance of 30 [mm] at adhesion measurement.

Figure 7 shows pressure dependence of adhesion characteristics. This result says the adhesion force and friction build up by increasing of degree of vacuum. This trend meets theory of suction cup adhesion. In these



(a) Adhesion force (b) Friction

Fig. 7 Pressure dependence of adhesion characteristics on the dry glass



(a) Adhesion force (b) Friction

Fig. 8 Pull speed dependence of adhesion characteristics on the dry glass

experiments, the condition of the pulling velocity was 10 [mm/s].

Figure 8-(a) indicates pull speed dependence of adhesion force. This result shows the maximum adhesion forces in each pulling speed are in direct proportion to pulling speed and this constant of proportion is approximately 19.5 [N/(mm/s)]. Figure 8-(b) says the maximum friction at each speed is directly proportional of which constant of proportion is approximately 2.9 [N/(mm/s)] to pulling speed at that time. This maximum friction means starting fiction. However, the frictions, 0.3 [s] or later in Figure 8-(b), which took enough time after maximum friction was record do not depend on pulling speed. It takes the steady value at around 15N at the time. This value is kinetic friction.

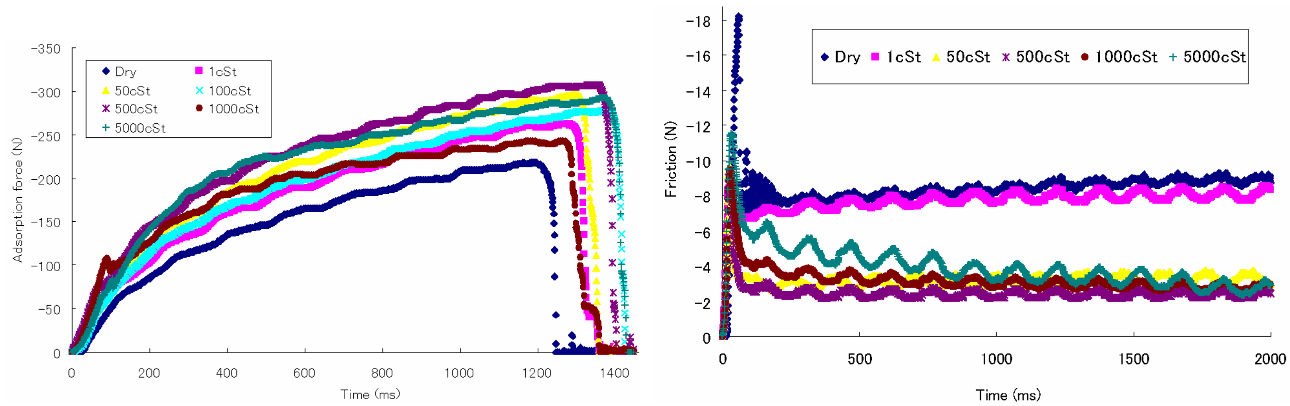
C. Experiments on viscosity dependence

Next experiments tested influences of viscosity of applied liquid on the adhered surface. In this experiment, visco-elastic-polymers which have known kinetic viscosity were used. The tested kinetic viscosities are 1, 50, 500, 1000 and 5000 [cSt (centi-stokes)]. Figure 9-(a) shows that the adhesion forces of every viscosity are higher than that of dry. I.e. The liquid promotes the adhesion force. This is considered as improvement of sealing performance by the applied liquid. In fact the applied liquid between suction cup and adhered surface helps to prevent inlet flow from the outside of suction cup. But the rate of rising of adhesion force does not correlate with viscosity in this experiment.

Then Figure 9-(b) tells that there is no difference between liquid of 1 [cSt] and dry condition. However, the frictions are reduced in proportion as the viscosity increases from 1 [cSt] to 500 [cSt]. But, when the viscosity increases further from 500 [cSt] to 1000 [cSt] and 5000 [cSt], the frictions move up again. This phenomenon is considered that the liquid of viscosity from 1cSt to 500 [cSt] works to reduce the friction by the lubricating action of the liquid. But, the liquids at the viscosity of 500 [cSt], 1000 [cSt] and 5000 [cSt] gradually makes the friction increased according to accretion of viscosity. This trend considered that it is comes from low flowability of the high viscosity liquids.

D. Experiments of adhering to rough surface with wet condition

Figure 10 says the adhesion force which the suction cup adheres on the concrete block of which dimensions are 300(W) x 300(D) x 30(H) [mm^3]. Different viscosities of test



(a) Adhesion force

(b) Friction

Fig. 9 Viscosity dependence of adhesion characteristics on wet adhesion system

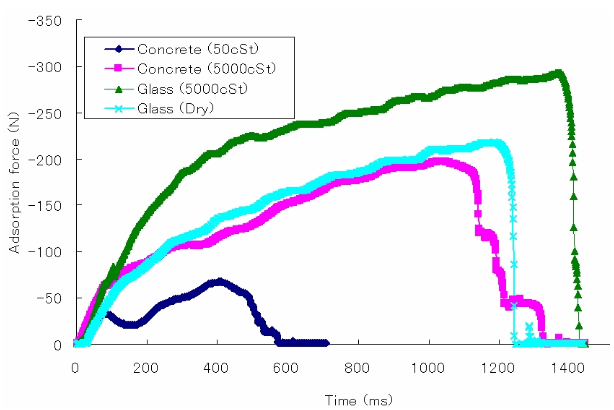


Fig. 10 Adhesion force when the suction cup adheres on concrete plate with wet adhesion system

liquid were used: 1[cSt], 50 [cSt] and 5000[cSt]. The cases of using 1[cSt], [cSt] and dry condition could not get adhesion force on the concrete block. The 50 [cSt] worked to get the adhesion force up to 70 [N]. And the 5000 [cSt] worked to get the adhesion force 2.5 times the 50 [cSt]. This force comes near the force which the suction cup adhere on the dry glass. Figure 10 shows that the curve of “concrete (5000 [cSt])” overlaps approximately with the curve of “Glass (Dry)” in whole period from start to end of pulling. By this experimental result, It is confirmed that the vacuum adhesion system under wet condition can get the adhesion force on rough surface. But the friction force in this condition could not measure for the reason of the ability of experimental setup.

IV. DISCUSSIONS AND CONCLUSIONS

This paper proposed the new adhesion system by vacuum adhesion using a liquid as a lubricant between a suction cup and surface of glass for the wall climbing machine. This paper reported the result of basic characteristics of adhesion force and friction on dry and wet conditions.

As the result of the experiments, it was confirmed that the adhesion force on smooth and rough surface increases in comparison with dry condition. On the other side, the friction of wet condition reduced by half in comparison with dry condition in the best assumption of viscosities of test liquid. By these results, the authors found the potential of feasibility of wall climbing robot which works on rough surface by proposed wet adhesion system. In the future works, the authors will test the feasibility of proposed system using prototyped wall climbing robot.

Additionally, wed adhesion system enables the robots to adhere on the wall with rough surface. A liquid between a suction cup and wall keeps high sealing performance and obtains the effect of filling the convexoconcave on the surface of wall.

For realizing the wet adhesion system, we should solve the following problems. They are:

1) Choosing the liquid in the points of viscosity and so on;
2) Designing the mechanism providing liquid into the gap between the suction cup and surface of wall;
3) Designing the mechanism retrieving liquid from the surface of wall.

REFERENCES

[1] Shigeo Hirose, Wall Climbing Vehicle Using Internally Balanced Magnetic Unit, Proc. of 6th RoManSy Symp., Cracow, Poland, pp. 1-8, 1986

[2] Shigeo Hirose, et al, Disk Rover: A Wall-Climbing Robot Using Permanent Magnet Disks, Proc. of IEEE/RSJ Int’l Conf. on Intelligent Robots and Systems, pp. 2074-2079, 1992

[3] Weimin Shen, et al., Permanent Magnetic System Design for the Wall-climbing Robot, Oroc. Of the IEEE Int’l Conf. on Mechatronics & Automation (ICMA), 2005

[4] Shinya Kitai, et al., The proposal of Swam Type Wall Climbing Robot system “Anchor Climber, Proc. IROS, pp. 3999-4004, 2005

[5] A Nishi, Development of wall climbing robots, Computer and Electrical Engineering, 22(2), pp. 123-149, 1996

[6] B. Bahr, et al., Design and suction cup analysis of a wall climbing robot, Computers Elect. Engng. Vol. 22, No. 3, pp. 193-209, 1996

[7] Werner Brockmann, Concept for energy-autarkic, autonomous climbing robots, Proc. of the 8th Int'l Conf. on Climbing and Walking Robots (CLAWAR), 2005 pp. 107-114
[8] Tomoki Yano, et al., Development of a Self-Contained Wall Climbing Robot with Scanning Type Suction Cups, Proc. of the IEEE/RSJ Int'l conf. on Intelligent Robots and Systems, pp249-254, 1998
[9] D Longo and G Muscato, Design of a climbing robot for wall exploration – a neural network approach for pressure control onboard the Alicia II prototype, 5th Int'l conf. On Climbing and Walking Robots, pp. 1021-1026, 2002.
[10] Jizhong Xiao et al, Design of Mobile Robots with Wall Climbing Capability, Proc. of the IEEE/ASME int'l Conf. on Advanced Intelligent Mechatronics, pp. 438-443, 2005
[11] Matt Elliot et al, City-Climber: A New Generation of Wall-climbing Robots, Proc. of the IEEE Int'l conf. on Robotics and Automation (ICRA), pp. 4413-4415, 2006
[12] H.Y. Fung, et al., Development of a Window-cleaning Robot, Workshop on Service Automation and Robotics, CIDAM2000, pp. 148-153. 2000.
[13] Y WANG, et al., The study and application of wall-climbing robot for cleaning, Third Int'l conf. On Climbing and Walking Robots, pp. 789-794, 2000.
[14] R.D. Schraft, et al., "Mechanical Design of an Autonomous, Lightweight Robot for window cleaning", Proc. of the 33rd Int'l Symp. on Robotics (ISR), 2002.
[15] Shigeo Hirose, et al., Machine that can Walk and Climb on Floors, Walls and Ceilings, Proc. of 5th ICAR, pp. 753-758, 1991
[16] T. Fukuda, et al., Wall Surface Mobile Robot Having Multiple Suckers on Variable Structural Crawler. Proc. of Int'l Symp. on Theory of Machines and Mechanisms, pp. 707-712, 1992
[17] S. W. Ryu, et al., Self-contained Wall-climbing Robot with Closed Link Mechanism. Proc. of the 2001 IEEE/RSJ Int'l Conf. on Intelligent Robots and Systems, pp. 839-844, 2001.
[18] K. Yoneda, et al.: Development of a Light-Weight Wall Climbing Quadruped with Reduced Degrees of Freedom, Proc. of the 4th Int'l Conf. on Climbing and Walking Robots (CLAWAR), pp.907-912, 2001.
[19] Jianzhong Shan el al., Design of a Climbing Robot for Inspecting Aircraft Wings and Fuselage, Proc. of the 9th Int'l Conf. on Climbing and Walking Robots (CLAWAR), pp 552-557, 2006
[20] F Cepolina, R C Michelini et. al., Gecko-Collie-home cleaning automation of floors, walls and cupboards, Third Int'l conf. On Climbing and Walking Ro-bots, pp. 803-811, 2000.
[21] M. Sitti and R. S. Fearing, Synthetic Gecko Foot-Hair Micro/Nanostructures for future Wall-Climbing Robots. Proc. of the IEEE Robotics and Automation Conf., 2003
[22] M. Sitti and R. S. Fearing, Synthetic Gecko Foot-Hair Micro/Nanostructures as Dry Adhesives, Journal of Adhesion Science and Technology, vol. 17, no. 5, 2003
[23] Kunio Takahashi, et al, Geckos' foot hair structure and their ability to hang from rough surfaces and move quickly, Int'l Journal od Adhesion & Adhesives, 26, pp 639-643, 2006
[24] Jose Berengueres, et al., Magnetic Hair for Wall Mobility, IEEE/RSJ Int'l Conf. on Intelligent Robots and Systems (IROS), 2006
[25] Qian Zhi-yuan, et al., Fuluid Model of Sliding Suction Cup of Wall-climbing Robots, Int'l Journal of Advanced Robotic Systems, Vol. 3, No3, pp. 275-284, 2006
[26] Alan T. Asbeck, et al., Scaling hard vertical surfaces with compliant microspine arrays, Proc. of Robotics Science and Systems Conf., 2005
[27] T. Miyake and H. Ishihara, Mechanisms and Basic Properties of Window Cleaning Robot, Proc. of the IEEE/ASME Int'l Conf. on Advanced Intelligent Mechatronics (AIM), pp. 1372-1377, 2003
[28] T. Miyake and H. Ishihara, WallWalker: Proposal of Locomotion Mechanism Cleaning Even at the Corner, Proc. of the 7th Int'l Conf. on Climbing and Walking Robots (CLAWAR), 2004
[29] T. Miyake, et al, WallWalker: Development of Small-size Window Cleaning Robot by Wall Climbing Mechanism, Proc. of the 9th Int'l Conf. on Climbing and Walking Robots (CLAWAR), 2006