A Novel Passive Adhesion Principle and Application for an Inspired Climbing Caterpillar Robot

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***Abstract*—This paper presents a novel passive adhesion principle which is used firstly for an inspired modular climbing caterpillar project. After a related survey on the natural creatures which can climb on the vertical surface with different materials, a systematical summarizing on four attachment methods adopted by climbing robots worldwide is given. Then a low-frequency vibrating passive attachment principle is presented in order to keep the merits and eliminate the shortcomings of using the normal active vacuum suckers. The adhesion principle, related mathematic model and rational testing are presented step by step. The new passive suckers based on this principle are used on an inspired modular climbing robot, which is currently under development in our consortium. On-site testing shows application of our passive suction method can free climbing robots from the heavy vacuum ejectors and realize an effective simple adsorption, furthermore improve the inspired technological level and flexibility of the locomotion capability.**

Index Terms—passive adhesion; climbing robot; inspired caterpillar robot

I. INTRODUCTION

Climbing is just as challenging a task for autonomous mobile robots as for human beings. Climbing robots are special mobile robots which can move and work vertically on the working targets to implement typical given tasks [1]. They feature the special working environment and mobility against gravity.

As a special potential sub-group of mobile technology, climbing and walking robots can work in unstructured environments [2]. Since the first climbing robot was developed in the 1980s, the last decades have seen an increasing interest in developing and employing climbing mobile robots for different applications. Many research projects on climbing robots have implemented in U.S.A., Japan, Europe, Australia and China, such as CLAWAR in Europe [3] which issued many impressive achievements to enhance the mobility and working capability of mobile climbing robots.

In the recent 15 years, there are considerable achievements on climbing robots research worldwide by exploring the potential four following applications in hazardous and unmanned environment.

a. Reliable non-destructive evaluation and diagnosis in hazardous environments such as the nuclear industry, the chemical industry and the power generation industry (Fig. 1a) [4] [5];

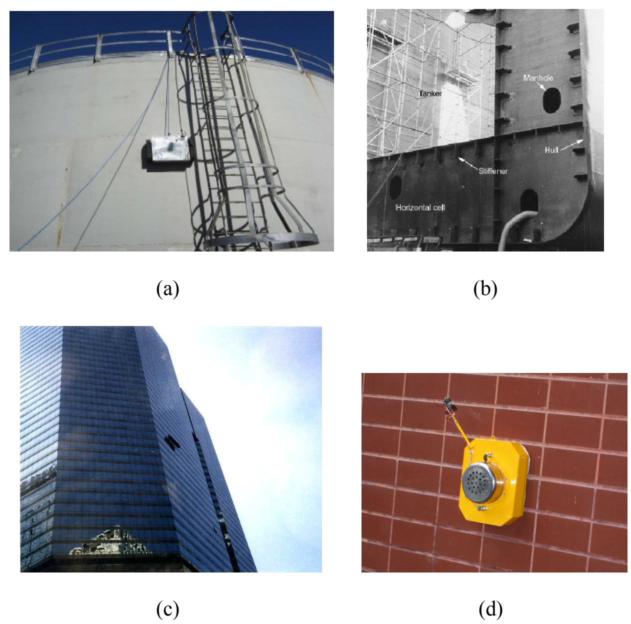

Fig. 1 Possible applications of climbing robots.

(Sources: (a) is from Ref. [4]; (b) is from Ref. [6];

(c) is from Ref.[7]; (d) is from Ref.[10])

b. Welding and manipulation in construction industry, especially of metallic structures such as in bridges, shipping, off-shore industries and buildings' skeletons usually involve a very high number of dangerous manual operations (Fig. 1b) [6];

c. Cleaning and maintenance for high-rise buildings (Fig. 1c) [7] [8].

d. Urban search and rescue, military reconnaissance and civil exploration (Fig. 1d) [9] [10].

The most important issue for climbing robots is the adhesion methods. The climbing robot has to be safely attached to the glass wall and has to overcome gravity. With the technological development, combining the techniques from the fields of electrical and mechanical engineering, bio-inspired technology, material engineering, and computer science will be necessary to provide climbing robotic systems suitable for practical use. For example, climbing robots do need some special devices to enable themselves for safety attachment to the vertical wall with different materials. New invented adhesion materials enhancing the climbing technology is a possible solution and would simplify the robotic system design.

The purpose of this paper is to present a novel passive adhesion principle for climbing robots based on an overview of the latest wide-range achievements in related issues of climbing and walking robotic technology.

This paper is organized as follows: section 2 introduces the inspired adhesion principles adopted by natural creatures. Then a systematical survey of the attachment principles of climbing robots is given. After that a low-frequency vibrating passive attachment principle is presented in section 3. Section 4 introduces the application of this attachment principle in our international cooperated climbing robotic project. In the end, conclusions and future work will be given as a final.

II. Review of Attachment Methods for Climbing Robots

Firstly we will have a look in the natural creatures which own climbing capabilities. The bio-inspired investigation is important and necessary for us to understand and design the possible adhesion methods for industrial climbing robots.

A. Attachment Mechanism of the Natural Creatures

Many animals, especially small creatures can move on the vertical surfaces. In them, caterpillars and snails feature the limbless kinematics and a soft-body structure.

Fig. 2 Caterpillar climbing mechanism.

Caterpillars are among the most successful climbers and can maneuver in complex three-dimensional environments, burrow, and hold on to the substrate using a very effective passive grasping system [11], as shown in Fig.2. Normally the caterpillars consist of a head, a torso part and a tail part in total. They use passive grip to secure themselves to complex branched substrates and can effect multidimensional movements. They are able to bend, twist and crumple in ways that are not possible with a rigid skeleton. The prolegs provide astonishing fault-tolerant maneuvering ability and stable, passive attachment. [12].

Without any leg-like structure, snails move by gliding along on their muscular foot, which is lubricated with mucus for safe and powerful passive adhesion in nature (Fig. 3). The locomotion movement is mainly implemented depending on the muscle's expansion and contraction. However, it is noted that snails are among the slowest-moving creatures on earth. From the bionics viewpoint, the torso structure is soft and thus hard to imitate based on the technological level of mechanical engineering and material engineering. Furthermore controlling the soft-body should be totally nonlinear.

Fig. 3 Snail climbing mechanism.

Cicadas and house centipedes use nails on the end of each leg to grip the texture of the material they crawl on to enable them to attach to vertical rough surfaces. Here we should emphasize that cicadas-like insects can only climb on roughness, as shown in Fig. 4. It is impossible for them to move on clean and smooth surfaces at all.

It is noted that cicadas use some nails on the end of each leg to grip the texture of the material. Even if the environment surface looks relatively smooth for human being to climb on, for cicadas it is rather rough and easy to grip. Actually this attachment principle is a totally mechanical grasping which is similar to that monkeys' flexible climbing on the trees, mountain goats' astonishing jumping on the mountain rock.

Fig. 4 Multi-legged climbing mechanism.

Gecko's foot features millions of micro-scale adhesive foot-hairs on each toe, which are arranged in a certain manner. On the ends of the foot-hairs of gecko feet are tiny twigs. The tops of these twigs feature curved shape structures like nano-scale suckers. On the one hand, these suckers endow the gecko with the capability of climbing amazingly and moving on different materials in three dimensions; while on the other hand, the geckos' climbing capability is totally dependent on the feature of millions of adhesive foot-hairs on each toe. From the authors' viewpoint, geckos are the most flexible climbing animals on our planet.

Fig. 5 Gecko and its foot.

Honey bees are the other small insects which can stay on the vertical surface for long time. First, on rough surfaces like trees and rocks, honey bees can grip the texture and gaps to move on them like cicadas. While on smooth surfaces like mirrors and glasses, they can stop in the air and keep their legs on the surface by controlling the speed and orientation of two wings, as shown in Fig. 6. From general view point, aerodynamic force enables the honeybee to attach to and "climb" a vertical smooth surface. Hovering honey bees flag two wings back and forth at a high angle of attack during each stroke to generate lifting and adhesion force at the same time. That means the counterforce of wing's high-speed movement effects a pushing benefit to keep the honeybee on the vertical surfaces well.

Fig. 6 Honey bee (Source: Ref. [13]).

Spiders with a special climbing capability are predatory invertebrate animals. They have a body with two segments, and eight legs. Spiders produce silk, which is a thin, strong protein strand extruded by the spider from spinnerets, to aid in forming smooth walls for burrows, building egg sacs, wrapping prey, etc. [14]. Fig. 7 shows its climbing capability. Spiders also use the silk for moving and climbing. Normally, they only slide or climb down the silk from a higher position to a lower one. The moving function is totally dependent on the intensity and reliability of the silk.

Fig. 7 Spider's climbing mechanism (Source: Ref. [15]).

B. *Investigation on Attachment Methods of Climbing Robots*

Generalized adsorptive force is used to maintain the robot on the wall surface safe and stable. There are four different principles of adhesion used by climbing robots: electromagnetic force; molecular force; vacuum and mechanical forces. Each one has advantages and disadvantages at the same time.

Electromagnet is quite efficient method for safety adhesion on ferromagnetic materials. Another advantage is easy to use and control. There is no corresponding climbing creature adopting this adhesion in nature. However electromagnetic force is not suitable for general climbing robots because of the validity only on the ferromagnetic surfaces. Meanwhile, for actuating the electromagnet it still needs a big heavy power supply. There is no possibility of application on light weight climbing robots except for some special cases [16].

Inspired by gecko bristles [17], the last few years have witnessed a strong interest in applying molecular force as a new attachment method for climbing robots. With the development of nanotechnology, some flexible climbing prototypes, like RiSE, are emerging [25]. It is a promising reliable attachment principle for climbing from the technical point of view. It is especially suitable for designing a mini-scale climbing robot. However, the benefits of this novel adhesive principle are offset by expensive manufacturing price and difficulties. Based on the technology level at the moment, it still will take some time for real industrial application. Similarly, recently some other research groups are also trying to use special materials such as PDMS elastomer [27], for adhesion. However how to keep the adhesion materials clean is a big problem for the real application.

There are some climbing prototypes using mechanical forces for attachment on the vertical surface. The attachment is inspired by cicadas and house centipedes. The grasping gripper is the relatively prevalent. Usually the climbing robots based on this attachment are working in some specialized environment such as metallic-based buildings [18] [19] [25]. Obviously, this adhesion principle will be adopted according to physical working constraints, thus make it uncommon and impossible for application on smooth surfaces.

A. Nishi and his colleagues developed a kind of wall-climbing robot using the propulsive force of propellers [20]. Inspiration of this attachment is as same as that of flying honey bees. The whole robot is relatively light compared with other climbing prototypes with the similar dimension. But the noise generated by propellers is too loud to use. Also it is hard to design a small climbing robot based on this attachment principle since the propeller has to be rather big to generate certain lifting and attaching forces.

Currently vacuum is still the most common idea for the attachment adopted by climbing robots. There are also two different sub principles to generate vacuum: negative pressure and vacuum suckers. Actuated by electrical motors [21] in its negative pressure chamber, the climbing robot can move on the wall flexibly and continuously. The negative pressure chamber is not sensitive to a leakage of air. However this method is not enough for the safe and reliable attachment to the vertical surface when the robot has to cross some high obstacles if there is one chamber on the robot. In the same attachment principle, recently a new climbing prototype Cromsci is presented, which is able to move and inspect vertical surfaces safely, fast [26]. The improved adhesion system of the climbing robot consists of seven single vacuum chambers which are supported by one large reservoir chamber at the top of the robot. The round shape with a complete diameter of 80cm; and the overall weight is at about 50kg with an additional payload of up to 10kg.

The vacuum in the suckers can easily established by vacuum ejectors or vacuum pumps [22]. The advantages of high reliability and easy-controlling of vacuum ejectors and vacuum pumps are offset by adding the long air tube or relatively heavy devices on the climbing robots, thus limit the application of this adsorption on smart wall-climbing robots.

To the best of our knowledge, there is currently no efficient passive attachment principle used by any climbing robotic prototype worldwide. The situation encourages us to investigate the new adhesion principle and propose our new findings.

III. New Passive Adhesion Principle

A. Low Frequency Vibrating Adhesion

A new low-frequency vibrating passive suction method is presented in order to keep the merits and eliminate the shortcomings of using the normal active vacuum suckers. Application of a new low-frequency vibrating passive suction method makes it possible to free climbing robots from the heavy vacuum ejectors and realize an effective simple adsorption [23].

Fig. 8 shows the principle of low-frequency vibrating suction attachment. Where P_1 is the minimum of the vacuum in the passive sucker for attachment; P_2 is the suitable negative pressure for reliable attachment; P_3 is the maximum of the vacuum inside the passive sucker.

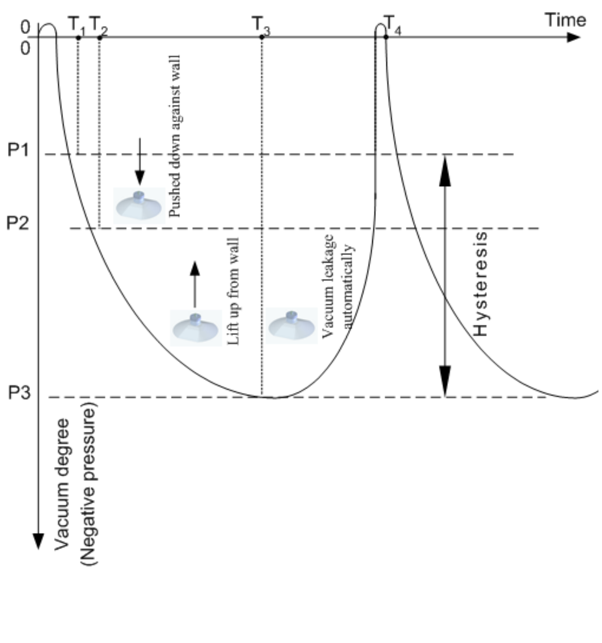

Fig. 8 Principle of low-frequency vibrating suckers.

From the beginning of the process, the passive sucker is pushed against on the vertical surface. It can be attached when the inside air is squeezed out so that the internal vacuum is established, as shown at T_1. At the T_2, when the squeezing process almost finished, the negative pressure will be increased to P_2. Then if the passive sucker is lift up suddenly by external force, the internal vacuum will increase a lot. The reason for this higher negative pressure P_3 is the sucker's internal volume increases remarkably while the internal air is as same amount as ever.

It is noted that the internal negative pressure will descend with the time due to the leakage of vacuum. It is only a matter of time that passive suckers will release down anyway. The adsorption time is dependent on the characteristics of the wall surface, such as smoothness and cleanness. However, if the passive sucker is pushed down again before it drops down at time T_4, the internal vacuum can be rebuilt for sure. It is a cycle from T_1 to T_4. As a result, the passive sucker will keep attachment reliably on the vertical wall for some longer time.

B. Simulation and Rational Testing

For idea gas, the following equations represent the passive suckers' attachment principle. In Fig. 9a, the passive sucker is at the initial state, where P_0, V_0, M_0, T_0 are the inside pressure, volume, mass of air, and temperature respectively; H is the initial height of passive sucker; r is the radius of the suckers; $\rho$is the density of the idea air; F is the force for squeezing and lifting. The inside volume of passive sucker is described as (1), and the mass of the air is (2).

$$V_0 = \frac{1}{3}\pi r^2 H \tag{1}$$

$$M_0 = \rho V_0 = \frac{1}{3}\pi r^2 \rho H \tag{2}$$

From Fig. 9a to 9b, firstly the inside air is getting less and less with the inside volume decreasing. During the squeezing process, within a certain very short period the pressure is higher than P_0; but we can consider that the inside pressure is almost as same level as P_0. After that, the outside force is disappeared, the inside volume will recover to V_0 since the sucker is an elastomer due to the compliance of the sucker's material. Then the negative pressure P_2 is generated due to the increasing the inside volume. The process can be described as (3), and (4) since the temperature is always unchangeable during the whole process. Where x is the change the sucker's height.

$$V_2 = \frac{1}{3}\pi r^2 (H - x) \tag{3}$$

$$P_2 = \frac{P_0 V_2}{V_0} = \frac{P_0 \frac{1}{3}\pi r^2 (H - x)}{\frac{1}{3}\pi r^2 H} = P_0 (1 - \frac{x}{H}) \tag{4}$$

This multifunctional climbing caterpillar will be capable of walking and climbing not only in different environment but also on the vertical surfaces and ceilings on the inside of buildings. It will possess locomotion capacities including pitching, yawing, lateral shift, and rotating; while features sensor-servo-based active perception of the environment.

Up to date, a cheap and easy-to-build prototype has been designed and manufactured as an experimental caterpillar version. A shell supports an RC servo with a pair of ears. A new designed passive sucker based on the low-frequency vibrating principle is implemented on the modular climbing robot, as shown in Fig. 11. An extra box on the back of the shell contains the battery, a simple controller and auxiliary connecting parts for passive suckers. The basic module is about 50 mm long, 30 mm wide and 30 mm high. All mechanical parts are manufactured from aluminum.

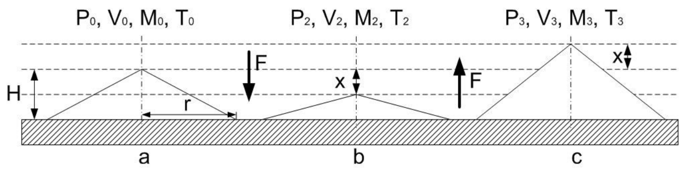

Fig. 9 Simulation of passive suckers.

From Fig. 9b to 9c is a following similar step. Due to the lifting force, the inside volume is increasing while the pressure decreases to P_3. In this step, we assume there is no air getting into the sucker. V_3 and P_3 are in (5), and (6).

$$V_3 = \frac{1}{3}\pi r^2 (H + x) \tag{5}$$

$$P_3 = P_0 \left(\frac{H - x}{H + x}\right) \tag{6}$$

After that, the air will get into the passive sucker with the time. When the volume increases to V_0, the inside air will be squeezed out again. It is noted that the squeezing process is under the control and faster than vacuum leakage. As a result, the negative pressure can be gotten periodically for some longer time.

Based on this principle, a DC motor is used as an oscillator to realize the pushing and lifting movement automatically, as shown in Fig. 10. The vacuum inside sucker is established by low frequency vibration of the cup against the wall surface so that the stability and reliability are met. This on-site test confirms principle described above [24].

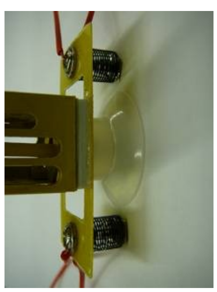

Fig. 10 The testing of a low-frequency vibrating sucker.

IV. On-site Test on a Climbing Caterpillar Robot

Since 2006 our international group has been working on an inspired modular climbing caterpillar which will be used as an intelligent demonstrator and test bed for the implementation of cognitive functions in robotic systems. We combine climbing techniques with a modular approach to realize a novel prototype as a flexible wall climbing robotic platform featuring an easy-to-build mechanical structure, and various locomotion capabilities. The robot consists of several connected modules for moving. Active joints actuated by RC servos endow the connecting modules with the ability of changing shapes in two dimensions.

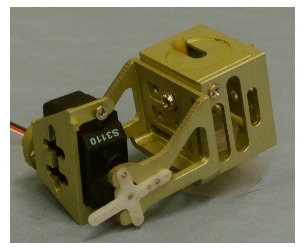

Fig. 11 Mechanical module of the inspired climbing caterpillar.

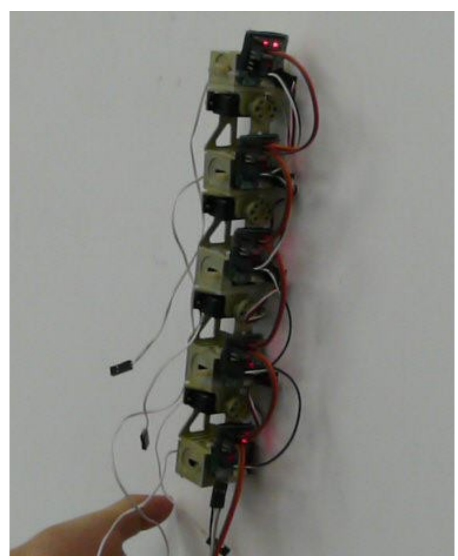

Fig. 12 Climbing experiments on the wall and flat surface.

When we applied symmetrical control to our experimental prototype, it can attach safely to a vertical wall while immobile. It could also perform several gaits on the wall, but eventually dropped down because the suckers were not adhered safe enough. When unsymmetrical control was applied, the robot could realize continuous motion on the vertical wall until a stop order was received. Fig. 12 depicts the procedure of the robot climbing on the flat wall using one gait by virtue of unsymmetrical control.

V. Conclusions

This paper introduces a new passive attachment method In order to find an efficient and effective attachment principle which can be adopted by a smart climbing caterpillar; we give an investigation on inspired climbing mechanisms of natural creatures. Based on it, a passive adhesion principle featuring the low-frequency vibrating, cheap and easy manufacturing is presented. This novel passive sucker make it possible to complete our cooperated climbing caterpillar idea which meets all requirements of functionality, safety, flexibility, extensibility and easy handling while being completely automatic and able to learn by the robot itself.

Now we are just in the beginning of this project. There is still a great amount of work for future research. Recently considering the importance and difficulty of the movement harmony among modules for realizing different gaits on surfaces of various materials, we are focusing on a kinematics model of the caterpillar's locomotion capabilities.

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References

[1] http://tams-www.informatik.uni-hamburg.de/people/hzhang/projects/skycleaners/

[2] H. Zhang, Edited Book "Climbing & Walking Robots Towards New Applications", ISBN 978-3-902613-16-5, 2007, I-Tech Education and Publishing.

[3] G. Virk, "The CLAWAR Project-Developments in the Oldest Robotics Thematic Network", 2005 IEEE Robotics & Automation Magazine, June, pp.14-20, 2005.

[4] P. Kalra, J. Gu, M. Meng, "A Wall Climbing Rbot for Oil Tank Inspection", Proceeding of the 2006 IEEE International Conference on Robotics and Biomimetics, Kunming, China, Dec. 17-20, 2006, pp.1523-1528, 2006.

[5] D. Longo,, G. Muscato, "A modular approach for the design of the Alicia3 climbing robot for industrial inspection", Industrial Robot: An International Journal, Vol.31, No.2, pp.148-158, 2004.

[6] M. Armada, P. Gonzalez de Santos, P. Prieto,, J.C. Grieco, "REST: A Sixlegged Climbing Robot," European Mechanics Colloquium, Euromech 375, Biology and Technology of Walking, pp. 159-164, 1998.

[7] H. Zhang, J. Zhang, W. Wang, R. Liu, G. Zong, "A Series of Pneumatics Glass-wall Cleaning Robots for High-rise Buildings", Industrial Robot: An International Journal, Vol.34, No.2, pp.150-160,2007.

[8] N. Elkmann,, T. Felsch,, M. Sack,, J. Saenz,, J. Hortig, "Innovative Service Robot Systems for Facade Cleaning of Difficult-to-Access Areas", Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems EPFL, Lausanne, Switzerland, October, pp.756-762, 2002.

[9] S Wu,. M Li,. S Xiao,. Y Li, "A Wireless Distributed Wall Climbing Robotic System for Reconnaissance Purpose", Proceeding of the 2006 IEEE International Conference on Mechatronics and Automation, Luoyang, China, June 25-28, 2006, pp.1308-1312, 2006.

[10] http://tams-www.informatik.uni-hamburg.de/people/hzhang/projects/index.php?content=Gecko

[11] S.Mezoff, N. papastathis, A. Takesianm and B.A. Trimmer, "The biomechanical and neural control of hydrostatic limb movements in Manduca sexta", J Exp Biol, Vol207,pp. 3043-3054, 2004.

[12] B. A. Trimmer, A. E. Takesian, B. M. Sweet, "Caterpillar Locomotion: A New Model for Softbodies Climbing and Burrowing Robots", Proceeding of 7the International Symposium and the Mine Problem, Monterey, CA May 2-5, 2006.

[13] http://en.wikipedia.org/wiki/bee

[14] http://en.wikipedia.org/wiki/Spider

[15] http://en.wikipedia.org/wiki/ Orb-weaver_spider

[16] T. Akinfiev, M. Armada, "The Influence of Gravity on Trajectory Planning for Climbing Robots with Non-Rigid Legs", Journal of Intelligent and Robotic Systems, Vol.35, pp.309-326, 2002.

[17] M. Sitti, R. Fearing, "Synthetic gecko foot-robots", Proceeding of IEEE international Conference on Robotics and Automation, Vol. pp.1164-110, Sept, 2003.

[18] M. Abderrahim, C. Balaguer, A. Giménez, J.M. Pastor and V.M, Padron, "ROMA: A Climbing Robot for Inspection Operations", Proceedings 1999 IEEE International conference on Robotics and Automation, Detroit, Michigan , May, pp.2303-2308, 1991.

[19] H. Zhang, J. Zhang, R. Liu, G. Zong, "Realization of a service robot for cleaning spherical surfaces", International Journal of Advanced Robotic Systems, Vol.2, No.1, pp. 53-58, 2005.

[20] A. Nishi, H. Miyagi, "Wall-climbing Robot Using Propulsive Force of a Propeller (Mechanism and Control System in a Mild Wind)", JSME International Journal Series C: Dynamics, Control, Robotics, Design and Manufacturing, Vol. 36, No. 3, pp.361-367, Sep, 1993.

[21] W. Wang, G. Zong, "Analysis on The Mechanics Stability for a New Kind of Robot", Journal of Robot, Vol.21, No.7, pp.642-648, 1999.

[22] H. Zhang, J. Zhang, W. Wang, R. Liu, G. Zong, "Sky Cleaner 3-A Real Pneumatic Climbing Robot for Glass-Wall Cleaning" IEEE Robotic & Automation Magazine,Vol.13, No.1 pp32-41, 2006.

[23] H. Zhang, J. Gonzalez-Gomez, S. Chen, W. Wang, R. Liu, D. Li, and J. Zhang, "A Novel Module Climbing Caterpillar Using Low-frequency Vibrating Passive Suckers", Proceeding of 2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, ETH Zurich, Switzerland, pp.85-90, Sept. 2007.

[24] T. Zhu, R. Liu, X.D. Wang, K. Wang, "Principle and Application of Vibrating Suction Method", Proceedings of the 2006 IEEE International Conference on Robotics and Biomimetics, December 17 - 20, 2006, Kunming, China, pp.491-495.

[25] M. J. Spenko, G. C. Haynes, J. A. Saunders, M. R. Cutkosky, A. A. Rizzi and R. J. Full, "Biologically Inspired Climbing with a Hexapedal Robot", Journal of Field Robotics, Volume 25, Issue 4-5, April, 2008, pp. 223-242.

[26] C. Hillenbrand, D. Schmidt, K. Berns, "Cromsci - A Climbing Robot With Multiple Sucking Chambers For Inspection Tasks", 11th International Conference on Climbing and Walking Robots (CLAWAR), September 08-10, 2008.

[27] O. Unver, A. Uneri, A. Aydemir, M, Sitti, "Geckobot: a gecko inspired climbing robot using elastomer adhesives", Proceedings 2006 IEEE International Conference on Robotics and Automation, 15-19 May, 2006, pp.2329-2335.