A Novel Modular Climbing Caterpillar Using Low-frequency Vibrating Passive Suckers

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Abstract— **This paper presents a novel modular climbing caterpillar named ZC-I. After a related survey on the topic, a systematical summarizing on basic functions provided by this system is given. ZC-I features fast-building mechanical structure and low-frequency vibrating passive attachment principle. Active joints actuated by RC servos endow the connecting modules with the ability of changing shapes in two dimensions. After that the discussion focuses on the various locomotion capabilities. Linear movement, turning movement, lateral movement, rotating and rolling movement are achieved based on an inspired control model to produce rhythmic motion. In the end a conclusion and future work are given.**

I. INTRODUCTION

THE last decade has seen an increasing interest in developing and employing climbing mobile robots for industrial inspection, conducting surveillance, urban search and rescue, military reconnaissance and civil exploration.

Recently there have been many research achievements in this field [1] [2]. Generally climbing robots are significantly relatively large. The size and weight of these prototypes is the choke point. Additionally, the intelligent technology in these climbing robots is not well developed. Some famous climbing robots are only semi-automatic or controlled by operators. The reason for this situation is that in designing a new prototype, attention was too focused on climbing kinematics and dynamics.

Modular approach enables the mobile robotic system the characteristics of versatility, robustness, low-cost and fast-prototyping. The robots have the capability of adopting different locomotion to match various tasks and suit complex environments [3] [4]. We combine climbing techniques with a modular approach to realize a novel prototype as a flexible wall climbing robotic platform featuring all the locomotion capabilities.

A novel modular climbing caterpillar named ZC-I is presented, which is based on the cooperation with Juan González-Gómez from the School of Engineering, Universidad Autonoma de Madrid in Spain and Robotics Institute at Beijing University of Aeronautics and Astronautics in China. In this paper the emphasis for discussion is on the prototype design and rational testing of the novel system at the moment. Firstly a related survey including kinematics of motion and attachment principle of climbing robots is given systematically. After summarizing the basic functions provided by this system, the mechanical structure and low-frequency vibrating passive attachment principle are introduced in detail. ZC-I features identical active joints actuated by RC servos which endow the connecting modules with the ability of changing shapes in two dimensions. After that the discussion focuses on the various locomotion capabilities. In the end a series of relative simulations and tests are given to confirm our design principles described above.

II. RELATED WORK

There are two important issues in designing a climbing robot: the attachment principle and the light weight mechanical structure.

A. Attachment Principles for Climbing Robots

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.

Two disadvantages are the bottlenecks for using the electromagnet in our project. Firstly electromagnetic force is not suitable for general climbing robots because of the validity only on the ferromagnetic surfaces. Meanwhile, even if the adhesion is reliable and easy-controlling, for actuating the electromagnet it still needs a big heavy power supply. There is no possibility of application on light weight climbing robots expect for some special cases [5].

Inspired by gecko bristles [6], the last few years have witnessed a strong interest in applying molecular force as a

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new attachment method for climbing robots. With the development of nanotechnology, some flexible climbing prototypes are emerging. It is a promising reliable attachment principle for climbing from the technical point of view. 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.

There are some climbing prototypes using mechanical forces for attachment on the vertical surface. 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 [7] [8]. In order to realize climbing movement, the mechanical structure of the robots is not designed modularly.

A propeller is another way to provide the mechanical attachment force. Akira Nishi and Hiromori Miyagi developed a kind of wall-climbing robot using the propulsive force of propellers [9]. It is very light but the noise generated by propellers is too loud to use. Meanwhile the adhesion is quite weak as a potential universal attachment method.

It is noted that suction cups are still the most common attachment devices for climbing robots. There are also two different sub principles to generate vacuum: negative pressure and vacuum suckers. Actuated by electrical motors [10] in its negative pressure chamber, the climbing robot can move on the wall flexibly and continuously. Even if the negative pressure chamber is not sensitive to a leakage of air, this method will not be enough for the safe and reliable attachment to the vertical surface when the robot has to cross some high obstacles.

The vacuum in the suckers is usually established by vacuum ejectors or vacuum pumps [11]. 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.

B. Kinematics of Climbing Robots

Currently there are several different kinds of kinematics for motion on smooth vertical surfaces: multiple legs, sliding frame, wheeled and chain-track vehicle. The robots with multiple-legs kinematics are complex due to a lot of degrees of freedom. This kind of robots which use vacuum suckers and grasping grippers for attachment to the buildings do not meet the requirements of miniaturization and low complexity.

Since 1996 our group has been developing a family of Sky Cleaner autonomous climbing robots with sliding frames for glass-wall cleaning [12]. The first two prototypes are mainly used for research and the last one is a real commercial product designed for cleaning the glass surface of the Shanghai Science and Technology Museum. The suitable working height of Sky Cleaners should be below fifty meters because the weight of the hoses providing air source and cleaning liquid from the ground has to be taken into account when the robots work in mid-air.

The robots with a wheeled and chain-track vehicle are usually portable. As mentioned before, the adhesion used by this kind of robots is negative pressure or propellers, therefore the robots can move continuously. It is possible to integrate the vacuum suckers with this kind of mechanism in our project in order to take advantages of simply structure and reliable attachment.

Our proposed climbing caterpillar is also a kind of inspired robot. Some snake-like robots are well developed with the time. The famous snake robot concept is the Active Cord Mechanism from Shigeo Hirose [13]. Klaassen also developed a mobile robot with six active segments and a head for the inspection of sewage pipes [14]. Twelve wheels on each module provide the driving force. Amphibious snake robot is proposed at school of computer and communication sciences, in Lausanne [15]. It can swim in the water and crawl on the ground. Another PolyBot [4] is able to optimize the way its parts connect to fit the specific task. It adopts its shape, becoming a rolling type to pass over flat ground, an earthworm type to move in narrow spaces and a spider type to stride over unknown hilly terrain.

To the best of our knowledge there is currently no similar robot that can both travel on the vertical surface and crawl with serpentine locomotion on ground. A smart climbing caterpillar is a completely novel prototype meeting all requirements of functionality, safety, flexibility, extensibility and easy handling while being completely automatic and able to learn by itself.

III. Prototype Design

A. Design Considerations

The most important requirement for our robotic system moving on the slope with different materials is the extraordinary motion capabilities. The basic functions of inspired climbing caterpillar include following aspects.

The climbing caterpillar has to be safely attached to the slope with different materials and has to overcome gravity. The mechanical structure for safe and reliable attachment to the vertical surface is needed. Now our research is focusing on the realization of new passive suckers which will save considerable power. Because of the unique vibrating adsorbing principle, the passive suckers can attach not only to glass, but also to a wall with aluminum tiles.

It will be also crucial to develop technically optimal designs that are mechanically robust in order to withstand stresses during climbing, when the weight of the whole robot has to be supported, as well as flexible enough, and are able to serve as manipulators for complex manipulation tasks. The robot should have a flexible mobility to get to every point in the work space. In order to finish a task in an unstructured environment, the ability to cross relatively high obstacles and span some gaps is indispensable. As a result, the robot should have different locomotion capabilities to match various tasks.

As an inspired robot, it should own intelligence as much as possible in order to imitate a real natural caterpillar. In order to move freely, it is important for the mobile robot not to be wired or otherwise connected to the environment. The robot should carry all devices: onboard power, the controller, and wireless communication.

B. Prototype Design

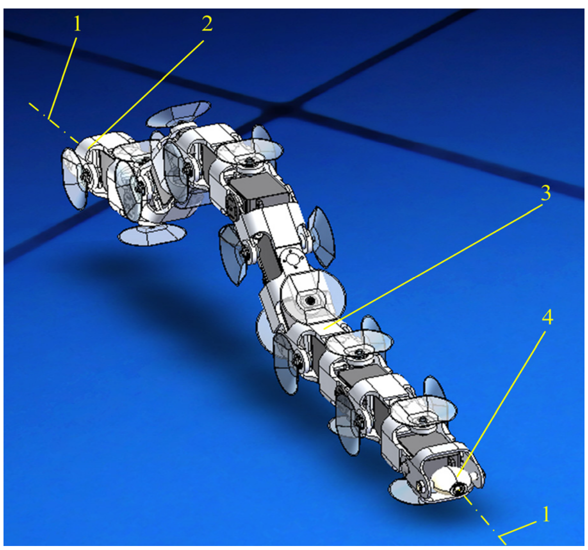
In this project, we combine climbing techniques with the idea of a modular robot to realize a novel prototype. This multifunctional climbing caterpillar ZC-I will be capable of:

1) Walking and climbing not only on rugged terrain but also on the vertical surfaces and ceilings on the inside of buildings;

2) Locomotion capacities including pitching, yawing, lateral shift, and rotating;

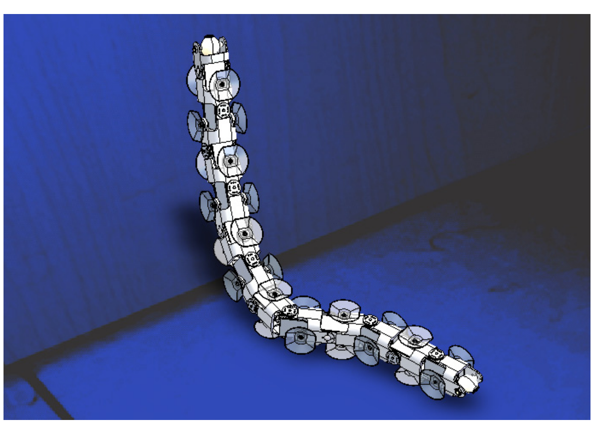
3) Sensor-servo-based active perception of the environment.

Fig. 1 shows pictures taken from a 3D-animation of the planned robotic caterpillar in a variety of postures. This system is currently under development in our consortium.



(a)

1. Axis of the body; 2. Head module; 3. Body modules; 4.Tail module



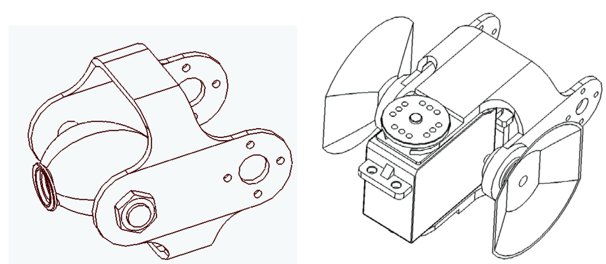
(b)

Fig.1 Prototype design

The major challenges in designing this robotic system are the smaller dimension and the ability to attach to the wall safely and move flexibly. The proposed climbing caterpillar should have various moving modes. Up to data, the system consists of eleven cross-connected modules for traveling. Actually only two kinds of modules are in the system: the head and tail module; the body module. The mechanical structure can be reconstructed and is flexible due to its similar modules and special connection joints.

The head and tail module consists of a CCD camera and mechanical shell with two pairs of ears (Fig 2a). There is no embedded DOF so that it cannot move actively. The CCD camera is connected to two ears using screws. On the other pair of ears, four small holes and a big central hole are designed for assembling with RC servos on a body module.

While the single body module is about 50 centimeters long, 50 centimeters wide and 50 centimeters high, as shown in Fig. 2b. It consists of a shell with three pairs of ears, a RC servo and a pair of small passive suckers which are fixed to the shell. A turning waist joint actuated by a RC servo connects adjacent modules. Fig. 3 shows two different ways to assembly the modules. The driving servo is fixed to a pair of ears on Module 1; while the rotating plate of the servo is fixed to another pair of ears on Module 2 through four holes separately. Two modules will setup together automatically when the rotating plate is fixed to the servo again. In this way, the caterpillar will be assembled around the horizontal axis and vertical axis alternately. As a result actuating by the servo, one DOF active rotating joint within ±90 degree enables the adjacent modules to adopt pitching and yawing movements to negotiate difficult tasks.



(a).Head and tail module (b). Body module

Fig. 2 Basic modules

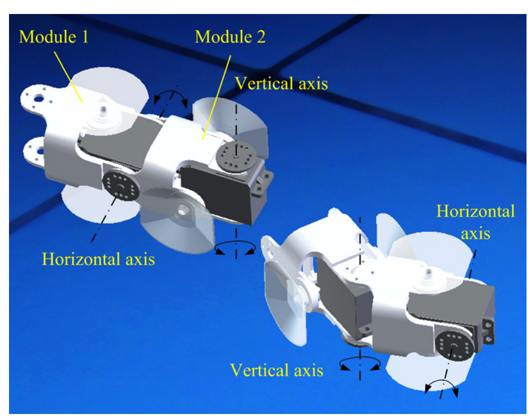


Fig. 3 Draft of connecting principle

To ensure its ability of performing tasks individually and keep the extensibility, there is enough space in each module for sensors, the onboard controller, and batteries. In order to achieve a dexterous movement mechanism, considerable stress is laid on weight reduction as well as on construction stiffness. The total robot will weigh approximately 2 kg including the batteries.

C. *Low-frequency Vibrating Passive Suckers*

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. There are two reasons for designing a passive sucker for climbing robots. Firstly, the climbing robot can be made lightweight and dexterous. 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, furthermore improve the inspired technological level and flexibility of the locomotion capability. Secondly, the attachment using suckers has the characteristic of passive compliance due to the compressibility of the material, thus makes the robot safer than other principles. Some previous work has been done recently in our consortium [16].

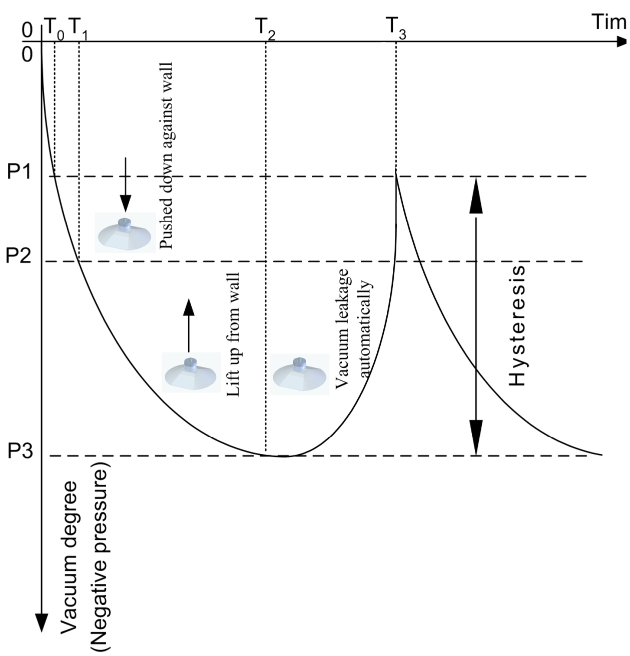


Fig. 4 The principle of Low-frequency vibrating suckers

Fig. 4 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.

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_0. At the T_1, 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 increases 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_3, the internal vacuum can be rebuilt for sure. It is a cycle from T_0 to T_3. As a result, the passive sucker will keep attachment reliably on the vertical wall 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. 5. 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. A wheel with passive suckers can move up-down smoothly on the wooden board. This on-site test confirms principle described above.

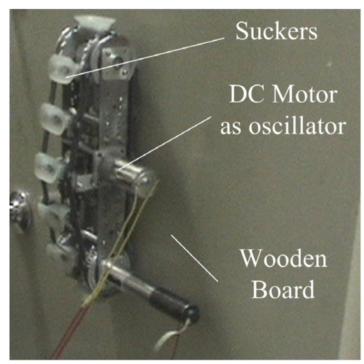


Fig. 5 The rational experiment of Low-frequency vibrating suckers

IV. Locomotion Control

Locomotion systems following biologically inspired ideas are currently dominated by walking machines [17]. The climbing caterpillar has to attach itself to the wall surface safely and reliably using vacuum suckers. That means there are always several point-constraints between the robotic system and the working space during the movement, while the robotic snake can slide on its work space without any constraints at all. The control of our caterpillar is based on sinusoidal generators to produce rhythmic motion. From the biological point of view, these generators act like the Central Pattern Generators (CPGs) located in the spinal cord of the animals to control variation of the rotation angle of each module.

The sinusoidal generators produce very smooth movements and have the advantage of making the controller much simpler. Our model is described by the following equation (1) [18]. Where y_i is the rotation angle of the corresponding module; A_i is the amplitude; T is the control period; t is time; Φ_i is the phase; O_i is the initial offset.

$$y_i = A_i \sin(\frac{2\pi}{T} t + \phi_i) + O_i \quad (1)$$

Fig. 6 shows a sketch map of the control algorithm. Eight sinusoidal generators are represented to actuate all modules to rotate. According to the connecting relationship of the modules, they are divided into horizontal and vertical groups, which are described as H_i and V_i respectively. Where i means the module number; $\Delta\Phi_V$ is the phase difference between two adjacent vertical modules; $\Delta\Phi_H$ is the phase difference between two adjacent horizontal modules; $\Delta\Phi_{HV}$ is the phase difference between two adjacent horizontal and vertical modules.

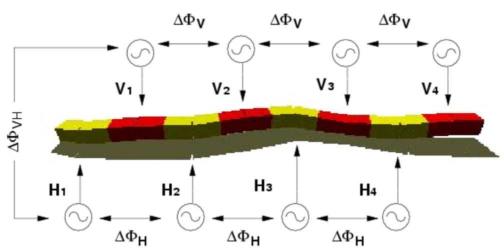
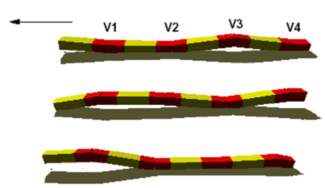
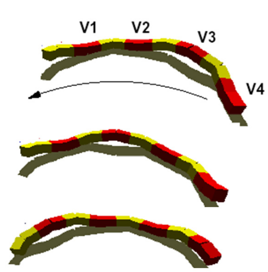


Fig. 6 Representation of the control algorithm

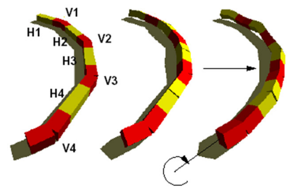
Five locomotion gaits including linear movement, turning movement, rolling movement, lateral movement and rotating movement have been achieved using the above sinusoidal generators. Fig. 7 shows the simulation results. The parameters for different locomotion capabilities are summarized in TABLE I.



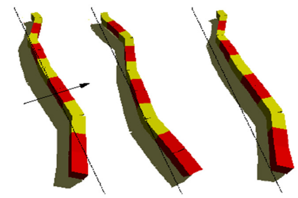
A. Linear movement



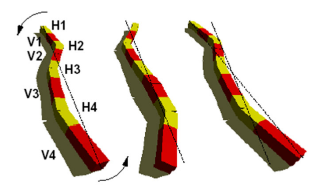
B. Turning movement



C. Rolling movement



D. Lateral movement



E. Rotation movement

Fig. 7 Simulation of five different locomotion gates

TABLE I
PARAMETER SUMMARY

Gate types	Parameters for sinusoidal generators	
Linear movement	$A_{Vi} \neq 0;$	$\Delta\Phi_V$=100-120, $O_{Hi} \neq 0$
Turning movement	$A_{Hi}=O_{Vi}=0$	$\Delta\Phi_V$=100-120, $O_{Hi}=0$
Rolling movement	$A_{Hi}, A_{Vi} \neq 0;$	$\Delta\Phi_V=\Delta\Phi_H=0$, $\Delta\Phi_{VH}=90$
Lateral movement	$O_{Hi}=O_{Vi}=0$	$\Delta\Phi_V=\Delta\Phi_H=100$, $\Delta\Phi_{VH}=0$
Rotation movement		$\Delta\Phi_V=120$, $\Delta\Phi_H=0$, $\Delta\Phi_{VH}=50$

V. IMPLEMENTATION

This system is currently under development in our consortium from 2006. The implementation includes following steps: reliability of the attachment, lightweight mechanical module and movement function realization. In order to shorten the research time-consumption, three parts are carried through at the same time.

Firstly, a series of the successful experiments with a modular reconfigurable robot (Fig. 8) were carried out recently, confirming the principles described above and sinusoidal generators controlling. All locomotion gates have been achieved on-site.

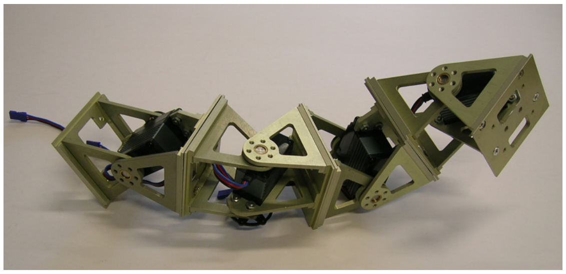


Fig. 8 Simulation of five different locomotion gates

Meanwhile, a very cheap and easy-building prototype is designed and manufactured as an experimental caterpillar version, as shown in Fig. 9. A shell supports a RC servo with a pair of ears. An extra box is on the back of shell, in which the battery, a simple controller and some auxiliary connecting parts for passive suckers are. The basic module is about 50 mm long, 30 mm wide and 30 mm high. All mechanical parts are manufactured from aluminum.

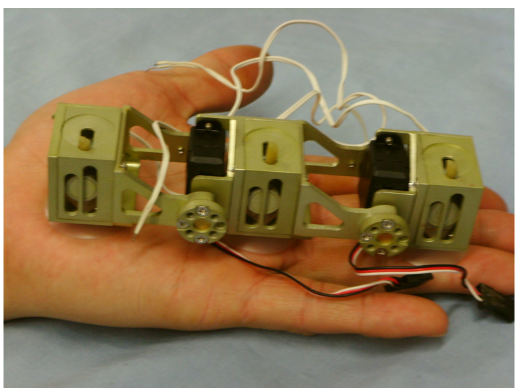


Fig. 9 The experimental body module and prototype connecting

VI. CONCLUSION AND FUTURE WORK

Our work in this paper involves highly integrated robotic systems such as walking machines and multi-foot systems. Combining the climbing techniques with the modular idea to realize this novel prototype will make the design and realization easier and more efficient.

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. The dynamics of the robot will be calculated with the Lagrange equation for system design and control purposes.

This prototype will be used as an intelligent demonstrator and test bed for the implementation of cognitive functions in robotic systems. It will have flexible mobility to get to every point on different surfaces in working space and will be able to carry multiple sensors and wireless communication.

REFERENCES

[1] B. Klaassen, and K.L. Paap, "GMD-SNAKE2: a snake-like robot driven by wheels and a method for motion control", Proceedings of IEEE International Conference on Robotics and Automation, Detroit, MI, 10-15 May, pp. 3014-3019,1999.

[2] G. Granosik, M. G. Hansen, Johann Borenstein, "The Omnitread Serpentine Robot for Industrial Inspection and Surveillance", Industrial Robot: An International Journal, Vol.32, No.2, pp.139-148, 2005.

[3] A. Castano, W.M. Shen, P. Will, "CONRO: Towards Miniature Self-Sufficient Metamorphic Robots", Autonomous Robots, Vol.13, pp.309-324, 2000.

[4] M. Yim, G. David, et al., "PolyBot: a Module Reconfigurable Robot", Proceedings of the 2000 IEEE International Conference on Robotics and Automation, San Francisco, CA, USA, April, 2000, pp.514-520, 2000.

[5] 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.

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

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] H. Zhang, J. Zhang, G. Zong, "Requirements of Glass Cleaning and Development of Climbing Robot Systems" , Proceedings of the 2004 IEEE International Conference on Intelligent Mechatronics and Automation, Chengdu, China, August 26-31, pp.101-106,2004.

[13] S. Hirose, "Biologically inspired robots (snake-like locomotor and manupultor)", Oxford University Press, 1993.

[14] B. Klaassen, and K.L. Paap, "GMD-SNAKE2: a snake-like robot driven by wheels and a method for motion control", Proceedings of IEEE International Conference on Robotics and Automation, Detroit, MI, 10-15 May, pp. 3014-3019,1999.

[15] A.J. Ijspeert, "A connectionist central pattern generator for the aquatic and terrestrial gaits of a simulated salamander", Biological Cybernetics, Vol.85, No. 5, pp. 331-348, 2001.

[16] 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.

[17] K. Zimmermann, I. Zeidis, J. Steigenberger, "On artificial worms as chain of mass points", Proceeding of Clawar 2004, pp11-18.

[18] J. González-Gómez, H. Zhang, et.al. "Locomotion Capabilities of a Modular Robot with Eight Pitch-Yaw-Connecting Modules", The 9th International Conference on Climbing and Walking Robots and their Supporting Technologies for Mobile Machines, CLAWAR2006, Brussels, Belgium, September 12-14, 2006.