The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Crawling Locomotion of Modular Climbing Caterpillar Robot with Changing Kinematic Chain

W. Wang, H. X. Zhang, *Member, IEEE,* J. W. Zhang, *Member*

***Abstract* — Based on the modular concept, this paper presents two caterpillar robot prototypes which are inspired by two typical caterpillars: Inchworm and Pine Caterpillar. The inchworm robot prototype features simplest kinematics and open chain architecture. Due to the fact that there is only one attachment module supporting the inchworm robot during crawling, we apply an Unsymmetrical Phase Method (UPM) to realize a stable crawling gait for it. A pine caterpillar robot is derived from combining two inchworm robots together. The crawling gait of it features a repetitive changing chain: Open-Closed-Open. Besides the UPM in open chain states, a four-links kinematic model is applied to control the corresponding joints to transfer the crawling wave along the robot body in the closed chain state. These two prototypes are all constructed and, and their crawling locomotion abilities have been tested on vertical glasses respectively.**

I. Introduction

Although climbing robots have been researched for many years, few practicable products have been developed to perform very risky work. This is due to two main difficulties in climbing robot design: finding a compromise between the weight and flexibility of the climbing mechanism and developing a mechanism with a simple climbing gait and sufficient degrees of.

The climbing caterpillar robot based on a modular concept provides an alternative to existing attempts to overcome the difficulty of realizing high flexibility and light weight simultaneously in climbing robot design. Compared with the known climbing robots with multi-legs, sliding frame, wheeled and chain-track kinematics, the modular climbing caterpillar robot has a reconfigurable structure, higher flexibility, and a lighter weight. In our previous paper [1], the kinematics and gaits of the modular climbing caterpillar robot were discussed. However, some questions were not studied in detail, such as the controlling parameters determining the features of the gaits, the locomotion methods of the joints to actuate the proposed gaits, and how to compensate the influence of the gravity. Therefore, this paper will focus on these technologies which are important to realize a reliable climbing motion on vertical walls and slopes.

This paper presents the continued research on the locomotion mechanism of our modular climbing caterpillar robot. The paper is organized as follows: section 2 presents the related work in the literature. Some key issues like current achievements and the challenging of climbing robotic research are also summarized in this section. Then a systematic overview of our modular climbing robotic caterpillar will be given in section 3. After that, section 4 presents the realization of crawling gaits. In order to confirm the locomotion principle and flexible capability, a series of on-site experiments are presented. In the end, conclusions and future work are outlined.

This project is supported by the "National Natural Science Foundation of China" (No. 50605001) and partly supported by the "Hi-Tech Research and Development Program of China" (No. 2006AA04Z250).

W. Wang works with the Robotics Institute, School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, 37 Xueyuan Road, 100083, Beijing, China. He is currently a guest researcher at the Dept of Informatics, University of Hamburg, Germany (as the corresponding author, e-mail: wangweilab@buaa.edu.cn, wang@informatik.uni-hamburg.de).

H. X. Zhang works with the Institute of Technical Aspects of Multimodal Systems, Department of Computer Science, University of Hamburg, Vogt-Koelln-Strasse 30, 22527, Hamburg, Germany (e-mail: hzhang@informatik.uni-hamburg.de, hxzhang@ieee.org).

J. W. Zhang works with the Institute of Technical Aspects of Multimodal Systems, Department of Computer Science, University of Hamburg, Hamburg, Germany(e-mail: zhang@informatik.uni-hamburg.de).

G.H. Zong works with the Robotics Institute, School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, 37 Xueyuan Road, 100083, Beijing, China.

II. Related Works

A number of different kinds of kinematics for motion on smooth vertical surfaces have been presented over the past decades. The robots with multiple-legs kinematics are complex due to a lot of degrees of freedom and the difficulty to realize a stable gait [2] [3]. This kind of robots which use vacuum suckers and grasping grippers for attaching to buildings do not meet the requirements of miniaturization and low complexity. The robots with a wheeled and chain-track vehicle are usually portable [4] [5] [6]. The attaching method used by this kind of robots is negative pressure or propellers, therefore the robots can move continuously. Although these robots feature simple kinematics, they are not easily miniaturized due to the necessary sucker area [7]. Since 1996, our group has been developing a family of autonomous climbing Sky Cleaner robots with sliding frames for glass-wall cleaning [8]. The sliding frame endows the climbing robot with a simple and reliable structure, but simultaneously limits its flexibility. Therefore, these robots can only work on smooth surfaces.

In [9] [10], a series biped climbing robots with 4 DOF are developed to transfer between the surfaces in different plate. The most attractive result in these papers is that the least DOFs of the climbing robot being able to transfer between surfaces are 4. Because of the minimized DOF, these robots are small and relatively flexible. But on the other hand, they are always in single foot adhering state and perform a sharp fluctuate of the center of gravity, and that is not favorable to enhance the safety of the climbing gait.

In nature, caterpillars are among the most successful of these climbers and can maneuver in complex three-dimensional environments. Also, caterpillars feature some very interesting aspects. First, caterpillars own a soft-body structure which is flexible and versatile and thus can negotiate different kinds of locomotion. Second, they are relatively low-level creatures which can organize their locomotion by efficient, simple, distributed control strategies such as Central Pattern Generator (CPG). Their example enables us to design a low-cost control system and to realize effective gaits. Those are some of the reasons why we have such a strong interest not only to understand their locomotion principle but also to try to build a robotic caterpillar.

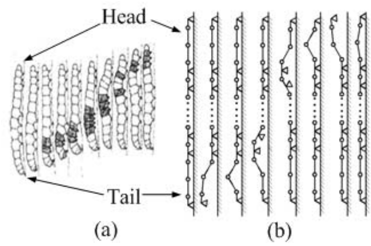

Fig. 1 The gait of a caterpillar

Normally, caterpillars consist of a head and neck part, a body with several segments and a tail end part, as shown in Fig.1. A half-wave will travel from the tail end to the head during a general movement. Sometimes more than one half-wave will occur in order to move fast or deal with special cases. From the mechanical viewpoint, the kinematics model of natural caterpillars can be considered as combining attachment modules and active joints for locomotion, which are represented by symbols △ and —○— on the right of Fig. 1 respectively.

III. Overview of The Robot Modules

The gait of a caterpillar robot is strictly related to its kinematics [1]. The modules constituting the caterpillar robot should be light and easy to assemble to a desired structure. Therefore, we designed two kinds of modules, a joint module and an attachment module, as shown in Fig.2.

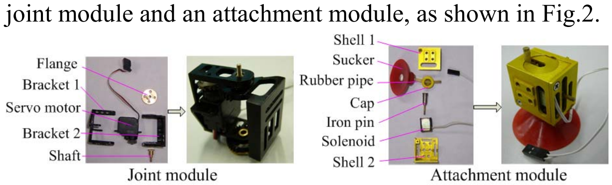

Fig. 2 Two kinds of modules

To simplify the structure, there is only one rotating joint driven by a mini servo motor in the joint module. Brackets 1 and 2 are fixed to the shell and axis of the servo motor respectively. When the motor is running, these two brackets rotate around the shaft in the middle. The mechanical interfaces on the outside plates of the brackets allow for the joint modules to be assembled either in parallel axes or perpendicular axes.

The attachment module is based on the passive attachment method to lighten the weight, which means that the vacuum in the sucker is generated only by the distortion of the sucker. A simple mechanism driven by a solenoid is used to release the vacuum in the passive sucker. When the solenoid is not actuated, a rubber pipe connecting the inner side of the sucker to the outside air is shut off by an iron pin and cap under the force of a spring. The sucker can be attached to some flat surfaces. If the solenoid is actuated, the iron pin will be drawn away from the cap to connect the inner of the sucker with outside through the pipe. The vacuum in the sucker is released, and the sucker can be lifted.

On the two shells of the attachment module, there are the same mechanical interfaces as those on the joint module. Thus the attachment module can be directly connected to the joint module. For the basic performances of the two modules listed in table 1, the elastic coefficients of the passive sucker deserve special attention because their influence is important for prototype design and gait realization.

TABLE I
The Performances of Modules

Specifications	Performances
Joint Module	
Size: length*width*height	35mm*37mm*30mm
Mass	19.2 g
Max Output Torque	0.2 Nm
Output Angle	-90° - +90°
Attachment Module	
Size: length*width*height	26mm*32mm*20mm
Mass	27.8 g
Max Attaching Force	40N
Max Permitted Sliding Force	15N
Max Permitted Turing Torque	0.1Nm
Elastic coefficient of sucker	
Compression	1.7 N/mm
Rotation	0.012 Nm/(°)

Although the general mechanical interface on the modules allows us to construct caterpillar robots that can move in a 3-D environment, this paper only discusses some basic and particular caterpillar structures in which all joints are serial-connected around the horizontal axes to perform 2-D locomotion.

Besides the mechanical modules, on-board controllers are also designed. Each controller has one channel of Pulse Width Modulation (PWM) output to control the servo motor, one on-off output to control the solenoid, three digital or analog sensor inputs to collect sensor data, one I^2C bus and one RS232 serial port. The number of the controllers in a caterpillar robot is determined by the number of the joint modules. The controllers can communicate with each other by the I^2C bus and receive the orders from a PC-based protocol through the RS232 serial port.

IV. INCHWORM GAIT BASED ON UPM

Though a caterpillar robot can be built with different numbers of joint and attachment modules, the inchworm configuration is the most basic structure, since an inchworm configuration is not only able to move independently, but is also an indispensable part of any caterpillar robot [1].

A. Structure of Inchworm Robot

To negotiate the shape change of the wall in 2-D, at least 3 degrees of freedom are needed to realize locomotion and reliable attachment for an inchworm robot. As a result, the simplest inchworm structure has to include 2 attachment modules and 3 joint modules. The same kinematics can be abstracted from a real inchworm, as shown in Fig. 4.

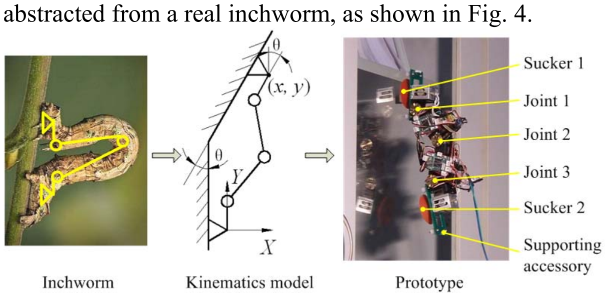

Fig. 4. Prototype of an inchworm robot

In the prototype shown in Fig. 4, besides the joint and attachment modules, two supporting accessories are installed at the head and tail respectively. This diminishes the rotation distortion of the sucker caused by gravity when only one sucker is attached to the wall. Otherwise, the attached module cannot provide a steady platform for the other modules, and a reliable gait is difficult to realize. The same structure is also noticeable in the real inchworm, whose multi pseudopodia at the head and tail perform the same function.

B. Inchworm Gait Based on Unsymmetrical Phase Method

Fig. 5 shows five typical steps in the gait of an inchworm robot climbing on a flat wall, as well as the angle of each joint and the state of each sucker in one control cycle. The state of the sucker is controlled by a corresponding solenoid which has only two states, actuated or inactive, and is presented by a step function. The high level means that the solenoid is actuated and the sucker is released. The low level means the inverse state.

At the beginning and end steps t_0 and t_4, the angle values of three joints are all zero. At the middle step t_2, the angle values should fulfill the condition shown in (1).

$$\theta_1=\theta_3=-(1/2)\theta_2 \quad (1)$$

As a result, the displacement D of one gait can be calculated in (2), where L is the distance between two joints.

$$D = 2L(1-\cos\theta_1) \quad (2)$$

Although the angle value of each joint follows a series of simple linear curves, two steps, at t_1 and t_3, require detailed discussion.

At time t_1, the robot lifts up sucker 2 with the angle values of joints shown in (3).

$$\theta_1-\Delta\theta=\theta_3=-(1/2)\theta_2 \quad (3)$$

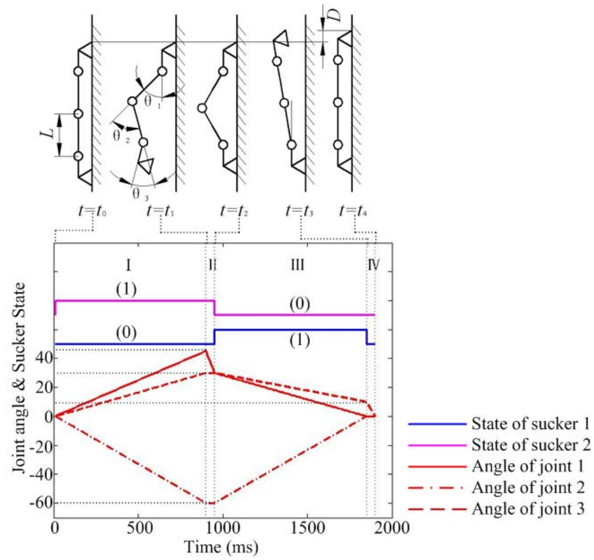

Fig. 5. The gait of an inchworm

In this way, sucker 2 moves not only forward but also up the wall. During the time between t_1 and t_2, the robot puts down sucker 2 by turning joint 1. It is obvious that the time between t_0 and t_1 is much longer than the time between t_1 and t_2. In our experiments, they are 950ms and 50ms respectively. It means that the sucker is lifted slowly but is put down relatively fast. From t_2 to t_4, sucker 1 is moved in the same way.

By defining the procedures of lifting and putting down a sucker as Up-phase and Down-phase respectively, the gait control method described above is named Unsymmetrical Phase Method (UPM). Unlike the other walking mobile robots which normally tend to reduce the velocity of their feet to zero in order to reduce the impact force acting on the foot during contact with the ground, the inchworm robot uses the impact force between the sucker and wall produced by UPM to compress the passive sucker well and to attach firmly and reliably to the wall.

In the Up-phase of UPM, the joint velocities of the robot are all low enough to diminish the inertial load on the single attached sucker, and to ensure the safety of the robot. In the Down-phase of UPM, when the sucker makes contact with the wall, the force acting on the sucker F can be expressed by (4).

$$F = F_1+F_2 = (M + I\omega/\delta t)/A \quad (4)$$

Where F_1 is the force produced by the joint driver whose output torque is M; F_2 is the force introduced by the impulse acing on the sucker; I is the turning inertia of all moving parts; ω is the joint velocity; A is the distance between the unattached sucker and rotating joint; and δt is the impulse time.

The values of some parameters in (4) can be calculated according to the performances of the real prototype, for example, at the t_4 step, A is equal to 0.13m, M is 0.2Nm and I is 1.62×10^{-4}kg m^2. The values of ω and t can be gotten in real experiments, for example, ω is 5.2rad/s and δt is 2×10^{-3}s. As a result, the values of F_1 and F_2 can be calculated in theory: F_1 is equal to 1.5N and F_2 is equal to 3.2N. That means the compression distortion values of the sucker produced by F_1 and F_2 are 0.9mm and 1.8mm respectively, according to the compression elastic coefficient of the sucker in table1. Since 1.5mm is the minimum compression value of the passive sucker required to ensure a reliable attachment, the contribution of the impulse force introduced by UPM is obvious, and this is also proven by the real experiments.

V. Closed Chain Control in Pine Caterpillar Gait

A. *Structure of Pine Caterpillar Robot*

Because the trunk part with several pseudopodia distinguishes the kinematics model of a pine caterpillar robot from that of an inchworm robot, and the three-joint-inchworm structure is a part of a pine caterpillar robot [5], it is reasonable to constitute a pine caterpillar robot with only two middle pseudopodia by combining two inchworm robots with a joint module, as shown in Fig. 6. The research result of this seven-joint-four-sucker caterpillar robot will be valuable to the other caterpillar robots with more joints.

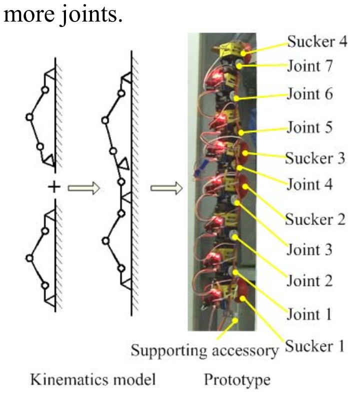

Fig. 6. Prototype of a pine caterpillar robot

B. *Gait and Joints Control of Pine Caterpillar Robot*

The proposed gait of the pine caterpillar robot is shown in Fig. 7, in which thirteen typical steps are deliberately presented. Fig. 7 also shows the angle control curve of each joint and the state of each sucker. Seven controllers are applied in this robot. Each of them controls one joint, and some of them are also responsible for controlling suckers. Therefore, in Fig. 7, seven curve charts present the outputs of the corresponding controllers, in which J and S are the abbreviations of Joint and Sucker.

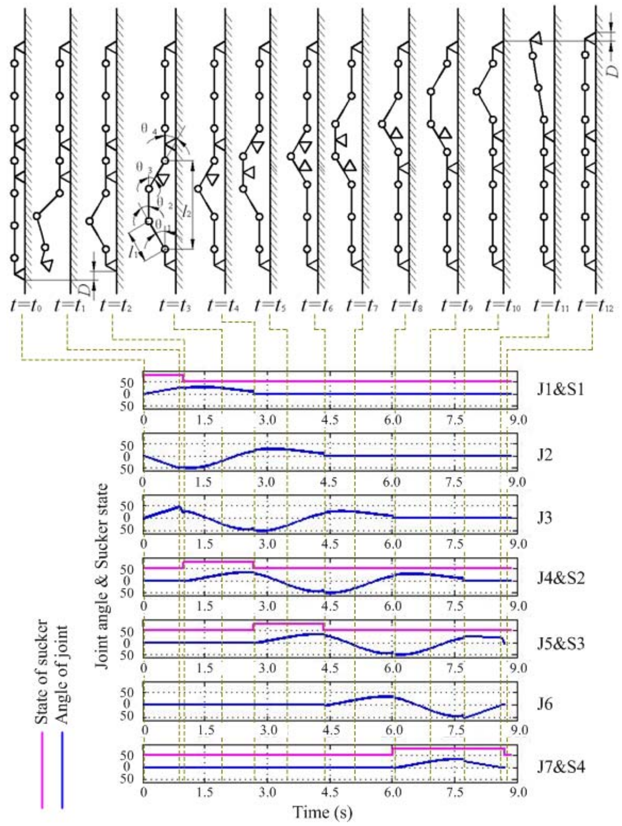

Fig. 7. The gait of a pine caterpillar robot

From t_0 to t_2, the sucker at the tail is lifted and put down to achieve a primary displacement D; and from t_{10} to t_{12}, the sucker at the head is moved to complete a whole final displacement. In these two periods, the gait of the pine caterpillar robot is similar to that of the inchworm robot, and all of the rotating joints work in an open chain state.

From t_2 to t_{10}, a wave is transmitted along the body of the caterpillar, and the rotating joints run in a closed chain state from the kinematics viewpoint, since there are at least two suckers attached to the two ends of the moving chain. The fixed constrains introduced by the suckers distinguish the gait of a caterpillar robot from the gaits of other modular robots crawling on the ground, which are normally produced by the rhythmic motion of all joints. Although certain rhythmic joint motions may satisfy the demand of the closed chain, it is difficult to find out the right parameters to realize not only the wave transmutation but also the reliable attachment of the suckers only by experiments. The reason is that the condition of attaching one sucker on the wall is very strict. As the first attempt to control the gait of a caterpillar robot, this paper presents a joint control method based on the traditional kinematics theory.

When the caterpillar is in the closed chain state, a four-link mechanism is taken into account to perform the wave transmission, as shown in the step at t_3 in Fig. 7. The reason for choosing this mechanism is that it employs the least number of moving components in a closed chain. At any time between t_2 and t_{10}, only 4 joints rotate, and their angle values should change according to (5) to (8).

$$\theta_1 = \sin \omega t \tag{5}$$

$$\theta_2 = \theta_1 + \arctan\frac{l_1 \sin\theta_1}{l_2 - l_1\cos\theta_1} - \arccos\frac{\sqrt{l_1^2 + l_2^2 - 2l_1l_2\cos\theta_1}}{2l_1} \tag{6}$$

$$\theta_3 = 2\arccos\frac{\sqrt{l_1^2 + l_2^2 - 2l_1l_2\cos\theta_1}}{2l_1} \tag{7}$$

$$\theta_4 = \arctan\frac{l_1 \sin\theta_1}{l_2 - l_1\cos\theta_1} + \arccos\frac{\sqrt{l_1^2 + l_2^2 - 2l_1l_2\cos\theta_1}}{2l_1} \tag{8}$$

Where θ_1 is the angle value of the joint closest to the sucker 1; l_1 is the distance between two joints; l_2 is the distance between the first and last joints in the four-link mechanism.

Although the control rule of θ_1 can be arbitrarily chosen, a sinusoidal function is applied to smooth the sharp turn in the control curve. The angle values of seven joints are calculated and shown in Fig. 7. It is interesting that the curves of joint angle values are a series of sinusoidal-like curves with different phases. That will be useful for developing a new gait control method in the future by virtue of some new algorithms, such as CPG.

Obviously, the four-link mechanism in a closed chain has only one degree of freedom, but the number of active joints in the pine caterpillar configuration is four. As a result, the robot always works in a redundant actuating state. Although the robot can avoid the unpredictable internal force according to the kinematics model presented by above equations, the real result should be further testified because the error of calculation and the clearance in the mechanism may invalidate the ideal conditions.

VI. Real Experiments

A. The Inchworm Robot Prototype Experiments

Before trying the climbing gait on the wall, we did a series of tests to find out the appropriate ω in (4). In these tests, one sucker of the inchworm robot is fixed on a glass wall by a clamp, and another one is lowered and lifted repeatedly. The compression value of the free sucker is recorded. To compress the sucker and lower it by 1.5mm, ω should be nearly 2.8rad/s; while for the maximum compression value of up to 3mm, ω should reach 6rad/s. Because a too-large joint velocity will interfere with the stability of the attached sucker when the robot is climbing on the wall, 5.2 rad/s is taken as the joint velocity in the down-phase.

Taking advantage of the UPM, the inchworm robot realizes continuous motion on the vertical wall successfully with the gait presented in Fig. 5. Fig.8 shows the procedure of the inchworm robot climbing up for the course of one gait; the maximal gait distance is 5mm, and the time of one gait cycle is 1.8s.

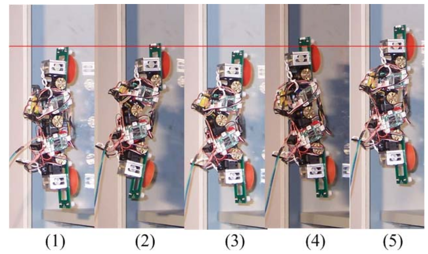

Fig. 8. One gait of the inchworm robot on vertical glass

Other experiments also prove that if the UPM is not applied and suckers are put down slowly, the inchworm robot can only take around three steps on the wall, then it will fall down.

B. The Pine Caterpillar Robot Prototype Experiments

To investigate the validity of the gait control method based on our kinematics model, a trunk part of the pine caterpillar robot is specially constituted by serially connected four-joint modules and five attachment modules, as shown in Fig. 9. In this experiment, the trunk prototype is put on an unattachable plate. If the four joints are actuated according to the equations (5) - (8), a half-wave will be transmitted from right (the first joint) to left, and in theory the suckers should not slip on the plate. But in the real experiment shown in Fig. 9, before the wave arrives at the last joint, the last left sucker moves forward in step (3), while in step (4), it returns to the original position, i.e. it slips. That means there is an internal force in the robot which is probably induced by a calculation error and the clearance in the mechanism.

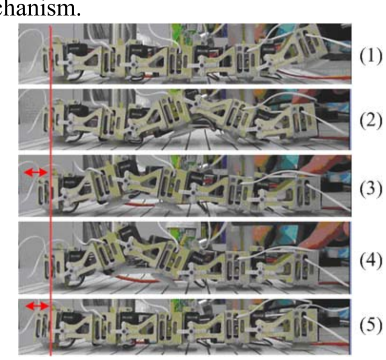

Fig. 9 Experiment on the trunk prototype

In spite of the inevitable internal force, the pine caterpillar robot has successfully performed the proposed climbing gait on a vertical glass wall recently, as shown in Fig. 10. At present, the robot is powered by an off-board DC power though a wire, and can crawl on a vertical glass continuously in a straight line until a "Stop" order is received. The maximum climbing distance having been reached is about 1.5m, which is limited the length of the wire. The maximal step length is 5mm, and the time of one step is 9s.

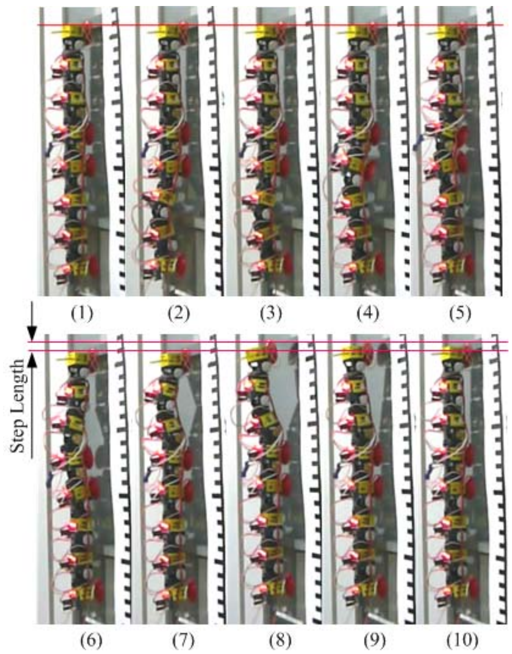

Fig. 10. One gait of the pine caterpillar robot on vertical glass

Although the four-link kinematics is taken into account, the internal forces between links are not eliminated completely, that can be observed from the sharp change of the current consumption during one step, from 0.8A to 1.3A. In fact, in a rigid over-actuated mechanism as the modular caterpillar robot, it is impossible to avoid the internal forces completely due to the control errors and the clearance between parts. This shortcoming will be unacceptable when the robot is powered by on-board batteries, and should be overcome in the future.

VII. CONCLUSIONS

This paper analyzes the kinematics models and possible gaits of two typical caterpillar-like robots. We also present the methods to realize climbing gaits on the wall, and create two climbing robot prototypes to testify the theories. Further discussions and experiments yield the following conclusions.

1) The UPM is a feasible method to enable an inchworm robot with passive suckers to climb on a vertical wall.

2) The kinematics of an inchworm robot is not only the simplest caterpillar model. Two inchworm-like structures can be considered as the head and tail parts of a pine caterpillar configuration, which also features several other body segments. As a result, the gait of an inchworm robot can be directly applied by a normal caterpillar robot.

3) The kinematics model based on a four-link mechanism is an effective way to find out an appropriate gait for a pine caterpillar robot, which often runs in the closed chain state.

4) The experiments show the slip of the sucker on the trunk prototype of a pine caterpillar robot. This due to the internal force caused by a calculation error and the clearance in the mechanism, and also proves the ability of the inchworm robot and the pine caterpillar robot to move on vertical glass walls.

Future research includes finding out new gait control methods to diminish the internal force in the caterpillar robot, and realizing complex motions, such as climbing between two plates in different plane, crossing a barrier on the wall etc. In addition, the turning mechanism, vibrating suckers and CPG control algorithm will also be applied in future prototypes.

ACKNOWLEDGMENT

This modular climbing caterpillar project is also based on the cooperation with TAMS, at the University of Hamburg, Germany. The authors would also like to thank Kun Wang and Yingying Wang from the Robotics Institute at Beijing University of Aeronautics and Astronautics, China, for their contribution to simulation and on-site testing.

REFERENCES

[1] W. Wang, H. Zhang, Y. Wang, K. Wang, J. Zhang, "Analysis of the Kinematics of Module Climbing Caterpillar Robots", Proceeding of 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronlics, Xi'an, China, 4 - 7 June, pp., 2008.

[2] 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.

[3] B. Luk, D. Cooke, S. Galt, A. Collie, and S. Chen, “Intelligent legged climbing service robot for remote maintenance applications in hazardous environments”, Journal of Robotics and Autonomous Systems, Vol. 10, No.1, pp. 101-112, 2005.

[4] 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.

[5] D. Longo and G. Muscato, “The Alicia climbing robot”, The IEEE robotics and automation magazine, Vol.13, No.1, pp. 42-50, 2006.

[6] F. Weise, J. Kohnen, H. Wiggenhauser, C. Hillenbrand, and K. Berns, “Non-destructive sensors for inspection of concrete structures with a climbing robot”, Proceedings of 4th international conference on climbing and walking robots CLAWAR 2001, Karlsruhe, Germany, pp.945-952,Sep. 2001.

[7] R. Schraft, F. Simons, T. Schafer, W. Keil, and S. Anderson, “Concept of a low-cost, window-cleaning robot”, Proc. 6th int. Conf. Climbing and Walking Robots, CLAWAR 2003, Catania, Italy, pp.785-792, Sep. 2003.

[8] H. Zhang, J. Zhang, W. Wang, R. Liu, and G. Zong, “Sky Cleaner 3-A Real Pneumatic Climbing Robot for Glass-Wall Cleaning”, IEEE Robotic and Automation Magazine, Vol.13, No.1, pp.32-41, March 2006.

[9] M. Minor and R. Mukherjee, “Under-Actuated Kinematic Structures for Miniature Climbing Robots”, Journal of Mechanical Design, Vol.125, pp.281-291, June 2003.

[10] M. Yue, M. Minor, N. Xi, and R. Mukherjee, “Kinematics Workspace Analyses of a Miniature Walking Robot”, Proc.1999 IEEE/RSJ International Conference on Intelligent Robots and Systems, Kyongju, Korea, pp. 1798-1803, 1999.