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A Bio-Inspired Small-Sized Wall-Climbing Caterpillar Robot

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1. Introduction

Climbing robots work in a special vertical environment and use mobility against gravity (Zhang, 2007). They are a special potential sub-group of mobile technology. In the recent 15 years, there have been considerable achievements in climbing robot research worldwide by exploring potential applications in hazardous and unmanned environments (Virk, 2005). The typical application of climbing robots includes reliable non-destructive evaluation and diagnosis in the nuclear industry, the chemical industry and the power generation industry (Longo, et al., 2004), welding and manipulation in the construction industry (Armada, et al., 1998), cleaning and maintenance for high-rise buildings in the service industry (Elkmann, et al., 2002) and urban search and rescue in military and civil applications (Wu, et al., 2006).

However, until now, there are few successful prototypes that are both small enough and move flexibly enough to negotiate surfaces with a complex structure. It is common to design rather big and heavy climbing robots. The difficulties of developing a flexible and small climbing robot with full locomotion capabilities include not only the weight reduction of the mechanism but also the miniaturization of the flexible construction. An additional problem is the fact that the intelligent technology in many climbing robotic prototypes is not developed enough.

The purpose of this paper is to present a novel bio-inspired climbing caterpillar robot which is currently under construction in our consortium. We combine the climbing technology with bio-inspired research to create a novel robotic prototype which has a cognitive potential and can climb and move flexibly in its working environment. This paper only concentrates on the design and realization of the current climbing robotic prototype. Other details such as gaits, motion kinematics and dynamics will be discussed in other publications.

This paper is organized as follows. First the related work on climbing robots and the biologically inspired mobile robotic system will be introduced systematically in section 2. At the beginning of section 3, we investigate the climbing locomotion mechanism adopted by caterpillars. Based on this, our on-going climbing robotic project will be introduced. Different aspects including system design, mechanical implementation and control realization will be presented in detail. Although we designed two climbing caterpillar robotic configurations, the simpler inchworm configuration is the focus for discussion in this paper. After pointing out future work, our conclusions are given in the end.

2. Related research in literature

2.1 Climbing mechanism of caterpillars

Climbing robots are a kind of mobile robots. There are two important issues for designing a successful climbing robotic prototype. The first one is the adhesion principle, the second one is mechanical kinematics.

Many climbing robots use legged structures with two (biped) to eight legs, where more limbs inherently provide redundant support during walking and can increase the load capacity and safety. The robots with multiple-leg kinematics are complex due to several degrees of freedom. This kind of robots which use vacuum suckers and grasping grippers for attachment to buildings are too big, too heavy and too complex. As the simplest kinematical model in this class, bipeds vary most significantly in the style of their middle joints. Robots by Nishi (Nishi, 1992) and the robot ROBIN (Pack, et al., 1997) use a revolute middle joint. A prismatic middle joint is used by ROSTAM IV (Bahr, et al., 1996), while the robot by Yano (Yano, et al., 1997) does not have a middle joint but simply a rigid central body. ROSTAM IV, the smallest robot in this class built to date, weighs approximately only 4 kg, but the reliability and safety of its movement is not satisfying.

The robot ROMA (Abderrahim, et al., 1991) is a multifunctional, self-supporting climbing robot which can travel into a complex metallic-based environment and self-support its locomotion system for 3D movements. Generally, construction and control of these robots is relatively complicated. The other problem is that the climbing robots based on the grasping method often work in a specialized environment such as metal-based buildings. In order to realize a climbing movement, the mechanical structure of the robots is not designed modularly.

Inspired by gecko bristles, the last few years have witnessed a strong interest in using molecular force as a new attachment method for climbing robots. Flexible climbing prototypes with multi-legs (Sitti, et al., 2003) and with wheels (Murphy, et al., 2006) have been emerging. From the locomotion viewpoint, there is no difference to the other climbing prototypes.

The prototypes with a wheeled and chain-track vehicle are usually portable. The adhesion used by this kind of robot is negative pressure or propellers, therefore the robots can move continuously. A smart mobile robot was proposed as a flexible mobile climbing platform carrying a CCD camera and other sensors. It uses a negative pressure chamber to attach to vertical surfaces. Even if this kind suction is not sensitive to a leakage of air, the negative pressure is not good enough for safe and reliable attachment to a vertical surface when the robot crosses window frames. An improved smart structure with two linked-track vehicles was proposed, which can be reconfigured so that the robot can move between surfaces standing at an angle of 0 - 90 degrees due to the pitching DOF actuated by the joint to

increase the flexibility (Wang, et al., 1999). Recently, many similar climbing prototypes with wheels and chain-tracks have been presented worldwide.
With sliding frames, a climbing robot can be made simpler and lighter from the kinematic point of view, which is one of the most important specifications for devices working off ground. This kind of climbing robots features pneumatic actuation, which can effect a linear sliding movement better than electric motor systems. In 1992, a pneumatic climbing robot with a sliding frame was developed for cleaning the glass surface of the Canadian Embassy in Japan (Nishigami, et al., 1992). However, the robot cannot move sideways. Since 1996, our group has been developing a family of Sky Cleaner autonomous climbing robots with sliding frames for glass-wall cleaning (Zhang, et al., 2005). The first two prototypes are mainly used for research, but the last one is a semi-commercial product designed for cleaning the glass surface of the Shanghai Science and Technology Museum. The benefits of this locomotion principle are offset by nonlinear control methods and difficulties of the pneumatic systems. As a conclusion, it can only be used for specialized environments such as glass curtain walls.
Some limbless robots are also capable of climbing. However, using friction, snake-like prototypes can only climb up and down a tube with a suitable diameter (Granosik, et al., 2005). The robot has to have a shape that allows as much contact as possible with the tube's inner surface. The other example of these kinds of limbless climbing robots is the Modsnake (Wright et al. 2007) developed at the CMU's Biorobotics Laboratory. This robot consists of 16 modules and it is capable of climbing on the inside or outside of a tube. Actually, these are pipe robots rather than climbing robots.

2.2 Bio-inspired mobile robots and control methods

The last few years have witnessed an increasing interest in implementing biological approaches for mobile robotic design and research. A lot of impressive work including multi-legged robots, snake-like robots, and robotic fish has been done on bio-inspired mobile robotic technology recently.
For example, the robot RiES (Spenko, et al., 2008) with 4-6 legs can climb glass surfaces using nano material and walk on wall surfaces using metal nails. This robot adapts to the cockroach's locomotion model, and its design implements the modular approach. At the Boston Dynamic Institute, two world-renowned bio-inspired mobile robots have been developed. The Littledog robot (Pongas, et al., 2007) with four legs is designed for research on learning locomotion to probe the fundamental relationships among motor learning, dynamic control, perception of the environment, and rough terrain locomotion. Then there is the BigDog robot (Raibert, et al., 2008), which is the alpha male of the Boston Dynamics family of robots. It is a quadruped robot that walks, runs, and climbs on rough terrain and carries heavy loads. These two mobile prototypes are not only well designed from the mechanical point of view, but also concerning their high level of intelligence.
Snake-like robots, also called limbless robots, make up the other big group in the bio-spired mobile robotic family. The snake-like robots were first studied by Hirose, who developed the Active Cord Mechanism (ACM) (Hirose, 1993). Recently some new versions have been developed in his group (Togawa, et. al., 2000). S. Ma et al. in Japan and his Chinese colleagues at the Robotics Laboratory of Shenyang Institute of Automation also developed their own yaw-connecting robot and studied the creeping motion on a plane and on a slope

(Chen, et. al., 2004). Other prototypes are SES-2 (Ute, et al., 2002), S5 (Miller, 2002), WormBot (Conradt, et al., 2003) and swimming Amphibot I (Crespi, 2005).
The classical approach to controlling limbless robots is based on the inverse kinematics. The joint's angles are obtained from the desired trajectory of the supporting points or the center of mass. The limbless robots can be considered as hyper-redundant manipulators, formed by infinite joints. Chirjkjian employed functions to describe the shapes that the manipulator must adopt, and got the angular expressions (Chirjkjian, et al., 1995). Lipkin found much success in applying a three-dimensional variation of this approach to generate crawling, climbing and swimming gaits for the Modsnake robot (Lipkin et al., 2007). Goldman examined the kinematics of climbing a pole and calculated the joint angles for fitting a snake robot body to a helical backbone curve (Goldman et al., 2007).
In nature the vertebrates and invertebrates have special neurons called Central Pattern Generators (CPGs). These centers oscillate and produce rhythms that control muscle activity to carry out actions such as breathing, bowel movements, masticating, locomotion, etc. Based on biological studies, mathematical models are constructed from these oscillators which are then applied to robots to control locomotion. One of the pioneers in applying CPG models to robotics is the EPFL's Bio-inspired Robotics Laboratory (Ijspeert, 1998). In 2004, together with Crespi, they implemented the first prototype of Amphibot, demonstrating the viability of his bio-inspired model for robot locomotion. All their research work on the use of CPGs for locomotion control in Robots is reviewed in (Ijpeert, 2008). In the Biological neuron-computation group of the Autonomous University of Madrid, Herrero-Carron modeled and implemented CPGs based on Rulkov's model to control an eight segment caterpillar robot (Herrero-Carron, 2007).

3. A Bio-inspired climbing caterpillar robot

3.1 Climbing mechanism of the caterpillars

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 (Mezoff, et al., 2004). They consist of a head and neck part, a body with several segments and a tail end part, as shown in Fig. 1 and Fig. 2. Their movement depends mainly on the muscle's expansion and contraction. Caterpillars 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.
Caterpillars have the following advantages of climbing compared with other animals from the system design viewpoint.
1) Good length to pitch-back moment ratio (Spenko, et al., 2008): A big length to pitch-back moment ratio of the robotic mechanical design is better to realize a reliable attachment and to decrease the danger of the climbing movement.
2) Distributed modular design: Caterpillars are with several segments which are similar to identical modules so that the mass of the body is distributed into all segments. During the climbing movement many segments are attached to the surface while only some numbers of segments are moving, thus makes the robot safer than other climbing kinematics principles.

There are two kinds of typical locomotion modes adapted by different caterpillars. The corresponding representative worms are the inchworm (Fig. 1) and Manduca sexta larvae (Fig. 2) respectively. Caterpillar kinematics models are also presented in two figures. In order to analyze the kinematics of caterpillars, an adhesion module is indicated as "△" and an active rotating joint module is indicated as "—○—" in our discussion.

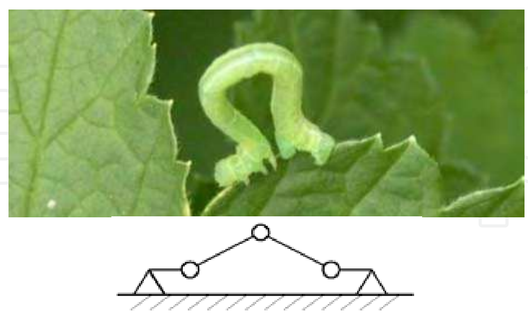

Fig. 1. Inchworm and its locomotion mechanism

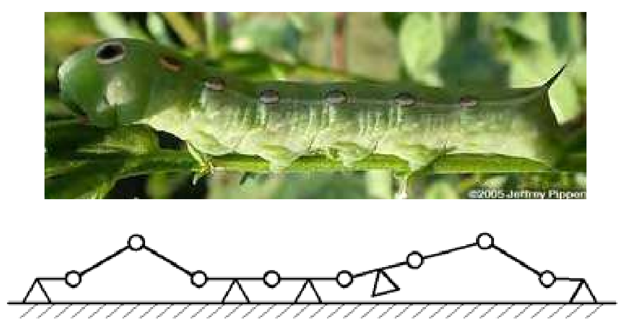

Fig. 2. Manduca sexta larvae and its locomotion mechanism

In this paper, we only concentrate on the inchworm configuration due to the following reasons.

1) The inchworm performs a gait different from that of normal caterpillars. Although the inchworm also consists of three limbs, the head, the tail and the trunk, the body limb is totally different since it possesses no proleg at all.

2) Due to its simple body structure, the inchworm has to adopt a simple gait to move. While crawling, it lifts the tail first, contracts the trunk, and then drops the tail a short distance from its original position in the forward direction. At this time, the inchworm is like a bow. Then, it lifts its head, stretches the trunk and drops the head. A gait is completed and a certain distance has been covered in a forward movement.

3) There is only one adhesion module adhering to the wall during motion; during the motion, the body delivers an incomplete wave.

In the following part of this chapter, we are going to present our climbing caterpillar robot design with an inchworm configuration. Different aspects will be introduced in detail.

3.2 Prototype design

Based on the investigation of natural climbing caterpillars, the most important requirement for our robotic system moving on a slope with different materials is extraordinary motion capabilities. Two mechanical units are definitely necessary for designing a light mechanical

climbing robot: structure with flexible locomotion capabilities and a safe and reliable attachment device.
On the other hand, as a bio-inspired robot imitating a natural caterpillar, the proposed climbing caterpillar robot should be as intelligent as possible. In order to move freely, it is also important for the mobile robot not to be wired or otherwise connected to the environment. The robot should carry all devices it requires: onboard power, the controller, and wireless communication.
In this project, 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, a low-frequency vibrating passive attachment principle and various locomotion capabilities (Zhang, et al., 2007). This multifunctional bio-inspired modular climbing caterpillar will:
1) be capable of walking and climbing not only in different environments but also on the vertical surfaces and ceilings on the inside of buildings;
2) possess locomotion capacities including pitching, yawing, lateral shift, and rotating;
3) feature sensor-servo-based active perception of the environment.
Fig. 3 shows pictures taken from a 3D-animation of the planned robotic caterpillar on a vertical wall. This system, which is currently under development at the University of Hamburg, is based on the technology that already exists in our consortium.


Fig. 3. 3D-animation of the planned robotic caterpillar

Another feature of this prototype lies in a new attachment principle. Currently, it is noted that four attachment principles are valid for climbing robot design. First there is no possibility of using magnetic force on general lightweight climbing robots except for some special cases that work on ferromagnetic surfaces (Akinfiev, et al., 2002). Molecular force (Sitti, et al., 2003) as a new attachment method for climbing robots is very promising; however, the benefits of this novel adhesive principle are offset by expensive manufacturing prices and difficulties. Based on the current technological level, real industrial application will still take some time.
The grasping gripper is relatively prevalent for designing a reliable attachment unit for a climbing robot. The climbing robots using grippers generally work in a specialized environment, such as metal-based buildings (Abderrahim, et al., 1991). As a result, we cannot implement this idea on our prototype either. This not the attachment mechanism adopted by natural climbing caterpillars.
Actually, natural caterpillars use the passive suckers on their prologs for moving and climbing, as mentioned above. The vacuum in these suckers is usually established by

vacuum ejectors or vacuum pumps which are easy to control. These advantages are offset by the long air tube or relatively heavy devices that need to be added to the climbing robots, which limit the application of this adsorption method to smart wall-climbing robots, such as our proposed caterpillar robot.

A new low-frequency vibrating passive suction method is presented in order to keep the merits and eliminate the shortcomings of using normal active vacuum suckers (Zhang, et. al., 2007.). This passive idea also comes from the natural caterpillars' adhesion principle. Application of a new low-frequency vibrating passive suction method makes it possible to forego the conventional heavy vacuum ejectors and realize an effective simple adsorption, furthermore to improve the inspired technological level and flexibility of the locomotion capability.

3.3 Mechanical module design and Inchworm configuration realization

As we mentioned above, this paper only concentrates on robotic inchworm design and realization, as shown in Fig. 4. Actually, the mechanical modules are uniform and identical, making it possible to use them to build a general caterpillar robotic configuration. For two reasons, the inchworm configuration is the first milestone in this long-term project.

1) It is the basic and simplest configuration as a robotic caterpillar; the other configuration can be based on it from the mechanical viewpoint. For example, a larvae robot can be created by connecting two inchworm prototypes.

2) The gaits of an inchworm robot are relatively simple. However, it is more challenging for us to validate our design, especially concerning the new passive attachment. All results will be valuable for our future research.

Fig. 4. Robotic inchworm design in CAD and real prototype

The inchworm robot consists of three serially connected modules for moving. Actually, the modular design is identical. Though it is possible to construct the robot with three uniform modules, in order to realize a mimic inchworm configuration, the first and the last modules feature passive suckers while the middle on has no attachment unit.

One body module includes an active joint and an attachment module, as shown in Fig. 5. The joint module consists of two brackets with some holes, an RC servo, a shaft, and a flange (Wang, et al., 2008). As a result of actuation by the servo, one DOF active rotating joint within ±90 degrees enables two brackets to adopt pitching movements. 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.

Fig. 5. Mechanical design of the joint module and attachment module

The attachment module without any embedded DOF consists of two shells, a passive sucker, a solenoid valve, and other small parts. 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 flat surfaces. If the solenoid is actuated, the iron pin will be withdrawn from the cap to connect the inside of the sucker with the outside air through the pipe. The vacuum in the sucker is released, and the sucker can be lifted. On the two shells of the attachment module, the mechanical interfaces are the same as those on the joint module. Thus the attachment module can be directly connected to the joint module. The basic performances of two modules are listed in Table 1, in which the elastic coefficient of the passive sucker deserves special attention, because its influence is important for the gait realization. In order to lighten the weight, all mechanical parts are manufactured from aluminum.

Joint Module	Performances	Adhesion Module	Performances
Size: length×width×height (mm^3)	35×37×30	Size: length×width×height (mm^3)	26×32×20
Weight (g)	19.2	Weight (g)	27.8
Max Output Torque (Nm)	0.2	Max Attaching Force, *Fn* (N)	40
Output Angle (Degrees)	0-180	Max Sliding Force, *Fq* (N)	15
		Max Turning Torque, *M* (Nm)	0.4
		Attaching force-to-weight Ratio	100

Table 1. Performance of the Demonstrated Modules

3.4 Control realization

The inchworm robot should own enough intelligence to imitate a natural creature. First, the robot should carry onboard power, the controller, and wireless communication units. Second, as we mentioned before, the system should be low-cost to be used for different applications such as locomotion analysis or bio-inspired investigation. As a result, to ensure its ability of performing different gaits, there is enough space in each module for sensors,

the onboard controller, and batteries. Considerable stress is laid on weight reduction as well as on construction stiffness to achieve a dexterous movement mechanism.
Fig. 6 shows the principle of a distributed control system. Each module has embedded intelligent capabilities with an independent onboard controller with two layers. On the one hand, each module is equal from the control view point. According to their different locomotion functions, various programs will run on the single module respectively. All motion commands can be sent to a certain module individually or broadcast to all modules through the I^2C bus according to the task requirements. On the other hand, any module can be nominated as a master control which is in charge of high-level control functions such as path planning, navigation, localization. At the moment, a PC is used as a consoler to set up the parameter configuration and generate locomotion gaits. It can also be directly connected to the bus through RS232. In this way, the PC can be considered as a virtual module in the robot system and plays the role of the master or a graphic user interface (GUI).

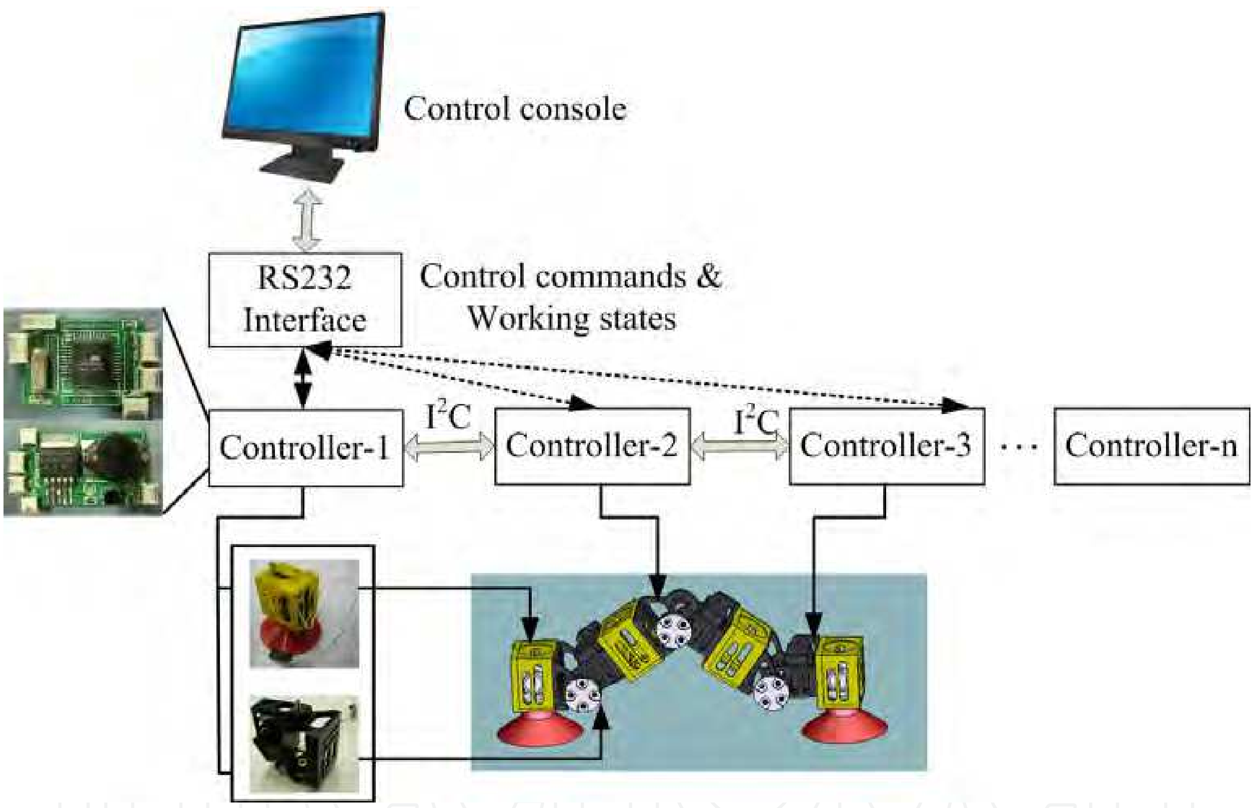

Fig. 6. Control realization

Each controller has one channel of Pulse Width Modulation (PWM) output to control the servo motor, one on-off output to control the solenoid valve, 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 modules. The controllers can communicate with each other by the I^2C bus and receive the orders from a console through the RS232 serial port. While the robot works, the information about its working state and the sensor data will be sent back to the console at the same time.

4. Locomotion and on-site experiments

4.1 Locomotion control

In order to control the climbing of the inchworm robot, an unsymmetrical phase method (UPM) is proposed. That means, the movement of attaching the suckers to the wall is faster than that of lifting the sucker from the wall. Fig. 7 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. At the beginning and end steps t_0 and t_4, the angle values of three joints are all zero.
The state of the sucker is controlled by a corresponding solenoid which has only two states, on or off. The high level means that the solenoid is actuated and the sucker is released. The low level denotes the inverse state.

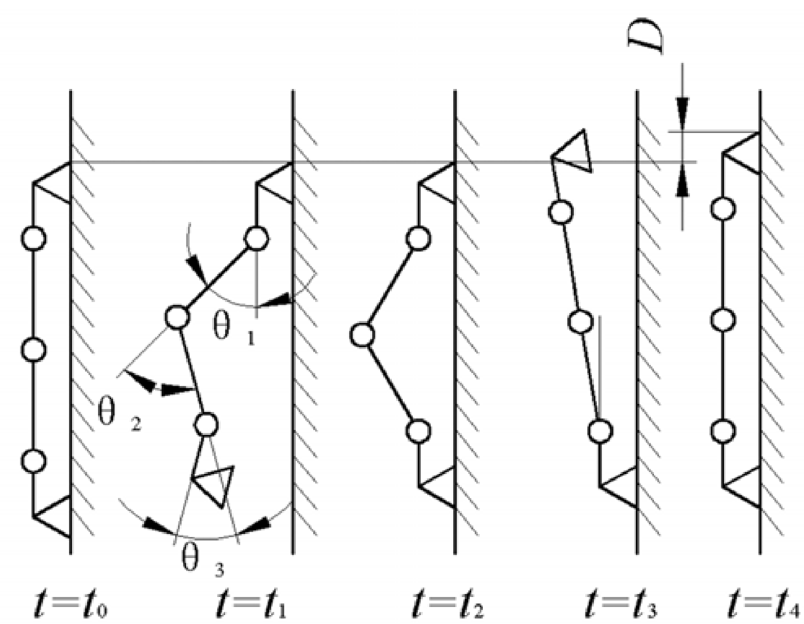

Fig. 7. The locomotion gaits of inchworm robot

At time t_1, the inchworm robot lifts the lower sucker when the angle values of its three joints fulfill the relationship shown in equation (1). Where $\Delta\theta_L$ is a constant which is named the impact angle and defined by experiments.

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

According to (1), this sucker moves not only forward but also up the wall. During the time between t_1 and t_2, the robot puts down the sucker by turning Joint 1. As mentioned above, the time between t_0 and t_1 is much longer than the time between t_1 and t_2, so the control phases are unsymmetrical during two periods. 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 lowering period of UPM, when the sucker makes contact with the wall, the force F acting on the sucker can be expressed by (2).

$$F=F_1+F_2=(M+I\omega/\delta_t)/A \quad (2)$$

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 acting 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;
δ_t is the impulse time.

The values of some parameters in (2) are shown below. At step t_1, A is equal to 0.13 m, M is 0.2 Nm and I is 1.62×10^{-4} kg m^2. The values of ω and t can be attained in real experiments, ω is 5.2 rad/s and δt is 2×10^{-3}s. As a result, F_1 is equal to 1.5N and F_2 is equal to 3.2N. That means that 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.

The joint trajectories in Fig. 7 are denoted by equations (3) - (5), which are loaded in the controllers to calculate the joint angles in real time. Details can be found in (Wang, et.al., 2009).

$$\theta_1(t)=\begin{cases}\dfrac{\theta_L+\Delta\theta_L}{t_1-t_0}t, & t\in[t_0,t_1]\\ \theta_L+\Delta\theta_L-\dfrac{\Delta\theta_L}{t_2-t_1}t, & t\in(t_1,t_2]\\ \theta_L(1-\dfrac{t}{t_3-t_2}), & t\in(t_2,t_3]\\ 0, & t\in(t_3,t_4]\end{cases} \quad (3)$$

$$\theta_2(t)=\begin{cases}-\dfrac{2\theta_L}{t_1-t_0}t, & t\in[t_0,t_1]\\ -2\theta_L, & t\in(t_1,t_2]\\ -2\theta_L(1-\dfrac{t}{t_3-t_2}), & t\in(t_2,t_3]\\ 0, & t\in(t_3,t_4]\end{cases} \quad (4)$$

$$\theta_3(t) = \begin{cases} \dfrac{\theta_L}{t_1 - t_0} t, & t \in [t_0, t_1] \\ \theta_L, & t \in (t_1, t_2] \\ \theta_L - \dfrac{\theta_L - \Delta\theta_L}{t_3 - t_2} t, & t \in (t_2, t_3] \\ \Delta\theta_L (1 - \dfrac{t}{t_4 - t_3}), & t \in (t_3, t_4] \end{cases} \quad (5)$$

4.2 Climbing tests

Recently, a series of on-site tests have been made to confirm our design and to find out the appropriate ω in the equation (2). In these tests, first 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 the wall, 5.2 rad/s is taken as the joint velocity during the lowering motion.

After that step, we made a climbing test on a glass surface. The inchworm robot realizes continuous motion on the vertical wall successfully with the gait presented in Fig. 7. Fig. 8 shows the procedure of the inchworm robot climbing up for the course of one gait; the maximal step length is 5mm, and the time of one step is 1.8s.

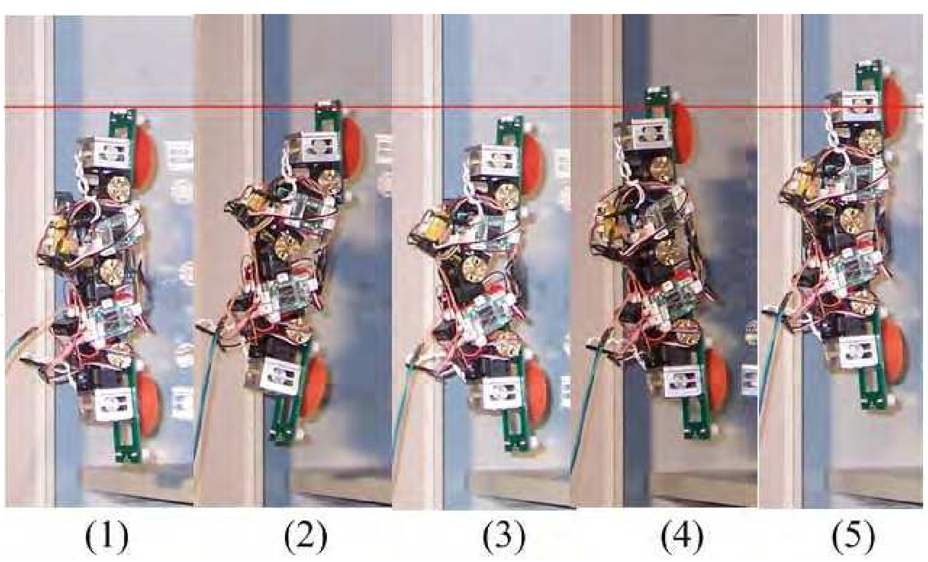

Fig. 8. Climbing testing on glass

5. Conclusions and future work

This paper presents a novel, bio-inspired, small climbing caterpillar robot. The discussion is focused on the inchworm configuration since it is the simplest and basic structure compared to the other climbing mechanisms adopted by natural caterpillars. All related aspects including design motivations, system integration, mechanical module design, control hardware, and locomotion realization are introduced in detail. In contrast to conventional theoretical research, the project introduced in this project successfully implements the following innovations:

1. It proposes a climbing robot based on a modular reconfiguration concept. The robot features a simple, light mechanical structure and a novel passive attachment.
2. The distributed control system completes the modular design. A UPM locomotion method enables the robot to climb vertical surfaces reliably.
3. Related tests have shown that the inchworm robot can implement safe climbing in a certain locomotion gait. This implies the mechanical feasibility, the rationality of the design and the flexible movement adaptability of the robot.

There are still a lot of technical problems for us to uncover, such as vibration during movement, evaluation of different locomotion parameters, even if the inchworm configuration is the simplest one. We should improve the gait control methods to diminish the internal force in the caterpillar robot, and realize more reliable motions, such as climbing between two surfaces in different planes, crossing a barrier on the wall etc.

Second, currently all of the locomotion capabilities are pre-programmed, as we mentioned. In future, our research will focus on the realization of real autonomy.

Third, other caterpillar robotic configurations will be designed and tested soon. Future research will include finding the rules of constructing a reasonable configuration with the passive joint and active joint, testing the feasibility of passive joints in the caterpillar model and selecting the safest climbing gait.

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Mechatronics, the synergistic blend of mechanics, electronics, and computer science, has evolved over the past twenty five years, leading to a novel stage of engineering design. By integrating the best design practices with the most advanced technologies, mechatronics aims at realizing high-quality products, guaranteeing at the same time a substantial reduction of time and costs of manufacturing. Mechatronic systems are manifold and range from machine components, motion generators, and power producing machines to more complex devices, such as robotic systems and transportation vehicles. With its twenty chapters, which collect contributions from many researchers worldwide, this book provides an excellent survey of recent work in the field of mechatronics with applications in various fields, like robotics, medical and assistive technology, human-machine interaction, unmanned vehicles, manufacturing, and education. We would like to thank all the authors who have invested a great deal of time to write such interesting chapters, which we are sure will be valuable to the readers. Chapters 1 to 6 deal with applications of mechatronics for the development of robotic systems. Medical and assistive technologies and human-machine interaction systems are the topic of chapters 7 to 13.Chapters 14 and 15 concern mechatronic systems for autonomous vehicles. Chapters 16-19 deal with mechatronics in manufacturing contexts. Chapter 20 concludes the book, describing a method for the installation of mechatronics education in schools.

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