A Novel Mechanism for Caterpillar-like Locomotion Using Asymmetric Oscillation

Guoyuan Li, Houxiang Zhang, Fernando Herrero-Carrón, Hans Petter Hildre and Jianwei Zhang

Abstract— **This paper presents a novel mechanism to implement caterpillar-like locomotion. First, the caterpillar-like locomotive pattern in nature is investigated and analyzed systematically. From a biological point of view, caterpillar locomotion can be abstracted as a body wave, called half wave. It is simple, but efficient. In this paper, a novel control mechanism, maintaining the half wave property, is integrated into an improved central pattern generator (CPG) model. For the first time, an asymmetric oscillation is employed on the model for gait generation. The movement is proved stable according to a kinematic analysis. Modulation is able to use to change the shape of the half wave during locomotion. A series of simulation shows the feasibility of using asymmetric oscillators for locomotion. Furthermore, the latest results obtained demonstrate that the proposed asymmetric locomotion mechanism is easy to implement while offering a satisfactory motion performance in on-site experiments.**

I. Introduction

Caterpillars are among the most successful climbers and can maneuver in complex three-dimensional environments [1]. There are three typical kinds of gaits adapted by natural caterpillars: forward moving, reverse moving, and rolling [2]. As the major "limb" of the caterpillar, the abdominal prolegs are employed on segments for the attachment to the substrate during the crawling process. From the kinematics viewpoint, a caterpillar's locomotion occurs as a result of serials of body waves. Here we define the wave propagation along the caterpillars' body as "half-wave" locomotion according to the shape of the body during the movement. This kind of locomotion mechanism is simple, but efficient. That is one of the reasons why we have an interest not only in understanding their locomotion principle but also in trying to build a control model to realize it.

A caterpillar-like configuration constitutes a modular design in a single chain and can be implemented to meet the requirements of flexible locomotion and lightweight structures [3]. For the locomotion control mechanism of the single chain type robots, the employed approaches include the following ideas. By analyzing the kinematics of snake motion, Hirose first designed a serpentine gait [4]. Kinematical models of the snake are used to set the joint angles along the body of the robot. In contrast to this method, Mark Yim developed a "gait control table" for discrete position control [5]. It permits the definition of sequences of movement "frame by frame". The sine-based method takes advantage of the explicit phase difference that exists in limbless animals to generate an effective gait. Based on a sinusoidal curve, Hatton et al. explored the use of chain fitting and wave extraction to generate rolling gaits for snake robots [6]. A CPG-based method is also widely used for locomotion control, which will be discussed in related work.

The research presented in this paper is related to our on-going DFG project "Biologically Inspired Modular Climbing Caterpillar Robot Using Passive Adhesion" (BICCA), in which we will combine climbing techniques with the concept of a modular robot to create a novel climbing caterpillar robot [7]. A hybrid control architecture including a reflex level, CPGs with biological locomotion features and a learning algorithm for sensor-servo-based behavior control is designed for the motion system. Here, we will concentrate our efforts on designing the low-level locomotion control mechanism that features caterpillar-like locomotive characteristics. The contributions of the research in this paper lie in the following points. First, this paper is devoted to a novel locomotion mechanism featuring caterpillar motion characteristics. This is the first time that a new integrated CPG model to generate an asymmetric oscillation is designed and proved feasible as a possible method for various caterpillar-like movements which are similar to those in nature. Second, the research work is not only tested in a simulation, but also in on-site tests. A series of successful on-site tests are provided to confirm the proposed CPG model and the locomotion efficiency.

The rest of this paper is organized as follows. The characteristics of caterpillar locomotion and CPG-based control models are outlined in Section II. Section III analyzes the stability of locomotion using asymmetric oscillation on each segment. Then the detail of asymmetric oscillator design is introduced in Section IV. Section V presents on-site experiment to verify the principles. Finally, a conclusion is given.

This work is supported by the Deutsche Forschungsgemeinschaft (DFG) (No. U-4-6-04-DFG-10-01).

G.Y. Li and J. W. Zhang are 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: li@informatik.uni-hamburg.de).

H. X. Zhang is with the Department of Technology and Nautical Sciences, Aalesund University College (AAUC), Postboks 1517, N-6025 Aalesund, Norway (As the corresponding author, e-mail: hxzhang@ieee.org).

H. P. Hildre is with the Department of Technology and Nautical Sciences, Aalesund University College (AAUC), Postboks 1517, N-6025 Aalesund, Norway (e-mail: hh@hials.no).

F. Herrero-Carrón is with Group of Neurocomputación Biológica (GNB), Universidad Autónoma de Madrid, Madrid, Spain. He is currently a visiting Ph.D. Student and working at the TAMS (email:fernando.herrero@uam.es).

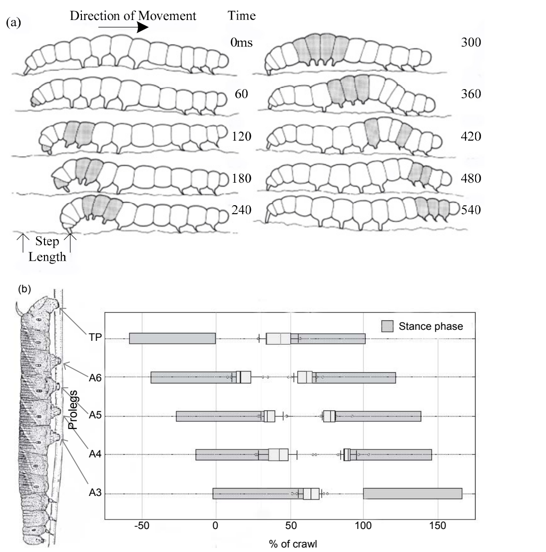

Fig. 1. Caterpillar locomotive features. (a) Kinematics of caterpillar locomotion. A half wave propagates forward from the tail to the head. A step length forms after one step cycle. The figure is cited from [2]. (b) The relative timing of the stance and swing phase of each proleg. Phase lag exists during a crawl. The figure is cited from [8].

II. Related Work

Two parts of related work will be presented here: the caterpillar locomotion and the CPG-based control models.

A. Caterpillar Locomotion

Caterpillar locomotion is achieved by serials of body waves. During locomotion a half wave runs along the caterpillar's body from tail to head, which produces a characteristic travelling 'hump' on the caterpillar's back. A step cycle begins with lifting up the terminal proleg (TP). The TP moves forward until it anchors the tail one step ahead. Once the TP is set, a half wave forms and propagates forward. As far as the head segment attaches to the substrate, the half wave disappears and one cycle is completed, as shown in Fig. 1(a).

In each segment, a stance phase and a swing phase appear alternately during the stepping pattern [8]. There is no further movement for the segments in the stance phase until the next cycle occurs. Fig. 1(b) shows the two phases and relative timing of proleg movement during one step cycle. Different muscles, acting like motors, are phase-delayed in different segments [9].

B. CPG-based Control Models

In robotics, CPGs work as an elegant solution for online trajectory generation [10]. Here a few representative CPG models are exhibited on different principles and different levels of detail modeling.

The first one is a bio-inspired model. Herrero-Carrón et al. designed a model for worm-like locomotion [11]. The neurons modeled with a rich-dynamics iterated map generate rhythmic activity in the form of bursts of spikes. This CPG model retains most biological properties. However, the complexity of the model as well as its poor modulation capability offset its effectiveness. The second one, which is implemented on the M-TRAN robot, has powerful adaptability for locomotion, such as dynamic walking and running on uneven ground [12]. In their model, the CPG is comprised of two mutually inhibiting neurons. The disadvantage of this model is that it is not easy to modulate with explicit parameters. Last, Ijspeert et al. use a high-level abstraction of CPG activity. Their model is designed to display a limit cycle corresponding to a circle in a cartesian plane [13]. The nonlinear oscillator is provided with amplitude, frequency and phase difference parameters to shape the body wave. Coordination of different modules is achieved through explicit knowledge of the relevant phases of oscillation within each circle.

According to the investigation of different CPG models, in the next sections, we will combine a CPG model with the locomotive properties of caterpillars to achieve caterpillar-like locomotion.

III. Kinematic Analysis

In this section, we concentrate on analyzing the kinematics of the half wave. Because there is no movement when the caterpillar's segments are in the stance phase, only the segments in the swing phase are depicted in the following analysis.

A. Body shape analysis

To study the body shape of the so called "half wave" during caterpillar-like movement, a wired model is employed as the segment of the caterpillar-like robot, as shown in Fig. 2(a). It is assumed that a positive angle α is generated when the right side bends upwards, while a negative angle is produced if it bends downwards.

Fig. 2(b) shows two types of "half wave" and its angle α oscillating over discrete time (T_1, T_2…). Although each body shape has a different number of segments, both of them reveal that the segment in the middle of the body arc bends oppositely twice as much as the segments at the ends. In this case, all the segments in each half wave have an asymmetric oscillation with a ratio of 2, as shown in the right of Fig. 2(b). Fig. 2(c) depicts how a half wave is generated over a discrete time sequence if the oscillating ratio reaches 2. At time T_4, the robot model lifts its tail. Then, a full half wave is generated after the tail is set on the ground at time T_6. Finally, the time T_8 presents a propagation of half wave from tail to head. The following sections will analyze a continuous time oscillation more systematically.

B. Joint Analysis

Assume that there is a large enough number of segments so that the body arc in the half wave is totally included during propagation. The fundamental requirement of caterpillar-like locomotion is that both ends of the robot should be parallel to the ground. The sum of joints in the half wave determines the

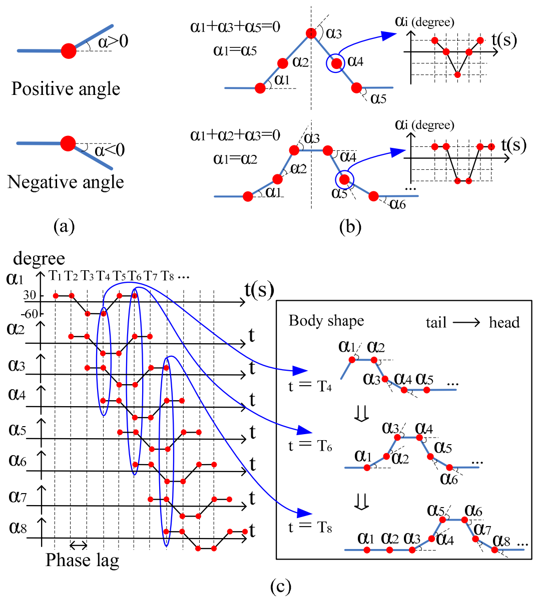

Fig. 2. Body shape analysis. (a) Wired model. (b) Two types of half wave, as well as their angle variation over discrete time. (c) Half wave generation over discrete time with an asymmetric oscillating ratio of 2.

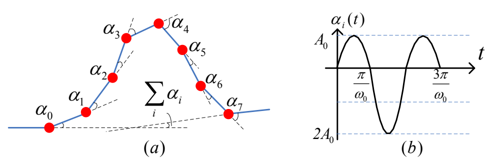

Fig. 3. Joint analysis. (a) The angles at both ends are determined by the sum of joints in the half wave. (b) Asymmetric oscillation over continuous time.

angle at both ends, as shown in Fig. 3(a). The requirement can be expressed as:

$$\sum_{i} \alpha_i = 0 \tag{1}$$

where α_i is the angle of the ith joint in the half wave. To make continuous oscillation, the segments in the half wave can be written as a sinusoidal function with a sign function *sgn()*:

$$\alpha_i = A_0 \cdot \mathrm{sgn}(t) \cdot \sin(\omega_0 t + i\varphi_0)$$
$$\mathrm{sgn}(t) = \begin{cases} 1 & if \;\; \sin(\omega_0 t + i\varphi_0) \geq 0 \\ 2 & otherwise \end{cases} \tag{2}$$

Similar to the discrete time sequence, the angle variation of each segment in the swing phase lasts a period of $3\pi/\omega_0$, as shown in Fig. 3(b). Assume that the phase difference φ_0 satisfies the equation (3):

$$\varphi_0 = \frac{\pi}{n}, \quad (n \in N,\, n \geq 2) \tag{3}$$

Combining (2) with (3), the number of segments m in the body arc should be:

$$m = \begin{cases} 3n-1 & \omega t = k\pi \\ 3n & \omega t \neq k\pi \end{cases} \quad (k \in N) \tag{4}$$

According to (2), (3) and (4), the sum of the angles in the half wave is:

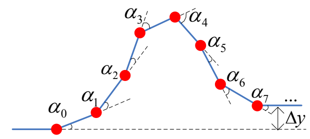

Fig. 4. Vertical displacement analysis. The vertical displacement at both ends has an effect on stable movement.

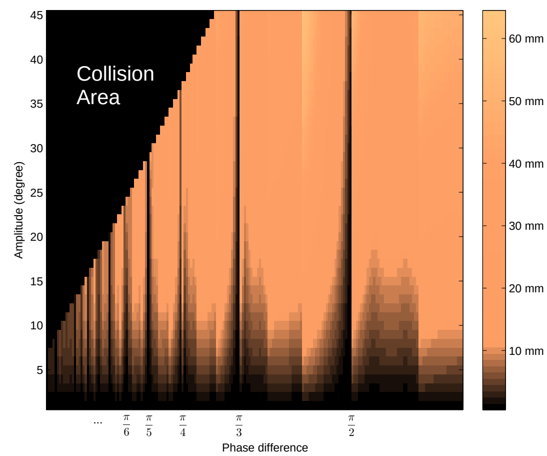

Fig. 5. The variation of vertical displacement. The collision area is derived from equation (7). The absolute value of vertical displacement is sharply reduced when the phase difference satisfies equation (3).

$$\sum_{i=0}^{3n-1} \alpha_i = \sum_{i=0}^{n-1} (\alpha_i + \alpha_{i+n} + \alpha_{i+2n}) = 0 \qquad \omega t \neq k\pi \tag{5}$$

The same result is achieved when ωt reaches $k\pi$. Note that both ends of the body are able to be parallel to the ground except for the body arc. From the locomotion point of view, the body shape featuring parallel ends provides the robot with a basic stability for its motion.

C. *Vertical Displacement Analysis*

The stability of the locomotion is not only related to the angles between both ends of the body, but also associated with the vertical displacement of both ends, as seen in Fig. 4. Via the geometry method, the vertical displacement at both ends is easy to achieve.

We set the origin at the left end of the robot and use P_i in equation (6) to represent the position of the ith joint from the origin. The relation of the joint positions is in equation (7):

$$p_i = [x_i \;\; y_i]^T \tag{6}$$

$$\begin{cases} p_0 = \left[\frac{L}{2} \;\; 0\right]^T \\ p_{i+1} = p_i + R_i \cdot [L \;\; 0]^T \\ R_i = \begin{bmatrix} \cos(\sum_{j=0}^{i} \alpha_j) & -\sin(\sum_{j=0}^{i} \alpha_j) \\ \sin(\sum_{j=0}^{i} \alpha_j) & \cos(\sum_{j=0}^{i} \alpha_j) \end{bmatrix} \end{cases} \tag{7}$$

where L is the module length. R is the rotation matrix. The vertical displacement of both ends is now represented as:

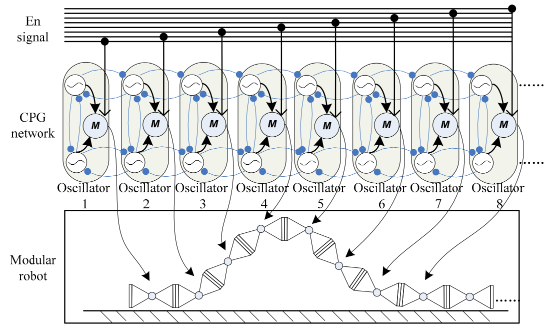

Fig. 6. CPG architecture. The CPG network involving a chain of coupled oscillators has an effect on the pitch-pitch connected modular robot. The enable signal drives the oscillators alternately into the swing and stance phase.

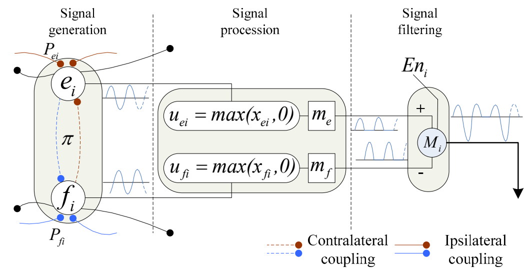

Fig. 7. CPG oscillator. The CPG oscillator consists of three components. Each component plays a role for signal output. As a result, the processed signal, which is also the desired angle, directly drives the segment joint.

$$\Delta y = y_m = L \cdot \sum_{i=0}^{m-1} \sin(\sum_{j=0}^{i} \alpha_j) \tag{8}$$

where m is the number of the segment in the half wave. Fig. 5 shows the absolute maximum value of vertical displacement in one cycle ($|\Delta y|_{\max}$) with arbitrary amplitude and phase difference. Notice there is a collision happened when the amplitude is set improper. Compared to the module length (76 mm), there is almost no vertical displacement (less than 1 mm) at either end when the phase difference satisfies equation (3).

IV. Asymmetric Oscillator Design

In this section, the CPG-based locomotion control architecture is improved taking the aforementioned continuous oscillation into account. A modular robot is used as a test-bed of our approach.

A. CPG model design

As shown in Fig. 6, the modular robot with pitch-pitch connection is controlled by servomotors. In the CPG network, each oscillator comprises two mutually inhibiting neurons, as well as a motor neuron which is responsible for driving the corresponding actuated joint on the modular robot. The oscillators set coupling bilaterally. A chain topology is formed to synchronize oscillators with desired phase difference. In addition to the CPG network, the enable signal is used to transform the state of the segment from the swing phase to the stance phase and back. The servomotor is set to zero value by use of the enable signal if the segment switches to the stance phase. Otherwise, it receives the CPG output as the desired value in the swing phase.

A CPG model is applied to each segment, as seen in Fig. 7. The model consists of three functional components. In the "signal generation" part, two types of coupling are employed for the purpose of phase lag generation. The ipsilateral coupling ensures a locking phenomenon among connected oscillators, while the contralateral coupling enables the two inhibiting neurons e and f to arrive at a steady anti-phase state after some oscillatory cycles. To further process the output of the two neurons, non-negative operation as well as asymmetric oscillating weight distribution is added as the "signal procession" component. In the "signal filtering" part, an enable signal influencing the motor neuron M is used to filter the integrated output periodically.

The dynamic system of coupled oscillators in the "signal generation" part is referenced from [14]:

$$\begin{cases} x'_{\{e,f\}i} = \omega y_{\{e,f\}i} + x_{\{e,f\}i}(A^2 - r^2) \\ y'_{\{e,f\}i} = -\omega x_{\{e,f\}i} + C_{\{e,f\}i} \end{cases} \tag{9}$$

$$r = \sqrt{x^2 + y^2} \tag{10}$$

$$\begin{aligned} C_{\{e,f\}i} = &\sum_j \frac{w}{A}(x_{\{e,f\}j} \sin\varphi + y_{\{e,f\}j} \cos\varphi - y_{\{e,f\}i}) \\ &- \frac{w}{A}(y_{\{f,e\}i} + y_{\{e,f\}i}) \end{aligned} \tag{11}$$

where x and y are the state variables of the neuron. The variable r stands for the radius in the polar coordinated system. The parameters A, ω and φ represent the intrinsic amplitude, frequency and phase difference separately. In the coupling part C, a coupling weight w is defined between two connected neurons. The subscript j stands for the ipsilateral neighboring neurons that connect to the ith neuron. The second term in equation (11) is the coupling between contralateral neurons, which indicates an anti-phase oscillating between the e and f neurons.

In order to integrate the swing phase and stance phase, as well as an asymmetric oscillating into each oscillator, the following additional equations are employed:

$$u_{\{e,f\}i} = \max(x_{\{e,f\}i}, 0) \tag{12}$$

$$En_i = \begin{cases} 1 & if \;\; t_f < t < t_f + 3\pi/\omega \\ 0 & otherwise \end{cases} \tag{13}$$

$$out_i = En_i(m_e u_{ei} - m_f u_{fi}) \tag{14}$$

The variable u records the non-negative value of the neuron. The enable signal En is defined piecewise, depending on the specific time when the motor neuron fires. The variable t_f is set as the times when the output of the motor neuron crosses a given threshold. As the neuron fires, a swing phase of the locomotion is considered to have occurred. Otherwise, the neuron will keep silent in the stance phase. Given the fact that the two inhibiting neurons in the oscillators will coordinate in

TABLE I
PARAMETERS OF THE CPG NETWORK

Parameters	Values	Description
ω	$(0, 2\pi]$	Oscillatory frequency
w	2.0	Coupling weight
m_e, m_f	1, 2	Oscillatory ratio
A	$(0, \pi/4]$	Desired amplitude
φ	$\pi/n \ (n \geq 2)$	Desired phase difference

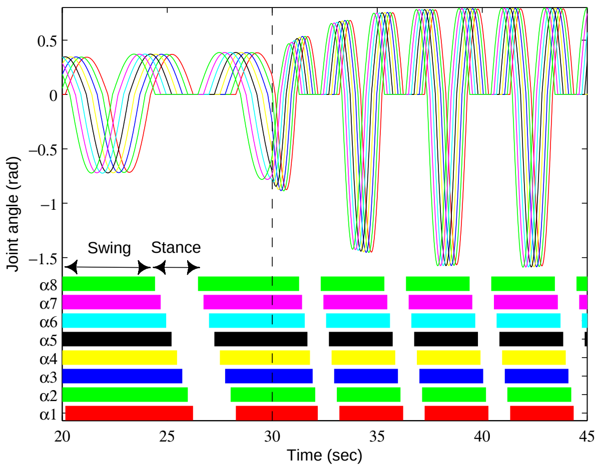

Fig. 8. Output pattern of CPG. The color bars indicate the duration of the swing phase for each segment joint. Otherwise a stance phase occurs in the cycle. The amplitude and frequency are doubled at t = 30 sec. The joints are coordinated in a few seconds.

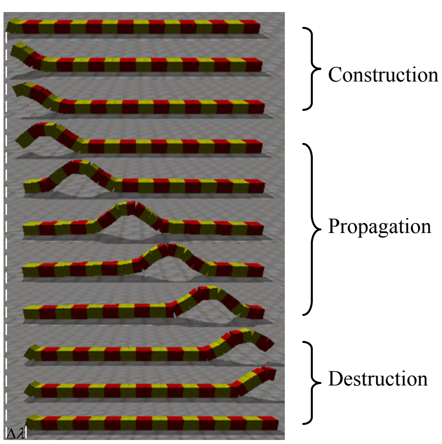

Fig. 9. One step cycle of caterpillar-like locomotion. Three phases emerge in this process. As the result of one step cycle, the robot moves forward in a step length Δλ.

the two inhibiting neurons in the oscillators will coordinate in the anti-phase, the output of the motor neuron *out* is a function oscillating by means of the two weight parameters m_e and m_f.

B. Caterpillar-like Locomotion Simulation

We tested the caterpillar-like locomotion using the CPG model with the parameters shown in Table I. Fig. 8 shows that the CPG model can generate a rhythmic pattern for each segment joint. It is noted that the swing phase and the stance phase appear alternately in one cycle. Furthermore, the parameters enable the model to modulate smoothly online.

In open dynamic engine (ODE) simulation [15], we implemented the model using the numerical method. Fig. 9 illustrates a complete process of a step cycle. We divide one cycle of the movement into 3 parts: construction, propagation and destruction phases. At the beginning, the robot anchors a step length ahead from the tail. The robot then displays an 'Ω' curve in the propagation phase where both ends are parallel to the ground. Finally the half wave is destructed with the head attached to the ground. Obviously, the movement pattern is similar to the behavior of caterpillars in the natural world.

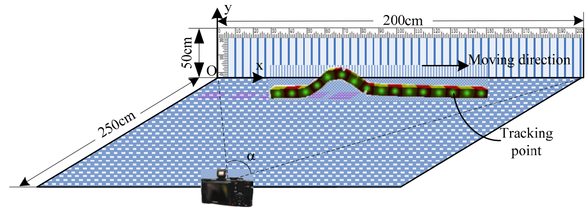

Fig. 10. On-site experimental setup. The modular robot is colored in each segment for video tracking.

Fig. 11. On-site experiment. A complete stepping cycle covers an approximate period of 4.8 s.

V. ON-SITE EXPERIMENT

An on-site experiment was carried out to illustrate how the robot performs in the real world. It compared the locomotive pattern of the robot and real caterpillars in nature. The experimental setup is shown in Fig. 10.

Fig. 11 shows the caterpillar-like gait as implemented in the modular robot. The displacement in the horizontal direction over time for each joint is shown in Fig. 12. The robot achieves a mean speed of about 1.4 cm/s. Compared with [16], the movement in the horizontal direction is the same except for the head segment. The head of the real caterpillar moves almost continuously, while the head segment of the robot moves cyclically. In spite of that, the difference does not seriously affect the movement.

In [17], Trimmer et al. have researched the crawling speed and stride frequency of caterpillars for proleg A3 (see Fig. 1(b)) in the horizontal orientation. Considering the position of A3, we analyzed joint α_4 of the robot, following the methodology in [18], as seen in Fig. 13. The top panel shows the periodic discipline for the displacement in the y-plane. In the bottom panel, the instantaneous rate is measured and smoothed based on video tracking. The horizontal velocity

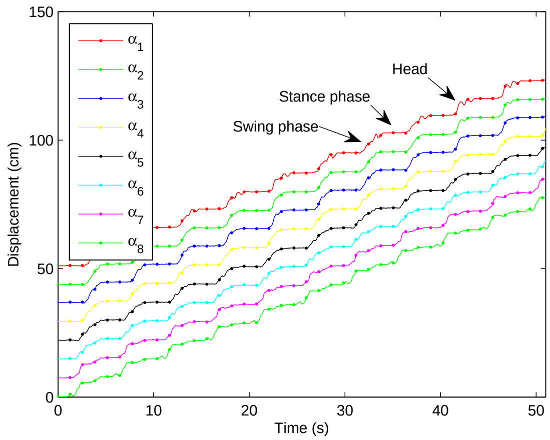

Fig. 12. The horizontal displacement with respect to time. It shows a cyclical forward locomotion with an approximate overall speed of 1.4 cm/s.

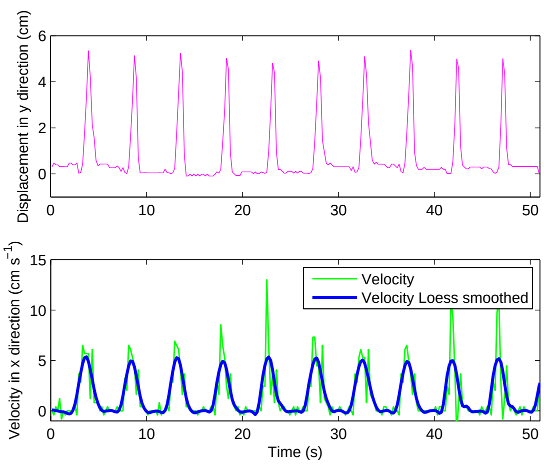

Fig. 13. Data analysis for joint α_4 according to video tracking. The maximum velocity in the x-plane and the maximum displacement in the y-plane are almost in phase.

varies in the swing phase and goes back to zero value when the segment switches to the stance phase. It is observed that a peak rate emerges when the displacement in the y-plane almost achieves maximum value. Here as in [18], there is the same trend of the maximum horizontal velocity and vertical displacement in the segment essentially being in phase.

VI. CONCLUSION

Since movement in robotics usually derives from nature, it is promising to involve biological features into control mechanism design. In this paper we introduced a novel mechanism for caterpillar-like locomotion using asymmetric oscillation. The motion pattern is first analyzed and proved stable according to the shape of a half wave. An asymmetric oscillation is employed for half wave generation. Then, the locomotive properties of caterpillars, including the state transition and phase delay between segments, are well blended into the model. Finally, through on-site experiment we have confirmed the feasibility of the newly designed control model.

Currently, we just carried out the first step on the design of the hierarchical control system. Our future work will attempt to add a reflex layer and integrate sensory feedback into the system to realize adaptive caterpillar-like locomotion. This will allow the robot to achieve more reasonable movement with the help of sensor information.

ACKNOWLEDGMENT

The author would like to thank the colleagues Gang Cheng, Manfred Grove and Bernd Schütz at the TAMS group for their helpful discussion and on-site testing.

REFERENCES

[1] H. Zhang, J. Zhang, W. Wang, "From the biological model to a small climbing caterpillar robot", *Int. J. Advanced Mechatronic Systems*, Vol. 2, No. 1/2, pp.90-98, 2010.

[2] J. Brackenbury, "Fast locomotion in caterpillars". *Journal of Insect Physiology,*Vol. 45, pp.525–533, 1997.

[3] 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, pp.84-89, 4 - 7 June, 2008.

[4] S. Hirose. *Biologically Inspired Robots: Snake-Like Locomotors and Manipulators*. Oxford University Press, 1993.

[5] M. Yim. "Locomotion with a unit-modular reconfigurable robot". PhD thesis, Dept. of Mech. Eng., Stanfofd University,December 1994.

[6] R.L. Hatton and H. Choset, "Generating Gaits for Snake Robots by Annealed Chain Fitting and Keyframe Wave Extraction". *Autonomous Robots*, vol. 28, No. 3, pp.271-281, 2010.

[7] H. Zhang, J. Gonzalez-Gomez, S. Chen, W. Wang, R. Liu, D. Li, J. Zhang, "A Novel Modular Climbing Caterpillar Using Low-frequency Vibrating Passive Suckers", *Proceeding of AIM 2007*, ETH Zurich, Switzerland, 4 - 7 Sept, 2007.

[8] H-t. Lin, and B.A. Trimmer, "The substrate as a skeleton: ground reaction forces from a soft-bodied legged animal". *Journal of Experimental Biology*. Vol. 213, pp. 1133-1142, 2010.

[9] B.A. Trimmer, "New challenges in biorobotics: incorporating soft tissue into control systems". *Applied Bionics and Biomechanics*, pp. 119-126, 2008.

[10] A.J. Ijspeert, "Central Pattern Generators for Locomotion Control in Animals and Robotics: a review", *Neural Networks*, vol. 21, pp.642-653, 2008.

[11] F. H. Carrón, "Study and application of central pattern generator circuits to the control of a modular robot," M.S. thesis, Dept. of Computer Eng., Madrid Univ., Spain, 2007.

[12] A. Kamimura, H. Kurokawa, E. Yoshida, E. Murata, K. Tomita, and S. Kokaji, "Distributed adaptive locomotion by a modular robotic system, M-TRAN II (from local adaptation to global coordinated motion using CPG controllers)", *in Proc. of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Japan, pp.2370-7, 2004.

[13] A.J. Ijspeert and A. Crespi. "Online trajectory generation in an amphibious snake robot using a lamprey-like central pattern generator model". In *Proceedings of the 2007 IEEE International Conference on Robotics and Automation, ICRA 2007*, Roma, Italy, pp.262-268, 2007.

[14] D. Marbach and A.J. Ijspeert. "Online Optimization of Modular Robot Locomotion", In: *Proceedings of the IEEE Int. Conference on Mechatronics and Automation (ICMA 2005)*, pp. 248-253, 2005.

[15] http://www.ode.org/

[16] T.M. Casey, "Energetics of caterpillar locomotion: Biomechanical constraints of a hydraulic skeleton". *Science* 252, pp.112–114, 1991.

[17] L.I. van Griethuijsen and B.A. Trimmer. "Kinematics of horizontal and vertical caterpillar crawling". Journal *of Experimental Biology* 212, pp.1455-1462, 2009.

[18] B.A. Trimmer and J. Issberner. "Kinematics of Soft-bodied, Legged Locomotion in Manduca sexta Larvae". *Biol.* Bull vol.212, pp. 130-142, 2007.