The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Decentralized Control of Serpentine Locomotion That Enables Well-balanced Coupling between Phasic and Tonic Control

Takeshi Kano, Takahide Sato, Ryo Kobayashi, and Akio Ishiguro

Abstract— **Decentralized control is a key concept to understand the mechanism of versatile and adaptive locomotion of animals under various environments. However, a systematic design of an autonomous decentralized control system has not been well established, because previous studies mainly focused on the control of phase relationship among body parts, *i.e.*, phasic control, but not on the control of the spatio-temporal dynamics of muscle tonus, *i.e.*, tonic control. In this paper, we propose a decentralized control scheme that enables to reconcile phasic control and tonic control, by taking serpentine locomotion as a practical example. Through modeling and simulations, we show that well-balanced coupling between the phasic and tonic control is crucial for the generation of adaptive and efficient locomotion.**

I. INTRODUCTION

Animals exhibit astoundingly adaptive, supple and versatile locomotion in real time under unpredictable real world constraints. To endow robots with similar capabilities, their bodies must have significantly many degrees of freedom equivalent to that of living organisms. For successfully coordinating movement with many degrees of freedom based on the various circumstances, *autonomous decentralized control* plays a pivotal role, and has therefore attracted considerable attention. In fact, living organisms nicely orchestrate and maneuver their many degrees of freedom in their bodies by distributed neural networks called *central pattern generators* (CPGs), which are responsible for generating rhythmic movements, particularly locomotion [1]. Based on this knowledge, various studies have been conducted to implement decentralized control schemes in robots so as to generate adaptive locomotion, in particular focusing on legged locomotion [2]-[6]. Thus, autonomous decentralized control method is expected to become an attractive tool for designing highly adaptive robots.

Despite its appeal, a systematic way of designing such autonomous decentralized controllers is still lacking because a methodology connecting local behavior to global behavior that induces useful functionalities, *e.g.*, adaptability and fault tolerance, has not yet been established. To alleviate this, we must consider the following issues:

(1) Dynamics of the individual components to be implemented, *i.e., intra-modular dynamics*.
(2) Interactions between the components to be implemented, *i.e., inter-modular dynamics*.
(3) Methods of coupling the control and mechanical systems, *i.e., brain-body interaction*.

As the pioneering studies done by Taga *et al.* [4]-[6] indicate, issues (1) and (2) are often modeled as coupled (nonlinear) oscillator systems. In contrast, for issue (3), interactions between control and mechanical systems have been designed on an ad-hoc basis for specific applications. In sum, we face an undeniable lack of consistent methodologies for designing the means of interaction between control and mechanical systems.

In light of these facts, we have previously employed a " back-to-basics " approach by focusing on *true slime mold* (*Physarum polycephalum*) which uses purely decentralized control mechanisms based on coupled biochemical oscillators similar to CPGs [7], and have introduced a systematic design methodology for the local sensory feedback mechanism based on "discrepancy function" [8], [9]. In this design methodology, discrepancy between the control system and the mechanical system is extracted based on local information of the body, which is fed back into the oscillator in the control system so that its phase is modified to reduce the discrepancy. By implementing this design methodology, we have developed robots that mimic amoeboid locomotion [9] and serpentine locomotion [10], and have shown that they are adaptable to environmental changes.

The abovementioned design methodology intensively focused on the control of "phasic" dynamics. Although it expressed an important aspect of the brain-body interaction, it is still not sufficient to fully describe the way of interaction between the control and mechanical systems, because actual living organisms exhibit locomotion with changing not only the phase relationship in their bodies but also their muscle tonus adaptively to environmental changes. Hence, it is clearly needed to design a methodology for the brain-body interaction in which phasic and tonic control are well reconciled.

To tackle this problem, we focus on serpentine locomotion, the reasons of which can be summarized as follows: First, since snakes locomote under various environments with nicely changing its shape and stiffness [11], it is expected that there exists a reasonable and universal principle concerning the brain-body interaction. Second, since the structure of

---

T. Kano and T. Sato are with Department of Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan {`kano`, `tsato`}`@cmplx.ecei.tohoku.ac.jp`

R. Kobayashi is with Department of Mathematical and Life Sciences, Hiroshima University, Higashi Hiroshima 739-8526, Japan, and is also with Japan Science and Technology Agency, CREST, Sanban-cho, Chiyoda-ku, Tokyo, 102-0075, Japan `ryo@math.sci.hiroshima-u.ac.jp`

A. Ishiguro is with Department of Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan, and is also with Japan Science and Technology Agency, CREST, Sanban-cho, Chiyoda-ku, Tokyo, 102-0075, Japan `ishiguro@ecei.tohoku.ac.jp`

978-1-4244-6676-4/10/$25.00 ©2010 IEEE

the body is relatively simple compared with higher organisms, it is tractable to model its dynamical behavior. As described above, we have already developed the serpentine robot which incorporates the phasic control [10]. In this paper, we will model serpentine locomotion by implementing both the phasic and tonic control, through which we aim to construct a systematic design methodology for the brain-body interaction.

The remainder of this paper is structured as follows. In section II, we will review the design methodology of the serpentine robot we have developed so far [10]. Section III explains the model that describes the serpentine locomotion in which the phasic control and tonic control are well reconciled. Section IV presents simulation results that ensure the validity of the proposed model. In section V, the conclusions and recommendations for future works are shown.

II. PREVIOUS STUDY

We will briefly review the design methodology of the serpentine robot we have developed so far [10]. A schematic of the robot is shown in Figs. 1 and 2. The robot consists of multiple homogeneous body segments that are concatenated one dimensionally via the joints, and each joint is driven by a motor positioned there. The robot locomotes on a flat terrain by lateral undulation, in which waves of lateral bending of the body are propagated from the head to tail. For effectively generating a propulsion force, passive wheel is attached on each segment so that the ground friction becomes relatively low along the longitudinal direction compared to the latitudinal direction.

Coupled oscillators are introduced as the control system, and the target angle on each joint is determined according to the phase of the oscillator. An elastic element is installed at each joint, which produces the discrepancy between the control and mechanical systems. The discrepancy is extracted based on locally-available information, which is fed back into the oscillator to modify its phase so that the discrepancy is reduced. By introducing this local sensory feedback, the robot could locomote under different ground frictions adaptively with changing its shape. However, its adaptability to environmental changes was still limited.

III. SERPENTINE ROBOT MODEL

A. Design concept

We will explain the design concept of the model using Fig. 3. This figure schematically shows the possible roles of the control and mechanical systems that contribute to the generation of locomotive behavior, where the slide bar points the contribution ratio of the control system to the mechanical system. Although the contribution of the control system dominates that of the mechanical system in most of robots developed so far, such design methodology does not ensure the adaptability to environmental changes, because of the limitation of physical resources in the mechanical system. To generate adaptive behaviors, the control system and the mechanical system should not be in "master-slave" relation, but should interact each other. Namely, the control system should leave a certain amount of its functional role to the mechanical system. This means that the slide bar should be in the region surrounded by the dashed lines in Fig. 3.

The local sensory feedback introduced in our previous study [8], [9], [10] shifted the slide bar to the right because the discrepancy was reduced through the modification of the phases of oscillators in the control system. However,

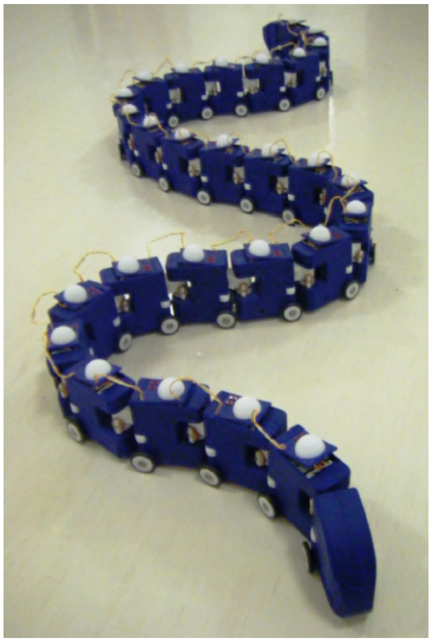

Fig. 1. Serpentine robot developed in our previous study [10].

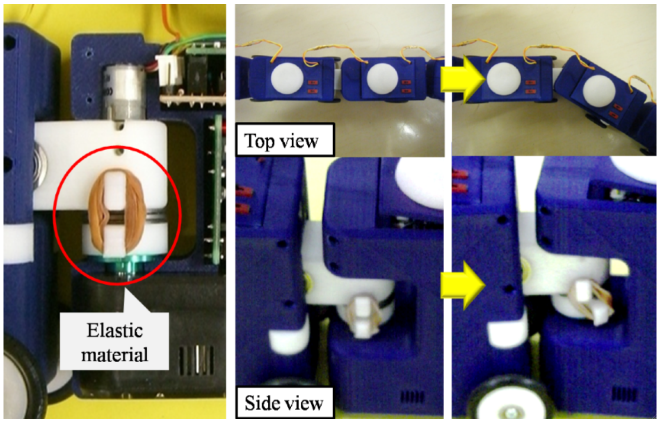

Fig. 2. Elastic material implemented on each joint of the serpentine robot developed in our previous study [10].

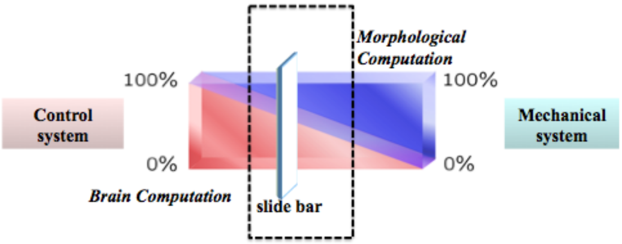

Fig. 3. Possible roles of the control and mechanical systems that contribute to the generation of locomotive behavior. The slide bar points the contribution ratio of the control system to the mechanical system.

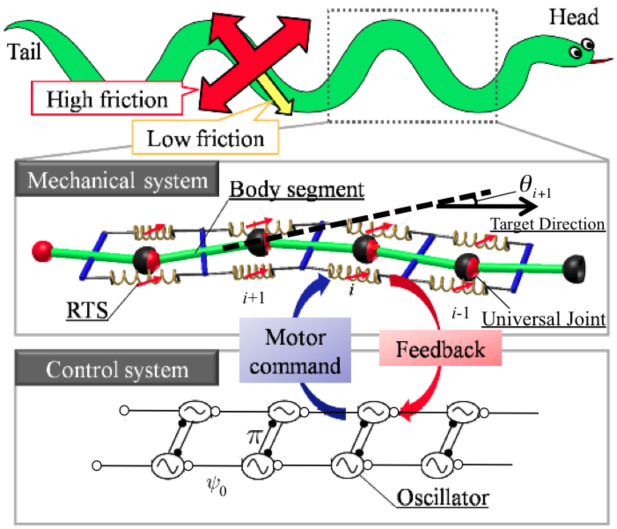

Fig. 4. Schematic illustration of control and mechanical systems. The links are connected by universal joints. Antagonistic muscles are modeled by a couple of Real-time Tunable Springs (RTSs) arranged around each joint. The CPG is described by coupled oscillators, where excitatory and inhibitory couplings are illustrated by empty and filled circles, respectively.

the previous design methodology had a problem that the controllability was lost when the slide bar was shifted to the right excessively. To solve this problem, we need to introduce a mechanism to increase the contribution of the control system, which shifts the slide bar to the left. In the following, we will show a design methodology where the contribution ratio of the control system to the mechanical system is properly adjusted by introducing the tonic control.

B. Mechanical system

The musculoskeltal system is schematically shown in Fig. 4. The skeltal system is composed of rigid links that are concatenated one dimensionally. The links are connected by universal joints, on each of which a passive rotational spring is embedded so that the body does not bend excessively. Antagonistic muscles are modeled by a couple of Real-time Tunable Springs (RTSs) arranged around each joint. Here, RTS is a spring whose natural lengths can be changed in an arbitrary manner, and thus, it contains not only passive but also active mechanical feature [9]. The force exerted by the RTS attached on the ith joint $F_{i,p}$, where $p = 0$ and 1 denote the left and right side, respectively, is expressed as follows:

$$F_{i,p} = \frac{\alpha}{\bar{l}_{i,p}}(l_{i,p} - \bar{l}_{i,p}), \tag{1}$$

where $l_{i,p}$ and $\bar{l}_{i,p}$ are the actual length and natural length of the RTS, respectively. $\alpha/\bar{l}_{i,p}$ is the spring constant of the RTS, where α is a constant given by the material and geometric property of the RTS. Thus, the muscle tonus is well described by the natural length of the RTS, because the spring constant becomes large as the natural length becomes short. Since forces generated by RTSs on both sides of a joint act antagonistically, difference torque acts on the joint, which produces undulation of the body.

The ground frictional force acts to the joints. Although real snake lifts its body at its flexions called "sinus lifting" [11], we assume that the joints contact the ground uniformly, for simplicity. For effectively generating a propulsion force, we assume that the ground friction is relatively low along the forward direction compared with those along the lateral and backward directions, as shown in Fig. 4. Note that this assumption is based on anatomical knowledge [11].

C. Control system

The control system is composed of distributed neural network *i.e.*, CPG. The network topology of the CPG is illustrated in Fig. 4. Limit cycle oscillators are arranged for each RTS. The oscillators on the contralateral side are mutually connected by inhibitory couplings. The oscillators on the ipsilateral side are unidirectionally connected from the head to tail by excitatory couplings. The dynamics of the oscillators are described using phase model as follows [12]:

$$\frac{d\phi_{i,p}}{dt} = \omega + \varepsilon_1 q(\phi_{i-1,p} - \phi_{i,p}) - \varepsilon_2 q(\phi_{i,1-p} - \phi_{i,p}) + f_{i,p}, \tag{2}$$

where $\phi_{i,p}$ is the oscillator phase of the ith joint on the pth side. ω is the intrinsic frequency, and ε_1 and ε_2 are positive constants. The second and third terms in the right hand side denote the couplings between the nearest oscillators on the ipsilateral side and between the oscillators on the contralateral side, where $q(\cdot)$ is the coupling function which characterizes the way of interaction between the oscillators. By considering the first-order Fourier component, for simplicity, the coupling function is described as

$$q(\psi) = \sin(\psi - \psi_0), \tag{3}$$

where ψ_0 is a constant. $f_{i,p}$ is a "phasic feedback" term which we will describe below. Note that the phase differences between the ipsilateral oscillators and between the contralateral oscillators are entrained to ψ_0 and π, respectively, in the absence of the phasic feedback term.

D. Brain-body interaction

The way of the brain-body interaction is schematically shown in Fig. 4. The mechanical system is driven by the motor command from the control system, which is modeled by active changes of the natural lengths of the RTSs. The natural length of the ith RTS on the pth side is set as follows:

$$\begin{aligned} \bar{l}_{i,p} &= a\cos\phi_{i,p} + b - g_{i,p} + (-1)^p c\theta_i \qquad (i \le n_{cont}), \\ \bar{l}_{i,p} &= a\cos\phi_{i,p} + b - g_{i,p} \qquad (i > n_{cont}), \end{aligned} \tag{4}$$

where a, b, and c are positive constants. Note that the natural length cannot be shorter than the minimum length l_{min}, because it is plausible to assume the existence of maximum muscle tonus. The natural length oscillates according to the periodic change of the phase ϕ_i, which produces lateral undulation. $g_{i,p}$ is a "tonic feedback" term which we will describe later. $(-1)^p c\theta_i$ is a term contributing to the direction control, which is introduced to only several joints in the head part so that the moving axis is slightly adjusted to the target direction, where θ_i is the angle between the target direction and the direction of the link that connects the ith and $i+1$th joints (see Fig. 4) and n_{cont} is the number of joints to which the direction control signal is applied from the brain. It should be noted that this direction control is the only mechanism the mechanical system is controlled in a centralized manner. Except the direction control, the motor command from the control system is applied fully in a decentralized mannner.

Although the control system drives the mechanical system, the mechanical system does not completely follow the motor command from the control system but is somewhat influenced by the surrounding environment owing to the elasticity of the RTSs. As a consequence, the discrepancy between the control and mechanical systems arises. To characterize the extent of the discrepancy, we introduce the discrepancy function $I_{i,p}$ which is composed of locally-available sensory information. Here, we define $I_{i,p}$ as

$$I_{i,p} = |F_{i,p}|. \tag{5}$$

Note that (5) contains an information about the extent of the discrepancy, because $F_{i,p}$ is proportional to the difference between $l_{i,p}$ and $\bar{l}_{i,p}$ which reflect the states of the mechanical and control systems, respectively, as shown in (1).

The phasic feedback term $f_{i,p}$ in (2) is defined using the discrepancy function as

$$f_{i,p} = -\rho_P \frac{\partial I_{i,p}}{\partial \phi_{i,p}}, \tag{6}$$

where ρ_P is a parameter which characterizes the magnitude of the phasic feedback. Due to this local sensory feedback, the discrepancy is reduced through phase modulation. Note that the concept of this feedback is the same as our previous studies [8], [9], [10].

On the other hand, the "tonic feedback" term $g_{i,p}$ is given by the time integral of the discrepancy function, that is,

$$g_{i,p}(t) = \rho_T \int_{-\infty}^{t} dt' I_{i,p}(t') e^{-(t-t')/\tau} \tag{7}$$

where ρ_T is a parameter which characterizes the magnitude of the tonic feedback. τ is the effective duration the discrepancy is integrated. Since the spring constant of the RTS increases as the natural length decreases, the increase of discrepancy induces gradual increase of the muscle tonus via the increase of $g_{i,p}$.

E. Key Points of the Model

The key points of the model proposed above are summarized as follows: First, we have purposefully implemented a "compliant" mechanism to produce the discrepancy between the control and mechanical systems by employing RTS, which works not only as an actuator but also as a passive element. Owing to this passivity, the RTS deforms in way favorable to the motion underway, which leads to inform how the robot and its environment are interacting each other. In sum, this compliant mechanism allows the robot to exploit "active perception" or "sensory-motor coordination" [13].

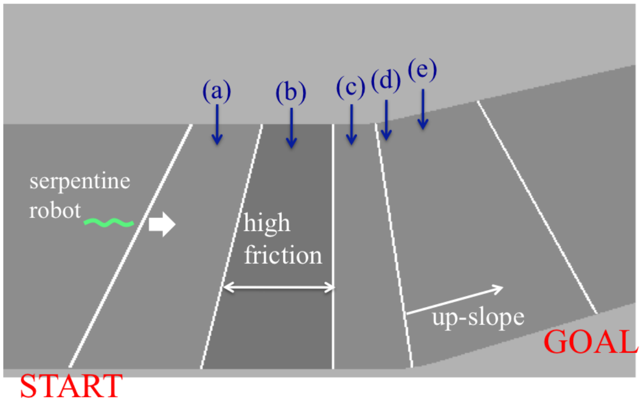

Fig. 5. Overview of course used in the simulation. The serpentine robot locomotes from the left to right. The ground friction is expressed by the darkness of the ground color. Notations (a)-(e) correspond to those in Fig. 6.

Second, we have implemented not only phasic but also tonic feedback control to reduce the discrepancy. The phasic feedback control modifies the dynamics of the control system so that the force generated at the RTS decreases. Although the energy consumption is reduced and supple locomotion is obtained by applying the phasic control, the phasic control itself cannot provide the robot rich adaptability under tough conditions such as the locomotion on an up-slope. On the other hand, the tonic feedback control allows the control system to dominate the mechanical system by increasing the stiffness of RTSs, which enables to produce "force-utilizing" locomotion. Thus, efficient locomotion can be realized by properly reconciling the phasic and tonic control.

IV. SIMULATION RESULTS

We have conducted simulations to verify the validity of the model proposed above. To investigate the adaptability to environmental changes, we have set a simulation course which contains high frictional terrain and up-slope, as shown in Fig. 5. The frictional coefficients to the backward and lateral directions are set to be 8 times larger than that to the forward direction. Those frictional coefficients at the high frictional terrain are set to be 4 times larger than those at the normal terrain. The slope angle is set at 14.6°. The other parameter values employed in the simulations are listed on Table I.

Fig. 6 illustrates the snapshots of the robot in the cases (i) without feedback control, (ii) with only the phasic feedback control, (iii) with only the tonic feedback control, and (iv)

TABLE I

PARAMETER VALUES EMPLOYED IN THE SIMULATIONS.

parameter	value	parameter	value
ω	0.2	ε_1	0.2
ε_2	0.1	ψ_0	0.38
a	1.15	b	6.91
c	0.69	τ	20.0
α	360.0	l_{min}	5.30
n_{cont}	3		

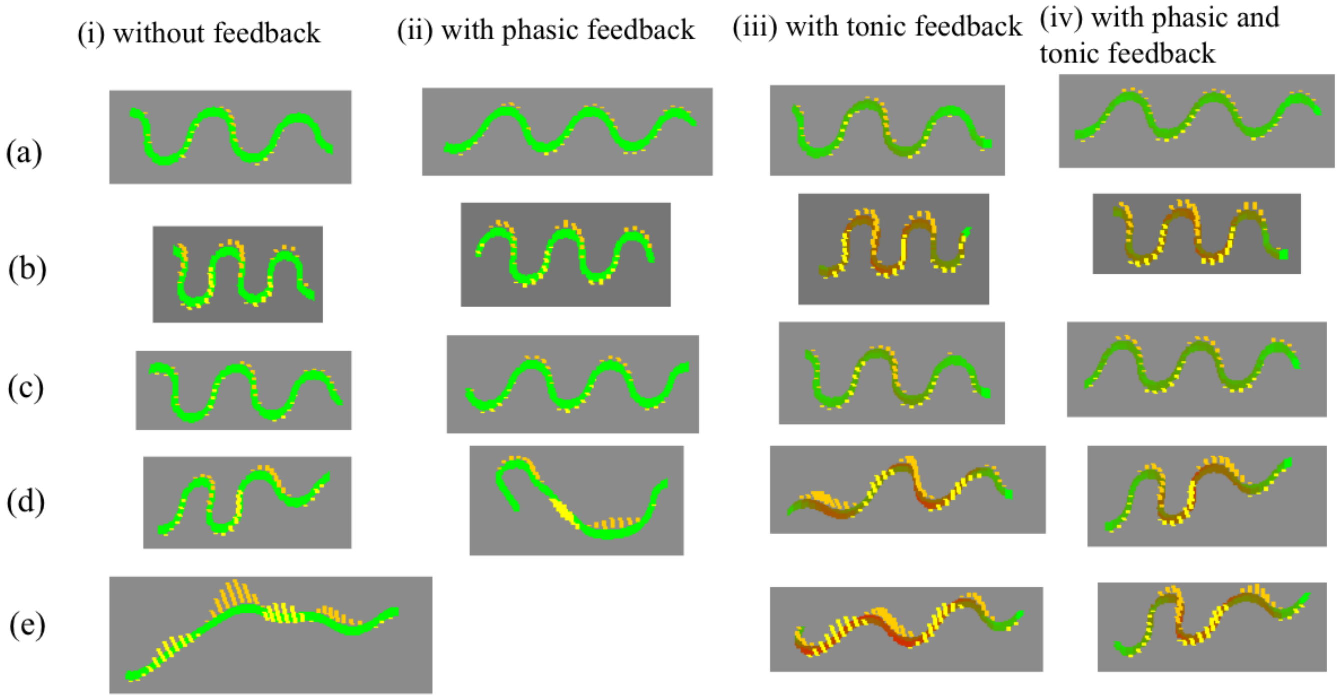

Fig. 6. Snapshots of a serpentine robot in the cases (i) without feedback control ($\rho_P = 0$ and $\rho_T = 0$), (ii) with phasic feedback control ($\rho_P = 0.0012$ and $\rho_T = 0$), (iii) with tonic feedback control ($\rho_P = 0$ and $\rho_T = 0.008$), and (iv) with phasic and tonic feedback control ($\rho_P = 0.0012$ and $\rho_T = 0.008$). The head is to the right. The color of the robot expresses the muscle tonus: it is red when $g_{i,p}$ is large. The yellow and orange bars indicate the contraction force generated at RTSs on the right and left side, respectively. Notations (a)-(e) correspond to those in Fig. 5.

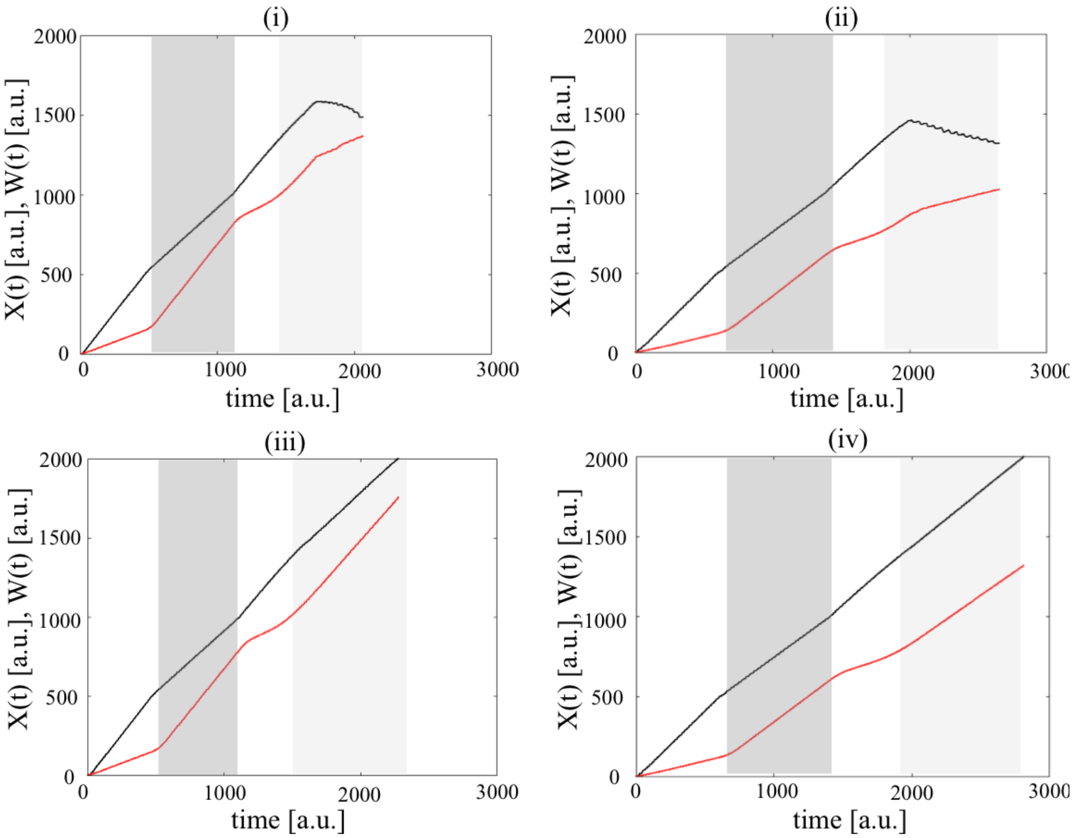

Fig. 7. Time evolutions of $X(t)$ (black line) and $W(t)$ (red line) in the cases (i) without feedback control ($\rho_P = 0$ and $\rho_T = 0$), (ii) with phasic feedback control ($\rho_P = 0.0012$ and $\rho_T = 0$), (iii) with tonic feedback control ($\rho_P = 0$ and $\rho_T = 0.008$), and (iv) with phasic and tonic feedback control ($\rho_P = 0.0012$ and $\rho_T = 0.008$). Dark and light gray regions express the regions where the head of the robot is on the high frictional terrain and on the up-slope, respectively.

with both the phasic and tonic feedback control. In all of these cases, the robot passes through the high frictional terrain with changing the waveform in its body (Figs. 6(i)-(iv)(b)); however, without the tonic control, it cannot keep undulation of the body on the up-slope (Fig. 6(i)(e) and (ii)(d)) and finally stops its locomotion. With the tonic control, muscle tonus increases on the high frictional terrain (Fig. 6(iii)-(iv)(b)) and on the up-slope (Figs. 6(iii)-(iv)(d), (iii)-(iv)(e)); consequently, the robot can keep its locomotion. Compared with the case with only the tonic feedback (case (iii)), the increase of the muscle tonus is relatively small in the case with both the phasic and tonic control (case (iv)).

To evaluate the locomotive behavior quantitatively, we have defined two variables, $X(t)$ and $W(t)$: $X(t)$ is the distance the robot locomoted and $W(t)$ is the total work needed to change the natural lengths of RTSs. Note that $W(t)$ means the work done from the control system to the mechanical system, which is almost equivalent to the energy consumed during locomotion.

Fig. 7 shows the time evolutions of $X(t)$ and $W(t)$ for the cases (i)-(iv). Without the tonic control (cases (i) and (ii)), the increase of $X(t)$ ceases when the robot is on the up-slope, which is followed by its gradual decrease; thus, the robot cannot clime the up-slope. The increase of $W(t)$ is smaller for the case (ii) than for the case (i), which owes to the phasic feedback control. With the tonic control (cases (iii) and (iv)), the increase rate of $X(t)$ remains almost constant even when the environment changes; thus, the robot can keep its locomotion under various environments owing to the tonic feedback control. Further, we notice that the increase rate of $W(t)$ is smaller for the case (iv) than for the case (iii), which means that the energy consumption is reduced due to the phasic feedback control. In sum, adaptive and efficient locomotion can be realized by reconciling the phasic and tonic feedback control.

V. CONCLUSION AND FUTURE WORK

In this paper, we developed an autonomous decentralized control scheme where phasic control and tonic control are well reconciled, by taking serpentine locomotion as a practical example. Simulation results showed that highly adaptive behavior emerged spontaneously without centralized control mechanism except the direction control, and that supple and efficient locomotion can be successfully realized by properly reconciling the phasic and tonic control.

In order to verify the validity of the proposed design scheme, we plan to develop a serpentine robot and conduct experiments in the real world. We also endeavor to further elaborate the design methodology of an autonomous decentralized control. Date and Takita have recently shown by theoretical and experimental studies that efficient serpentine locomotion can be realized by applying torque proportional to the curvature derivative of the body curve [14]. It is of significant interest to clarify how such “reflexive” control and the CPG-based control proposed in this study are coupled so as to produce adaptive locomotion.

ACKNOWLEDGMENTS

We thank Dr. Toshiyuki Nakagaki of Future University of Hakodate for their insightful suggestions.

REFERENCES

[1] S. Grillner, O. Ekeberg, A. Manira, A. Lansner, D. Parker, J. Tegner and P. Wallen, Intrinsic function of a neuronal network - a vertebrate central pattern generator, *Brain Res. Reviews*, vol. 26, pp. 184-197, 1998.

[2] H. Kimura, Y. Fukuoka and H. Nakamura, “Biologically inspired adaptive dynamic walking of the quadruped on irregular terrain”, *in Proc. of ISRR99*, pp. 271-278, 1999.

[3] H. Kimura, S. Akiyama and K. Sakurama, Realization of Dynamic Walking and Running of the Quadruped Using Neural Oscillator, *Autonomous Robots*, vol. 7, no. 3, pp. 247-258, 1999.

[4] G. Taga, Y. Yamaguchi and H. Shimizu, Self-organized control of bipedal locomotion by neural oscillators, *Biol. Cybern.*, vol. 65, pp. 147-159, 1991.

[5] G. Taga, Emergence of bipedal locomotion through entrainment among the neuro-musculo-skeletal system and the environment, *Physica D: Nonlinear Phenomena*, vol. 75, no. 1-3, pp. 190-208, 1994.

[6] G. Taga, A model of the neuro-musculo-skeletal system for human locomotion - II. Real-time adaptability under various constraints, *Biol. Cybern.*, vol. 73, pp. 97-111, 1995.

[7] A. Takamatsu, R. Tanaka, H. Yamada, T. Nakagaki, T. Fujii and I. Endo, Spatio-temporal symmetry in rings of coupled biological oscillators of Physarum plasmodium, *Phys. Rev. Lett.*, vol. 87, pp. 0781021-4, 2001.

[8] R. Kobayashi, A. Tero and T. Nakagaki, Mathematical model for rhythmic protoplasmic movement in the true slime mold, *J.Math.Biol.*, vol. 53, pp. 273-286, 2006.

[9] T. Umedachi, K. Takeda, T. Nakagaki, R. Kobayashi, and A. Ishiguro, Fully Decentralized Control of a Soft-bodied Robot Inspired by True Slime Mold, *Biological Cybernetics*, vol. 102, pp. 261-269, 2010.

[10] T. Sato, W. Watanabe, and A. Ishiguro, An Adaptive Decentralized Control of a Serpentine Robot Based on the Discrepancy between Body, Brain and Environment, *2010 IEEE International Conference on Robotics and Automation (ICRA2010)*, pp. 709-714, 2010.

[11] S. Hirose, Biologically Inspired Robots (Snake-like Locomotor and Manipulator), Oxford University Press, 1993.

[12] Y. Kuramoto, Chemical oscillations, Waves, and Turbulence. Springer-Verlag, Berlin, 1984.

[13] R. Pfeifer and C. Scheier, Understanding Intelligence, MIT Press, 1999.

[14] H. Date and Y. Takita, An Electricity-Free Snake-Like Propulsion Mechanism Driven and Controlled by Fluids, *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2009)*, pp. 3637-3642, 2009.