Decentralized Control Mechanism Underlying Interlimb Coordination of Centipedes

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1 Introduction

Centipedes can walk in unstructured environments by coordinating their numerous legs. This adaptive locomotion is achieved by propagating leg density waves along the body axis [1]. It is also known that this form of leg density waves varies according to circumstances, such as changes in walking speed [2]. Hence, there might exist ingenious control mechanisms for the interlimb coordination of centipedes, and clarifying this would help enhance the adaptability of legged robots and provide new insights into biology.

The key to understanding this control mechanism is autonomous decentralized control, in which the nontrivial macroscopic behavior of an entire system emerges through the coordination of simple individual components. In fact, several decentralized control schemes for the interlimb coordination of myriapods have been proposed [3, 4]. Although the control schemes proposed in these studies contributed to the adaptability enhancement of myriapod robots, they could not sufficiently reproduce the adaptive locomotion of real myriapods. Hence, the decentralized control mechanism underlying adaptive centipede locomotion remains elusive.

To tackle this problem, we employed a synthetic approach in which a mathematical model is constructed on the basis of behavioral experiments using real centipedes. We previously observed the response when part of the terrain was removed during locomotion. We found that the legs over the gap stop periodic movement and remain at certain positions, while the other legs continue to move periodically [5]. However, the proposed model based on this finding could not fully reproduce the innate behavior. Accordingly, here, we reconsidered the results of the behavioral experiment above and constructed a new mathematical model. We performed simulations by using the proposed control scheme, and succeeded in reproducing behavior that was qualitatively equivalent to the real centipedes.

2 Behavioral experiment

We reconsider the behavioral experiment conducted in our previous study [5], in which centipede locomotion on terrain with a gap was observed. The experiment investigated the effects of leg-ground contact on centipede locomotion. With regard to the result shown in Fig. 1, we found the following qualitative behavior:

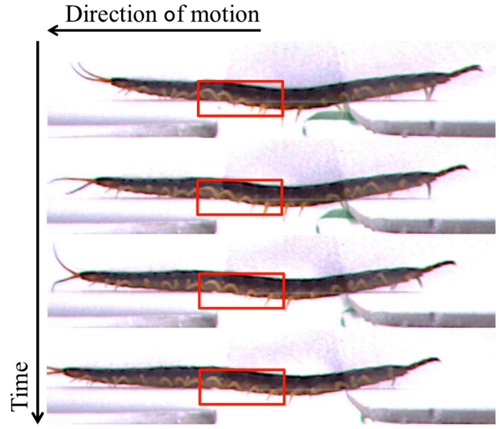

Figure 1: Snapshots of centipede locomotion on terrain with a gap. Red squares denote the resting legs.

(A) The legs over the gap stop periodic movement and remain at higher positions, while the other legs continue to move periodically.
(B) The resting legs over the gap start to move periodically again when their anterior legs touch the ground.

3 Model

3.1 Physical model

As we described in our previous study [5], we simply modeled the body two dimensionally, that is, each segment has only one leg (Fig.2). The body trunk consists of mass points connected one dimensionally via rigid links. Each leg has a mass at its tip and is connected to the body trunk via a parallel combination of a real-time tunable spring (RTS) and a damper, where the RTS is a spring whose natural length can be actively changed [6]. As shown in Fig. 3, a phase oscillator is implemented in each leg, and the leg trajectory is controlled according to the oscillator phase. The leg tends to be in the swing and stance phases when the oscillator phase is between 0 and π, and between π and 2π, respectively.

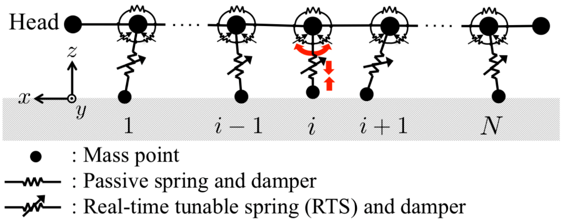

Figure 2: Schematic of the physical model.

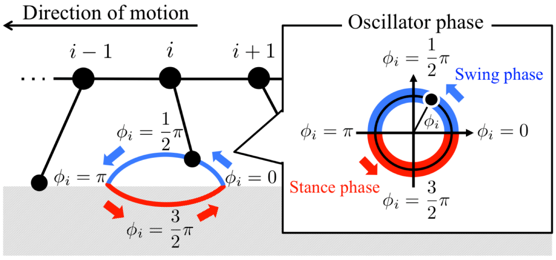

Figure 3: Relationship between oscillator phase and leg trajectory.

3.2 Control Scheme

Here, we propose a control scheme for interlimb coordination based on the behavioral experiment. The time evolution of the oscillator phase is described as follows:

$$\dot{\phi}_i = \omega + (a - \sigma_1 \tilde{N}_i(t) - \sigma_2 \tilde{N}_{i-1}(t))\cos\phi_i, \tag{1}$$

$$\tilde{N}_i(t) = \frac{1}{\tau}\int_0^{\infty} \mathrm{e}^{-\frac{T}{\tau}} N_i(t-T)dT. \tag{2}$$

Here, ϕ_i is the phase of ith oscillator, ω is the intrinsic angular velocity, a, σ_1, σ_2 are positive constants, and $a > \omega$. $N_i(t)$ is the ground reaction force acting on the ith leg at the time t. τ is time constant. As we defined in eq. (2), we assume that centipedes exploit the ground reaction forces with a time delay.

The physical meaning of Eqs.(1)–(2) is explained as follows. When a leg (ith leg) and its anterior leg ($i-1$th leg) are over the gap, $N_i = N_{i-1} = 0$ and both $\tilde{N}_i$ and $\tilde{N}_{i-1}$ converge to zero as time passes. If $\omega < a - \sigma_1\tilde{N}_i - \sigma_2\tilde{N}_{i-1}$, $\dot{\phi}_i = 0$ has two solutions, where one is stable and the other is unstable. Thus, the leg tends to stay at the position corresponding to the stable solution [Fig. 4(a)]. On the other hand, when a leg or its anterior leg makes contact with the ground and the ground reaction forces (N_i, N_{i-1}) increase, it becomes $\omega > a - \sigma_1\tilde{N}_i - \sigma_2\tilde{N}_{i-1}$ and the stable and unstable solutions disappear. Then, the leg starts to move periodically [Fig. 4(b)].

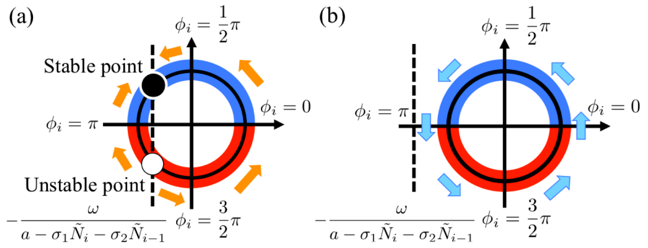

Figure 4: Schematic of ith leg's phase in the proposed control scheme: (a) without ground contact, (b) with ground contact.

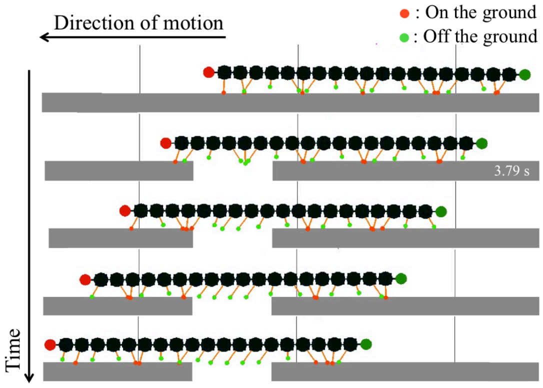

Figure 5: Simulated centipede's walk by the proposed control scheme on terrain with a gap.

4 Simulation Result

We conducted simulations to verify the validity of the proposed control scheme. The parameter values employed in the simulations are as follows: $\omega = 19.76[\mathrm{s}^{-1}]$, $\tau = 0.20[\mathrm{s}]$, $a = 25.67[\mathrm{s}^{-1}]$, $\sigma_1 = 3.06 \times 10^3[\mathrm{kg}^{-1}\mathrm{m}^{-1}\mathrm{s}]$, $\sigma_2 = 2.45 \times 10^3[\mathrm{kg}^{-1}\mathrm{m}^{-1}\mathrm{s}]$. The time step in the simulations is set to $1.26 \times 10^{-5}[\mathrm{s}]$. All the legs are perpendicular to the body trunk, and their phases are set to $3\pi/2$ in the initial condition.

We examined the locomotion on terrain with a gap. More specifically, a part of the terrain was removed at 3.79 s. Fig. 5 shows snapshots of the simulation results. At the beginning of the experiment, the simulated centipede formed leg density waves that propagated backward. After part of the terrain was removed, the legs over the gap stopped periodic movement and remained at a higher position, while the other legs continued to move periodically. Thus, our proposed model could reproduce the qualitative behavior observed in the behavioral experiment.

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