Decentralized Control of an Earthworm-like Robot That Fully Exploits Mechanical Interaction

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Abstract: To clarify the mechanism of mechanical interaction between individual components of a body, which contributes to the emergence of animal behavior, we focus on the locomotion of an earthworm. We theoretically analyze the locomotion of earthworms on the basis of a continuum model, and we derive the optimal force distribution that enables efficient locomotion. We propose a decentralized control scheme on the basis of the optimal force distribution, and we verify its validity through simulations.

Keywords: Autonomous decentralized control, Earthworm, Continuum model

1. INTRODUCTION

Animals exhibit adaptive and efficient locomotion in real time under unpredictable real-world constraints. A key mechanism underlying such functionality of animals is autonomous decentralized control, whereby nontrivial macroscopic behavior or functionality emerges through coordination between simple individual components. Thus, autonomous decentralized control is expected to be employed as a useful tool for designing robots that are as intelligent as animals.

The design of the interaction between individual components is an important issue for the development of robots based on autonomous decentralized control. The interaction can be designed in two forms: informational (neural) interaction and mechanical interaction. The former has been systematically studied on the basis of coupled-oscillator systems [1], whereas the latter has been designed on an ad-hoc and tailor-made basis for specific applications, although this approach can lead to the emergence of highly adaptive and efficient behavior as a consequence of interaction between the body and the environment [2]. Thus, we need to establish a systematic method for designing the mechanical interaction on the basis of a suitable model of a living organism.

To address this issue, we focus on an earthworm, which locomotes by propagating waves of bodily contractions from the head to the tail. Because this wave propagation is significantly slower than neuronal signal propagation, the mechanical interaction in an earthworm is expected to be governed by an inherent autonomous decentralized control mechanism. In this study, we analyze the locomotion of earthworms on the basis of a continuum model that was previously developed for snake locomotion [3], and we derive the optimal force distribution for efficient locomotion. We propose an autonomous decentralized control scheme on the basis of this result, and we verify its validity through simulations.

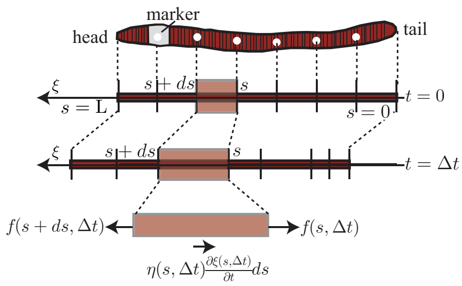

Fig. 1 Schematic illustration of continuum model of an earthworm.

2. CONTROL SCHEME BASED ON THEORETICAL ANALYSES

The adopted model is shown in Fig. 1. The body consists of a continuous line of length L. Forces of compression and tension can be actively generated in each section of the body; according to these forces and ground frictional forces, which we will describe later, each section of the body contracts or extends. Here, we disregard the viscoelasticity of the body for simplicity. The body is parameterized by the arc length s, which is defined as the distance of a point from the tail end when the body does not contract or extend. $\xi(s, t)$ denotes the absolute coordinate of the point expressed by the arc length s at time t. The actively generated forces of compression and tension are denoted by $f(s, t)$, where the tensional force is taken as positive. The ground friction is modeled by the viscous friction; the coefficient of the viscous friction, $\eta(s, t)$, is assumed to vary depending on the rate of expansion and contraction as follows:

$$\eta(s, t) = \frac{1}{au(s, t) - b}, \tag{1}$$

where a and b are positive constants, and $u(s, t)$ is the ratio of expansion to contraction.

Under the assumption that the inertia of the body is negligible, the force-balance equation in each section of the body is expressed as follows:

$$\eta(s, t)\frac{\partial \xi(s, t)}{\partial t} = \frac{\partial f(s, t)}{\partial s}. \tag{2}$$

From Eqs. (1) and (2), the velocity of the center of mass v_g is given as follows:

$$v_g = \frac{1}{L}\int_0^L \frac{\partial \xi(s,t)}{\partial t} ds, = \frac{1}{L}\int_0^L (au(s,t)-b)\frac{\partial f(s,t)}{\partial s} ds. \quad (3)$$

When we assume that the body does not generate forces at the head and tail ends, *i.e.*, $f(0,t) = f(L,t) = 0$, Eq. (3) can be rewritten as

$$v_g = -\frac{a}{L}\int_0^L \frac{\partial u(s,t)}{\partial s} f(s,t) ds. \quad (4)$$

Now, we derive the optimal force distribution for efficient locomotion of an earthworm. It can be obtained by deriving the functional form of $f(s,t)$ that maximizes v_g under the following isoperimetric condition:

$$\int_0^L f^2(s,t) ds = c_1^2, \quad (5)$$

where c_1 is a positive constant. Using the Lagrange multiplier method, we obtain

$$f(s,t) = -\frac{c_1}{\sqrt{\int_0^L \left(\frac{\partial u(s,t)}{\partial s}\right)^2 ds}} \frac{\partial u(s,t)}{\partial s}. \quad (6)$$

Thus, to maximize v_g, $f(s,t)$ needs to be proportional to $\partial u(s,t)/\partial s$. This result would suggest that an earthworm locomotes efficiently when it generates a force proportional to the derivative of the ratio of expansion to contraction.

Next, we propose an autonomous decentralized control scheme that would enable an earthworm-like robot to realize efficient locomotion. The body of the robot consists of N links concatenated one-dimensionally. Each link can actively generate forces of compression and tension, through which it contracts and extends. The frictional coefficient of each link decreases as it extends. Except for the link at the head end whose length can be manipulated by the robot controller, the force generated by the ith link from the head end, f_i (tensional force is taken as positive), is designed on the basis of the theoretical result derived above. By replacing $\partial u(s,t)/\partial s$ with $u_{i-1} - u_i$, where u_i is the ratio of expansion to contraction of the ith link, f_i is designed as

$$f_i = -k(u_{i-1} - u_i), \quad (7)$$

where k is a positive constant. By employing this design scheme, efficient locomotion can be realized on the basis of autonomous decentralized control.

3. SIMULATION RESULTS

We performed simulations on the basis of the autonomous decentralized control scheme proposed in the previous section. We designed u_1 of the first link from the head end as follows:

$$u_1 = \mathrm{A}\sin\omega\mathrm{t} + \mathrm{B}, \quad (8)$$

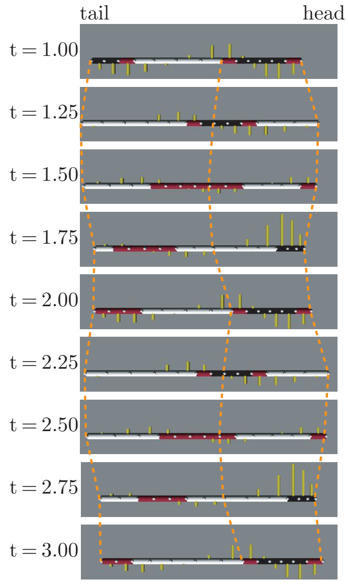

Fig. 2 Snapshots of simulation results. The color of the body is black, red, and white when $u_i < 0.9$, $0.9 \leq u_i \leq 1.1$, and $u_i > 1.1$, respectively. The yellow bars indicate the value of f_i (upper bars indicate positive values). The dotted lines track the 1st, 7th, and 14th body segments.

where A and B are positive constants, and ω is the angular frequency. Fig. 2 shows the snapshots of simulation results. We find that the robot locomotes by propagating waves of bodily contractions from the head to the tail. This result is qualitatively in good agreement with the locomotion of real earthworms.

4. CONCLUSION

To clarify the mechanism of mechanical interaction between individual components of the body, which contributes to the emergence of adaptive behavior, we focused on the locomotion of an earthworm. We theoretically analyzed the locomotion of earthworms on the basis of a continuum model, and we derived an optimal force distribution that enables efficient locomotion. On the basis of this result, we proposed an autonomous decentralized control scheme for the efficient locomotion of an earthworm-like robot, whereby a force proportional to the derivative of the ratio of expansion to contraction is generated. The results showed that the robot locomoted efficiently.

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