# Decentralized Control of Earthworm-like Robot Based on *Tegotae* Function

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## 1 Introduction

Earthworms can move on unstructured terrain by propagating bodily waves of contraction and expansion from head to tail with contracted parts anchored to the ground (Fig. 1) [1]. This locomotion has attracted the attention of engineers because earthworm-like robots can be used in areas where legged or wheeled robots are unable to function properly, such as disaster areas and lumen in human body. Accordingly, several extant studies focused on developing earthworm-like robots in recent years [2–5].

With respect to the above-described applications, it is desirable that earthworm-like robots have adaptability and fault tolerance. A key to satisfy these requirements is related to an autonomous decentralized control in which a non-trivial macroscopic function emerges through the interaction of individual components. However, the above requirements were not ensured sufficiently in the previous studies, and this indicates that there is scope for further improvement in terms of control schemes.

In this study, a decentralized control scheme for earthworm-like robots was proposed by focusing on *Tegotae*, which is a Japanese concept that describes the extent to which a perceived reaction matches an expectation [6–8]. Specifically, a *Tegotae* function that quantifies *Tegotae* was defined, and a control scheme in which *Tegotae* is increased at each body part was designed. The proposed control scheme was validated via simulations.

## 2 Model

The mass points are concatenated one-dimensionally via parallel combinations of dampers and real-time tunable springs (RTSs) (Fig. 2). An RTS is a spring in which the resting length can be changed arbitrarily [9]. The resting and real length of the RTS that connects the $i$th and $i+1$th mass points are denoted by $\bar{l}_{i+\frac{1}{2}}$ and $l_{i+\frac{1}{2}}$, respectively.

The friction between the mass points and the ground is described as viscous friction, and the friction coefficient of the $i$th mass point, $\eta_i$, is given by $\eta_i = b/\tilde{l}_i^n$, where $\tilde{l}_i = (l_{i+\frac{1}{2}} + l_{i-\frac{1}{2}})/2$, and $b$ and $n$ denote positive constants. Thus, the friction coefficient increases as the RTS contracts, and this mimics the property of a real earthworm (Fig. 1(a)).

An oscillator is implemented in each RTS, and the resting length of the $i+\frac{1}{2}$th RTS, $\bar{l}_{i+\frac{1}{2}}$, is determined based on the corresponding oscillator phase, $\theta_{i+\frac{1}{2}}$, as follows:

$$\bar{l}_{i+\frac{1}{2}} = L + a\sin\theta_{i+\frac{1}{2}}, \tag{1}$$

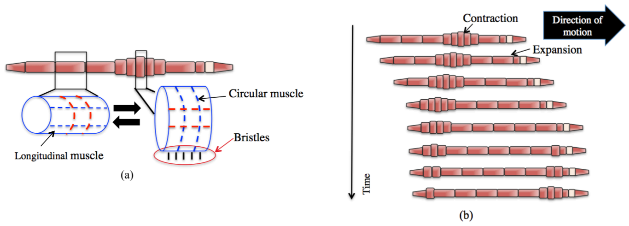


**Figure 1:** A schematic of (a) body structure and (b) locomotion.

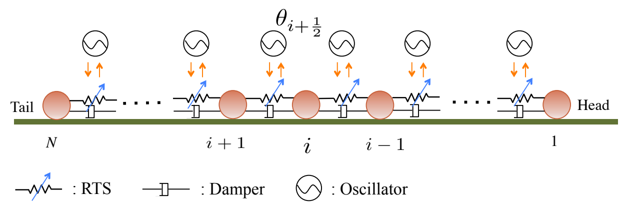


**Figure 2:** A schematic of the proposed model.

where $a$ and $L$ denote positive constants.

The time evolution of the oscillator phase is given by the following expression:

$$\dot{\theta}_{i+\frac{1}{2}} = \omega + \sigma\frac{\partial T_{i+\frac{1}{2}}}{\partial \theta_{i+\frac{1}{2}}}, \tag{2}$$

where $\omega$ denotes the intrinsic angular frequency, and $\sigma$ denotes a positive constant specifying the feedback strength. The function $T_{i+1/2}$ denotes the *Tegotae* function, and it is defined as follows:

$$T_{i+\frac{1}{2}} = -\sin\theta_{i+\frac{1}{2}} \cdot S_i, \tag{3}$$

where $S_i$ denotes the reaction force from the environment along the direction of motion. It corresponds to the shear stress acting on the body of a real earthworm (as shown in the bottom part of Fig. 3).

The meaning of the *Tegotae* function $T_{i+1/2}$ can be explained as follows. When the $i$th mass point anchors to the ground and obtains a propulsive reaction force, *i.e.*, $S_i$ is positive, it is desirable for the RTS that connects the $i$th and $(i+1)$th mass points to contract. Hence, $\bar{l}_{i+1/2}$ becomes small or $-\sin\theta_{i+1/2}$ becomes large to pull the posterior part of the body forward. Therefore, the *Tegotae* function can be defined as the product of $(-\sin\theta_{i+1/2})$ and $S_i$. The second term on the right-hand side of Eq. (2) operates such that the oscillator phase is modified to increase the *Tegotae*. Specifically, the *Tegotae*-based sensory feedback converges

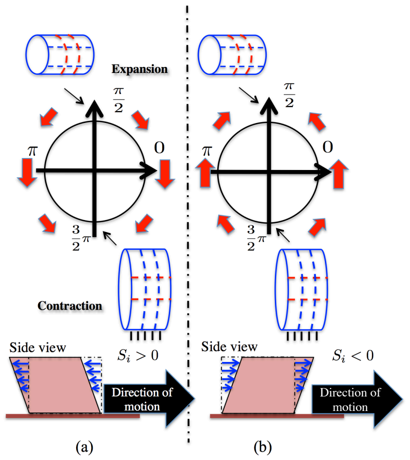


**Figure 3:** Effect of local sensory feedback: (a) $S_i > 0$ and (b) $S_i < 0$.

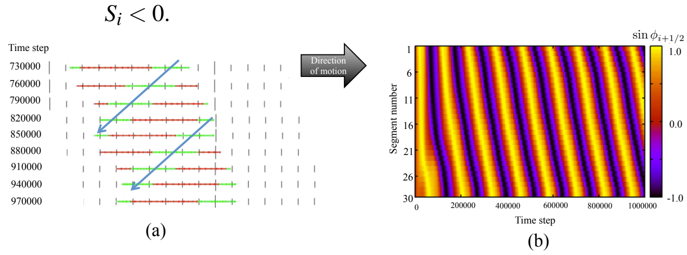


**Figure 4:** (a) Locomotion of the simulated earthworm. Contracted and expanded segments are shown in green and red, respectively. (b) The spatiotemporal plot of phase. The color indicates the value of $\sin\theta_{i+\frac{1}{2}}$.

the phase to $3\pi/2$ and $\pi/2$ when $S_i$ is positive and negative, respectively (Fig. 3).

## 3 Simulation

Simulations were conducted to validate the proposed control scheme. The parameter values were determined by trial-and-error. The initial value of $\theta_{i+\frac{1}{2}}$ $(1 \leq i \leq N-1)$ is set as 0. Figure 4 shows snapshots and the spatiotemporal plot of the phase under a uniform environment. The body effectively moved forward by propagating the wave of contraction from the head to the tail as in the case of a real earthworm immediately after the simulation commenced (Fig 4. (a)). The oscillator phase also propagated from the head to the tail (Fig. 4(b)). Figure 5 shows the result when a simulated earthworm traversed a terrain with nonuniform friction. The simulated earthworm moved effectively by exploiting high friction areas (Fig. 5(a)). The oscillator phases were modified to adapt to changes in the friction of the ground (Fig. 5(b)). Figure 6 shows the result when a few of the RTSs were replaced with passive springs to investigate the fault tolerance of the proposed control scheme. A wave of contraction was generated from the head to the tail, and it passed through the area in which the RTSs were replaced with passive springs. Thus, the adaptability and fault tolerance of the proposed scheme were confirmed.

## Acknowledgments

This work was supported by Japan Science and Technology Agency, CREST. The authors thank Prof. Yoshifumi Saijo and Hironori Chiba of the Graduate School of Biomedical Engineering, Tohoku University.

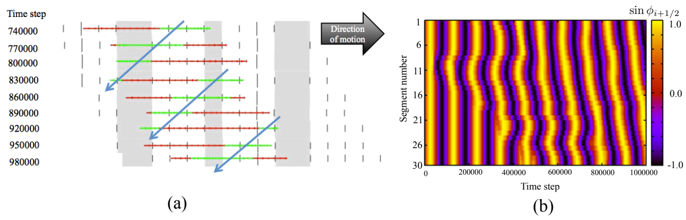


**Figure 5:** (a) Locomotion of the simulated earthworm on a terrain with nonuniform friction. Dense colors indicate high friction areas. (b) The spatiotemporal plot of phase.

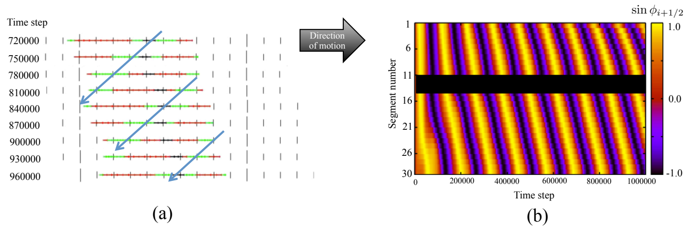


**Figure 6:** (a) Locomotion of the simulated earthworm when several RTSs are replaced by passive springs. Segments replaced by passive springs are shown in black. (b) The spatiotemporal plot of phase. The black regions represent the segments replaced by passive springs.

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