Non-trivial behaviors emerging from a simple decentralized rules (Part 1): A case study with one-dimensional crawling locomotion

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1 Introduction

In many research fields including the field of adaptive motion of animals, mathematical models have been developed to understand essential mechanisms underlying certain phenomena or to achieve certain tasks. Our approach in this study is different: we propose mathematical models that generate non-trivial behaviors just for curiosity, after which we discuss their applications.

In this study, we propose a mathematical model for one-dimensional crawling locomotion using an extremely simple decentralized control rule. We demonstrate via simulations that non-trivial macroscopic behaviors emerge in spite of its simplicity. This model was not proposed to reproduce locomotion patterns of real animals, and is not based on any biological finding. However, the emerging macroscopic behaviors are lifelike, and thus, we believe that this study helps understand the design principle of living systems at an abstract level as well as design robots that move and function like animals.

2 Model

The mass points are concatenated one-dimensionally via parallel combinations of actuators, passive springs, and dampers (Fig. 1). Mass points are numbered by i ($i = 1, 2, \cdots, N$) from the head, and the parallel combination of the actuator, passive spring, and damper that connects the ith and $(i+1)$th mass points are numbered by $i+1/2$. Each actuator can generate a contraction or expansion force. The force generated by the $(i+1/2)$th actuator is denoted by $f_{i+1/2}$.

The friction between the mass points and the ground is described as viscous friction, and the friction coefficient of the ith mass point, η_i is given by

$$\eta_i = a(x_i)\{p - q\ \mathrm{sgn}(\dot{x}_i)\}, \tag{1}$$

where x_i is the position of the ith mass point, $a(x_i)$ denotes the roughness of the ground at x_i, and p and q are positive constants satisfying $p > q$. The term $\{p - q\ \mathrm{sgn}(\dot{x}_i)\}$ means that the friction coefficient is smaller when the ith mass point moves forward ($\dot{x}_i > 0$) than when it moves backward ($\dot{x}_i < 0$).

The time evolution of the actuation force $f_{i+1/2}$ is given by the following expression:

$$\dot{f}_{i+1/2} = h \tanh\left(\sigma_1 \sum_{j=i-n_f+1}^{i} \max(S_j, 0) - \sigma_2 \sum_{j=i+1}^{i+n_b} \max(S_j, 0)\right) - \sigma_3 f_{i+1/2}, \tag{2}$$

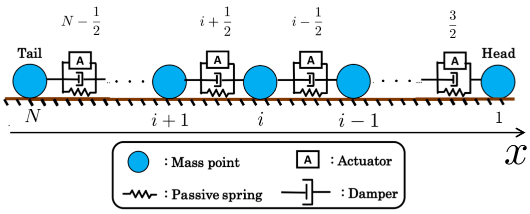

Figure 1: Schematic of the model.

where S_i denotes the reaction force from the ground along the moving direction, σ_1, σ_2, and σ_3 are positive constants, h denotes the feedback strength, and n_f and n_b denote the number of forward and backward segments, respectively, to which sensory information is fed back.

The first term on the right-hand side of Eq. (2) works as follows. When several mass points anterior to the $(i+1/2)$th actuator receive propulsive reaction forces, the $(i+1/2)$th actuator increases a contraction force so that the posterior body part is pulled forward. Meanwhile, when several mass points posterior to the $(i+1/2)$th actuator receive propulsive reaction forces, the $(i+1/2)$th actuator increases an expansion force so that the anterior body part is pushed forward. Thus, it is expected that the body can move forward effectively by exploiting the environment. In contrast, the second term on the right-hand side works to decay the actuation force; thus, waste of energy can be prevented.

3 Simulation

We performed simulations of the proposed model. Mass points were initially arranged with a distance equal to the natural length of the passive springs; exceptionally, original position of the most anterior mass point was slightly shifted to the direction of movement, because otherwise mass points did not begin moving. Parameter values shown in Table 1 were used. The roughness of the terrain was set to be spatially uniform ($a(x_i) = 1.0$). To examine the adaptability to changes in the environment, an external force to the moving direction $f_{\mathrm{ext},i}$ was added to each mass point, where $f_{\mathrm{ext},i}$ was set to be 0, 0.004, and -0.002 when $x_i < 100$, $100 \le x_i < 400$, and $400 \le x_i$, respectively.

Snapshots for the body movement and the spatiotemporal plot of $f_{i+1/2}$ are shown in Figs. 2 and 3, respectively. When $f_{\mathrm{ext},i} = 0$, a bodily wave of contraction and expansion moved forward and backward repetitively. When the body entered the area where external forces to the moving

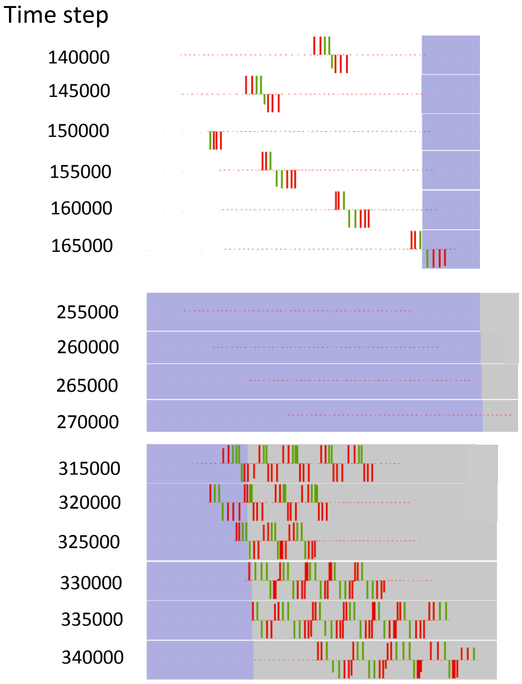

Figure 2: Snapshots for the body movement. Red dots denote mass points. Bars radiating upward and downward from the mass points denote contraction and expansion forces generated by actuators, respectively. The color of the bars are red and green when the friction coefficient is small and large, respectively. White, blue and gray areas denote areas with $f_{\text{ext},i} = 0, 0.004, -0.002$, respectively.

direction ($f_{\text{ext},i} = 0.004$) were added, the waves of contraction and expansion disappeared and the body moved forward without any actuation. When the body entered the area where external forces to the direction opposite to the movement ($f_{\text{ext},i} = -0.002$) were added, train of bodily waves moved forward and backward repetitively.

We also found that behaviors change depending on initial conditions and parameter values (data not shown).

4 Discussion and conclusions

We have proposed a mathematical model for one-dimensional crawling locomotion using an extremely simple decentralized control rule and demonstrated via simulations that non-trivial behaviors emerge. Although we did not determine a specific goal when we proposed this model, our findings suggest the following outcomes.

First, the proposed model can be used for designing one-dimensional crawling robots that can move efficiently and adaptively like animals. One-dimensional crawling robots have recently attracted attention because they are applicable to search-and-rescue operations, pipe inspections, and endoscopes [1–5]. We expect that the proposed decentralized control rule is useful for these applications because it enables energy efficient locomotion under various environments (for example, the body can move forward without any actuation on a down-slope).

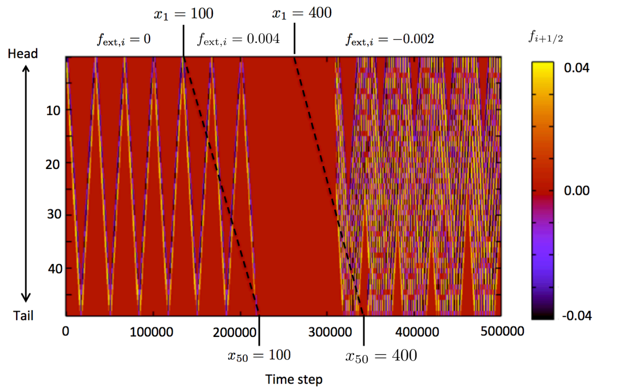

Figure 3: Spatiotemporal plot of the actuation force $f_{i+1/2}$. Dashed lines connect points of $x_1 = 100$ and $x_{50} = 100$ and those of $x_1 = 400$ and $x_{50} = 400$.

Table 1: Parameter valued employed in the simulation.

Variable	Value
Mass	0.01
Natural length of the spring	2.5
Spring coefficient	0.1
Damper coefficient	0.01
N	50
p	0.0055
q	0.0045
h	12.0
n_f	3
n_b	3
σ_1	500.0
σ_2	500.0
σ_3	300.0

Second, this study contributes to deepen understanding of living systems. We feel "life" when we observe living organisms on earth. However, it is still unclear what kind of control principles make us feel life. We believe that our findings impart an insight into this issue, although it might be a philosophical problem and essentially difficult to solve.

Acknowledgments

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