Title	Self-tunable Tegotae-based Control for Snake Locomotion
Author(s)	Yasui, Kotaro; Otaki, Noriyuki; Kano, Takeshi et al.
Citation	The 9.5th International Symposium on Adaptive Motion of Animals and Machines (AMAM2021). 2021, p. 22
Version Type	VoR
URL	https://doi.org/10.18910/84863
rights	
Note	

Self-tunable *Tegotae*-based Control for Snake Locomotion

Kotaro Yasui[a, b], Noriyuki Otaki[b,c], Takeshi Kano[b], Akio Ishiguro[b]
[a]Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai, Japan
k.yasui@riec.tohoku.ac.jp
[b]Research Institute of Electrical Communication, Tohoku University, Sendai, Japan
[c]Graduate School of Engineering, Tohoku University, Sendai, Japan

1 Introduction

Snakes exhibit versatile locomotor patterns, such as lateral undulation, concertina locomotion, sinus-lifting, and sidewinding in response to their environment [1]. Clarifying the control mechanisms underlying such adaptive locomotion in snakes will help us develop functional robots that can move in complex environments, such as rough terrain in disaster areas. However, many previously developed snake-like robots were designed to produce specific locomotor patterns [2], and as such, control principles for generating situation-dependent locomotor patterns still remain elusive.

To tackle this problem, we previously proposed a decentralized control scheme with local sensory feedback based on *Tegotae* [3], which is a Japanese concept that describes how well a perceived reaction matches an expectation. Using simulations [3] and a real physical robot [4], we demonstrated that qualitatively different locomotor patterns in snakes, *i.e.*, concertina locomotion in a narrow aisle and scaffold-based locomotion on terrain with pegs, can be reproduced without changing any control parameters. Although these results highlighted our progress in understanding the control principles underlying snake locomotion, there exist some adaptability limitations in the control scheme. Specifically, when the robot attempts to move across different environments, *e.g.*, narrow aisle and terrain with pegs, it sometimes fails to move forwards due to conflict between local sensory feedback in different body parts.

In this study, we aimed to extend our previous control scheme to improve its adaptability to environmental changes during locomotion by addressing the above-mentioned limitation. Specifically, we introduced an adjustment function for local feedback gain in response to the reaction force from the environment. Finally, the proposed control scheme was validated through simulations.

2 Model

2.1 Physical model

The snake body was simply modeled by a mass-spring-damper system, wherein mass points are connected one-dimensionally via parallel combinations of a spring and damper (Fig. 1). Each body segment can actively bend in the yaw direction with a rotational actuator implemented at each mass point. Friction between the body mass and environment was modeled based on the frictional properties of real snakes, where the coefficient of Coulomb friction in the forward-backward direction (μ_t) is lower than that in the lateral direction (μ_n) [5].

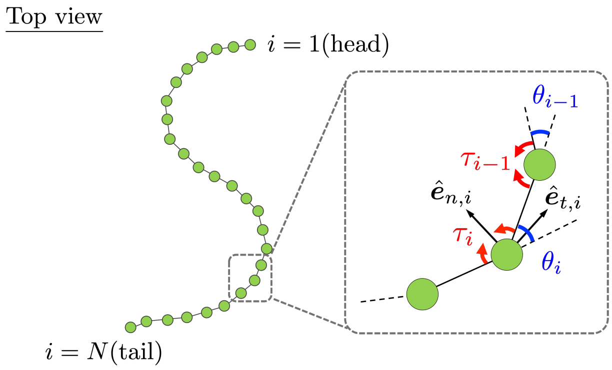


Figure 1: Schematic of the physical snake robot model.

2.2 Control scheme

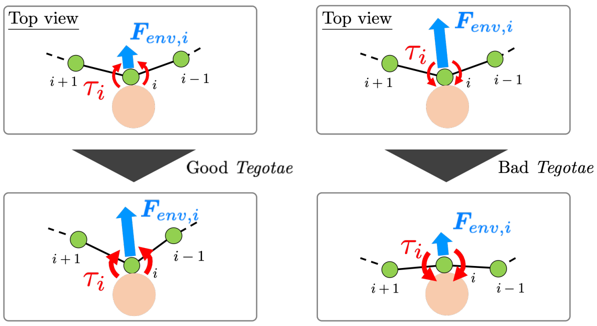
We designed a decentralized controller for generating body motions, except that the most anterior body segments were controlled by a motor command from a higher-level controller. The target joint angles of each body segment were defined as follows:

$$\bar{\theta}_i = \theta_{i-1} + \sigma_i \tanh\left(\alpha \sum_{i-n_a}^{i+n_p} \tau_i |F_{env,i} \cdot \hat{e}_{n,i}|\right), \quad (1)$$

$$\sigma_i = \frac{a_{max} - a_{min}}{1 + \exp\{-b(T_i + c)\}} + a_{min}, \quad (2)$$

$$T_i = \sum_{i-m_a}^{i+m_p} (F_{env,i} \cdot \hat{e}_{t,i}), \quad (3)$$

where α, n_a, n_p, m_a, and m_p are positive integers that determine the feedback range, and a_{max}, a_{min}, b, and c are positive constants. τ_i denotes the torque generated at the ith segment, and $F_{env,i}$ denotes the vector of reaction force from the environment detected at the ith mass point. $\hat{e}_{t,i}$ and $\hat{e}_{n,i}$ are unit vectors in the axial and lateral direction, respectively. The first term on the right-hand side of Eq. (1) represents the curvature derivative control [6], where torques proportional to the derivative of the body curvature are generated such that undulatory waves propagate from the head to the tail.



(a) (b)

Figure 2: Schematic of the *Tegotae*-based control for snake locomotion when the body obtained (a) good *Tegotae* and (b) bad *Tegotae*.

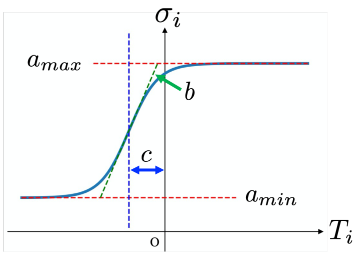


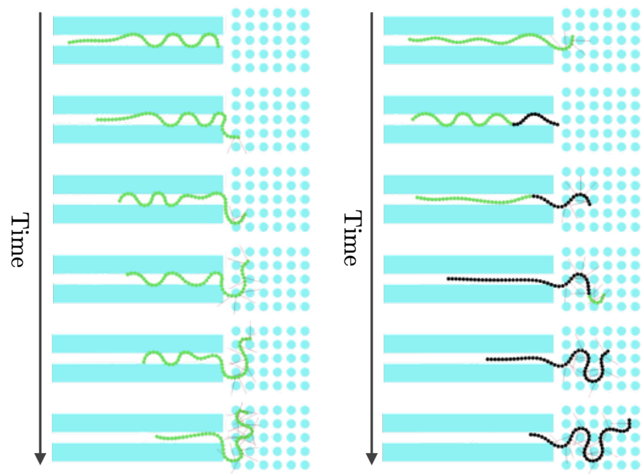
Figure 3: Schematic of the adjustment function of local feedback gain (σ_i) depending on the reaction force (T_i).

The second term on the right-hand side of Eq. (1) represents a sensory feedback based on *Tegotae* [3], which is defined as the product of the torque, *i.e.*, intended action, and reaction force. The effect of this sensory feedback is illustrated in Fig. 2. When the body generates torque to bend leftward, reaction force from the right matches an expectation that the body obtains scaffold from the environment. Then, the feedback leads to further torque generation, thus increasing the reaction force (Fig. 2a). In contrast, when the body generates torque to bend rightward, reaction force from the right is against the expectation of obtaining scaffold from the environment. Then, the feedback generates further torque such that the undesired reaction force decreases (Fig. 2b).

Eqs. (2) and (3) represent the sensitivity adjustment function of the *Tegotae*-based feedback, which is newly proposed in this paper to prevent conflict between the feedback working at different body parts. A schematic of this function is shown in Fig. 3. When a body part detects reaction force from the environment in the forward direction along the body axis ($T_i > 0$), the local feedback gain σ_i takes a higher value to further exploit the propulsive force. In contrast, when a body part detects reaction force in the backward direction along the body axis ($T_i < 0$), σ_i takes a lower value so as not to impede the current effective propulsion.

3 Simulation result

We performed simulation experiments to validate the proposed control scheme in the case of the snake-like robot moving from a narrow aisle to terrain with many pegs. The parameter values employed in the simulations were as follows: $N = 50$, $\alpha = 1.0 \times 10^{-8}$, $n_a = 1$, $n_p = 3$, $m_a = 5$, $m_p = 5$, $a_{max} = 0.5$, $a_{min} = 0.1$, $b = 0.01$, $c = 200.0$, $\mu_t =$



(a) (b)

Figure 4: Simulation results (a) without and (b) with adjustment of feedback gain in our *Tegotae*-based controller. Black-colored segments indicate the body parts where the local feedback gain σ_i shifted to a lower value.

0.1, and $\mu_n = 0.5$.

First, we simulated the previous model by fixing the gain value of *Tegotae*-based feedback ($\sigma_i = 0.5$). As shown in Fig. 4a, sometimes the robot became stuck temporarily and could not move forwards effectively. This is mainly due to the conflict between the *Tegotae*-based feedback working at each contact point with the side wall and pegs. In contrast, our newly proposed model could realize spatio-temporal modulation of the local feedback gain in response to the reaction force (Fig. 4b), generating a smooth transition from concertina locomotion in the narrow aisle to scaffold-based locomotion on the terrain with pegs. Thus, our proposed model is expected to enhance the adaptability of snake-like robots in various environments. Quantitative evaluation of the locomotor performance with our model remains as future work.

Acknowledgements

This work was supported by the Human Frontier Science Program (RGP0027/2017) and Frontier Research Institute for Interdisciplinary Sciences, Tohoku University. We would like to thank Dr. Hitoshi Aonuma of Hokkaido University and Dr. Kosuke Inoue of Ibaraki University for their helpful discussion.

References

[1] B. C. Jayne. What defines different modes of snake locomotion?, *Integrative and comparative biology*, 60, 1, 156-170 (2020).

[2] P. Liljebäck et al. Snake robots—Modelling, mechatronics, and control, *Springer-Verlag London* (2012).

[3] T. Kano, R. Yoshizawa, & A. Ishiguro. Tegotae-based decentralised control scheme for autonomous gait transition of snake-like robots, *Bioinspiration and biomimetics*, 12, 046009 (2017).

[4] T. Kano, R. Yoshizawa, & A. Ishiguro. Snake-like robot that can generate versatile gait patterns by using Tegotae-based control, In: *Conf. on Biomimetic and Biohybrid Systems*, 249-254 (2018).

[5] D. L. Hu et al. The Mechanics of Slithering Locomotion, *Proc. Natl. Acad. Sci. USA*, 106, 10081-10085 (2009).

[6] H. Date & Y. Takita. Adaptive locomotion of a snake like robot based on curvature derivatives, In: *IEEE/RSJ Int.Conf. on Intelligent Robots and Systems*, 3554-3559 (2007).