Proceedings of the 2025 SICE Festival with Annual Conference
September 9-12, 2025, Chiang Mai, Thailand

Active sensing control for exploratory navigation of centipedes using antennal and trunk motion

Kotaro Yasui[1†] and Kozue Shiomi[1]

[1]Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai, Japan
(Tel: +81-22-217-5465; E-mail: kotaro.yasui.b8@tohoku.ac.jp)

Abstract: Centipedes, despite lacking advanced vision, can adaptively navigate complex environments through active and exploratory sensing using their antennae and the anterior part of their body. This study aims to construct a mathematical model that integrates environmental sensing and autonomous decentralized locomotor control to understand the inherent mechanisms of this exploratory navigation.

Keywords: active sensing, antenna, sensory feedback, decentralized control, multi-legged locomotion

1. INTRODUCTION

Animals can skillfully maneuver their bodies to move through complex and unpredictable natural environments. This superior ability to traverse environments is realized by animals perceiving their situation through sensory organs and immediately generating adaptive movement strategies to determine the direction and manner of movement. Understanding the principles of locomotor control behind this ability is expected to contribute to designing control systems for bio-inspired robots that can autonomously move even in unknown environments without prior information.

Generally, animal locomotion is thought to be produced by the interaction between control by higher centers, such as the brain, and autonomous decentralized neural networks called Central Pattern Generators (CPGs) located in the spinal cord and ganglia [1]. Specifically, higher centers are responsible for global movement strategies such as initiating and stopping movement, adjusting speed, and determining direction, while generating movement patterns is largely entrusted to lower CPGs and peripheral sensory feedback [2]. Based on these biological insights, various studies have attempted to mathematically model and understand animal locomotor control mechanisms [3]. However, most of these studies have treated higher central control and lower autonomous decentralized movement generation control separately, and understanding how these interact to produce adaptive behavior in the environment remains insufficient.

To address this issue, this study focuses on the exploratory navigation of centipedes. Centipedes, despite lacking well-developed vision [4], can walk through complex uneven environments. This high terrain traversal ability is realized not only by generating adaptive walking patterns with many legs but also by active and exploratory environmental sensing using antennae and the anterior part of the body (Fig. 1), and movement adjustments based on this sensing information. Therefore, this centipede behavior is a suitable example for investigating the integration of higher central control based on environmental sensing and lower autonomous decentralized locomotor control. This paper reports the construction of a mathematical model that integrates environmental sensing using antennae and the body with decentralized locomotor control and verifies its behavior in uneven environments through simulations.

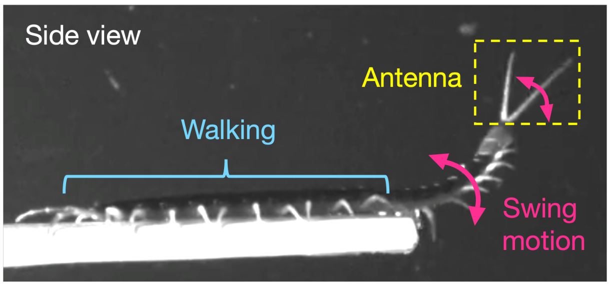

Fig. 1 Active sensing behavior of a centipede when it reached the edge of the ground.

2. MODEL

2.1. Overview of mechanical system

Since handling the three-dimensional movements exhibited by actual centipedes is complex, this study initially constructs a two-dimensional plane model focusing on sagittal plane movements (Fig. 2). The body mechanism of the centipede is represented by a spring-mass system, with 20 segments and legs. The body consists of mass points connected by linear springs and dampers, with legs attached to each segment. Leg movements during walking are realized by linear actuators for vertical movements and rotary actuators at the base for forward and backward movements. The body can bend through rotary actuators installed around each mass point. Additionally, the head has one antenna, which can perform exploratory movements through a rotary actuator at its base. To represent the antenna's flexibility, a passive rotary joint is installed between the head and the antenna tip.

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† Kotaro Yasui is the presenter of this paper.

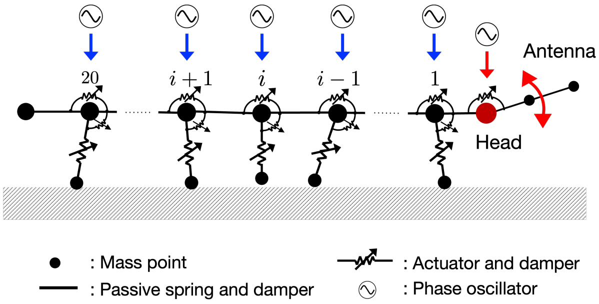

Fig. 2 Schematic of the physical model of centipedes.

2.2. Proposed neural control system

This study proposes control mechanisms for sensing movements using antennae and the body (Section 2.2.1) and for adjusting movement direction based on sensing information (Section 2.2.2), and attempts to integrate these with the autonomous decentralized control for reproducing centipede walking patterns proposed in our previous study (Section 2.2.3).

2.2.1. Active sensing using antennae and trunk motion

First, to represent the periodic swinging motion of the antenna, a phase oscillator is assumed in the head, and movements are generated based on the phase of the oscillator. Specifically, the antenna is controlled to swing up when the phase ϕ_{ant} is between 0 and π, and to swing down when the phase is between π and 2π. The time evolution equation of the phase is expressed as follows:

$$\dot{\phi}_{\text{ant}} = \omega_{\text{ant}}. \tag{1}$$

Here ω_{ant} is a constant representing the intrinsic angular velocity. In this model, the antenna tip and leg tips can detect reaction forces from the environment, which are recognized as ground contact sensations with a certain time delay:

$$c_{\text{ant}}\dot{S}_{\text{ant}} = -S_{\text{ant}} + \tanh(N_{\text{ant}}), \tag{2}$$

$$c_{\text{leg}}\dot{S}_{\text{leg},i} = -S_{\text{leg},i} + \tanh(N_{\text{leg},i}). \tag{3}$$

Here, S_{ant} and $S_{\text{leg},i}$ represent the ground contact sensation information of the antenna and legs, N_{ant} and $N_{\text{leg},i}$ represent the reaction forces received by the antenna and legs from the environment, and c_{ant} and c_{leg} represent time constants.

Next, the control of body bending movements for environmental sensing is described. From observations of actual centipede behavior, the following qualitative tendencies were found:

(A) While the entire body is walking on the ground, the dorsal-ventral bending movements of the body are relatively suppressed, and sensing is mainly performed using the antenna.

(B) When the head or anterior part of the body enters a space not in contact with the ground, the anterior part of the body begins to bend significantly in the dorsal-ventral direction.

Based on these findings, this study hypothesizes that the ground contact sensation information of the legs and antenna suppresses the body bending movements for sensing. Specifically, the active bending torque τ_i generated in the i-th body segment is controlled by the following equations:

$$\tau_1 = k_{\text{act},1}(\bar{\theta}_1 - \theta_1), \tag{4}$$

$$\tau_i = k_{\text{act},i}(\theta_{i-1} - \theta_i) \quad (i \geq 2), \tag{5}$$

$$k_{\text{act},1} = \bar{k} \cdot \max(0, 1 - c_1 S_{\text{ant}} - c_2 S_{\text{leg},1}), \tag{6}$$

$$k_{\text{act},i} = \bar{k} \cdot \max(0, 1 - c_2 S_{\text{leg},i}) \quad (i \geq 2). \tag{7}$$

Here, $k_{\text{act},1}$ and $k_{\text{act},i}$ represent the gain of body bending movements, $\bar{\theta}_1$ and θ_1 represent the target and actual bending angles of the first body segment, and θ_i represents the actual bending angle of the i-th body segment. $\bar{k}$, c_1, and c_2 are positive constants. Equations (4) and (5) control the first body segment to follow a target angle $\bar{\theta}_1$ (details of $\bar{\theta}_1$ are described in the next section), and subsequent body segments to follow the bending angle of the previous segment. Equations (6) and (7) suppress the intensity of these bending movements based on the ground contact sensation inputs of the respective segments' legs and antenna. This allows the intensity of body bending movements for sensing to flexibly change according to the situation of the body.

2.2.2. Adjusting movement direction based on sensory information

To effectively move through uneven environments with mixed elevations and spaces without footholds, it is important to perceive the ground that can serve as footholds and adjust the body's movement direction along the terrain. Therefore, this model proposes control to adjust the movement direction of the body based on environmental information obtained by the antenna. Specifically, the target bending angle $\bar{\theta}_1$ of the first body segment is controlled by the following equations:

$$\bar{\theta}_1 = \theta_{\text{neut}} + A_1 \sin \phi_{\text{ant}}, \tag{8}$$

$$c_n\dot{\theta}_{\text{neut}} = -\theta_{\text{neut}} + \sigma_n \max(0, \theta_{\text{ant}} + \theta_{\text{joint}}). \tag{9}$$

Here, θ_{neut} represents the neutral position of the bending movements of the first body segment, and θ_{ant} and θ_{joint} represent the bending angles of the antenna base and the passive joint, respectively. A_1 represents the amplitude of the first body segment, and c_n and σ_n are positive constants. Equation (8) controls the first body segment to periodically bend according to the movement phase of the antenna, and equation (9) adjusts the neutral position of the bending movements according to the actual shape of the antenna. For example, when the antenna is in contact with the ground and bent upward ($\theta_{\text{ant}} + \theta_{\text{joint}} > 0$), the posture is adjusted to bend the body more upward. This allows the adjustment of the movement direction along the terrain in front of the body.

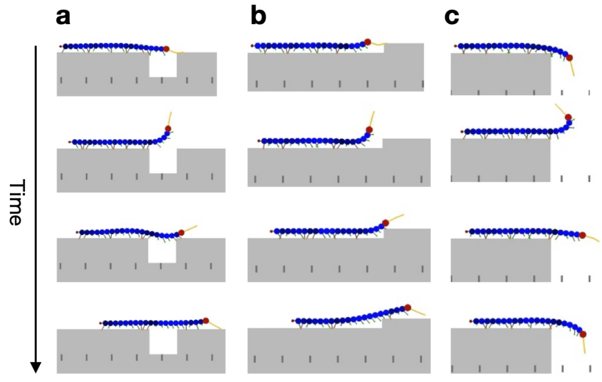

Fig. 3 Simulation results using the proposed model. (a) Gap crossing, (b) Step climbing, (c) Spatial exploration.

2.2.3. Decentralized control for generating walking patterns

Finally, the walking control laws adopted in this model are briefly introduced (for details, refer to the literature [5]). Similar to the periodic movements of the antenna, the periodic movements of the legs during walking are also assumed to be controlled based on the phase of an oscillator. Specifically, the phase $\phi_{\text{leg},i}$ of the i-th leg generates a swing phase when it is between 0 and π, and a stance phase when it is between π and 2π. The time evolution equation of the phase is expressed as follows:

$$\dot{\phi}_{\text{leg},i} = \omega_{\text{leg}} + (a - \sigma_1 S_{\text{leg},i} - \sigma_2 S_{\text{leg},i-1}) \cos \phi_{\text{leg},i}. \quad (10)$$

Here, ω_{leg} represents the intrinsic angular velocity, and a, σ_1, and σ_2 are positive constants. This control law has been reported to self-organize the travelling wave of leg movements observed in centipedes by locally feeding back the ground contact sensation information of the leg itself and the leg of the previous segment.

3. SIMULATION RESULTS

Simulation experiments were conducted to verify whether the proposed control laws can reproduce the high uneven terrain traversal ability exhibited by centipedes. Specifically, we first examined whether the model could traverse ground with gaps and steps. The results are summarized in snapshots. The simulated centipede, when faced with gaps (Fig. 3a) or steps (Fig. 3b), was able to continue moving without getting stuck on the ground irregularities by slightly lifting its head based on the ground contact sensation information from the antenna. Additionally, when entering a space with no footholds in the forward direction, the anterior part of the body exhibited large bending movements to explore a wider area of space (Fig. 3c). These results qualitatively match the behavior of actual centipedes. In the future, we plan to verify the functionality of the proposed control laws in more complex terrains and extend the model to reproduce three-dimensional movements.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI (grant numbers: JP23K13349) and research fund from the Creative Interdisciplinary Collaboration Program of Frontier Research Institute for Interdisciplinary Sciences, Tohoku University.

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