Doing Well in Narrow Aisle! Decentralized Control Mechanism Underlying Adaptive Concertina Locomotion of Snakes

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Abstract—Snakes exhibit various gait patterns in response to the environment. To elucidate the mechanism underlying this ability of snakes, we previously proposed a model based on autonomous decentralized control. Although it could reproduce various gait patterns, it could not reproduce concertina locomotion, which is a typical gait pattern in narrow aisles. In this study, we added a local reflexive mechanism to our previous model and successfully simulated concertina locomotion in a narrow aisle.

1. Introduction

Snakes can move by adapting to their environment in real time despite their simple body structure. Surprisingly, they have various gait patterns that are qualitatively different from each other, *e.g.*, lateral undulation, concertina locomotion, and sidewinding (Fig. 1) [1, 2]. Snakes use these gaits appropriately according to the circumstances. This ability has been honed by evolutionary selection pressure, and ingenious mechanisms are likely underlying this behavior. Clarifying these remarkable mechanisms will benefit the development of robots that function well in extreme environments such as disaster areas.

Thus far, the snake locomotion mechanism has been investigated and exploited for practical applications in the robotics field [1, 2]. However, most of these robots operate in pre-defined environments and can only exhibit specific types of gait patterns. Several snake-like robots have implemented sensory feedback mechanisms to adapt to their environments [1-4]; however, this adaptability is still limited, and these robots cannot truly reproduce the innate behavior of real snakes. Thus, the mechanism of adaptive, versatile snake locomotion is not yet truly understood.

Autonomous decentralized control could be the key to solving this problem. Because it imparts non-trivial macroscopic behavior or functionalities through the coordination of simple individual components, autonomous decentralized control may help in achieving the adaptive and versatile locomotion of animals. In our previous work, we investigated an autonomous decentralized control mechanism underlying versatile snake locomotion through modeling and simulations [5, 6]. Based on the fact that points of body contact with the ground depend significantly on gait patterns (Fig. 1) [1, 2], we added a three-dimensional effect to the curvature derivative control where the target angle of each joint is determined according to the angle of its anterior joint [7]. We showed via simulations that various gait patterns can be reproduced by changing a small number of parameters [5].

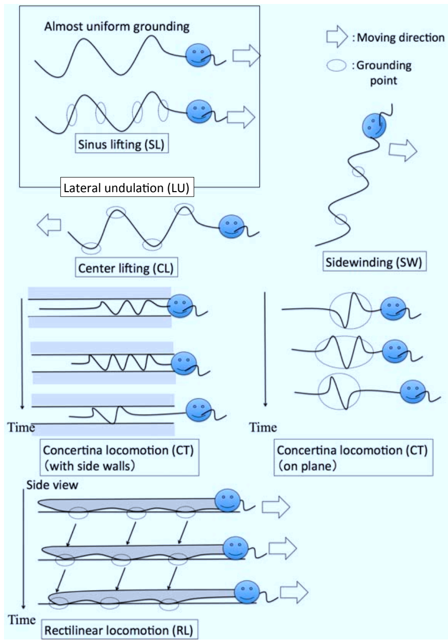

Figure 1: Schematic of gait patterns of snakes.

However, our previous model could not reproduce locomotion in a narrow aisle although real snakes often adapt to narrow aisles by changing their gait pattern to concertina locomotion (*i.e.*, the tail part of the body is first pulled forward with the head part anchored followed by extension of

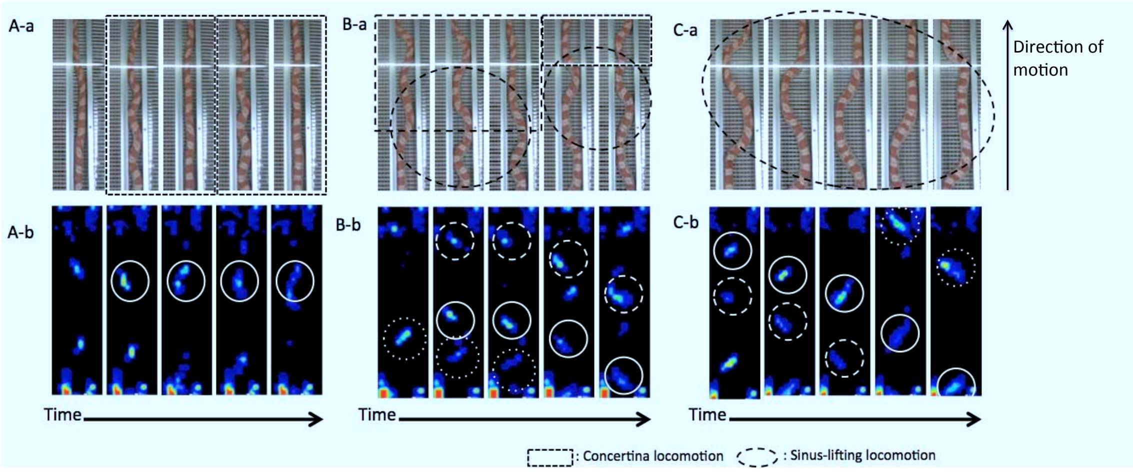

Figure 2: Photographs of real snake locomotion in narrow space. The widths of the aisles are (A) 4, (B) 6, and (C) 8cm. The lower photographs show the output of the pressure sensor sheet. High-pressure areas are marked with white circles.

the head part with the tail part anchored (Figs. 1 and 2)) [1, 2]. In this study, we added local sensory feedback to our previous model to reproduce concertina locomotion in a narrow space. Simulation results showed that the gait pattern changed smoothly from sinus-lifting locomotion (*i.e.*, the body contacts the ground around the inflection point of the body curve and moves by gliding along the body curve (Fig. 1)) to concertina locomotion as the aisle width decreased, which agreed well with the results of behavioral experiments using a real snake.

2. Behavioral Experiments

We performed behavioral experiments using a real snake. We constructed an aisle from aluminum plates and covered it with a transparent acrylic plate. A corn snake (*Pantherophis outtatus*) was placed in the aisle, and its locomotion was monitored by a digital video camera. The ground reaction force was measured by a pressure sensor sheet (Nitta Corp., BIG-MAT) on the floor.

Figure 2 shows the results for aisle widths of 4–8 cm. When the width was 4 cm (Fig. 2A), the snake first pulled the tail part forward with the head part anchored, and then the head part extended with the tail part anchored: *i.e.*, concertina locomotion. The ground reaction force was large at some inflection points of the body curve. When the width was 8 cm (Fig. 2C), the snake moved forward by gliding its body on the floor, where the ground reaction force was large around the inflection points of the body curve: *i.e.*, sinus-lifting locomotion. When the width was 6 cm (Fig. 2B), the snake moved forward both by pushing its body against the walls on both sides of the aisle and by gliding its body on the floor; *i.e.*, concertina locomotion and sinus-lifting locomotion were mixed.

We can conclude from these findings that concertina locomotion and sinus-lifting locomotion are not completely separate but connected continuously; a continuous transition between the two gait patterns can be induced by changing the aisle width.

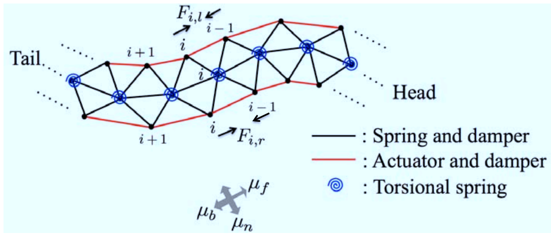

Figure 3: Model of musculoskeletal structure.

3. Model

3.1. Musculoskeletal Structure

We describe the musculoskeletal system as a simple mass-spring-damper model on a two-dimensional plane (Fig. 3) to consider its dynamics. The backbone consists of particles connected one-dimensionally via springs and dampers. A torsional spring is embedded in each particle to represent the anatomical constraint of each backbone joint. Particles that represent the body walls on both sides are connected to adjacent backbone particles via springs and dampers. The spring constant should be large enough that the distance between the particles would not change considerably. Particles on both sides of the body are connected to their adjacent particles via actuators and dampers to mimic muscles. The ground frictional force acting on the backbone particles is modeled as a combination of Coulomb friction and viscous friction, where the coefficient of Coulomb friction in the forward direction is assumed to be smaller than those in the lateral and backward directions on the basis of biological findings [8].

3.2. Actuation

Forces generated by the actuators are modeled based on autonomous decentralized control except for the head part, for which the actuation forces are determined according to motor commands from a higher center. Except for several segments from the head, the force generated by the actuator on the right-hand sides of ith segment $F_{i,r}$ is given by

$$
\begin{aligned}
F_{i,r} &= F^c_{i,r} + F^p_{i,r} \\
F^c_{i,r} &= k(l_{i,r} - l_{i-1,r}) \qquad (1)
\end{aligned}
$$

where $l_{i,r}$ is the length of the actuator on the right-hand side of the ith segment and k is a positive constant. The forces generated by the actuators on the left-hand side are described in the same way (subscript "i, r" in Eq. (1) is replaced by "i, l"). The term $F^c_{i,r}$ represents curvature derivative control, which is a control scheme to generate torques proportional to the curvature derivative of the body curve [7]. Although this control scheme was developed by analytically deriving the condition for the body to move efficiently during lateral undulation, we previously showed that it forms the basic mechanism for achieving various gait patterns such as sinus-lifting locomotion, center-lifting locomotion, and sidewinding [5]. The term $F^p_{i,r}$ represents the newly introduced local sensory feedback, which we describe in section 3.4.

3.3. Three-dimensional Effect

Real snakes have several muscles on both sides of the body. Contractions of these muscles make the body bend vertically and horizontally. Although the vertical displacement of the body is smaller than the horizontal one when snakes move on an almost flat terrain, the vertical motion plays a significant role in changing the contact point of the body with the ground. Here, we introduced the effect of vertical motion to our two-dimensional model (see section 3.1) phenomenologically instead of analyzing three-dimensional dynamics strictly.

We define the vertical displacement of the ith backbone particle as z_i and describe its dynamics phenomenologically as

$$
\begin{aligned}
m\ddot{z}_i &= -mg + N_i + k_z(\Phi_{i-1} - 2\Phi_i + \Phi_{i+1}) \\
&\quad + c_z(\dot{\Phi}_{i-1} - 2\dot{\Phi}_i + \dot{\Phi}_{i+1}) \\
&\quad + \alpha_r(F^c_{i-1,r} - 2F^c_{i,r} + F^c_{i+1,r}) \\
&\quad + \alpha_l(F^c_{i-1,l} - 2F^c_{i,l} + F^c_{i-1,l}). \qquad (2)
\end{aligned}
$$

where m is the mass of the particle; k_z is the spring constant of the torsional spring in the backbone joint that works in the vertical direction; c_z is the damping coefficient of the damper aligned along the torsional spring working in the vertical direction; $\Phi_i \equiv -z_{i-1} + 2z_i - z_{i+1}$ represents vertical bending of the body, and g is the gravitational acceleration. The ground is modeled by using springs and dampers, and the ground reaction force N_i is described as

$$
N_i = \begin{cases} \max[-k_{\text{floor}} z_i - c_{\text{floor}} \dot{z}_i, 0], & (z_i \leq 0) \\ 0, & (z_i > 0) \end{cases} \qquad (3)
$$

where k_{floor} and c_{floor} are the spring constant and damping coefficient of the ground.

The fifth and sixth terms on the right-hand side of Eq. (2) represent the effect of the actuation. Contact points between the body and ground vary depending on the values of α_r and α_l. For example, when α_r is positive and the ith RTS on the right-hand side generates a contraction force, the ith backbone particle is pushed against the ground and the $i-1$th and $i+1$th particles lift off the ground.

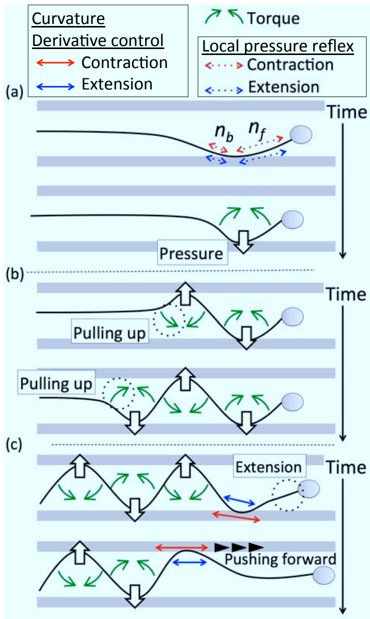

Figure 4: Mechanism of concertina locomotion.

3.4. Local Sensory Feedback

The local sensory feedback terms $F^p_{i,r}$ and $F^p_{i,l}$ (see Eq. (1)) is introduced to reproduce concertina locomotion in narrow space. It is given as

$$
F^p_{i,r} = \sigma \left\{ \tanh \sum_{j=i-n_b}^{i+n_f} (\beta f_{j,l}) - \tanh \sum_{j=i-n_b}^{i+n_f} (\beta f_{j,r}) \right\}, \qquad (4)
$$

where σ and β are positive constants, $f_{j,r}$ and $f_{j,l}$ are the forces acting from walls to the particles on the right- and left-hand sides of the jth segment, and n_f and n_b denote numbers of segments to which the local sensory feedback is applied. The local sensory feedback term on the left-hand side $F^p_{i,l}$ is described similarly. Fig. 4 explains the effect of this local sensory feedback term. When some particle in the body contacts the wall, actuators on the contralateral and ipsilateral sides of the contact point generate contraction and expansion forces, respectively. Then, torque is generated around the contact point, which leads the body to push against the wall (Fig. 4(a)). The posterior part of the body is pulled forward owing to the feedback, and then the posterior part of the body contacts the wall on the other side. In this way, the body contacts the walls subsequently (Fig. 4(b)). When the head part extends, the posterior part of the body also extends owing to the effect of curvature derivative control. Thus, the body moves forward (Fig. 4(c)). Concertina locomotion can be achieved by repeating this process.

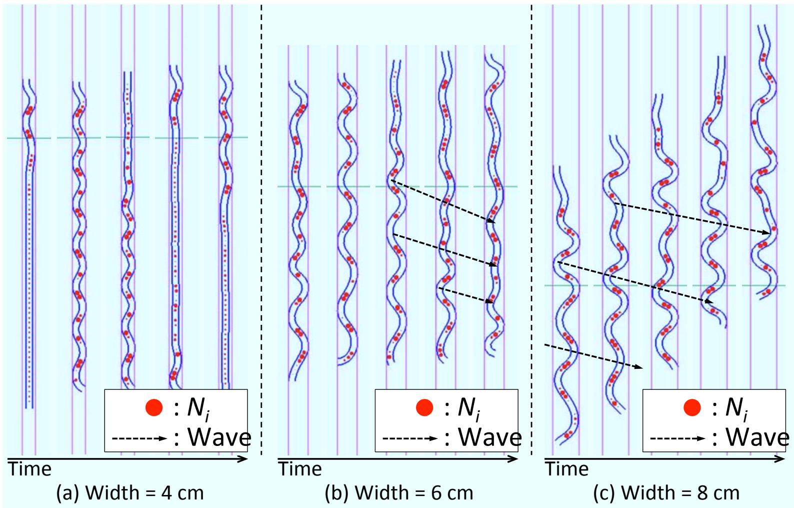

Figure 5: Simulation result. The width of the aisles are (a) 4, (b) 6, and (c) 8 cm. The radius of the red circles represents the magnitude of the ground reaction force. The dotted arrows indicate body waves transmitted from the head to the tail.

4. Simulation

We conducted simulations to validate our proposed control scheme. We set both α_r and α_l to be positive and controlled the motion of the head part by keyboard manipulation. The parameter values were determined by trial and error.

Fig. 5 shows the simulation result. When the aisle width was 4 cm, the simulated snake moved forward by bending and extending the body repetitively: *i.e.*, concertina locomotion. On the other hand, when the width was 8 cm, the body glided forward by pushing against the ground at the inflections: *i.e.*, sinus-lifting locomotion. When the width was 6 cm, both concertina locomotion and sinus-lifting locomotion were observed. These results agreed well with the results of the behavioral experiments (see Section 2).

5. Conclusion and Future Works

To reproduce versatile gait patterns of snakes, we modeled their behavior based on autonomous decentralized control. We added a local sensory feedback mechanism to our previous model [5] to achieve concertina locomotion in a narrow space. We demonstrated through simulations that the gait pattern smoothly changed from sinus-lifting locomotion to concertina locomotion as the aisle width decreased, which agreed well with the results of the behavioral experiments. In the future, we intend to develop a real robot and validate the proposed control scheme in the real world.

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