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Simple Decentralized Control Scheme Can Reproduce Versatile Gait Patterns of Snakes

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Abstract—Snakes change their gait patterns according to the circumstances encountered. The objective of this study was to understand the decentralized control mechanism underlying this adaptive and versatile locomotion via modeling and simulations. We introduced a three-dimensional effect to the curvature derivative control proposed previously and demonstrated through simulations that various gait patterns can be reproduced via only a change in a small number of parameters.

1. Introduction

Snakes can move by adapting to their environment in real time, in spite of their simple body structure. They have various gait patterns that are qualitatively different from each other, *e.g.*, lateral undulation, concertina locomotion, and sidewinding (see Fig. 1 and details in Sec. 2) [1, 2], and use these gaits appropriately according to the current circumstances encountered by changing the contact points with the ground spatiotemporally (Fig. 2). This ability has been honed by evolutionary selection pressure, and it is likely that there are ingenious mechanisms underlying this behavior. Clarification of these remarkable mechanisms will benefit the development of robots that function well, even in harsh environments such as disaster areas.

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

To overcome this problem, we focused on autonomous decentralized control because it imparts non-trivial macroscopic behavior or functionalities, *e.g.*, adaptability and versatility, through the coordination of simple individual components. We modeled snake locomotion on the basis of "curvature derivative control," [5] in which the target angle of each joint is determined according to the angle of its anterior joint, and showed that this control scheme works effectively in producing adaptive behavior [6]. However, our previous model could not reproduce gait patterns other than lateral undulation.

In this study, our aim was to understand an autonomous decentralized control mechanism underlying various gait patterns of snakes. For this purpose, we first observed and classified the gait patterns of real snakes, and we then introduced a three-dimensional effect to the curvature derivative control. The three-dimensional effect causes the ground contact not to be uniform over the entire body, which allows the gait patterns to change drastically. The validity of the proposed control scheme is investigated via simulations, and the results show that versatile gait patterns can be reproduced via only a change in a small number of parameters.

2. Classification of gait patterns

Although various gait patterns of snakes are known [1, 2], previous classifications of gait patterns are somewhat inconvenient for explaining the simulation results in this paper. Thus, we reclassified the gait patterns on the basis of detailed observations and behavioral experiments. The classifications are summarized in Table 1 and Fig. 1. The typical photographs and spatial distributions of the ground reaction force are shown in Fig. 2.

We identified six distinct gait patterns: lateral undulation (LU), sinus-lifting locomotion (SL), sidewinding (SW), concertina locomotion (CT), rectilinear locomotion (RL), and center-lifting locomotion (CL). To the best of our knowledge, the observation of CL in a real snake has not been reported, although it has been reported as a gait pattern of a snake-like robot [7].

All the species we observed (*Ovophis okinavensis*, *Cerastes vipera*, *Eunectes notaeus*, *Elaphe climacophora*, and *Bitis arietans*) could move by properly adjusting their gait patterns in response to their environment. Gait patterns that could not be classified clearly, *e.g.*, the intermediate between LU and SW, were also often observed. These facts suggest that the gait patterns are not completely independent but are connected to each other continuously.

Table 1: Gait patterns of snakes.

Gait pattern	Characteristics
Lateral undulation (LU)	The body contacts the ground almost uniformly and moves by gliding along the body curve.
Sinus-lifting locomotion (SL)	The body contacts the ground around the inflection point of the body curve and moves by gliding along the body curve. This gait is more efficient than LU.
Sidewinding (SW)	The body anchors the ground between the left (right) flexion parts to their adjacent right (left) flexion parts and moves laterally by exploiting the anchor points.
Concertina locomotion (CT)	The motion is carried out by first pulling the caudal part forward with the cranial part anchored, followed by the extension of the cranial part with the caudal part anchored.
Rectilinear locomotion (RL)	The motion is carried out by propagating a wave of contraction and expansion of the ventral skin toward the posterior. The body anchors the ground at the points where the ventral skin contracts.
Center-lifting locomotion (CL)	The body anchors the ground at the flexion parts and moves backward by exploiting the anchor points.

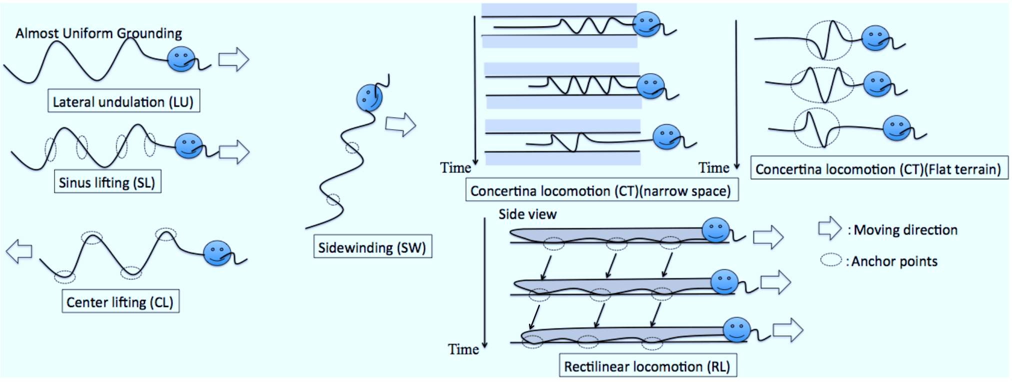

Figure 1: Schematics of snake gait patterns.

3. Model

3.1. Musculoskeletal structure

We describe the musculoskeletal system by a simple mass–spring–damper model in a two-dimensional plane (Fig. 3) and consider its dynamics. The backbone consists of particles connected one-dimensionally via springs and dampers. The weight of each particle on the tail side is smaller than that on the head side considering the weight balance of real snakes. A torsional spring is embedded in each of these particles, which represents 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 is taken to be large enough so that the distance between the particles does not change considerably. Particles on both sides of the body are connected to their adjacent particles via actuators and dampers, which mimic muscles. The ground frictional force acting on the backbone particles is modeled by the Coulomb friction, where the friction coefficient in the forward direction is assumed to be smaller than those in the lateral and the backward directions on the basis of biological findings [8].

3.2. Actuation

Forces generated by the actuators are modeled on the basis of autonomous decentralized control except for the head part in which the actuation forces are determined according to the motor command 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 as

$$F_{i,r} = k_i(l_{i,r} - l_{i-1,r}), \quad (1)$$

where $l_{i,r}$ is the length of the actuator on the right-hand side of the ith segment. The gain k_i is assumed to decrease as i increases, considering the force balance of real snakes. The forces generated by actuators on the left-hand side are described in the same way (subscript "i, r" in Eq. (1) is replaced by "i, l"). Equation (1) represents curvature derivative control, which is a control scheme that generates torques proportional to the curvature derivative of the body curve [5]. In fact, $l_{i,r}$ (or $l_{i,l}$) is a measure of the curvature and its difference $l_{i,r} - l_{i-1,r}$ gives spatial derivative of the curvature in the continuum limit.

3.3. Three-dimensional effect

Real snakes have several muscles on both sides of the body. Contractions of these muscles cause the body to

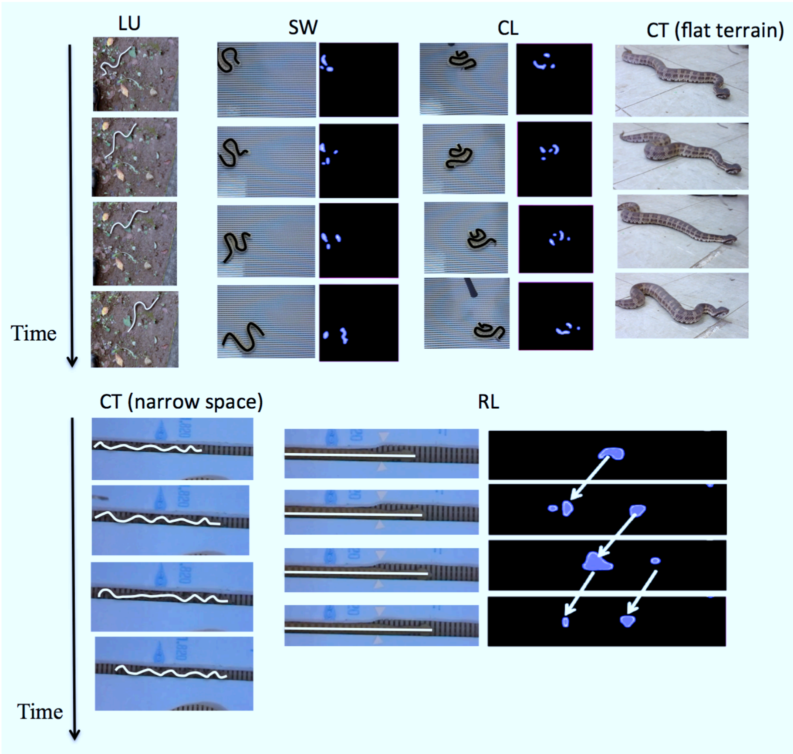

Figure 2: Photographs of real snake locomotion: LU and CT (flat terrain) of *Ovophis okinavensis* and SW, CT, RL, and CL (narrow space) of *Cerastes vipera*. Black and white solid curves on the photographs indicate the body trunk. The spatial distribution of the ground reaction force is shown on the right-hand side, except for the LU and CT motions. Gray areas indicate areas where the ground reaction force is large.

bend vertically as well as horizontally. Although the vertical displacement of the body is smaller than the horizontal displacement when snakes move on almost flat terrain, vertical motion plays a significant role in changing the contact point of the body with the ground. Here, we introduce the effect of vertical motion to our two-dimensional model (Fig. 3) phenomenologically instead of strictly analyzing the three-dimensional dynamics.

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

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

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

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

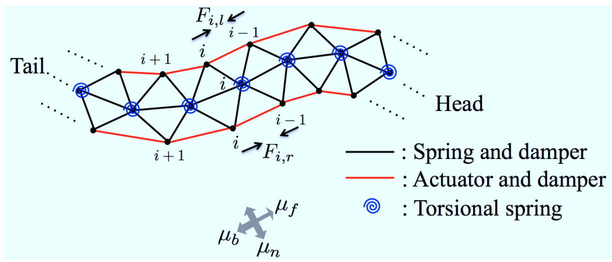

Figure 3: Model of the musculoskeletal structure.

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

The fifth and sixth terms on the right-hand side of Eq. (2) represent the effect of actuation. The contact points between the body and ground vary depending on the values of α_r and α_l, which are given by the motor command from a higher center. For example, when α_r is positive, and the actuator of the ith segment 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. Thus, α_r and α_l are key parameters for achieving versatile gait patterns.

4. Simulation

We conducted simulations to validate our proposed control scheme. In the following simulations, the forces generated by actuators on the head part were preprogrammed by using a sinusoidal function so that the body moves periodically. The parameter values were determined by trial and error.

Fig. 4 shows the photographs and trajectory of the simulated snake for several values of α_r and α_l. As is expected, LU was observed when $(\alpha_r, \alpha_l) = (0.0, 0.0)$. When $(\alpha_r, \alpha_l) = (1.2, 1.2)$, SL was observed. The locomotion velocity in this case was 1.36 times faster than that in the LU case, which is in good agreement with the previous findings that SL makes the body move forward more effectively than LU [1]. When $(\alpha_r, \alpha_l) = (1.2, 0.0)$, SW was observed. The body anchored the ground at the areas where the right muscles contracted, and these areas shifted toward the posterior. SW was also observed when $(\alpha_r, \alpha_l) = (-1.2, 0.0)$; however, the direction of motion was the opposite in this case. Finally, when $(\alpha_r, \alpha_l) = (-2.4, -2.4)$, CL was observed. The body anchored the ground at the flexion points and moved backward by exploiting these anchor points.

5. Conclusion and future work

Our aim was to understand the mechanism underlying the adaptive, versatile locomotion of snakes. We observed the versatile gait patterns of real snakes, and on this basis, we developed an autonomous decentralized control scheme in which a three-dimensional effect is introduced to the curvature derivative control proposed previously [6]. The validity of the proposed control scheme was investigated via simulations, and the results showed that various gait patterns can be reproduced via only a change in a small number of parameters. In our future work, we intend to develop a robot and validate the proposed control scheme in the real world.

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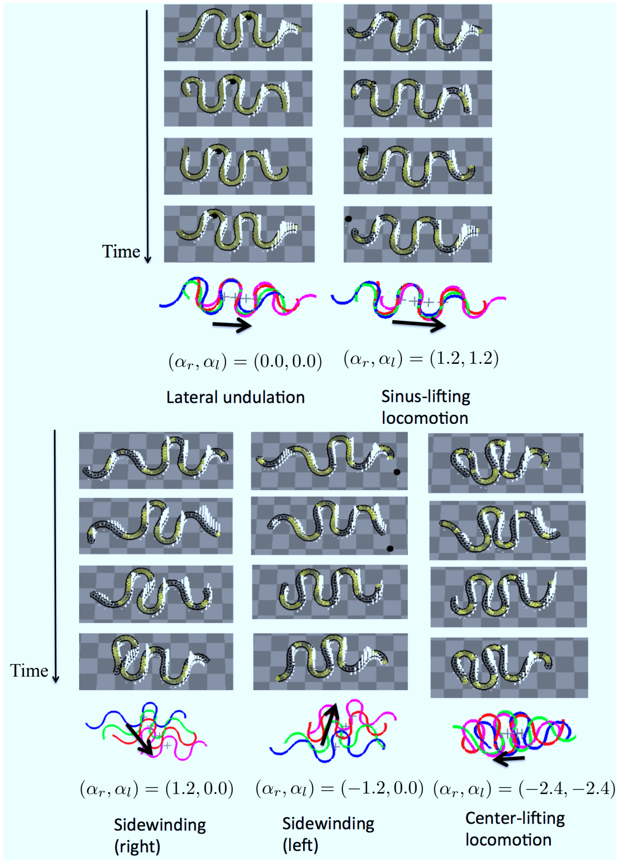

Figure 4: Simulation results: (top) snapshots and (bottom) the trajectory. Yellow segments are the segments where the ground reaction force (N_i) is large. White bars on the lateral side of each segment indicate the magnitude of the forces generated by actuators ($F_{i,r}$ and $F_{i,l}$). Black points express the initial position of the head. The plus symbols and black arrows in the trajectory photographs indicate the center of mass and the direction of movement, respectively.

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