Decentralized Control for Morphology-Adaptive Gait Generation in Sprawling Quadruped Locomotion

Shura Suzuki[1], Satoshi Maeda[1, 2], Kotaro Yasui[1, 3], Akio Ishiguro[1]
[1]Research Institute of Electrical Communication, Tohoku University, Japan
shura.suzuki.c6@tohoku.ac.jp
[2]Department of Electrical Engineering, Tohoku University, Sendai, Japan
[3]Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Japan

1 Introduction

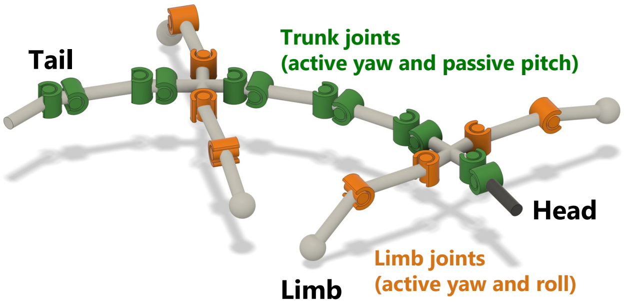
Quadruped animals orchestrate their bodily degrees of freedom to achieve agile and adaptive locomotion. Sprawling locomotion, characterized by walking gaits with lateral trunk bending, presents an intriguing model behavior for investigating underlying motor control principles. This locomotion pattern is observed across amphibians, reptiles, and mammals [1]. Moreover, paleontological evidence suggests that this behavior was also present in extinct primitive tetrapods [2], indicating that sprawling locomotion likely encapsulates fundamental principles for whole-body coordination in quadruped motor control.

A key characteristic of sprawling locomotion is its adaptive gait patterns. For instance, salamanders modulate both their footfall patterns and axial movements according to speed [3]. They employ a walking gait at slow speeds and transition to a walking trot gait at higher speeds. Similarly, their axial flexion manifests as a standing wave at slower speeds and transforms into a traveling wave at higher speeds. Additionally, axial movements adapt in response to morphological features. Species with short trunks exhibit traveling axial motion with long wavelengths relative to their body length, whereas species with long trunks display motion patterns with shorter wavelengths [4]. These adaptive gait generations represent a fundamental property of motor control in sprawling locomotion.

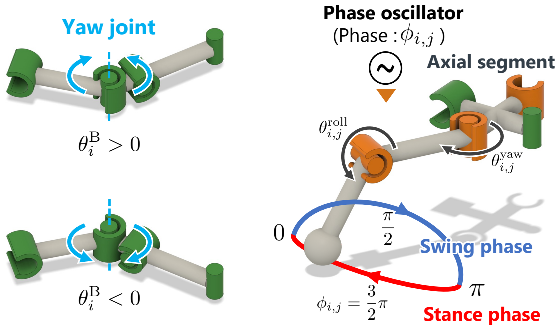
This study aims to investigate the underlying control mechanisms for adaptive motor control in sprawling locomotion through mathematical modeling and computational simulations. In our previous work, we proposed a decentralized control framework utilizing sensory feedback for axial–limb coordination, successfully reproducing speed-dependent gait transitions in a simulated model [5]. Based on this work, we developed a control mechanism capable of morphology-adaptive gait generation and considered shared principles for whole-body coordination in quadruped motor control.

2 Model

We present a quadruped model with a flexible trunk, as illustrated in Figure 1. The model consists of multiple axial segments connected to four limb segments. The axial segments form a chained structure through trunk joints, each incorporating an active yaw and a passive pitch hinge. Each leg features two rotary actuators in the yaw and roll directions, with their movements governed by phase oscillators.



(a) Overview

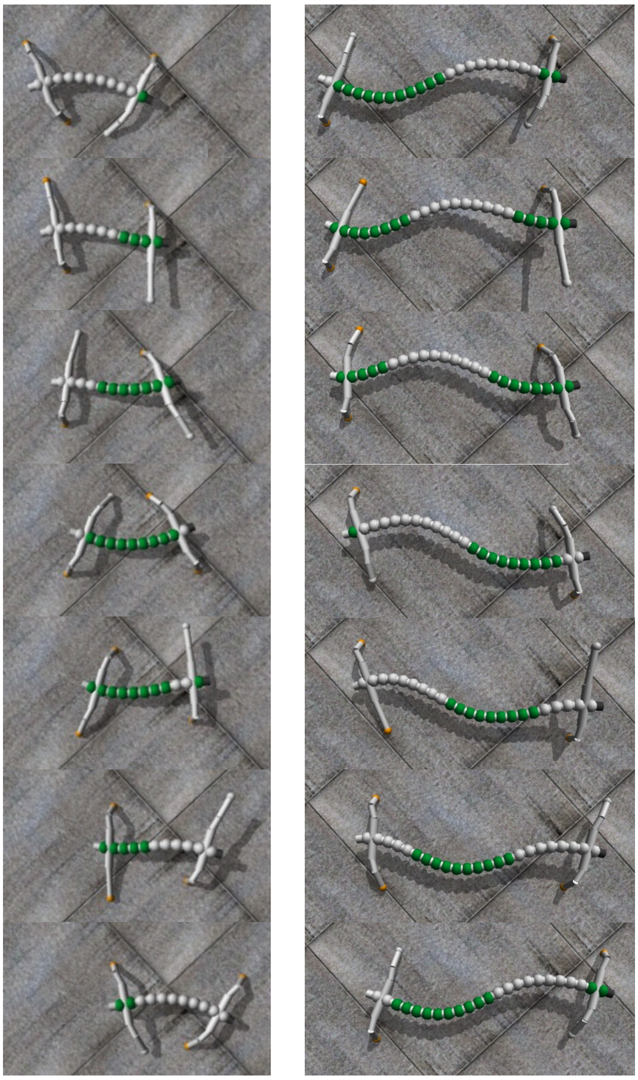


(b) Trunk actuation (c) Limb actuation

Figure 1: Proposed quadruped model.

The controller is based on the previous work [5]. The actuators in each segment are individually controlled by distributed controllers. Specifically, the limb actuators are controlled by a proportional-derivative (PD) controller, where the target position is determined by the oscillator phase $\phi_{i,j}$. Here, i denotes the trunk segment number to which the leg connects, and j indicates the left-right position (l or r). When $0 < \phi_{i,j} \leq \pi$, the leg rises and swings forward; otherwise, it descends and swings backward (Fig. 1c).

The time evolution of the oscillator phase is described as



(a) 9 trunk joints (b) 21 trunk joints

Figure 2: Simulation results.

follows:

$$\dot{\phi}_{i,l} = \omega - \sigma_{\mathrm{LL}} N_{i,l} \cos\phi_{i,l} + \sigma_{\mathrm{BL}} R_i \cos\phi_{i,l}, \quad (1)$$

$$\dot{\phi}_{i,r} = \omega - \sigma_{\mathrm{LL}} N_{i,r} \cos\phi_{i,r} - \sigma_{\mathrm{BL}} R_i \cos\phi_{i,r}, \quad (2)$$

$$R_i = \tau_{i-1} - \tau_i, \quad (3)$$

where ω represents the intrinsic angular velocity of the oscillator, and σ_{LL} and σ_{BL} are the weights of feedback gain; $N_{i,j}$ is the normal force at the foot and R_i is the actuation of neighboring trunk joints, where $R_i > 0$ indicates the trunk link rotates right. The second term on the right side of Eqs. 1 and 2 is local sensory feedback that organizes interlimb coordination [6]. The third term on the right side of Eqs. 1 and 2 modifies the oscillator phase in response to body actuation. For example, when the trunk link rotates right ($R_i > 0$), the feedback modifies the phase of the right leg to $3\pi/2$ and the left leg to $\pi/2$, so that the right leg operates in the stance phase while the left leg functions in the swing phase. The bidirectional feedback between the trunk and limb generates adaptive axial–limb coordination.

Figure 3: Simulation shows trunk flexion (green/white) and foot ground contact phases (orange/white).

The axial actuators are controlled by normal force feedback and anterior joint angle feedback:

$$\dot{\bar{\theta}}_i = \sigma_{\mathrm{LB}} \tilde{N}_i + \sigma_{\mathrm{BB}} (\theta_{i-1} - \theta_i), \quad (4)$$

$$\tilde{N}_i = \tanh(\gamma N_{i,l}) - \tanh(\gamma N_{i,r}) \quad (5)$$

where $\dot{\bar{\theta}}_i$ is the time evolution of the target angle $\bar{\theta}_i$ of the ith trunk segment; σ_{LB}, σ_{BB}, γ are the weights of feedback gain. The normal force feedback generates lateral bending, where the trunk joint bends left when the left leg obtains the normal force and vice versa. The angle feedback makes the joint angle follow the actual angle of the anterior trunk joint. The target angle is achieved by PD control.

3 Results

We conducted simulation experiments and observed the behavior in two cases with a short trunk (9 joints) and a long trunk (21 trunk joints), as shown in Fig. 2, with the same control parameters as follows: $\omega = 2.5$ [rad/s], $\sigma_{\mathrm{LL}} = 0.1$ [rad/Ns], $\sigma_{\mathrm{BL}} = 2.2$ [rad/Nms], $\sigma_{\mathrm{LB}} = 1.0$ [rad/s], $\sigma_{\mathrm{BB}} = 8.0$ [1/s], $\gamma = 0.1$ [1/N]. The color of the simulated model indicates trunk flexion where the green trunk joint bends left and the white joint bends right. The orange foot is on the ground and the white foot is off the ground (Fig. 3).

Figure 2a showed that the short trunk model exhibited a walking gait combined with a traveling wave of lateral bending. The wavelength exceeds two body lengths, and at certain points in time, all trunk joints simultaneously bend in the same direction. Figure 2b showed that the long trunk model also exhibited a walking gait combined with a traveling wave of lateral bending. The wavelength approximates one body length, as indicated by one complete wave observed along the trunk. The wavelength variation likely comes from the first-order delay of axial joint control (Eq. 4). The first-order delay affects the phase delay of axial bending, and the wavelength is related to the number of body segments. These results demonstrated that the proposed model flexibly changes the trunk movement in response to the body length, similar to actual animals, and suggested that different axial–limb coordination patterns between species can be generated from a single control principle.

Acknowledgements

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