Walk-Trot-Gallop Transition with Spinal Flexion in a Quadruped Model

Shura Suzuki[1], Goku Sawada[1, 2], Kotaro Yasui[1, 3], Akira Fukuhara[1], 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 change their gait patterns in response to speeds, such as walk, trot and gallop [1]. Previous studies have considered that gait transitions contribute to energy efficiency [2] or locomotor stability [3]. Understanding the control mechanism underlying speed-dependent gait transition contributes to developing the control principle providing legged robots with animal-like agility.

Quadruped gaits involve coordinated movements of legs, trunk, head and tail. This sophisticated behavior is mainly controlled by a distributed control system comprising of central pattern generators (CPGs) and peripheral sensory feedback [4]. Modeling studies presented that CPG-based controller with local sensory feedback can coordinate four-leg movements and achieve speed-dependent gait transition [5]. However, the whole-body coordination mechanisms in speed-dependent gait transition remain elusive.

This study investigated the whole-body coordination mechanisms in speed-dependent gait transitions through mathematical modeling and simulations. This paper proposes a quadruped model that generates speed-dependent gait transitions incorporating trunk movements. The simulation results demonstrated that local communication of sensory information achieved self-organized movements and walk-trot-gallop gait transition.

2 Model

We present a simple quadruped model to investigate a distributed control mechanism that coordinates trunk and four-leg movements. We adopted a two-dimensional model in the sagittal plane on flat terrain as shown in Fig. 1. This robot model consists of a trunk, and four legs. The trunk comprises three chained rhombic structures formed by mass points with passive spring-damper connections. The pairs of trunk actuators regulate the angles between rhombic structures. Each leg has two actuators, one for rotation and another for linear motion.

The controller has a decentralized structure. Each trunk actuator is controlled by ground reaction force (GRF) feedback from the nearest limbs, while each limb actuator is controlled by a phase oscillator, as a CPG model, incorporating dual sensory feedback from local GRF and body trunk actuation. The nearest trunk and limb controller share the sensory information mutually, and the bidirectional sensory feedback generates adaptive trunk–limb coordination.

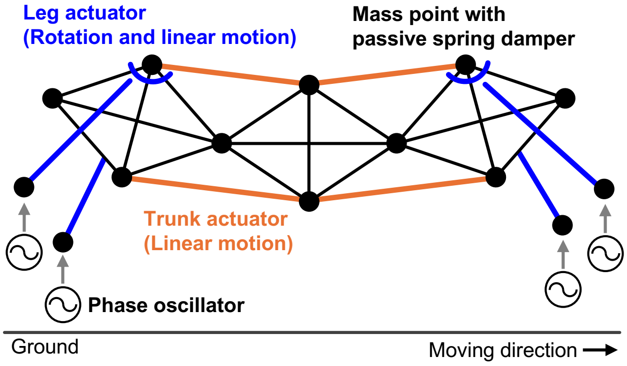


Figure 1: Proposed quadruped model.

The target length of the trunk actuator is determined by GRFs and achieved by proportional-derivative (PD) control.

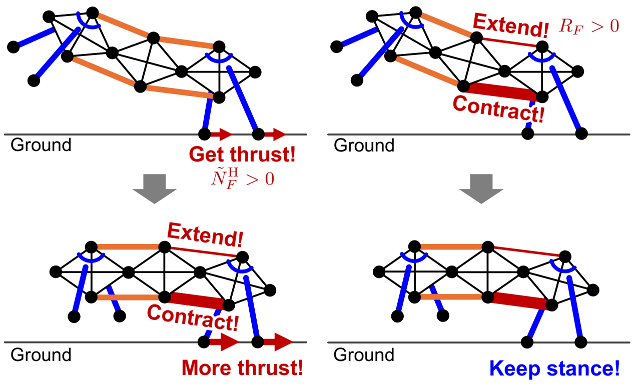
$$\bar{l}_F^{\mathrm{D}} = l_0^{\mathrm{B}} + \sigma_{\mathrm{LB}}\tilde{N}_F^{\mathrm{H}}, \qquad \bar{l}_F^{\mathrm{V}} = l_0^{\mathrm{B}} - \sigma_{\mathrm{LB}}\tilde{N}_F^{\mathrm{H}}, \tag{1}$$

$$\bar{l}_H^{\mathrm{D}} = l_0^{\mathrm{B}} - \sigma_{\mathrm{LB}}\tilde{N}_H^{\mathrm{H}}, \qquad \bar{l}_H^{\mathrm{V}} = l_0^{\mathrm{B}} + \sigma_{\mathrm{LB}}\tilde{N}_H^{\mathrm{H}}, \tag{2}$$

$$\tilde{N}_p^{\mathrm{H}} = \max[0, \tanh(\gamma N_{p,L}^{\mathrm{H}})] + \max[0, \tanh(\gamma N_{p,R}^{\mathrm{H}})], \tag{3}$$

where $\bar{l}_F^{\mathrm{D}}$ and $\bar{l}_F^{\mathrm{V}}$ are the target length of fore dorsal and ventral trunk actuators, and $\bar{l}_H^{\mathrm{D}}$ and $\bar{l}_H^{\mathrm{V}}$ are the target length of hind dorsal and ventral trunk actuators, respectively; l_0^{B} represents a neutral length of trunk actuator and σ_{LB}, γ are the weights of feedback gain, $N_{p,q}^{\mathrm{H}}$ denotes thrust component of GRF at the leg, where p indicates fore-hind position (F, H) and q indicates left-right position (L, R); The variable $\tilde{N}_p^{\mathrm{H}}$ is related to the leg thrust information at p side. The GRF feedback generates spinal flexion, as shown in Figure 2a.

The limbs are also controlled by PD control and the target position is determined by a phase oscillator implemented in each limb (Fig. 1),



(a) Limb-to-body feedback (b) Body-to-limb feedback

Figure 2: Bidirectional feedback between body trunk and limb.

$$\bar{l}_{p,q} = \begin{cases} l_0^{\mathrm{L}} - l_{\mathrm{sw}} \sin\phi_{p,q} & (0 \le \phi_{p,q} < \pi) \\ l_0^{\mathrm{L}} - l_{\mathrm{st}} \sin\phi_{p,q} & (\pi \le \phi_{p,q} < 2\pi) \end{cases} \tag{4}$$

$$\bar{\theta}_{p,q} = -\theta_{\mathrm{amp}} \cos\phi_{p,q}, \tag{5}$$

where $\bar{l}_{p,q}$ and $\bar{\theta}_{p,q}$ denotes the target length and angle of the leg actuator for each leg ($p \in \{F, H\}$: fore/hind, $q \in \{L, R\}$: left/right); l_0^{L} is the neutral length of the leg actuator and l_{sw} and l_{st} are the amplitude of leg linear actuator in swing and stance phase, respectively. The variable $\phi_{p,q}$ is the oscillator phase and θ_{amp} is the amplitude of leg rotary actuator. These trigonometric equations generate elliptical trajectories for each leg.

The time evolution of the oscillator phase is described as follows:

$$\dot{\phi}_{p,F} = \omega - \sigma_{\mathrm{LL}} N_{p,F}^{\mathrm{V}} \cos\phi_{p,F} - \sigma_{\mathrm{BL}} R_F \cos\phi_{p,F}, \tag{6}$$

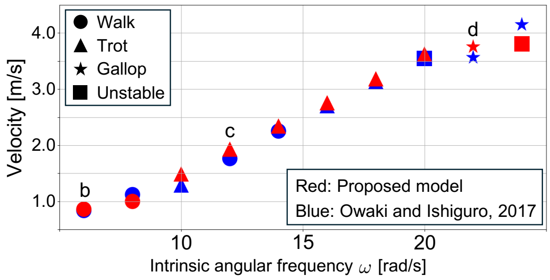
$$\dot{\phi}_{p,H} = \omega - \sigma_{\mathrm{LL}} N_{p,H}^{\mathrm{V}} \cos\phi_{p,H} + \sigma_{\mathrm{BL}} R_H \cos\phi_{p,H}, \tag{7}$$

$$R_F = f_F^{\mathrm{V}} - f_F^{\mathrm{D}} \quad R_H = f_H^{\mathrm{V}} - f_H^{\mathrm{D}}, \tag{8}$$

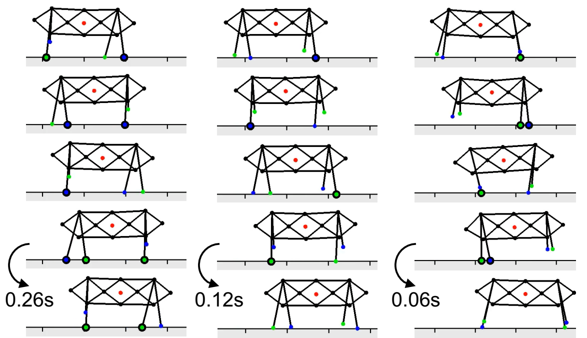
where ω represents the intrinsic angular velocity of the oscillator, and σ_{LL} and σ_{BL} are the weights of feedback gain; $N_{p,q}^{\mathrm{V}}$ is the normal component of GRF, and R_p is the balance of dorsal f_p^{D} and ventral f_p^{V} spinal actuation forces on the p side. The second term on the right side of Eqs. 6 and 7 is local sensory feedback that coordinates speed-dependent interlimb coordination [5]. The third term on the right side of Eqs. 6 and 7 modify the oscillator phase in response to body actuation. For example, when the fore trunk bends ventrally ($R_F > 0$), the fore legs remain stance phase as shown in Fig. 2b. The bidirectional feedback between the trunk and limb, as shown in Figure 2, generates adaptive trunk–limb coordination.

3 Results

We conducted simulation experiments and observed the speed and gait patterns in each intrinsic frequency ω, as shown in Figure 3. In a broader range of parameters, the proposed model is faster than the interlimb coordination control model without spinal flexion [5] (Fig. 3a). The gait pattern changes in response to the speed, such as walk ($\omega = 6.0$, Fig. 3b), trot ($\omega = 12.0$, Fig. 3c), gallop ($\omega = 22.0$, Fig. 3d). Walking gait is the four-beat gait pattern; the feet touch down in the following order: hind, fore, hind, fore, and moderate spinal flexion enhances thrust. Trotting is the two-beat gait pattern; pairs of fore and hind feet were nearly synchronized, and spinal flexion was suppressed relative to other gaits. Gallop is the four-beat gait pattern with two aerial phases; the feet touch down in the following order: hind, hind, fore, fore, and considerable spinal flexion is observed. The unstable gait showed a gallop-like pattern, but the footfall timing is variable in each gait cycle. The instability of the footfall pattern likely comes from the discrepancy between the rhythm of CPGs and the body dynamics.



(a) Speed and gait patterns



(b) walk ($\omega = 6.0$) (c) trot ($\omega = 12.0$) (d) gallop ($\omega = 22.0$)

Figure 3: Simulation results.

The results demonstrate that the proposed model reproduced the speed-dependent gait change, including spinal flexion contributing to speed by tuning a single parameter. The proposed model would potentially serve as an intuitive controller for quadruped robots with spinal flexion, and experimental validation remains as future work. Moreover, elucidating the factors behind biphase gait generation would offer significant insights that enhance our understanding of gait generation in quadrupedal animals.

Acknowledgements

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