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Decentralized Control Mechanisms Underlying Neck–limb Coordination in Horse Walking and Trotting

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1 Introduction

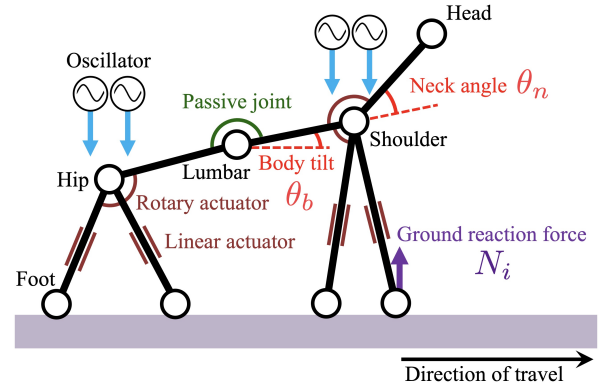
The horse shows a nodding motion, swinging the head up and down, whose rhythm changes in response to locomotion speeds and footfall patterns [1]. At slow walking, the frequency of nodding motions is twice a gait cycle, and at fast galloping, it is once a gait cycle. Interestingly, at trotting with an intermediate speed, the horse does not show an apparent nodding motion. Such speed-dependent neck–limb coordination would contribute to energy-efficient locomotion because horse tends to use the optimal gait pattern to minimize energy consumption [2]. However, the underlying control principle of this coordination remains elusive.

Thus far, we have attempted to understand the mechanisms of neck–limb coordination using mathematical modeling and simulations. Our previous models demonstrate that nodding motions contribute to efficient walking [3] and smooth gait transition [4]. However, these models did not explain the speed-dependent neck–limb coordination mechanisms. To address this issue, in this paper, we proposed a decentralized control that utilizes the body pitch tilt to modulate the neck and limb movements. The body tilt feedback establishes a proper relationship between the neck and limbs indirectly. The simulation results showed that the proposed model generates horse-like walking and trotting gaits.

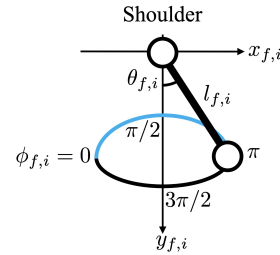
2 The Model

2.1 Body Structure

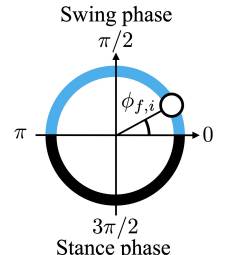
We employ a quadruped robot body to walk in a sagittal-plane on flat terrain as shown in Fig. 1a. This robot model consists of a trunk, head and four limbs (i.e. two forelimbs and two hindlimbs). The trunk has a single pitch joint (lumbar joint), and connects to the head, forelimbs and hindlimbs with a single pitch joint (neck, shoulder and hip joint), respectively. Each limb has two degrees of freedom, one for rotation and one for linear motion. The body dynamics is described as a mass-spring-damper system, where point-masses are located at the head, shoulder, lumbar, hip, fore feet and hind feet. The linear spring between the head, lumbar, shoulder and hip point-masses are defined to be stiff to ensure that the links remain rigid.



(a)



(b)



(c)

Figure 1: Body model, (a) overview, (b) foot trajectory and (c) phase oscillator for limb control.

2.2 Control Algorithm

The limbs are controlled by proportional-derivative (PD) control so that they approach their target positions. The target position is determined by the phase oscillator implemented in each limb (Figs. 1b and c). The time evolution of the oscillator phase is described as follows:

$$\begin{aligned}\dot{\phi}_i^f &= \omega - \sigma_{LL} N_i \cos \phi_i^f + \sigma_{BL} \dot{\theta}_b \cos \phi_i^f \\ \dot{\phi}_i^h &= \omega - \sigma_{LL} N_i \cos \phi_i^h - \sigma_{BL} \dot{\theta}_b \cos \phi_i^h,\end{aligned}\quad (1)$$

where ϕ_i^f and ϕ_i^h denote the oscillator phases for forelimbs and hindlimbs, respectively. The subscript i denotes the index of the left and right limbs ($i = 0, 1$). The variable ω represents intrinsic angular velocity of oscillators, σ_{LL} and σ_{LB} are the weights of sensory feedback, N_i represents the normal force from the ground detected at the foot tip, and θ_b

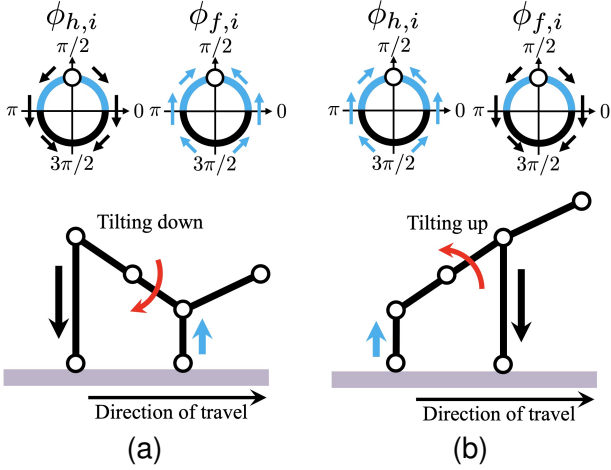


Figure 2: Body-to-limb feedback, (a) when body tilting down ($\dot{\theta}_b > 0$), (b) when body tilting up ($\dot{\theta}_b < 0$).

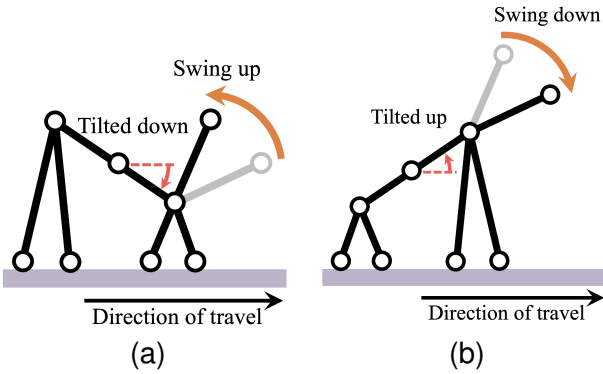


Figure 3: Body-to-neck feedback, (a) when body tilted down ($\theta_b > 0$), (b) when body tilted up ($\theta_b < 0$).

is the angle of the body tilt.

The second term on the right side of Eq. (1) is local sensory feedback due to normal forces, proposed by Owaki et al. [5] and it generates interlimb coordination in response to the intrinsic rhythm of oscillator.

The third term on the right side of Eq. (1) is the body-tilt feedback. When the body tilting down ($\dot{\theta}_b > 0$), the oscillator phases of forelimbs are modulated toward $\pi/2$ to contract the limbs and the oscillator phases of hindlimbs are modulated toward $3\pi/2$ to extend the limbs (Fig. 2a). This phase modification enables the limbs to avoid receiving excessive loads.

The neck joint is controlled as follows:

$$\tau_n = -k_p \theta_n - k_d \dot{\theta}_n - \sigma_{BN} \theta_b, \quad (2)$$

where the first and second terms on the right side of Eq. (2) originate from the passive spring and damper, respectively. The third term on the right side of Eq. (2) is the body tilt feedback. When the body tilted down ($\theta_b > 0$), the neck swings up ($\tau_n < 0$) and vice versa (Fig. 3). Due to the feedback, the head moves in anti-phase to the body tilt.

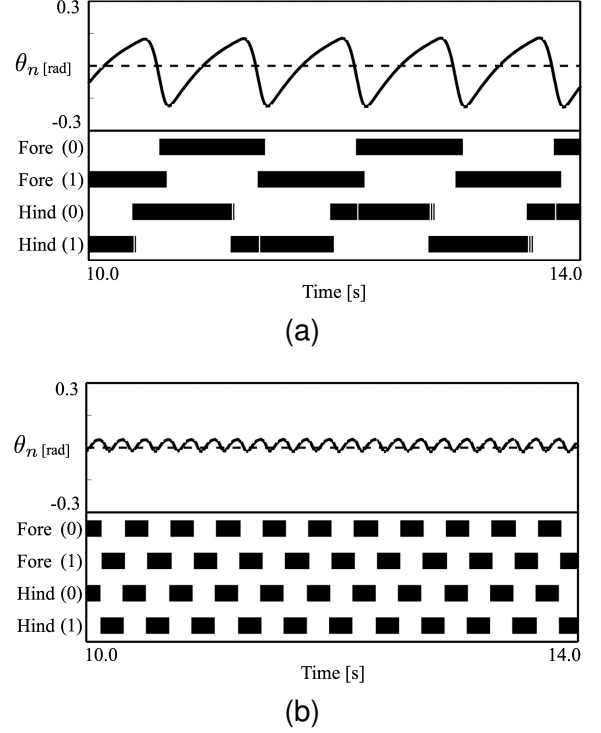


Figure 4: Gait patterns, (a) $\omega = 4.0$, (b) $\omega = 17.0$.

3 Simulation Result

We conducted the simulation experiments and observed the gait patterns (Fig. 4) that show the time evolution of the neck angle and the duration of the foot on the ground. When lower frequency of the oscillator $\omega = 4.0$, the model shows a walking gait with twice nodding a gait cycle. When higher frequency of the oscillator $\omega = 17.0$, the model shows a trotting gait without an apparent nodding. Thus, the proposed model reproduced the neck–limb coordination in response to locomotion speeds and gait patterns.

Acknowledgements

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