Gait Transition of Quadruped Robot without Interlimb Neural Connections

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1 Introduction

Quadrupeds exhibit versatile gait patterns (walk, trot, pace, bound, etc.) in response to locomotion speed [1, 2]. These locomotor patterns are generated via the coordination between limb movements, *i.e.*, *interlimb coordination*. However, the interlimb coordination mechanism for the generation of such locomotor patterns requires further investigation because it has not been clarified thus far.

Well-known experiments using decerebrated cats [3] have provided us with important insights into the locomotion of quadrupeds, and the results indicate that locomotion is controlled in part by an intraspinal neural network called the *central pattern generator* (CPG) [4]. These biological findings have encouraged many researchers to investigate the self-organized locomotor patterns of quadrupeds, and various types of CPG network models have been proposed [5]-[7]. This forms the basis for current control paradigms of interlimb coordination. However, these control paradigms have limitations because they ignore the effect of body dynamics and environment on the resulting locomotor patterns. Hence, the interlimb neural connections have been designed on a completely ad-hoc basis.

To address these issues, we propose an alternative control paradigm based on a CPG model. Animal locomotion is generated not merely from neural systems but also from the close interaction between the neural system, the musculoskeletal system, and the environment [8]. Therefore, we hypothesize that interlimb coordination relies more on physical (or nonneural) interaction among leg movements generated by body dynamics than on interlimb neural communication. In this study, we present an unconventional CPG model that consists of four decoupled oscillators with only local force feedback in each leg. In addition, we construct a quadruped robot and experimentally verify the validity of the proposed control scheme using the constructed quadruped robot. We find that the robot exhibits surprisingly smooth gait transition between walk and trot gaits by changing only locomotion speed.

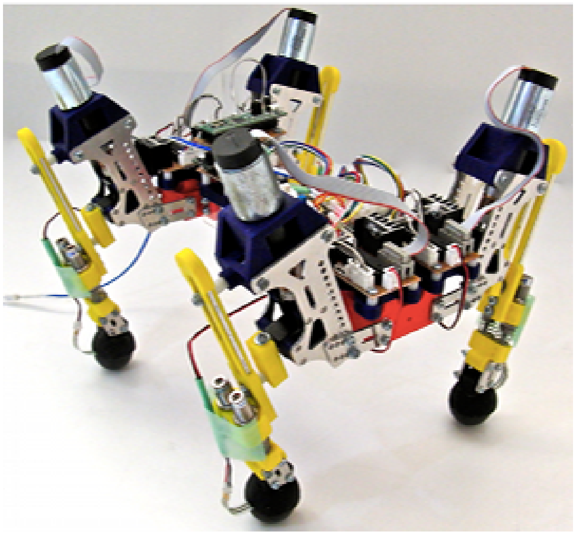


Figure 1: Constructed quadruped robot, *OSCILLEX 2*.

2 Quadruped robot

To design a quadruped robot based on a minimalist approach, we employ three major simplifications: (i) A *phase oscillator* is used as the basic component of the CPG model; (ii) A simple leg structure (no knee or ankle) allows us to ignore the *intralimb coordination* in each leg, *i.e.*, the coordination between joint movements within each leg; and (iii) The interlimb neural connection between the oscillators is ignored in order to generate interlimb coordination by exploiting only local sensory information about the force in each leg, thereby yielding physical interactions among leg movements.

Figure 1 shows the complete structure of the constructed quadruped robot. The robot consists of a backbone segment and four leg segments with microprocessors. The total weight of the robot is approximately 1.8 kg. The lengths of the backbone and each leg are 0.26 m and 0.18 m, respectively. The backbone has roll torsional springs and a pitch torsional spring. These mechanisms allow the backbone to deform according to the terrain when the robot is in motion.

Each leg segment has one DC motor (Maxon Japan Corporation; RE-max24, MR, and GP22C) and is equipped with a gear box (Kyouiku Gear Manufacturing CO. Ltd.; B-BOX(BS)BS35L-001) to incline the rotational axis of the DC motor at 90° from the original one, as shown in Fig. 1. Crank mechanisms convert the rotational motion of the DC motor into the leg motion in *stance* and *swing* phases. To detect ground reaction forces (GRFs), we attached pressure sensors (Interlink Electronics Inc.; FSR402) to the feet of the robot. Each leg has a microprocessor (AVR ATmega 328P) for computing the phase of the corresponding oscillator. By using proportional-integral-derivative (PID) control, we control each DC motor such that its rotational angle corresponds to the oscillator phase ϕ_i. Note that the ith leg tends to lift off the ground (*swing phase*) when $0 \leq \phi_i < \pi$, whereas it tends to remain on the ground to support the body (*stance phase*) when $\pi \leq \phi_i < 2\pi$.

For rhythmic movement of the legs, we introduce a phase ϕ_i in the oscillator of the CPG for each leg. For simplicity, we design each leg such that it is controlled by only one of the oscillators in our CPG model. To ensure that interlimb coordination relies more on physical (or nonneural) interaction, we do not consider the direct interactions (*i.e.*, neural connections) among the oscillators of the CPG; instead, we focus on local sensory feedback from the force sensor in each foot. We describe each phase oscillator as

$$\dot{\phi}_i = \omega - \sigma N_i \cos\phi_i, \tag{1}$$

where ω is the intrinsic angular velocity, σ is a positive constant that denotes the magnitude of the feedback to the corresponding oscillator, and N_i is the GRF acting on the ith leg, which is detected by the pressure sensor in each foot.

To understand the physical effect of local sensory feedback, we note that the phase is mostly modulated toward $3\pi/2$ in the stance phase when $N_i > 0$ because of the influence of local sensory feedback (Fig. 2). For example, if a leg (*e.g.*, the right hind (RH) leg) continues to bear a load ($N_i > 0$) at the end of its stance phase ($\phi_i \approx 2\pi$), a phase delay is introduced, as shown in Fig. 3 (a), to prevent the robot from entering an unstable two-legged-support state. This phase delay, which is introduced when $\sigma N_i \cos\phi_i > 0$, allows sufficient time for another leg (*e.g.*, the right fore (RF) leg) to enter the stance phase. As the other leg begins to support the body, the load on the RH leg decreases; consequently, the feedback effect decreases, allowing the RH leg to enter the swing phase (Fig. 3 (b)). Therefore, the local sensory feedback, which allows the legs to maintain the stance phase by exploiting only the local force sensory information N_i obtained from each foot, maintains an appropriate relationship between the phases of the decoupled oscillators and the leg movements.

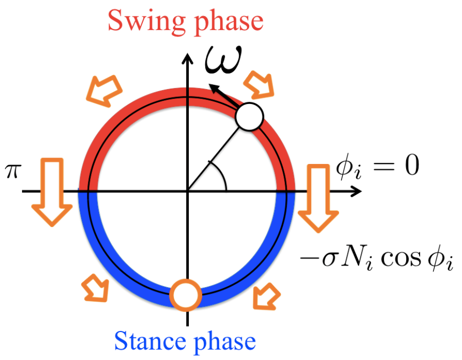
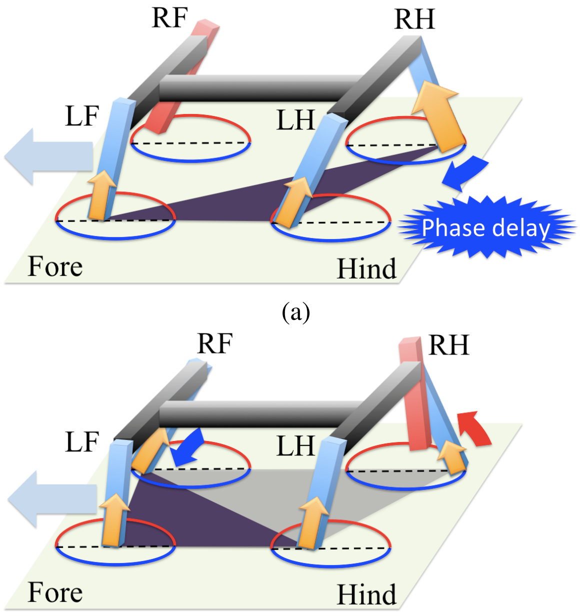


Figure 2: Schematic of the dynamics in the phase oscillator depending on local sensory feedback.



(a)

(b)

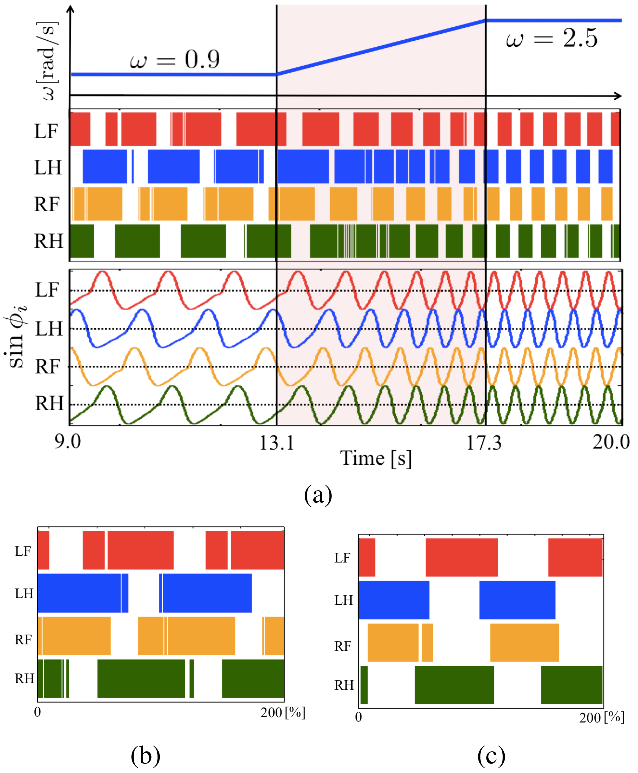
Figure 3: Schematic showing the physical effect of local sensory feedback.

3 Gait Transition between Walking and Trotting

To verify the validity of the proposed control scheme, we conducted experiments using the quadruped robot, and we investigated the effect of local sensory feedback on the gait transition between walking and trotting.

3.1 From walking to trotting

Figure 4 (a) shows the experimental results of the transition from walking to trotting by changing ω. In this figure, the top graph shows the profile of ω, the middle graph shows the gait diagram, and the bottom graph shows the corresponding phases. In the gait diagram, the colored regions represent the stance phase, which is distinguished by using the threshold data value from the pressure sensor. In this experiment, we changed ω from 0.9 to 2.5 rad/s for $t = 13.1$ to 17.3 s (indicated by the shaded region). Figures. 4 (b) and (c) show steady walk gait (ω = 0.9 rad/s) and trot gait (ω = 2.5 rad/s) over two cycles. As indicated by the figures, the proposed control scheme allows the robot to achieve a rapid and stable walk-trot gait transition by only changing parameter ω.



(a)

(b)

(c)

Figure 4: (a) Experimental results showing the transition from walking to trotting by changing ω. (b) Steady walk gait $\omega = 0.9$ rad/s. (c) Steady trot gait $\omega = 2.5$ rad/s.

3.2 From trotting to walking

Figure 5 shows the experimental results of the transition from trotting to walking by changing ω (ω is changed from 2.5 to 0.9 rad/s for $t = 10.5$ to 14.7 s). The results indicate that the proposed model exhibits a spontaneous transition from trotting to walking.

4 Open questions

It is interesting to note that our model exhibits stable motion according to the control parameter ω without any neural communication among the oscillators. One plausible explanation for these results is that the proposed local sensory feedback system allows each leg to recognize the positional relationship of all the other legs, *i.e.*, the manner in which the legs support the body at a particular moment, without incurring high computational costs. For example, the shift from the stance phase to the swing phase of the jth leg influences the phase of the ith oscillator ($j \neq i$) because of the increase in N_i. This mechanism enables appropriate physical communication among the oscillators in the robot body without neural communication.

In the future, we intend to clarify the mechanism of gait transition. Although we observed only walk-trot gait transition in the present study, we intend to further investigate the proposed model, and we expect accurate gait patterns, such as a pacing or galloping, to be spontaneously exhibited according to the locomotion speed, the properties of the robot body, and the environment. We expect these findings to provide new insights into the generation of highly adaptive and resilient quadruped locomotion.

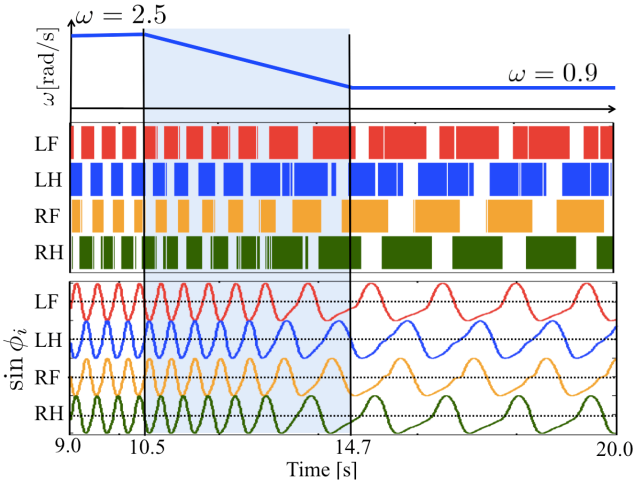


Figure 5: Experimental results showing the transition from trotting to walking by changing ω.

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