Gait Transition and Adaptation Using the Spinal Cat Model

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1 Introduction

It has been generally accepted that adaptive motion of animals emerges through the interaction among the central neural system, the body, and environment. We intend to understand mechanisms in the emergence of adaptive motion at the level of sensorimotor functions by the constructive approach. Since we are interested in how the spinal cord of cats utilizes their body natural dynamics, we propose the spinal cat model and simulate the gait generation, transition and adaptation. The hat ˆ, the bar ¯, and the tilde ˜ symbols are respectively used to represent the nominal, the measured, and the reference values of a single variable. The leg index i is often eliminated if it is obvious. The details and related movies can be seen at *http://www.robotlocomotion.kit.ac.jp/*

2 Leg Controller (LC) As the Spinal Cat Model

The LC (Figure 1) is the spinal cat model consisting of a CPG and an Output Motor Stage (OMS) [1]. The CPG is divided into the RG (Rhythm Generator) and the PF (Pattern Formation). The PF is implemented as the trajectory generation of the leg tip position and the inverse kinematics to calculate the reference angle of joints. The PD-controller at the joints simply corresponds to the OMS. As a result, each leg steps in the pitch plane.

Each leg has two phases, the swing (*sw*) and the stance (*st*). The *sw*-to-*st* and *st*-to-*sw* transitions are touch-down (TD) and lift-off (LO), respectively. The gait is determined by the time of TD and LO. As the role of afferent inputs, it was shown in decerebrate cats that hip flexion (Pearson 2005) contributes to the timing of TD and that both hip extension (Grillner 1978) and leg unloading (Pearson 1980) contribute to the timing of LO. Referring to [2, 3] utilizing such neurophysiological knowledge, we newly designed an original RG (**RG**∗) (Kodono 2023) for the transition between *sw* and *st*. In Figure 1, RG∗ determines TD by Eq.(3) and LO by Eq.(4).

RG∗ is associated with the phase ϕ for convenience sake of implementing the trajectory generation, but it has no eigenfrequency since the transition to *sw* should be delayed until Eq.(4) is satisfied. In this sense, RG∗ is a *non-oscillator with phase dynamics*, while eliminating the important property seen in fictive locomotion with no afferent [1]. RG∗ itself acts as a state machine. However, if there exists one oscillation such as rolling motion, RG∗ is entrained with this oscillation, since rolling motion influences leg unload-

ing. In addition, RG∗s influence rolling motion by TD and LO of legs. Consequently, being entrained mutually, each RG∗ generates the rhythm with the specific duty ratio and the same frequency with a rolling motion. Here, the rhythm emerges utilizing the natural dynamics of the body. Such interaction seems to be *Reflex Chain*, where once initiated motion continues by the chain of spinal reflexes.

Eq.(3) represents the TD decision and avoidance of early TD. The hip flexor activity (α_F) in Eq.(4) is defined using hip flexion ($\bar{r}_{flx}$), hip extension ($\bar{r}_{ext}$) and leg load ($\bar{f}_n$).

$$\alpha_F^i = C_{hip} \cdot \{\max(\bar{r}_{ext}^i, 0) - \max(\bar{r}_{flx}^i, 0)\}/(\hat{D}/2)$$
$$+ C_{frc} \cdot \{\hat{\chi}_{LO} - \min(\bar{f}_n^i, \mu\hat{\chi}_{LO})\} / \hat{\chi}_{TD} \qquad (15)$$

where i is the leg index, $\bar{r}_{flx} = (\bar{r})_x$, $\bar{r}_{ext} = -\bar{r}_{flx}$, r is the leg tip position in Figure 1, $\hat{\chi}_{LO}$ and $\hat{\chi}_{TD}$ are leg load thresholds, and others are constant parameters. In the early stance phase, $\bar{r}_{flx}$ and $\bar{f}_n$ are large, thus inhibiting LO. In the late stance phase, $\bar{r}_{ext}$ is large and $\bar{f}_n$ is small, thus exciting LO.

The inter-leg coordination is employed by using α_F^{cntr} in the LO condition (Eq.(4)), where *cntr* means the contralateral leg. Previous studies [2, 3] showed that such RG∗s network is not necessary for the simple gait generation since the leg load transfer between *cntr*'s caused by rolling motion implicitly coordinates the alternative stepping of the legs. However, the RG∗s network plays an important role in split-belt adaptation described in Section 3.

In addition, in order to simulate the split-belt adaptation of spinal cats [4], we employ the following two responses in the detection of the large hip extension of the stance leg (the backward stretched leg: *bstr*). Those responses being inspired by the stretch reflex on the hip flexor of *bstr* and the crossed extension reflex on the hip extensor of *cntr* are named SAS (self adjustment of the swing phase duration) and CAS (contralateral adjustment of the swing phase duration), respectively. SAS and CAS are defined by Eq.(16).

$$\tilde{\omega}^{bstr} = \hat{\phi}_{AEP}/(\hat{T}_{sw}+g_{sas} \cdot \delta_{ext}^{bstr}), \quad \tilde{\omega}^{cntr} = \hat{\phi}_{AEP}/(\hat{T}_{sw}-g_{cas} \cdot \alpha_F^{bstr})$$
$$(16)$$

where $\delta_{ext}^{bstr}(= \bar{r}_{ext}^{bstr} - r_{xs})$ is the degree of hip extension in LO, $r_{xs}(=0.4\hat{D})$ is the threshold, and g_{sas} & g_{cas} are the positive gain constants.

3 Simulation of Hindlimbs Locomotion on Treadmill

In order to the simulate locomotion of spinal cats with hindlimbs on the treadmill [1, 4] as similarly as possible, we constructed a biped model with the 6-axes fixture and
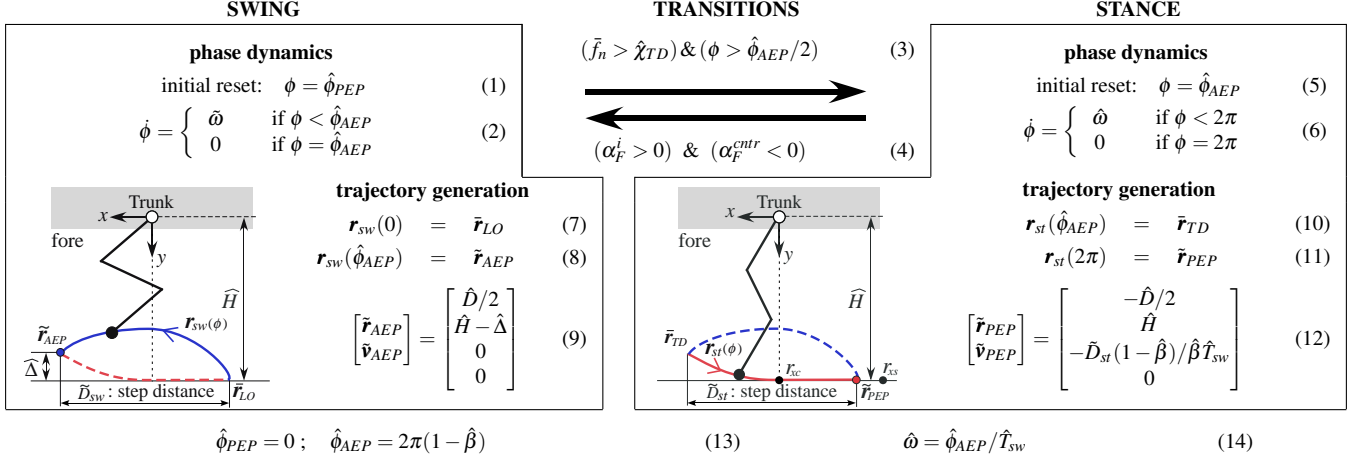
Figure 1: LC [3]. The positions of the leg tip at the *sw*-to-*st* and *st*-to-*sw* transition are named AEP & PEP (anterior & posterior extreme position). $\hat{\Delta}$ is 0. For nominal parameters, when we determine the duration of the swing phase: $\hat{T}_{sw}$ and the duty ratio: $\hat{\beta}$, we can obtain $\hat{\phi}_{AEP}$ and $\hat{\omega}$ from Eqs.(13), (14). As measured values, $\bar{T}_{sw}$ is dependent on the TD timing determined by Eq.(3), and $\bar{T}_{st}$ is dependent on the LO timing determined by Eq.(4), where α_F is defined by Eq.(15). When one of responses is activated by timing described in Section 2, the reference value: $\tilde{\omega}$ in Eq.(2) is recalculated by Eq.(16). Consequently, the newly generated trajectory changes the TD timing and $\bar{T}_{sw}$. While not being activated, the reference is equal to the nominal.

carried out two simulations (Kodono 2023). The fixation condition (free, spring&damper or firmly fixed) in each axis of the fixture depends on each simulation.

Spinal cats [1, 5] showed the walk-to-run gait transition according to the increase of the belt speed, where they simultaneously showed the gait transition from 'out of phase' to 'in phase.' By using RG* without the inter-leg coordination by α_F^{cntr}, we successfully simulated such autonomous walk-to-run gait transition (Figure 2(a)), where rolling motion generated the rhythm of locomotion, naturally generated pitching motion of the trunk caused the transition by affecting load (f_n) of each leg, and RG* played an important role behind such emergence of the gait. While using constant nominal parameter values, measured values of the important indexes of legged locomotion ($\bar{T}_{st}$, $\bar{\beta}$, frequency, and PEP: $(\bar{r}_{LO})_x$) changed according to locomotion speed emergently as the result of interaction with the environment. The gait transition in phases is under investigation.

Spinal cats [4] could show the symmetrical gait while keeping the TD phase difference be almost π in tied-belt locomotion and even in normal split-belt locomotion. However, in slower split-belt locomotion, spinal cats could not show the symmetrical gait, but often showed the gait switch from the single-step to the double-steps of the fast-leg. By employing two responses into RG* , with fixed values of parameters, we successfully simulated such symmetrical gait in normal split-belt locomotion, and the gait switch to the double-steps in slower split-belt locomotion (Figure 2(b)).

4 Discussion and Future Work

Please note that we designed the CPG of the LC such that $\bar{T}_{sw}$ and AEP: $(\bar{r}_{TD})_x$ were kept almost constant against the change of locomotion speed in similar to that of an intact cat [1]. Other similarities in spinal cats [1,5] and in the simulation such as the emergence of the body pitching and the

decrease of PEP in the walk-run transition were the result of natural dynamics. By employing the inter-leg coordination by α_F^{cntr} and CAS into RG*, we obtained very similar gait patterns ($\bar{T}_{sw}$, $\bar{T}_{st}$, and AEP&PEP) according to the speed ratio to those in split-belt locomotion of spinal cats [4]. As the result of these dynamics simulations, it was confirmed that the design concept of RG* works well, and that the proposed spinal cat model has the validity. These results might indicate such possibility that the **basic** locomotion pattern of an intact cat is emergently generated in the spinal cord primarily by afferent inputs.

As future work, we intend to confirm the role of the spinal cord by simulating that the MLR output just increases the propulsive force [1] to increase locomotion speed in the gait transition, and that the cerebellum contributes by learning (Yanagihara 1993) to the adjustment of the TD timing (Aoi 2021) in the split-belt adaptation.
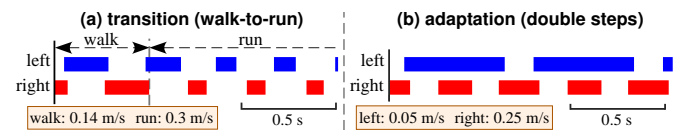

Figure 2: Gait diagrams in the simulations.

References

[1] G.N. Orlovsky, T.G. Deliagina and S. Grillner, "Neural control of locomotion," Chap.10&11, pp.62–204, *Oxford Univ. Press*, NY, 1999.

[2] O. Ekeberg and K. Pearson, "Computer simulation of stepping in the hind legs of the cat: an examination of mechanisms regulating the stance-to-swing transition," *Neurophysiol.*, Vol.94, pp.4256–4268, 2005.

[3] C. Maufroy, H. Kimura *et al.*, "Integration of posture and rhythmic motion controls in quadrupedal dynamic walking using phase modulations based on leg loading/unloading," *Auto. Robots*, Vol.28, pp.331–353, 2010.

[4] A. Frigon, E. Desrochers, Y. Thibaudier *et al.*, "Left-right coordination from simple to extreme conditions during split-belt locomotion in the chronic spinal adult cat," *Physiol.*, Vol.595, No.01, pp.341–361, 2017.

[5] H. Forssberg, S. Grillner, J. Halbertsma *et al.*, "The locomotion of the low spinal cat. II. Interlimb coordination," *Acta Physiol. Scand.*, Vol.108, pp.283–295, 1980.