Stable Dynamic Walking of a Quadruped Robot "Kotetsu" against Perturbations on Posture and Rhythmic Motion

Christophe Maufroy[1] and Hiroshi Kimura[2]

[1]Locomotion Lab., University of Jena, Jena, Germany
(Tel: +49-3641-9-45743; E-mail: christophe.maufroy@uni-jena.de)
[2]Division of Mechanical and System Engineering, Kyoto Institute of Technology, Kyoto, Japan
(Tel: +81-75-724-7352; E-mail: kimura61@kit.ac.jp)

Abstract: We are developing a general quadrupedal locomotion controller by using a neural model involving a CPG (Central Pattern Generator) utilizing normal ground reaction force (leg loading) sensory feedback for both rolling motion (posture) and gait (rhythmic motion) control. In this abstract, we report the results of experiments using a quadruped robot "Kotetsu" in order to verify the results of our previous simulation study. Movies and detailed specifications of the robot can be seen at: *http://robotics.mech.kit.ac.jp/kotetsu/*.

Keywords: Quadruped Robot, Leg Unloading, Phase Modulation, CPG, Lateral Perturbation

1. INTRODUCTION

It is known about the stance-to-swing transition in animals that the transition is initiated by hip extension in decerebrate cats[1]. It is also known that the stance phase is indeterminately prolongated as long as the leg loading is over a given threshold[2]. Being motivated by the study[3], we showed in simulations that rhythmic motion of each leg is achieved as a result of the phase modulations based on leg unloading and leg coordination (gait) emerges allowing to realize dynamic walking in the low- to medium-speed range[4]. In addition, we reported the result of first experiments using a quadruped robot "Kotetsu" while comparing to the result of simulations[5]. Recently, we considered perturbations to rhythmic motion such as split-belt treadmill walking and obtained primitive results[6] combining leg unloading and hip extension for the stance-to-swing phase transition referring to[3]. In this abstract, we report on integration of posture and rhythmic motion control based on leg unloading and show experimental results using Kotetsu against perturbations to posture (rolling motion).

2. PHASE MODULATIONS BASED ON LEG UNLOADING

2.1 Single Leg Controller

Each leg is actuated by a control unit called the Leg Controller (LC). Each LC is associated with a simple oscillator with a constant and unitary amplitude and a variable phase ϕ^i, where i is the leg index[1]. The desired trajectories are calculated using the oscillator phase ϕ^i. The positions of the foot at the swing-to-stance and stance-to-swing transition are named as AEP (anterior extreme position) and PEP (posterior extreme position). We consider dynamics of an oscillator phase ϕ^i, where $\dot{\phi}^i = \hat{\omega} + \omega_{mod}$ (ω_{mod}=0 in the stance phase).

Resetting of ϕ^i is employed so that $\phi^i = \hat{\phi}_{AEP}$ and $\phi^i = \hat{\phi}_{PEP}$ at the onset of stance and swing phases, respectively. The phase transition is initiated by using normal ground reaction force: f_n^i (leg loading) and force thresholds[3]. That is, [swing-to-stance transition:] $f_n^i > \hat{\chi}_{TD}$ & $\phi^i > \hat{\phi}_{AEP}/2$ and [stance-to-swing transition:] $f_n^i < \chi_{LO}^i$. The force threshold: χ_{LO}^i of hind legs is expressed as follows[2]:

$$\chi_{LO}^{\{LH,RH\}} = \begin{cases} -5(N) & \text{if } \phi^i \leq \phi_{AEP} + \pi/2 \\ \hat{\chi}_{LO} & \text{otherwise} \end{cases} \quad (1)$$

χ_{LO}^i of forelegs is described in the next section as ACM.

Rolling motion (lateral posture) can be stabilized by using such leg phase modulations based on leg unloading.

2.2 Ascending Coordination Mechanism (ACM)

In our previous simulation study[4], it was shown that the lateral perturbation preventing alternation of leg loading between contralateral legs caused a conflict between the control of the rhythmic pitching motions of the legs and the posture control in the frontal plane when we employed no explicit inter-leg coordination among LCs. Therefore, we employed the two-fold ACM in order to solve such conflict and confirmed its effectiveness in simulations.

When we implemented such ACM in the control system of Kotetsu, we found in the experiments that a foreleg sometimes caused the stance-to-swing phase transition before the ipsilateral hind leg and the gait shifted to the pace. As the reason of such disorder of phase transitions, we noticed the following:

- Since CoM of the body of Kotetsu is slightly backward than the kinematical center of the body, the leg loading of a foreleg becomes smaller than that of the ipsilateral hind leg.

In order to solve such disorder of phase transitions, we slightly modified the first part of ACM in simulations, which modulates force threshold of the foreleg.

---

[1] Respectively, LH and RH mean for the left and right hind legs, and LF and RF mean for the left and right forelegs. The hat ˆ symbol is used to represent the nominal value of a single variable.

[2] The value: -5 is not important and it works as far as the value is negative.

Consequently, we implemented the following ACM. In eq.(2), firstly the force threshold of the foreleg χ_{LO}^{sF} (where s stands for either R or L) is linearly increased from 0 to $\hat{\chi}_{LO}$ as the phase of the ipsilateral hind leg: ϕ^{sH} increases in order to delay (or inhibit) the stance-to-swing transition of the foreleg (ACM$_{inh}$) and prevent disorder of the phase transition above described. Secondly, χ_{LO}^{sF} is linearly increased from χ_{LO}^{sF} to $\chi_{LO}^{sF} + \hat{\chi}_{ampl}$ as ϕ^{sH} increases to promote (or excite) the stance-to-swing transition of the ipsilateral foreleg (ACM$_{exc}$) and keep alternation of leg loading between contralateral legs against the lateral perturbation. Thirdly, the stance-to-swing transition of the foreleg is inhibited during the stance phase of the ipsilateral hind leg.

$$\chi_{LO}^{sF} = \begin{cases} \tau_{acm} \cdot \hat{\chi}_{LO} & \text{if } \phi^{sH} < \hat{\phi}_{acm} \\ \hat{\chi}_{LO} + \chi_{mod} & \text{if } \phi^{sH} \in [\hat{\phi}_{acm}; \hat{\phi}_{AEP}] \\ -5(N) & \text{if } \phi^{sH} > \hat{\phi}_{AEP} \end{cases} \tag{2}$$

$$\chi_{mod} = \tau_{mod}(\phi^{sH}) \cdot \hat{\chi}_{ampl}$$

where $\hat{\phi}_{acm} = 0.5 \cdot \hat{\phi}_{AEP}$, $\tau_{acm} = \phi^{sH} / \hat{\phi}_{acm}$ and

$$\tau_{mod}(\phi) = (\phi - \hat{\phi}_{acm})/(\hat{\phi}_{AEP} - \hat{\phi}_{acm}).$$

In eq.(3), ϕ_{LO}^{sH} is the LC phase of the hind leg at the moment when the foreleg transits to the swing phase. If ϕ_{LO}^{sH} is greater than $\hat{\phi}_{acm}$, it means that the transition to the swing phase of the foreleg is delayed. Therefore, we make the swing motion of the foreleg become faster in order to compensate such delay of the transition (ACM$_{\omega}$).

$$\omega^{sF} = \hat{\omega} + \omega_{mod}^{sF} \tag{3}$$

$$\omega_{mod}^{sF} = \begin{cases} 0.5 \cdot \tau_{mod}(\phi_{LO}^{sH}) \cdot \hat{\omega} & \text{if } \phi_{LO}^{sH} \in [\hat{\phi}_{acm}; \hat{\phi}_{AEP}] \\ 0 & \text{otherwise} \end{cases}$$

3. RESULTS OF EXPERIMENTS

As the lateral perturbation disturbing ordinary rolling motion, an impulse of 0.56 (Kgm/s), that pushed the center of the body to the right was applied at the timing where left fore and hind legs are in the swing phase. The results of experiments are shown in Fig. 1 and Fig. 2, where ACM$_{inh}$ was employed in both cases. In both figures, the gait (solid lines mean the stance phase), leg loading of RF and body roll angle (rotation to the right is positive) are shown. We can see the effectiveness of ACM$_{exc}$, and can not see the effectiveness of ACM$_{\omega}$ in Fig. 2. But ACM$_{\omega}$ contributed to make RF land on the correct position and prevent the robot from falling down by stumbling of RF. As a result, we confirmed the validity of our simulation study[4] even though we used a little different ACM to cope with disturbances by the different position of CoM and noise of force sensor output in Kotetsu.

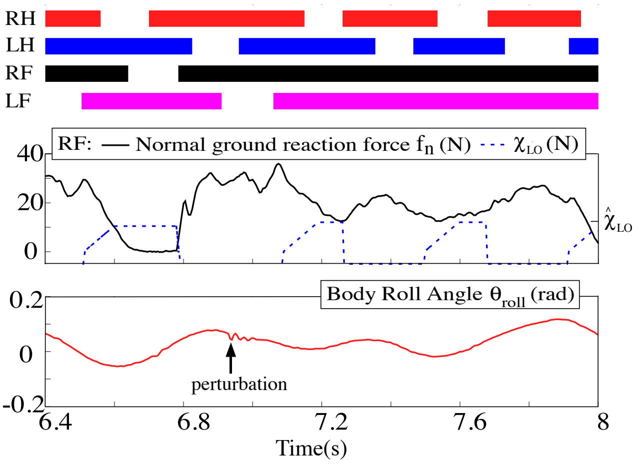

Fig. 1 Results of an experiment against the lateral perturbation without ACM$_{exc}$ and ACM$_{\omega}$. Alternation of leg loading between contralateral legs was prevented, and leg loading of RF was kept high. Since max value of χ_{LO} was constant, the stance-to-swing phase transition of RF was not initiated. Consequently Kotetsu fell down to the right side.

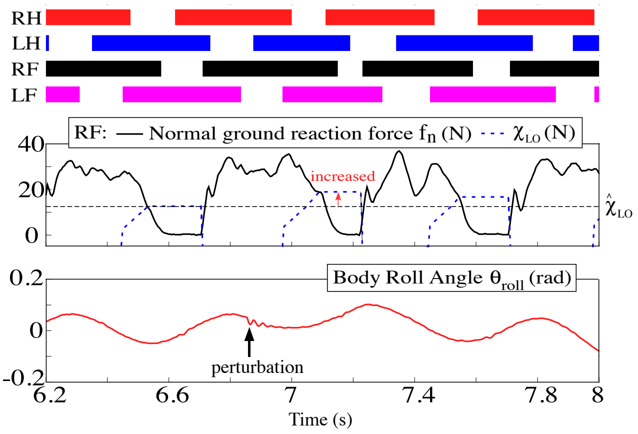

Fig. 2 Results of an experiment against the lateral perturbations with ACM$_{exc}$ and ACM$_{\omega}$. Although leg loading of RF was kept high, the stance-to-swing phase transition of RF was initiated because max value of χ_{LO} was increased by ACM$_{exc}$. Consequently the gait was stabilized and Kotetsu kept walking.

REFERENCES

[1] Hiebert, G., et al. (1996) Contribution of hind limb flexor muscle afferents to the timing of phase transitions in the cat step cycle, *J. of Neurophys.*, 75, 1126-1137.

[2] Duysens, J. & Pearson, K.G. (1980). Inhibition of flexor burst generation by loading ankle extensor muscles in walking cats. *Brain Res.*, 187, 321-32.

[3] Ekeberg, O. & Pearson, K. (2005). Computer simulation of stepping in the hind legs of the cat: an examination of mechanisms regulating the stance-to-swing transition. *J. of Neurophysiology*, 94(6), 4256-68.

[4] Maufroy, C., Kimura, H. & Takase, K. (2010). Integration of Posture and Rhythmic Motion Controls in Quadrupedal Dynamic Walking using Phase Modulations based on Leg Loading/Unloading, *Autonomous Robots* 28(3), 331-353.

[5] Maufroy, C., Nishikawa, T. & Kimura, H. (2009). Stable dynamic walking of a quadruped Robot "Kotetsu" using phase modulations based on leg loading/unloading. *Proc. of ICRA 2010*, 5225-5230.

[6] Imaoka, D., Higashi, Y. & Kimura, H. (2011) Gait adaptation of a quadruped robot in split-belt treadmill walking using leg phase adjustment. *Proc. of 38th SICE Symp. on Intelligent Sys.*, 349-354.