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Stable Dynamic Walking of a Quadruped Robot "Kotetsu" Using Phase Modulations Based on Leg Loading/Unloading

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Abstract— **In this study, we intend to show the basis of a general legged locomotion controller with the ability to integrate both posture and rhythmic motion controls and shift continuously from one control method to the other according to the walking speed. The rhythmic motion of each leg in the sagittal plane is generated by a single leg controller which controls the swing-to-stance and stance-to-swing phase transitions using respectively leg loading and unloading information. Since rolling motion induced by inverted pendulum motion during the two-legged stance phases results in the transfer of the load between the contralateral legs, leg loading/unloading involves posture information in the frontal plane. As a result of the phase modulations based on leg loading/unloading, rhythmic motion of each leg is achieved and leg coordination (resulting in a gait) emerges, even without explicit coordination among the leg controllers, allowing to realize dynamic walking in the low- to medium-speed range. But an additional ascending coordination mechanism between ipsilateral leg controllers helps to improve the stability. In this paper, we report the result of experiments using a newly constructed quadruped robot "Kotetsu" in order to verify the results of simulations. Details of trajectory generation and movies can be seen at:** *http://robotics.mech.kit.ac.jp/kotetsu/*.

I. INTRODUCTION

Traditional methods for dynamic legged locomotion control are generally classified into Zero Moment Point (ZMP) based control and limit-cycle based control. ZMP based control is effective for controlling posture and low-speed walking of biped and quadruped. However, it is not good from the standpoint of energy consumption for medium or high-speed walking since a body with a large mass needs to be accelerated and decelerated by the actuators to satisfy the ZMP constraints, defined to preserve the "dynamic balance" at each instant of the gait [1]. In contrast, limit-cycle-based control methods do not have such constraints. This creates more freedom to optimize energy efficiency by taking advantage of the natural dynamics[1] of the system [2], but there exists an upper bound of the period of the walking cycle, in which stable dynamic walking can be realized [3], [4].

Based on limit-cycle based approach, quadrupedal dynamic walking on irregular terrain was realized with the robot Tekken [5], [6] using a neural controller made of a Central Pattern Generator [7] (CPG) and a set of reflexes. However, it was not clear how much the phase modulations at the CPG level and the reflexes respectively contributed to the stability. Moreover, dynamic walk with a long cyclic period could not be realized because increasing the period caused large rolling motion of the body, leading to instabilities of posture in the frontal plane.

Usual quadrupeds have long and narrow bodies and contralateral legs are never simultaneously in the swing phase during walking. Therefore, posture in the sagittal plane is easy to stabilize, and the main issue is to control the posture in the frontal plane [8], that is, to stabilize the lateral (rolling) motion of the body. Stabilization of the rolling motion can be achieved by phase modulations which consist in modulations of the respective durations of the stance and swing phases of the legs during the walking cycle.

In our previous study [9], [10], we respectively used leg loading and unloading for the phase transition from swing-to-stance and stance-to-swing, and showed the following in 3D model simulations:

- The rhythmic motion of each leg in the sagittal plane was generated. As local leg loading/unloading information reflects both the current phasic state of a leg (swing or stance) and the global posture of the body, our approach allowed to simultaneously coordinate the rhythmic motion of the legs in the sagittal plane and control the posture of the body in the frontal plane with no explicit inter-leg coordination mechanism.
- The proposed method had resistance ability against lateral perturbations to some extent even with no explicit inter-leg coordination mechanism, but that an additional ascending coordination mechanism between ipsilateral legs was necessary to withstand perturbations decreasing the rolling motion amplitude. Without stepping reflex using vestibular information, our control system enabled low speed dynamic walking with long cyclic period and on uneven terrain, which was not realized in our former studies [5], [6].

Hence, rhythmic motion control including inter-leg coordination and its integration with posture control were achieved while utilizing the body dynamics and the characteristics of legged locomotion under a gravity field.

In this paper, we report the result of first experiments using a newly constructed quadruped robot "Kotetsu" while comparing to the result of those simulations.

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[1]normal and inverted pendulum motion, natural oscillation in compliant systems, ...

II. QUADRUPED ROBOT

The quadruped robot "Kotetsu" is shown in Fig. 1. Each leg consists of three segments (thigh, shank and foot) articulated with three rotational joints around the pitch axis (hip, knee and ankle). At the tip of each foot is a force sensor used to measure the normal ground reaction force f_n.

In order to apply sensor-dependent adaptive control, the mechanical system should be well designed to have good dynamic properties (i.e. small moment of inertia, low friction, high backdrivability and so on). In addition, performance of dynamic walking such as adaptability on irregular terrain, energy efficiency, maximum speed and so on highly depends on the mechanical design. The design concepts of Kotetsu are similar with those of Tekken1[5]&2[6], as following.

- high power actuators and small moment of inertia of legs for quick motion and response,
- relatively small gear reduction ratio for small friction and high backdrivability to increase passive compliance of pitch axis joints,
- small mass of the lowest link of legs to decrease impact force at collision,
- small contacting area at toes to increase adaptability on irregular terrain.

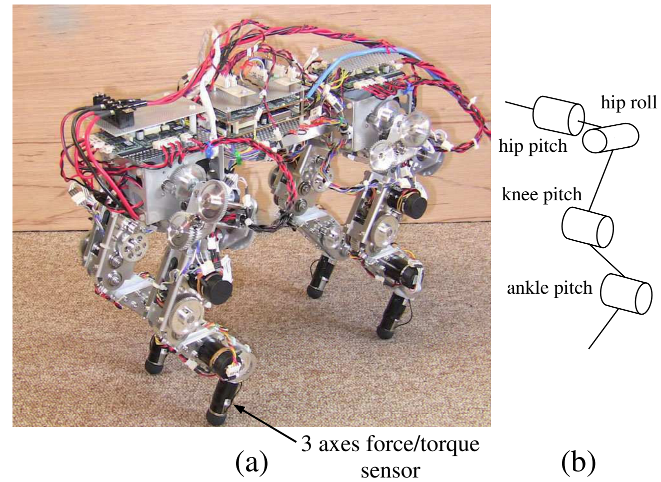
In the simulation model of our previous study [9], [10], the legs have no joint around the roll axis in order to investigate the effectiveness of phase modulations based on leg loading/unloading for posture control in the frontal plane. Hence, although Kotetsu has a roll joint on each leg for the purpose of future extensions, they are mechanically fixed in the experiments presented in this paper for the sake of similarity with the simulation model. Nevertheless, rolling motion of the body in the frontal plane (with the roll angle represented by θ_{roll}) is still naturally induced due to the inverted pendulum motion that occurs during the two-legged stance phases

A gait is a locomotion pattern characterized by phase differences ($\gamma \in [0, 1]$) between the legs during their pitching motion. In the range of low- to medium-speed locomotion, medium sized mammals (like the cat and the dog) mainly use the walk gait [7]. Using γ^{cntr} and γ^{ipsi} to refer respectively to the phase difference between contralateral and ipsilateral legs, the walk gait is characterized by: $\gamma^{cntr} = 0.50$ and $\gamma^{ipsi} \simeq 0.25$. In this study, we consider the control method to generate the walk gait in Kotetsu.

III. CPG ARCHITECTURE

The phase dynamics part of a leg controller described in Section IV-A is a simple model of a CPG, which generates basic rhythm and inter-leg coordinations, and modulates the leg phase according to sensory inputs [7].

[4], [11] used leg contact information feedback to the CPG. They proposed to modulate the swing phase duration of a leg by resetting the phase of its associated oscillator to the stance phase when the leg touched the ground, and reported that such phase resetting enhanced the stability against perturbations.



whole size	length: 34, width: 19∼25, height: 35 (cm)
distance	fore&hind legs: 25, left&right legs: 12∼18 (cm)
link length	thigh: 9, shank: 11, foot: 8 (cm)
leg length	18∼22 (cm) at standing
mass	5.2 (Kg)
DC motors	hip, knee and ankle pitch: 20 (W), hip roll: 11 (W)
gear reduction ratio	hip pitch: 46, knee pitch:: 50, ankle pitch: 40 hip roll: 122
sensors	encoder, rate gyro (pitch&roll), 3 axes accelerometer 3 axes (force: 1 axis, torque: 2 axes) sensor

Fig. 1. Kotetsu. Upper: photo and joint configuration. Lower: specifications. Kotetsu is not self-contained, and it is tethered by power and LAN cables. But the motion of Kotetsu is very little disturbed by cables.

On the other hand, it is known for the stance-to-swing transition in animals that stance phase is indeterminately prolongated as long as the leg loading is over a given threshold [12]. Being motivated by this fact, [13] investigated the respective importance of hip extension and leg unloading information for stance termination by simulating 2D alternative stepping of the hind legs in the sagittal plane using a musculoskeletal model of cats. They found that modulation of the stance phase duration using leg unloading plays an essential role in the emergence and stabilization of stable alternate stepping.

In [14], leg loading was used to modulate swing and stance phases durations in a CPG control system. However, gait generation was considered at the CPG level (via the settings of the couplings between the leg oscillators) and the contribution of phase modulations to leg coordination and posture stabilization was not detailed. On the other hand, we aim at achieving leg coordination in 3D walking in an emergent fashion, through a process involving interactions with the rolling motion in the frontal plane relayed by leg loading/unloading information, rather than by explicit couplings among the leg control entities.

Such CPG architecture is also motivated by the fact that the locomotion CPG in vertebrates is distributed [7] and the argument by [15] that "local rules exploiting feedback loops and the mechanical properties of the body can produce the basic rhythm and can explain a considerable part of the coordination." Using such architecture, we might be able to integrate posture and rhythmic motion controls in a more sensor-dependent way in order to generate appropriate leg coordination according to the walking speed, hence realizing walking both at low and medium speeds using the same control system.

IV. Phase Modulations Based on Leg Loading/Unloading

The hat ˆ, the bar ¯ and the tilde ˜ symbols are respectively used to represent the nominal value, the real value measured by sensors and the reference value of a single variable.

A. Single Leg Controller

1) Overview: Our control system is based on the Central Pattern Generator (CPG) paradigm and each of the four legs is associated with a control entity that will be referred to as *leg controller* (LC), whose internal organization is schematically represented in Fig. 2 using eq.(1)∼(13). Each LC has two phases, *swing* (sw) and *stance* (st), and the transfer of activity between them is regulated using sensory information related to the load supported by the leg, or *leg loading*.

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 [4], [11]. Such representation involving an oscillator was introduced for the sake of simplicity, in order to facilitate the trajectory generation process and the definition of phase relationships between the legs. However, as the phase transitions are regulated using sensory feedback, sensory input has a large influence on the locomotion rhythm.

The trajectory of the foot is generated according to the current locomotion phase. For that purpose, a few specific positions need to be defined. The position of the foot where the swing-to-stance transition is desired to happen is called the *anterior extreme position* $\hat{\boldsymbol{r}}_{AEP}$, while the position where it really happens is the *touchdown position* $\boldsymbol{r}_{TD}$. Similarly, the position where the stance-to-swing transition is desired to happen is the *posterior extreme position* $\hat{\boldsymbol{r}}_{PEP}$, while the position where it really happens is the *liftoff position* $\boldsymbol{r}_{LO}$.

Constant parameter values of a LC used in the simulations are shown in Fig. 4.

2) Phase dynamics: When a phase transition occurs, ϕ is reset (to $\hat{\phi}_{PEP}$ at the swing onset (eq.(1)) or to $\hat{\phi}_{AEP}$ at the stance onset (eq.(7)). The phase then increases constantly with a rate given by the angular velocity $\hat{\omega}$, until it reaches a maximum value (as expressed by eq.(2) and eq.(8)). Parameters $\hat{\phi}_{AEP}$, $\hat{\phi}_{PEP}$ and $\hat{\omega}$ are defined as functions of the nominal swing phase duration $\hat{T}_{sw}$ and the nominal duty ratio $\hat{\beta}$ (eq.(11) and (12)).

3) Foot trajectory generation and joint PD control: For each locomotion phase, the foot trajectory is computed between the initial measured position ($\boldsymbol{r}_{LO}$ or $\boldsymbol{r}_{TD}$) and the nominal final position ($\hat{\boldsymbol{r}}_{AEP}$ or $\hat{\boldsymbol{r}}_{PEP}$), in a way that guaranties the continuity of the speed at the transitions. The velocity profiles of the x and y components of the trajectory are computed and parameterized using the phase ϕ and the nominal foot position is obtained by temporally integrating them. Based on the nominal position and nominal speed, the reference joint angles and angular velocities ($\tilde{\theta}^i_j$ and $\dot{\tilde{\theta}}^i_j$, with subscript j being the joint index) are computed using the inverse kinematics model of the leg. As the leg is made tri-segmented, we constrained the knee and ankle joint angles to be equal. The joint torques Γ^i_j are then generated using the following PD control law:

$$\Gamma^i_j = K^i_{Pj,p}(\tilde{\theta}^i_j - \bar{\theta}^i_j) + K^i_{Dj,p}(\dot{\tilde{\theta}}^i_j - \dot{\bar{\theta}}^i_j) \qquad (14)$$

4) Transition conditions: The transitions between the swing and stance phases in each LC are regulated using conditions based on the normal ground reaction force f_n (measured by the foot force sensor) which is used as leg loading information. The transition from swing to stance is triggered when the contact of the foot with the ground is detected, or equivalently when the leg loading becomes bigger than $\hat{\chi}_{TD}$ (eq.(3)). On the other hand, the transition from stance to swing is prevented as long as the leg loading is over a certain threshold (eq.(5)). The nominal force threshold $\hat{\chi}_{LO}$ is set to a value slightly inferior to one quarter of the model weight. In this paper, the force threshold: χ_{LO} of a hind leg is $\hat{\chi}_{LO}$, and χ_{LO} of a foreleg is adjusted as described in Section IV-B.

Conditions based on ϕ (eq.(4) and eq.(6)) are added just to prevent undesired early transitions, just after the transfer from one phase to the other, by leaving the time to f_n to sufficiently increase (resp. decrease) just after the touchdown (resp. the liftoff).

B. Ascending Coordination Mechanism (ACM)

In our previous simulation study [9], [10], it was shown that the lateral perturbation decreasing the rolling motion amplitude 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 following two-fold ACM referring to [16] in order to solve such conflict and confirmed its effectiveness in simulations.

- The force threshold of the foreleg χ^{sF}_{LO} (where s stands for either R or L) for the stance-to-swing transition is linearly increased as ϕ^{sH} increases during the swing phase of the hind leg.
- The duration of the next swing phase of the foreleg is shortened.

We have a plan to implement such ACM in the control system of Kotetsu for the experiments of walking under the lateral perturbation and on uneven terrain in near future. But we have not yet implemented it at this moment.

On the other hand, we found that a foreleg sometimes caused the stance-to-swing phase transition before the ipsilateral hind leg in the experiments using Kotetsu. Such disorder of phase transitions meant that the gait shifted to the pace, and never occurred in simulations. As the reason of such disorder of phase transitions, we noticed the following two:

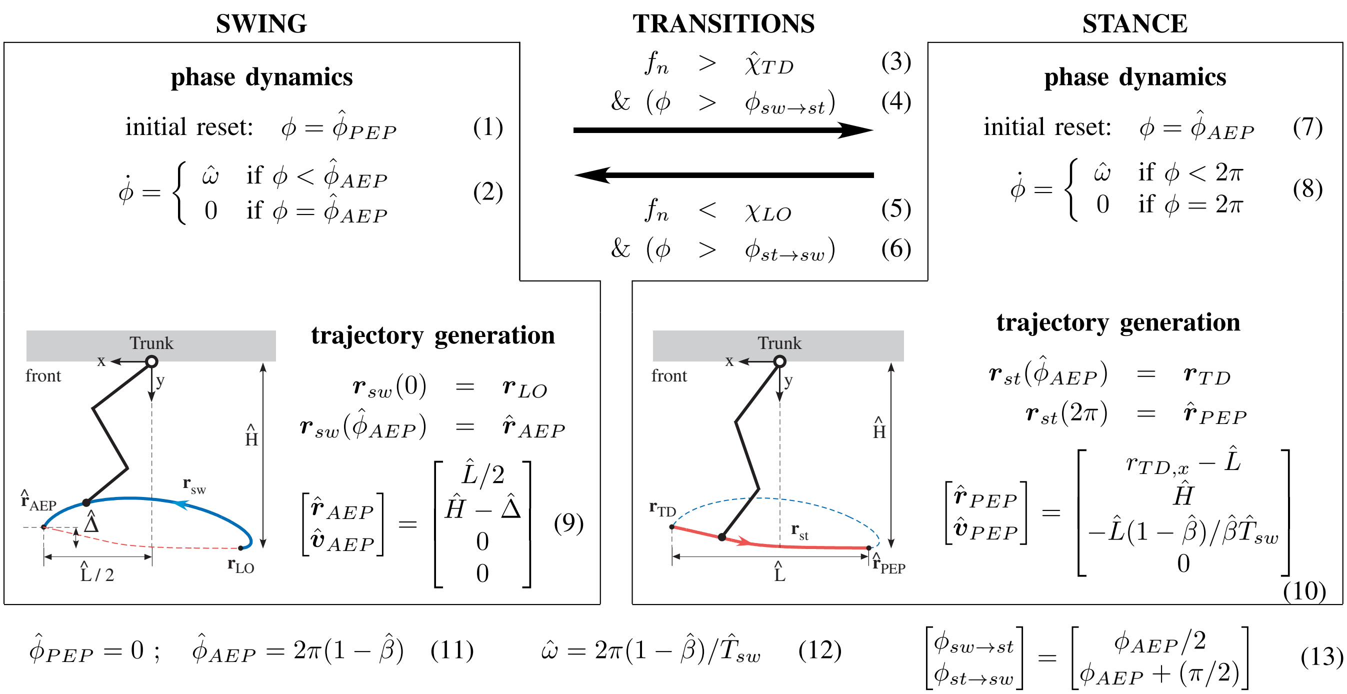


Fig. 2. Leg Controller structure. The foot trajectories are expressed in the Cartesian coordinate system fixed to the trunk and centered at the hip joint ($*_x$ and $*_y$ refer respectively to the x and y coordinates, while $\boldsymbol{r}$ and $\boldsymbol{v}$ are the position and the speed vectors).

1) Since the tunable range of P-gains in Kotetsu at this moment is smaller than that in simulations, the rolling motion amplitude becomes larger and the resultant gait shifted to the pace.
2) Since the center of mass of Kotetsu's body is slightly backward than the center of the body, the leg loading of a foreleg becomes smaller than that of the ipsilateral hind leg.

In order to solve this problem, we employed another ACM expressed by eq.(15) rather than tuning P-gains and the center of mass of the body. This ACM inhibits a foreleg (sF) from the stance-to-swing phase transition until the ipsilateral hind leg (sH) is in the latter of the swing phase.

$$\chi_{LO}^{sF} = \begin{cases} \hat{\chi}_{LO} & \text{if } \phi^{sH} \in [\phi_{acm}; \hat{\phi}_{AEP}] \\ -5 \text{ (N)} & \text{otherwise} \end{cases} \quad (15)$$

where $\hat{\phi}_{acm}$ is the modulation threshold, and is set to 0.55 $\hat{\phi}_{AEP}$, which is slightly bigger than the half value of ϕ^{sH} at which the transition occurs in normal conditions. The threshold value must be negative but the exact value is not really important. However, as it can happen that the measured ground reaction force becomes negative due to the noise on the signal given by the force sensor, the value must not be too close from zero. For that reason, we chosed to set it to -5N, which gives a comfortable buffer.

V. Inter-leg Coordination and Posture Control

In this section, we describe how the simple control method described in Section IV can generate stable walking while integrating posture and rhythmic motion controls.

A. Emergence of Alternate Coordination

The simplest control system configuration, i.e four leg controllers operating *independently*, was first investigated in simulations. Even in that situation, coordinate locomotion patterns emerge and maintain in a broad range of parameters values when a rolling motion of a sufficient amplitude is induced at the beginning of the simulation. All the gaits observed are characterized by the alternating stepping of the right and the left legs, i.e. $\gamma^{cntr} = 0.5$ and $\gamma^{ipsi} \in [-0.25; 0.25]$.

The emergence of the alternate coordination can be explained the following way. As the swing phase of ipsilateral legs overlap, rolling motion is induced by the gravity, as the system is equivalent to an inverted pendulum during the two-legged support phase. As rolling motion is linked to the lateral motion of the body, after the touchdown of the swinging legs, the load due to the body weight is transferred laterally, in the same direction as the rolling motion (this load transfer mechanism will be referred to as *lateral transfer of leg loading*). This unloads the former supporting legs so that the transition to swing is triggered (when $f_n < \chi_{LO}$). As a result, rolling motion is induced in the other direction and the same sequence of events repeat symmetrically. Hence, alternate coordination emerges as the result of the entrainment between the leg stepping, the rolling motion and the lateral transfer of leg loading.

B. Adjustment of the Ipsilateral Phase Difference

If the same parameters are used for the fore and hind legs LCs, γ^{ipsi} does not exceed 0.1, so that, to realize a walk gait, an additional mechanism is needed to delay the stepping of the forelegs relative to the hind legs. Although this could be done by introducing an explicit coupling between the LCs, we found that the adjustment of the relative values of $\hat{\Delta}$ (see eq.(9)) in the fore and hind legs LCs could also fulfill this task, with the benefit of keeping the LCs independent. As the body rotates around its roll axis due to the rolling motion, setting $\hat{\Delta}^{*F} > \hat{\Delta}^{*H}$ delays the touchdown of the forelegs compared to the hind legs, hence increasing γ^{ipsi}.

C. Posture Stabilization in the Frontal Plane

In contrast to simulations, there always exist some kinds of perturbations to some extent even when a robot walks on flat floor, and the influence of such perturbations is significant if the cyclic period is long. Therefore, we have to pay much attention to the posture control in the frontal plane (rolling motion control) in low speed walking with a long cyclic period.

The stabilization mechanism provided by the phase modulations based on leg loading/unloading is schematically represented in Fig. 3. Considering first the case where a perturbation directed to the left is applied, the rolling motion of the body becomes asymmetric so that the model is leaning toward the left side during the walking. In other words, the average body rolling angle over the cyclic period when the perturbation is applied becomes negative, i.e. $< \theta_{roll} >_k < 0$ ($< * >$ representing the average value over a period [9]). The asymmetry of the rolling motion causes a similar asymmetry in the load supported by the legs so that $< f_n^{L*} >_k$ becomes greater than $< f_n^{R*} >_k$.

As f_n is used to modulate the transition from the stance to the swing phase, the increase of $< f_n >_k$ (for the left legs) leads to the prolongation of the stance phase, while it is shortened when $< f_n >_k$ decreases (for the right legs). Consequently, the effective duty ratios of the left legs increase, while they decrease for the right legs ($\bar{\beta}_k^{L*} > \bar{\beta}_k^{R*}$), amplifying the original asymmetry of the $< f_n >_k$. Hence, via the automatic adjustment of the duty ratios, a torque is generated that tends to cancel the asymmetry of the rolling motion and bring $< \theta_{roll} >_{k+1}$ back to 0 and therefore contributes to stabilize the posture in the frontal plane. The same argumentation can also be applied, of course, for perturbations that cause an asymmetry of the body rolling motion in the opposite direction.

VI. RESULTS OF EXPERIMENTS

While using the control method described in Section IV, we realized stable dynamic walking of Kotetsu. The result of the experiment is shown in Fig. 4. We can see that the walk gait was generated and this was dynamic walking since there were two legs stance phase.

This figure represents a walking pattern characterized by a cyclic period $\bar{T} \simeq 0.64s$, a duty ratio $\bar{\beta} \simeq 0.71$, an ipsilateral phase difference $\gamma^{ipsi} \simeq 0.21$ and the walking speed 0.2m/s. These values are quite different from the values that would be expected when considering the nominal parameters (given in the lower table): $\hat{\beta} = 0.75$ and $\hat{T}_{sw} = 0.25s$, resulting

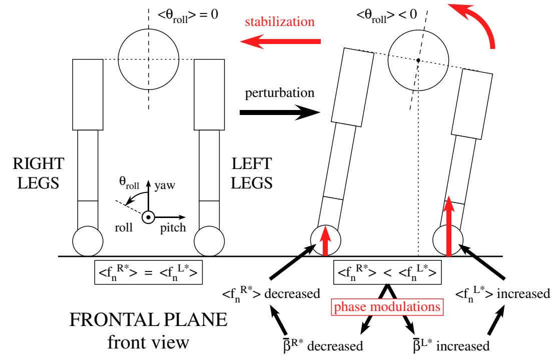


Fig. 3. Stabilization mechanism provided by the phase modulations based on leg unloading information. In this figure, only the case of a perturbation directed to the left is represented but the same arguments hold of course for a perturbation directed to the opposite direction.

in $\hat{T} = 1.0s$. This shows that the motion was strongly influenced by the phase modulations.

We can see in Fig. 4 that the swing-to-stance phase transition of all legs occurred when the leg loading: f_n became bigger than $\hat{\chi}_{TD}$. The stance-to-swing phase transition of hind legs occurred when f_n became smaller than $\hat{\chi}_{LO}$. On the other hand, the stance-to-swing phase transition of forelegs was inhibited by ACM (eq.(15)) even when f_n becomes smaller than $\hat{\chi}_{LO}$, and activated when the LC phase of the ipsilateral hind leg became bigger than ϕ_{acm}. The real stance-to-swing phase transition of hind legs occurred approx. 36msec later than the stance-to-swing phase transition of LC, since it took time for f_n to be small enough. But the real stance-to-swing phase transition of forelegs occurred immediately, since f_n became small sufficiently as the result of inhibition by ACM.

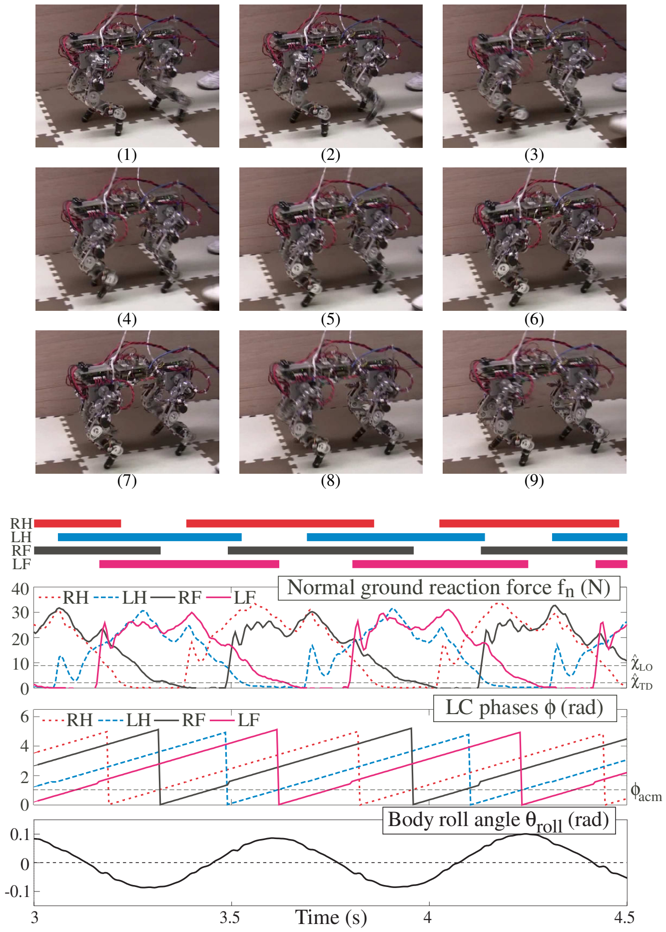
The range of the body roll angle is approx. ± 0.1 rad ($\sim$ 6 deg). This is similar to the value observed in simulations for the same cyclic period ([10]).

Preliminary experiments were also carried out with perturbations applied during walking (lateral push at various instants during the walking cycle and walking up and down steps). The tendencies observed are globally similar to the results gained in simulation, in the case where no ACM is implemented ([9], [10]): the control system can withstand to a certain degree perturbations increasing the amplitude of the body rolling motion, while the controller robustness is much lower against perturbations decreasing the amplitude of the body rolling motion suddenly. However, further investigations are needed to refine this statement so that the results will be reported ulteriorly.

VII. DISCUSSIONS

A. Dependence on Parameter Adjustments

The main drawback of using an approach strongly relying on sensory feedback is that the performances of the system become more dependent on the mechanical properties of the body and on the way it interacts with the environment. Therefore, some parameters of our system at the level of the motor command generation (i.e. $\hat{\Delta}^i$ and so on) had to be adjusted when the walking patterns were modulated. This



Constant parameter settings					
$\hat{H}$	(m)	0.22	$\hat{L}$	(m)	0.10
$\hat{\chi}_{LO}$	(N)	9	$\hat{\chi}_{TD}$	(N)	2
Variable parameter settings					
$\hat{T}_{sw}$	(s)	0.20	$\hat{\beta}$		0.75
$\hat{\Delta}^{*F}$	(m)	0.01	$\hat{\Delta}^{*H}$	(m)	0.00

Fig. 4. Result of the experiment. The top figure shows snapshots at every 65msec. The middle figure shows the gait (solid lines mean the stance phase), leg loading, LC phase and rolling motion (measured using a system combining an accelerometer and a gyroscope).

could complicate the implementation of the control method on other platforms, mechanically different from the simulation model, because appropriate parameter adjustments should be found again. However, this should likely be only a minor difficulty because the number of parameters to tune is quite limited.

B. Adding the Stepping Reflex

In order to improve posture stability, we consider to employ the sideway stepping reflex, which adjusts the lateral touchdown angle of the swinging legs using vestibular information, observed in a cat [8] and often used in robots [3], [5], [6] in future. However, we believe that phase modulations based on leg loading/unloading is a fundamental mechanism, contributing to posture control but also leg coordination, and that it would give redundant and robust functions when adding the stepping reflex.

VIII. CONCLUSIONS

We intended to show the basis of a general legged locomotion controller with the ability to integrate both posture and rhythmic motion controls and shift continuously from one control method to the other according to the walking speed. For this purpose, we proposed a simple leg controller which controls the swing-to-stance and stance-to-swing phase transitions using respectively leg loading and unloading. We employed just one ascending coordination mechanism for the inter-leg coordination, and no reflex such as a sideway stepping reflex. While using parameter values similar with those in simulations, we successfully obtained stable walking in the walk gait of Kotetsu similar with that in simulations. As a next step, we will realize walking with various speeds and investigate in details the robustness of the proposed controller strategy when the robot is subjected to lateral perturbations or walks on uneven terrain.

REFERENCES

[1] Vukobratović M. & Borovac, B. (2004). Zero-Moment Point - Thirty Five Years of its Life. *Int. J. of Humanoid Robotics*, 1(1), 157-173.

[2] Hobbelen, D.G., Wisse, M. (2008). Controlling the walking speed in limit cycle walking. *Int. J. of Robotics Research*, 27(9), 989-1005.

[3] Kimura, H., Shimoyama, I. & Miura, H. (1990). Dynamics in the dynamic walk of a quadruped robot. *Advanced Robotics*, 4(3), 283-301.

[4] Aoi, S. & Tsuchiya, K. (2006). Stability analysis of a simple walking model driven by an oscillator with a phase reset using sensory feedback. *IEEE trans. on Robotics* 22(2), 391-397.

[5] Fukuoka, Y., Kimura, H. & Cohen, A. H. (2003). Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts. *Int. J. of Robotics Research*, 22(3-4), 187-202.

[6] Kimura, H., Fukuoka, Y. & Cohen, A. H. (2007). Adaptive dynamic walking of a quadruped robot on natural ground based on biological concepts. *Int. J. of Robotics Research*, 26(5), 475-490.

[7] Orlovsky, G. N., Deliagina, T. G., & Grillner, S. (1999). *Neural control of locomotion*. Oxford Univ. Press, New York.

[8] Karayannidou, A., Zelenin, P. V., Orlovsky, G. N., Sirota, M. G., Beloozerova,I. N. and Deliagina, T. G. (2009). Maintenance of Lateral Stability During Standing and Walking in the Cat, *J. of Neurophysiol.*, 101, 8-19.

[9] Maufroy, C., Kimura, H. & Takase, K. (2009). Stable dynamic walking of a quadruped via phase modulations against small disturbances. In *Proc. of ICRA 2009*, 4201-4206.

[10] 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* (in Press).

[11] Tsujita, K., Tsuchiya, K. & Onat, A. (2001). Adaptive gait pattern control of a quadruped locomotion Robot. In *Proc. of IROS2001*, 2318-2325.

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

[13] 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.

[14] Righetti, L. & Ijspeert, A. (2008). Pattern generators with sensory feedback for the control of quadruped locomotion. In *Proc. of ICRA 2008*, 819-824.

[15] Cruse, H. (2002). The functional sense of central oscillations in walking. *Biol. Cybern*, 86, 271-280.

[16] Akay, T., Mc Vea, D.A., Tachibana, A. & Pearson, K.G. (2006). Coordination of fore and hind leg stepping in cats on a transversely-split treadmill. *Exp. Brain Res.*, 175, 211-222.