Dynamic Turning Control of a Quadruped Robot using Oscillator Network

Katsuyoshi Tsujita, Hiroomi Toui and Kazuo Tsuchiya
Dept. of Aeronautics and Astronautics,
Graduate School of Engineering,
Kyoto University,
Yoshida Hon-machi, Sakyo, Kyoto 606–8501
Email: tsujita@kuaero.kyoto-u.ac.jp

***Abstract*— The author have proposed a dynamic turning control system of a quadruped robot by using nonlinear oscillators. It is composed of a motion controller and a motion planner. The motion controller drives the actuators of the legs by using local feedback control. The motion planner involves nonlinear oscillators with mutual interactions. In this paper, capability of dynamic turning motion of the proposed control system is verified through numerical simulations: In the slow speed turning, the robot has strong constraints geometrically. Whereas in the high speed turning, the robot has great influences of dynamic forces. These constraints conditions makes the motion of the robot asymmetry in terms of duty ratio, stride and center of force acting points. The proposed controller actively and adaptively controls the waist joint of the main body to satisfy the geometrical constraints during turning, and also controls the shoulder joints to incline the main body to cancel the centrifugal force in high speed turning by use of gravity force.**

I. Introduction

Locomotion is one of the basic functions of a mobile robot. Using legs is one of the strategies for accomplishing locomotion. It allows the robot to move on rough terrain. Therefore, a considerable amount of research has been done on motion control of legged locomotion robots. This paper deals with the motion control of a quadruped robot.

Usually, motion control of a walking robot has been achieved by using a model-based approach[1][2]. The model-based approach is based on control theory; the design of the trajectories of the legs are implemented through optimization based on the model of the robot. The motion controller which realizes the designed trajectories of the legs is also based on the model of the robot.

In the future, a walking robot will be required which can carry out tasks in the real world, where the geometric and kinematic conditions of the environment are not specially structured. A walking robot is required to realize the real-time adaptability to a changing environment and manouverability to generate voluntary motion accorging to context of changing environment. However, it is difficult for the robot with the model-based control system to carry out various tasks in a changing environment or to adapt to variations of the environment.

The walking motion of an animal seems to offer a solution to the problem; During a walking, a lot of joints and muscles are organized into a collective unit to be controlled as if it had fewer degrees of freedom but to retain the necessary flexibility for a changing environment[3].

On the other hand, research has been done on a control system for walking robot which enables to adapt to variances of the environment based on the CPG(Central Pattern Generator) principle[4]–[8].

However, not so many researches treat the maneuverability of a quadruped robot. In order to make a voluntary motion such as turning motion, it is very important for the robot to have maneuverability. Jindrich et al.[9] investigated coodination of all legs of hexapods during turning, and clarified the maneuverability of hexapod insects in terms of the role of each leg. Holmes et al. clarified that the turning motion of a hexapod locomotion is caused by the mechanical relationship between COM(Center Of Mass) and COP(Center Of Pressure). According to them, straight locomotion becomes unstable and turning motion becomes stable under a condition of COM and COP.

This paper deals with the design of the turning control system of a quadruped robot by using nonlinear oscillators: A nonlinear oscillator is assigned to each leg. The nominal trajectory of the leg is determined as a function of phase of its oscillator. We design the local feedback controller for each joint of the legs using the nominal trajectories as the reference. Touch sensors at the tips of the legs are used as triggers on which the dynamic interactions of the legs are based. The mutual entrainment of the oscillators with each other generate a certain combination of phase differences, which leads to the gait pattern. Farthurmore, in this article, a dynamic turning controller is proposed. In the slow speed turning, the robot has strong constraints geometrically. Whereas in the high speed turning, the robot has great influences of dynamic forces. These constraints conditions makes the motion of the robot asymmetry in terms of duty ratio, stride and center of force acting points. The proposed controller actively and adaptively controls the waist joint of the main body to satisfy the geometrical constraints during turning, and also controls the shoulder joints to incline the main body to cancel the centrifugal force in high speed turning by use of gravity force.

The performance of the proposed control system is verified by numerical simulations.

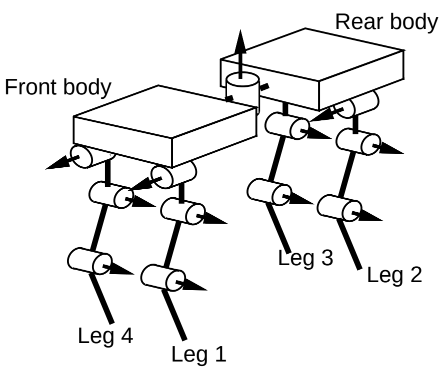


Fig. 1. Schematic model of a quadruped robot

II. Model

Consider the quadruped robot shown in Fig. 1, which has four legs and a main body. Each leg is composed of tree links which are connected to each other through a one degree of freedom (DOF) rotational joint. The main body is composed of two parts, front body and rear body. The front body and the rear body are connected through a rotational joint. Each leg is connected to the main body through a one DOF rotational joint. Legs are enumerated from leg 1 to 4, as shown in Fig. 1. The joint of the main body at waist is numbered as joint 0, and the joints of each leg are numbered as joint 1, 2, and 3 from the main body toward the end of the leg. We define $r_i^{(0)}$ and $\theta_i^{(0)}$ $(i = 1,\ 2,\ 3)$ as the components of position vector and Euler angle from inertial space to the coordinate system which is fixed on the main body, respectively. $theta^{(B)}$ is defined as the joint angle of the rear body to front body in yaw axis. We also define $\theta_j^{(i)}$ as the joint angle of link j of leg i.

The state variable is defined as follows;

$$q^T = \left[\begin{array}{cccc} r_k^{(0)} & \theta_k^{(0)} & \theta^{(B)} & \theta_j^{(i)} \end{array}\right] \qquad (1)$$
$$(i = 1, \cdots, 4, \quad j = 1, 2, 3, \quad k = 1, 2, 3)$$

Equations of motion for state variable q are derived using Lagrangian formulation as follows;

$$M\ddot{q} + H(q,\ \dot{q}) = G + \sum(\tau_j^{(i)}) + \Lambda \qquad (2)$$

where M is the generalized mass matrix and the term $M\ddot{q}$ expresses the inertia. $H(q,\ \dot{q})$ is the nonlinear term which includes Coriolis forces and centrifugal forces. G is the gravity term. $\tau_j^{(i)}$ is the input torque of the actuator at joint j of leg i. Λ is the reaction force from the ground at the point where the tip of the leg makes contact. We assume that there is no slip between the ends of the legs and the ground.

III. Control system

The architecture of the proposed control system is shown in Fig. 2. The control system is composed of motion controllers and a motion planner. The motion planner is composed of a motion generator and a trajectory generator. The motion generator involves nonlinear oscillators corresponding to each leg. The motion generator receives the commanded signal of the nominal gait pattern as the reference. It also receives the feedback signals from the touch sensors at the tips of the legs. The gait pattern is determined by the phase differences between the nonlinear oscillators. A modified gait pattern is generated from the nominal gait pattern through the mutual entrainment of the oscillators with the feedback signals of the touch sensors. The trajectory generator encodes the nominal trajectory of each joint angle in terms of phase of the oscillators, which is given to the motion controller as the commanded signal. The motion controllers drive all the joint actuators of the legs so as to realize the desired motions that are generated by the motion planner.

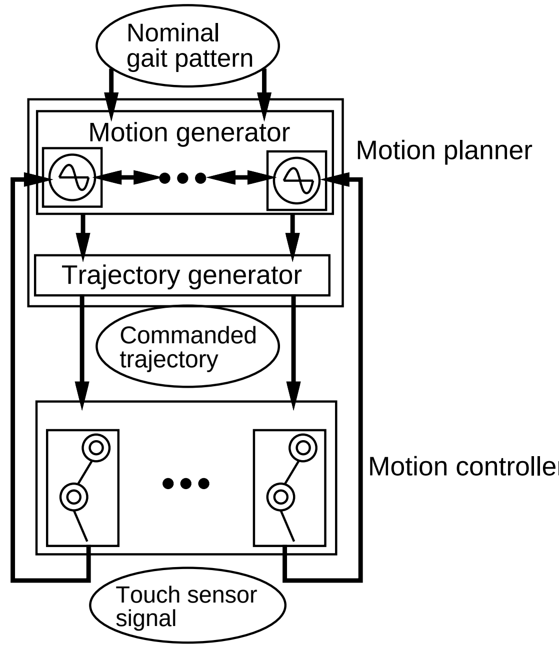


Fig. 2. Architecture of the control system

A. Design of the trajectories of the legs

The position of the tip of the leg where the transition from the swinging stage to the supporting stage occurs is called the anterior extreme position (AEP). Similarly, the position where the transition from the supporting stage to the swinging stage occurs is called the posterior extreme position (PEP)[12]. We determine the nominal trajectories which are expressed in the coordinate system which is fixed on the main body. First, we define the nominal PEP $\hat{r}_{eP}^{(i)}$ and the nominal AEP $\hat{r}_{eA}^{(i)}$. The index $\hat{*}$ indicates the nominal value.

The trajectory for the swinging stage is a closed curve given as the nominal trajectory $\hat{r}_{eF}^{(i)}$. This curve involves the points $\hat{r}_{eA}^{(i)}$ and $\hat{r}_{eP}^{(i)}$. On the other hand, the trajectory for the supporting stage is a linear trajectory given as $\hat{r}_{eS}^{(i)}$. This linear trajectory also involves the points $\hat{r}_{eA}^{(i)}$ and $\hat{r}_{eP}^{(i)}$. The position of each leg on these trajectories is given as functions of the phase of the corresponding oscillator. The state of the oscillator for leg i is expressed as follows;

$$z^{(i)} = \exp(j\ \phi^{(i)}) \tag{3}$$

where $z^{(i)}$ is a complex number representing the state of the oscillator, $\phi^{(i)}$ is the phase of the oscillator and j is the imaginary unit.

The nominal phases at AEP and PEP are determined as follows;

$$\hat{\phi}^{(i)} = \hat{\phi}_A^{(i)} \quad \text{at AEP}, \qquad \hat{\phi}^{(i)} = \hat{0} \quad \text{at PEP} \tag{4}$$

The nominal trajectories for swinging sage $\hat{r}_{eF}^{(i)}$ and for supporting stage $\hat{r}_{eS}^{(i)}$ are given as functions of the phase $\hat{\phi}^{(i)}$ of the oscillator and are alternatively switched at every step of AEP and PEP.

$$\hat{r}_e^{(i)}(\hat{\phi}^{(i)}) = \begin{cases} \hat{r}_{eF}^{(i)}(\hat{\phi}^{(i)}) & 0 \le \hat{\phi}^{(i)} < \hat{\phi}_A^{(i)} \\ \hat{r}_{eS}^{(i)}(\hat{\phi}^{(i)}) & \hat{\phi}_A^{(i)} \le \hat{\phi}^{(i)} < 2\pi \end{cases} \tag{5}$$

The nominal duty ratio $\hat{\beta}^{(i)}$ for leg i is defined to represent the ratio between the nominal time for the supporting stage and the period of one cycle of the nominal locomotion.

$$\hat{\beta}^{(i)} = 1 - \frac{\hat{\phi}_A^{(i)}}{2\pi} \tag{6}$$

B. Design of the gait pattern

The gait patterns, which are the relationships between motions of the legs, are designed. The gait patterns for a quadruped robot are divided into three groups: One is group of the patterns in which three legs support the main body at any instant during locomotion such as Walk. Another is group of the patterns in which two legs support the main body at any instant during locomotion such as Trot, Pace, Bounce. The other is group of the patterns in which less than one leg support the main body at any instant during locomotion such as Gallop. In this paper, the former two groups are considered.

Each pattern is represented by a matrix of phase differences $\Gamma_{ij}^{(m)}$ as follows;

$$\phi^{(j)} = \phi^{(i)} + \Gamma_{ij}^{(m)} \tag{7}$$

where, $m = 1, 2$ represent transverse walk pattern and rotary walk pattern, respectively. $m = 3, 4, 5$ represent trot pattern, pace pattern and bounce pattern, respectively.

C. Leg motion control

The angle of joint j of leg i is derived from the geometrical relationship between the trajectory $\hat{r}_e^{(i)}(\hat{\phi}^{(i)})$ and the joint angle. $\hat{\theta}_j^{(i)}$ is written as a function of phase $\hat{\phi}^{(i)}$ as follows;

$$\hat{\theta}_j^{(i)} = \hat{\theta}_j^{(i)}(\hat{\phi}^{(i)}) \tag{8}$$

where $\hat{*}$ indicates the nominal value. The commanded torque at each joint of the leg is obtained by using local feedback control as follows;

$$\tau^{(B)} = K_{PB}(\hat{\theta}^{(B)} - \theta^{(B)})^3 + K_{DB}(\dot{\hat{\theta}}^{(B)} - \dot{\theta}^{(B)}) \tag{9}$$

$$\tau_1^{(i)} = K_{P1}(\hat{\theta}_1^{(i)} - \theta_1^{(i)})^3 + K_{D1}(\dot{\hat{\theta}}_1^{(i)} - \dot{\theta}_1^{(i)}) \tag{10}$$

$$\tau_j^{(i)} = K_{Pj}(\hat{\theta}_j^{(i)} - \theta_j^{(i)}) + K_{Dj}(\dot{\hat{\theta}}_j^{(i)} - \dot{\theta}_j^{(i)}) \tag{11}$$

$$(i = 1, \cdots, 4, j = 2, 3)$$

where $\tau^{(B)}$ and $\tau_j^{(i)}$ are the actuator torques at the connection joint between front body and rear body, and at joint j of leg i, respectively.

D. Gait pattern control

We design the phase dynamics of the oscillators corresponding to each leg as follows;

$$\dot{\phi}^{(i)} = \omega + g_1^{(i)} + g_2^{(2)} \qquad (i = 1,\ \cdots,\ 4) \tag{12}$$

$$g_1^{(i)} = -K\left(\phi^{(i)} - \phi^{(j)} - \Gamma_{ij}^{(m)}\right) \tag{13}$$

$$g_2^{(i)} = (\hat{\phi}^{(i)} - \phi_A^{(i)})\delta(t - t_0) \tag{14}$$

t_0 : the moment leg i touches the ground

where K is a constant number and δ is Delta-Function.

The oscillators form a dynamic system that affect each other through two types of interactions. One is continuous interactions from $g_1^{(i)}$ which depends on the nominal gait pattern. The other is the pulse-like interactions $g_2^{(i)}$ which is caused by the feedback signals from the touch sensor. Through these interactions, the oscillators generate gait patterns that satisfy the requirements of the environment.

IV. Turning control

In order to realize the turning motion voluntarily, the robot has to coordinate many degrees of freedom under kinematic or dynamic constraint conditions. In the turning motion, there may be considered two typical cases: One is kinematic turn and the other is dynamic turn. In the kinematic turn, locmotion velocity is slow and the dynamic influences such as centrifugal forces or other nonlinear dynamic forces can be ignorable, but geometrical and kinematic constraint conditions are dominant and determines the turning motion. On the other hand, in dynamic turn, locomotion velocity is fast and obtained gait patterns are two-legs supporting gait such as trot, pace and bounce. In this case, there are less number of the geometrical and the kinematic constraints than the 'slow speed locomotion.' However, dynamic forces act on the system during turning motion and those cannot be ignorable. For example, centrifugal forces act on the system in the opposite direction of the center of the arc of turning trajectory. Therefore, the robot needs to be compensated for the influences of several kinds of forces such as centrifugal force.

A. Kinematic turn

In the kinematic turn, locmotion velocity is slow in general and three-legs supporting gaits, such as walk gait, crawl gait, etc., are mostly observed. These gait pattern are the patterns in which three legs support the main body at any instant during locomotion. Therefore, the dynamic influences such as centrifugal forces or other nonlinear dynamic forces can be ignorable, but geometrical and kinematic constraint conditions are dominant and determines the turning trajectory. Figure 3 expresses a simple model for kinematic turn. In this model, there are several assumptions as follows;

1) Motion of the robot is ristricted in two-dimensional motion. i.e. Rolling and pitching motions of the robot are ignored.
2) All legs generates continuous propulsion velocity.
3) There is no slip between the legs and the ground.

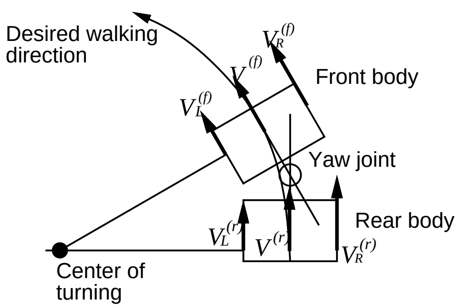


Fig. 3. Kinematics of turning motion

There are nine state variables of this simple model as follows;

1) $v_j^{(i)}$: Propulsion velocity of leg j of body i. $(i = f\ (front),\ r\ (rear),\ j = L\ (Left),\ R\ (Right))$
2) $v^{(i)}$: Propulsion velocity at the geometrical center of body i. $(i = f, r)$
3) $\hat{R}$: Desired radius of arc for turning trajectory.
4) ΔR: Distance of turning trajectories between the front and the rear bodies.
5) θ_w: Yaw angle of joint 0.

$$\frac{v_R^{(f)}}{\hat{R} + \frac{W^{(f)}}{2}} = \frac{v^{(f)}}{\hat{R}} = \frac{v_L^{(f)}}{\hat{R} - \frac{W^{(f)}}{2}} \tag{15}$$

$$\frac{v_R^{(r)}}{\hat{R}\Delta R + \frac{W^{(f)}}{2}} = \frac{v^{(r)}}{\hat{R}} = \frac{v_L^{(r)}}{\hat{R} + \Delta R - \frac{W^{(f)}}{2}} \tag{16}$$

$$\frac{v^{(f)}}{\hat{R}} = \frac{v^{(r)}}{\hat{R} + \Delta R} \tag{17}$$

$$\hat{R}^2 + L^{(f)2} = (\hat{R} + \Delta R)^2 + L^{(r)2} \tag{18}$$

$$\theta_w = \tan^{-1}\left(\frac{L^{(f)}}{\hat{R}}\right) + \tan^{-1}\left(\frac{L^{(r)}}{\hat{R} + \Delta R}\right) \tag{19}$$

where, $L^{(i)}$ and $W^{(i)}$ $(i = f, r)$ are distance between center of mass of body i and joint 0, and distance between the left and the right legs of body i, respectively.

We obtain these seven constraint conditions. These constraint conditions determines following geometrical and kinematical constraints.

1) Equations (15),(16) are kinematical constraints and determine the propulsion velocities of the legs if the velocities of the front and the rear part of the main body are given.
2) The velocities of the front and the rear of the main body are not independent. If one is given, the other is determined from Eq.(17).
3) Equation (18) expresses the geometrical relationship among the center of arc for turning trajectory, two parts of the main body and joint 0.
4) Equation (19) determines yaw angle of joint 0 if radius of arc for turning trajectory is given.

From eqs. (15) $\sim$ (19), the turning trajectory is completely determined when two parameters are given, radius of arc for turning trajectory $\hat{R}$ and walking velocity $v^{(f)}$. In other words, this simple model has no redundant degrees of freedom for turning motion. Therefore, if there is a slight fluctuation of motion such as rolling and pitching motion of the main body, the robot is difficult to follow the desired turning trajectory.

In this article, joint 1 for each leg is adaptively controlled to compensate the influences of model error or disturbances as the redundant degree of freedom.

B. Dynamic turn

In dynamic turn, locomotion velocity is fast and obtained gait patterns are two-legs supporting gait such as trot, pace and bounce. In this case, there are less number of the geometrical and the kinematic constraints than the slow speed locomotion. However, dynamic forces act on the system during turning motion and those cannot be ignorable. The robot needs to be compensated for the influences of several kinds of forces such as centrifugal force. Centrifugal force is proportional to square of locomotion velocity and reciprocal of radius of arc for turning trajectory. This force generates a torque around the supporting points for the main body as to goes outside of turning trajectory. On the other hand, there is a gravity torque around the supporting points. In dynamic turn, time periods for swinging stage for each leg deviate among outer legs and inner legs for turning trajectory because of centrifugal force. Time period for swinging stage is shorter in outer than in inner. This asymmetry of swinging duration between the left and the right causes differences of duty ratio between the motion of outer legs and that of inner legs.

In this article, joint 1 of each leg is adaptively controlled combining with control of yaw angle at joint 0 to compensate the influences of dynamic forces and gravity force. The actuator of joint 1 of each leg is controlled to degrade the asymmetry of the duty ratio between the left and the right. On the other hand, yaw angle at joint 0 is controlled as to satisfy the geometrical and kinematic constraint conditions during turning motion.

C. Turning controller

The turning controller is designed as follows: First, when desired walking direction $\hat{\theta}_{turn}$ and desired walking speed $\hat{V}$ are given, which may be given from a visin system as a

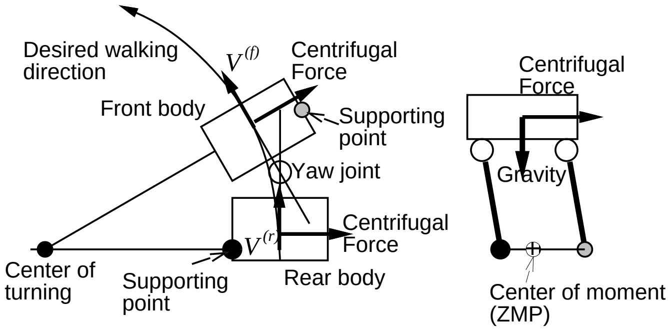


Fig. 4. Dynamic property of turning motion

commanded signal, those are regarded as the nominal values for control parameters.

$$\hat{\theta}_w = \hat{\theta}_{turn} \tag{20}$$
$$\hat{v}^{(f)} = \hat{V} \tag{21}$$

From Eq.(19), nominal radius of arc of turning trajectory $\hat{R}$ is determined.

$$\hat{R} = \frac{-\Delta R \sin\frac{\theta_w}{2} + \sqrt{-\Delta R^2 \cos^2\frac{\theta_w}{2} + \alpha}}{2\sin\frac{\theta_w}{2}} \tag{22}$$
$$\alpha = L^{(f)2} + L^{(r)2} + 2L^{(f)}L^{(r)}\cos\theta_w \tag{23}$$

From Eqs.(15) $\sim$ (17), the nominal propulsion velocity for each leg is determined.

$$\hat{v}_L^{(f)} = v^{(1)} = \frac{\hat{R} - \frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{24}$$
$$\hat{v}_R^{(f)} = v^{(2)} = \frac{\hat{R} + \frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{25}$$
$$\hat{v}_L^{(r)} = v^{(3)} = \frac{\hat{R} + \Delta R - \frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{26}$$
$$\hat{v}_R^{(r)} = v^{(4)} = \frac{\hat{R} + \Delta R + \frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{27}$$

The nominal stride for each leg is calculated from eqs.(24) $\sim$ (27) by using nominal duty ratio $\beta^{(i)}$.

$$\hat{S}^{(1)} = \frac{\beta^{(1)}T_{sw}}{1-\hat{\beta}^{(1)}}\frac{\hat{R} + \frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{28}$$
$$\hat{S}^{(2)} = \frac{\beta^{(2)}T_{sw}}{1-\hat{\beta}^{(2)}}\frac{\hat{R} + \frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{29}$$
$$\hat{S}^{(3)} = \frac{\beta^{(3)}T_{sw}}{1-\hat{\beta}^{(3)}}\frac{\hat{R} + \Delta R - \frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{30}$$
$$\hat{S}^{(4)} = \frac{\beta^{(4)}T_{sw}}{1-\hat{\beta}^{(4)}}\frac{\hat{R} + \Delta R + \frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{31}$$

These nominal values of strides are given to the trajectory generator in the motion planning system.

The input torques at joint 0 and joint 1 of each leg are designed as follows;

Joint 0

$$\tau_0 = K_{P0}(\hat{\theta}_w - \theta_0) - K_{D0}\dot{\theta}_0 \tag{32}$$

Joint 1 of each leg

$$\dot{\hat{\theta}}_1^{(i)} = K_S(\beta^{(I)} - \beta^{(O)}) \quad O: \text{outer leg},\ I: \text{inner leg}$$
$$\tau_1^{(i)} = K_{P1}(\hat{\theta}_1^{(i)} - \theta_1^{(i)}) - K_{D0}\dot{\theta}_1^{(i)} \tag{33}$$

V. Numerical simulation

Numerical simulations are implemented to verify the performances of the proposed control system. Table 1 shows the physical parameters of the robot which are used in numerical simulations.

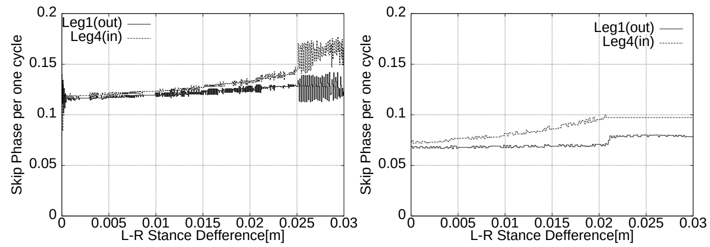
Table 1

Main body		
Width	0.20	[m]
Length	0.36	[m]
Height	0.05	[m]
Total Mass	8.4	[kg]
Legs		
Length of link 1	0.188	[m]
Length of link 2	0.193	[m]
Mass of link 1	0.918	[kg]
Mass of link 2	0.595	[kg]

The nominal time period of the swinging stage is chosen as 0.20 [sec].

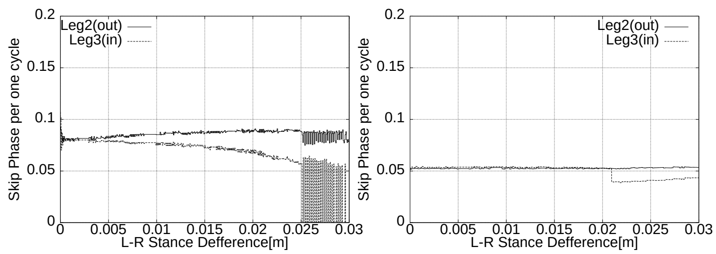
First, asymmetry of duty ratio during motion is investigated. Figiure (5),(6) show the ratio of the value of phase-reset of the oscillator at the moment of leg's contact on the ground against the total locomotion cycle. Asymmetry of the nominal stride between the left and the right is selected as a parameter. These cases are without the proposed turning controller. From the results, the greater the asymmetry of the stride between the left and the right becomes, the larger the asymmetry of the ratio of the value of phase-reset of the oscillator becomes. The case of $\hat{\beta} = 0.55$, that is, high speed dynamic locomotion, is extremely remarkable. These results imply that the system is constrained by kinematic constraint condition in the kinematic turn, while it considerably has influences from the centrifugal force and gravity force in the dynamic turn. In the dynamic turn, asymmetry of duty ratio is caused by the centrifugal force primarily. Therefore, it is effective to control the joint 1 of each leg to incline the main body to inside of turning trajectory by using the asymmetry of the duty ratio.

Figure (7) shows the turning trajectory of the quadruped robot with the proposed control system. Figure (7.a) shows the case of $\hat{\beta} = 0.75$, that is, kinematic turn at slow walking velocity in walk pattern. While, Fig. (7.b) shows the case of $\hat{\beta} = 0.50$, that is, dynamic turn at considerably high speed walking in trot pattern. The center of the desired turning curve(circle) is (0 [m],-1.65[m]), and the nominal radius of the circle is given as $\hat{R} = 1.65$ [m]. From these figures, the robot with the proposed control system can follow the desired trajectory with small tracking errors and established steady and stable locomotions. The effectiveness of the proposed control system is verified through these results.



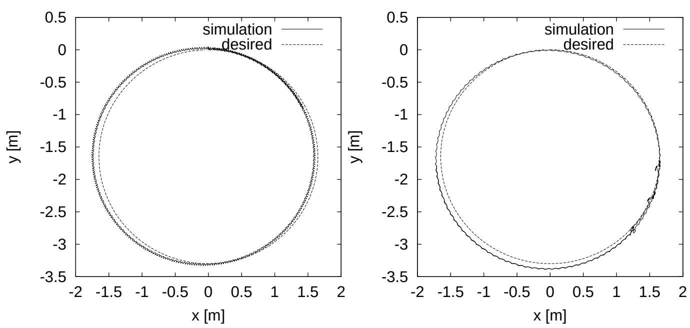
(a) $\hat{\beta} = 0.55$ (b) $\hat{\beta} = 0.80$

Fig. 5. Reset values of oscillator phase.(Front legs)



(a) $\hat{\beta} = 0.55$ (b) $\hat{\beta} = 0.80$

Fig. 6. Reset values of oscillator phase.(Rear legs)



(a) $\hat{\beta} = 0.75$ (b) $\hat{\beta} = 0.50$

Fig. 7. Reset of turning trajectory

VI. Conclusion

We proposed a control system for a walking robot with a hierarchical architecture which is composed of motion controllers and a motion planner. The motion controller drives the actuators at the joints of the legs by use of high-gain local feedback based on the commanded signal from the gait pattern controller. Whereas the motion planner alternates the motion primitives by synchronizing with the signals from the touch sensors at the tips of the legs, and stabilizes the phase differences among the motions of the legs adaptively. Farthurmore, in this article, a dynamic turning controller is proposed. In the slow speed turning, the robot has strong constraints geometrically. Whereas in the high speed turning, the robot has great influences of dynamic forces. These constraints conditions makes the motion of the robot asymmetry in terms of duty ratio, stride and center of force acting points. The proposed controller actively and adaptively controls the waist joint of the main body to satisfy the geometrical constraints during turning, and also controls the shoulder joints to incline the main body to cancel the centrifugal force in high speed turning by use of gravity force.

In the future, we are planning to design the control system in which the voluntary motions are selected or generated according to the state of the robot by utilizing the external sensors such as vision system. Using such a control system, it is expected that adaptability of the robot to variations of the environment will be highly improved.

Acknowledgment

The authors were funded by grants from the The Japan Society for the Promotion of Science (JSPS) as the Research for the Future program (RFTF) and from the Japan Science and Technology Corporation (JST) as the Core Research for Evolutional Science and Technology program (CREST).

References

[1] T. Mita and T. Ikeda, *Proposal of a Variable Constraint Control for SMS with Application to a Running and Quadruped*, Proc. of the 1999 IEEE International Conference on System, Man and Cybernetics, Vol. III, pp. 140-145, 1999

[2] J.Estremera and P.G. Santos, *Free Gaits for Quadruped Robots over Irregular Terrain*, The International Journal of Robotics Research, Vol.21, No.2, pp.115-130, 2002

[3] N.A.Berstein, *Co-ordination and regulation of movements*, Oxford, Pergamon press, New York, 1967

[4] Y.Fukuoka, H.Kimura and A.Cohen, *Adaptive Dynamic Walking of a Quadruped Robot on Irregular Terrain Based on Biological Concepts*, The International Journal of Robotics Research 22, No. 3, pp.187-202, 2003

[5] A.J.Ijspeert, J.Nkanishi and S.Schaal, *Learning Rhythmic Movements by Demonstration using Nonlinear Oscillators*, Proc. of the IEEE/RSJ Int. Conference on Intelligent Robots and Systems (IROS2002), pp.958-963, 2002

[6] M.A.Lewis, R.E.Cummings, A.H.Cohen and M. Hartman, *Toward Biomorphic Control Using Custom a VLSI CPG Chips*, Proc. of International Conference on Robotics and Automation 2000

[7] K. Akimoto, S. Watanabe and M. Yano, *A insect robot controlled by emergence of gait patterns*, Proc. of International Symposium on Artificial Life and Robotics, Vol. 3, No. 2, pp. 102-105, 1999

[8] K. Tsujita, K. Tsuchiya and A. Onat, *Adaptive Gait Pattern Control of a Quadruped Locomotion Robot*, Proc. IEEE/RSJ Int Conf on Intelligent Robots and Systems (IROS 2001), pp.2318–2325, 2001

[9] D.L.Jindrich and R.J.Full, *Many-legged maneuverability: Dynamics of turning in hexapods*, The journal of Experimental Biology 202, pp.1603-1623, 1999

[10] J.Schmitt, M.Garcia, R.C.Razo, P.Holmes and R.J.Full, *Dynamics and stability of legged locomotion in the horizontal plane: a test case using insects*, Biological Cybernetics 86, pp.343-353, 2002