Dynamic Turning Control of a Quadruped Locomotion Robot using Oscillators

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Abstract

The authors have proposed a dynamic turning control system of a quadruped robot by using nonlinear oscillators. It is composed of a spontaneous locomotion controller and voluntary motion controller. In this article, capability of dynamic turning motion of the proposed control system is verified through numerical simulations and hardware experiments: Various turning speed and orientation make the motion of the robot asymmetry in terms of duty ratio, stride and center of pressure. The proposed controller actively and adaptively controls redundant DOF to cancel the dynamic asymmetry and established stable turning motion at various locomotion speed and turning orientation.

keywords: Quadruped locomotion robot, Oscillators, Turning motion

1   INTRODUCTION

Locomotion is one of the basic functions of a mobile robot. Using leg 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 article treats the motion control of a quadruped robot, with emphasis on the dynamic turning control.

In the future, a walking robot will be required which can carry out various tasks on unstructured terrain. The walking robot is required to realize the real-time adaptability to a changing environment and maneuverability to generate voluntary motion according to context of changing environment.

Biological research of the last years has made great contributions to overcome such difficulties; during a spontaneous motion such as straight 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. On the other hand, during a voluntary motion such as turning walk, another organized collective unit emerges selectively according to the commanded signal[1].

The knowledge inspired robotics researchers and a considerable amount of research has been done on biologically inspired control systems for walking robots which enable to adapt to variances of the environment based on the CPG(Central Pattern Generator) principle[2]–[6].

However, not so many researches treat the maneuverability of quadruped robots. In order to make a voluntary motion such as turning motion, it is very important for the robot to have maneuverability. Jindrich et al.[7] investigated coordination 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.

The controller for turning locomotion is usually designed as a sequence of programmed stable motions. In this type of controller, it is difficult to generate the appropriate succeeding step keeping stability and adaptability on real-time. Therefore, many of these types of controllers treat static locomotion with the static balance.

In this article, a new control system is proposed for dynamic turning motion of a quadruped robot by using nonlinear oscillators. The proposed control system consists of a spontaneous locomotion controller and a voluntary motion controller. The spontaneous locomotion controller is designed as a oscillator network that have mutual interactions among the oscillators with the feedback signals of the external sensors and generates an adaptive gait pattern according to the variance of the environment through the mutual entrainments. On the other hand, the voluntary motion controller controls the posture of the main body and also tunes some locomotion parameters of the spontaneous locomotion controller according to the various locomotion speed and the various turning orientation.

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

2 MODEL

Consider the quadruped robot shown in Figure 1, which has four legs and a main body. Each leg consists of three links that 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 Figure 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.
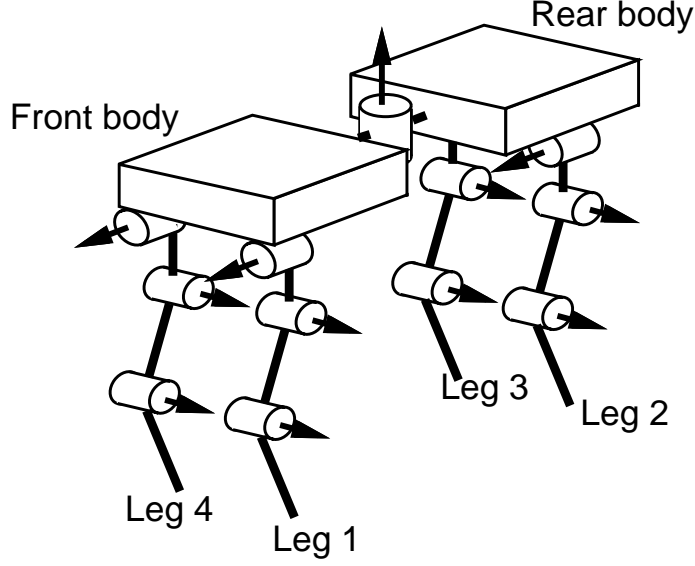
Figure 1: Schematic model of a quadruped robot

The state variable is defined as follows;

$$q^T = \left[\begin{array}{cccc} r_k^{(0)} & \theta_k^{(0)} & \theta^{(B)} & \theta_j^{(i)} \end{array} \right] \tag{1}$$

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

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

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

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.

3 CONTROL SYSTEM

The architecture of the proposed control system is shown in Figure 2. The proposed control system has a two-block architecture. One is a spontaneous locomotion controller and the other is a voluntary motion controller. The spontaneous locomotion controller is designed as follows: The motion generator involves nonlinear oscillators corresponding to each leg. The motion generator receives the outer command of the locomotion conditions, such as locomotion speed, turning orientation, etc. It also receives the feedback signals from the touch sensors at the tips of the legs. These dynamic interactions make adjustment of the phase difference through the mutual entrainment of the oscillators, and an appropriate gait pattern
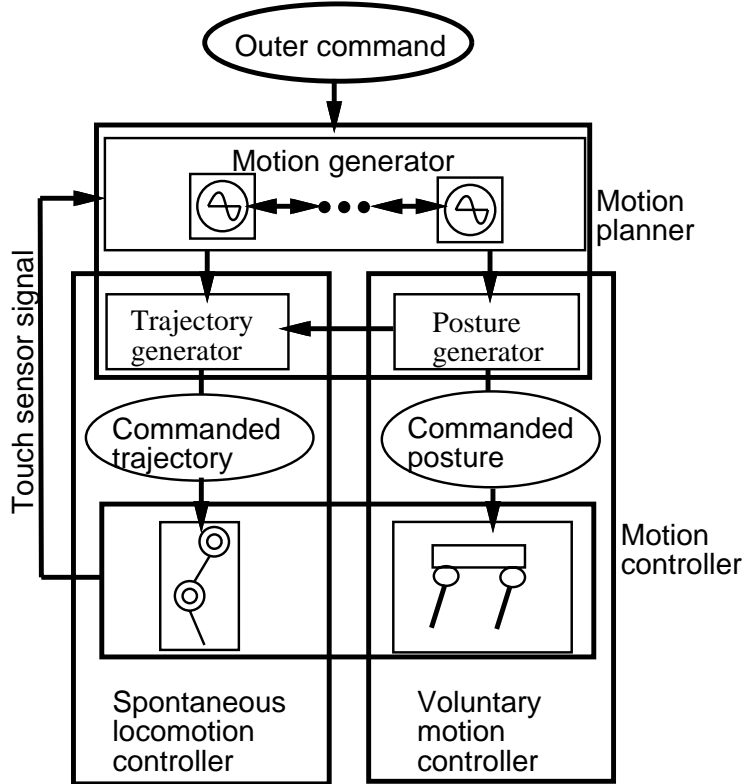
Figure 2: Architecture of the control system

is generated. The trajectory generator encodes the nominal trajectory of each joint angle of the leg in terms of phase of the oscillator, which is given to the motion controller as the commanded signal. The motion controller drives the legs' joint actuators so as to realize the desired motions.

On the other hand, the voluntary motion controller is designed as follows: The posture generator receives the signals of the oscillator's phase and locomotion conditions. It generates the posture command of the main body to cancel the asymmetry of the swinging time of the legs between the inner and the outer side of the turning curve. It also tunes the locomotion parameters in the trajectory generator adaptively, and modifies the legs' trajectories so as to satisfy the geometrical constraints during the turning motion. The motion controller drives the shoulder and the hip joints, and the waist joint of the main body so as to realize the commanded posture which is given from the posture generator.

4   SPONTANEOUS LOCOMOTION CONTROLLER

4.1   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). We determine the nominal trajectories that are expressed in the coordinate system which is fixed on the

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main body. First, we define the nominal PEP $\hat{r}_{eP}^{(i)}$ and the nominal AEP $\hat{r}_{eA}^{(i)}$ (Figure 3). 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.
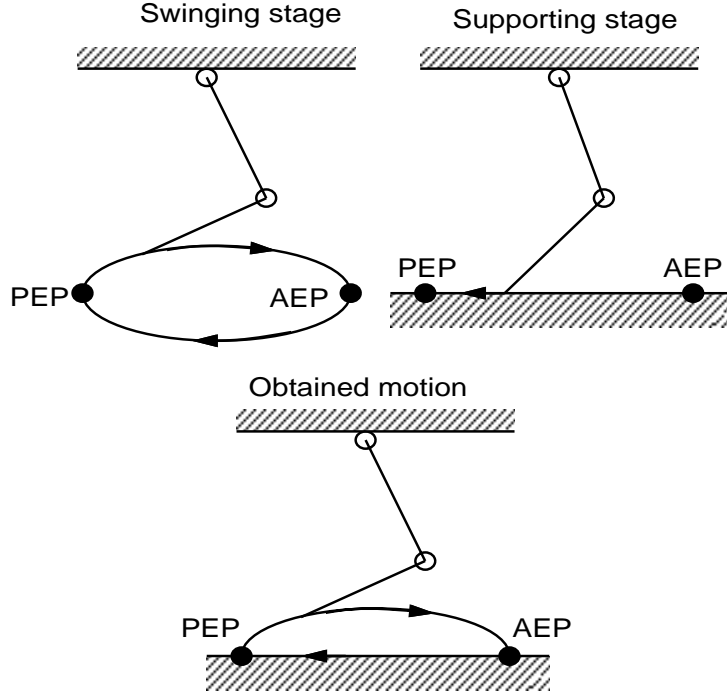

Figure 3: Trajectory of the leg

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;

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

The nominal trajectories for swinging stage $\hat{r}_{eF}^{(i)}$ 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.

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

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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.

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

4.2 Design of the gait pattern

The gait patterns, which are the relationships between motions of the legs, are designed.

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.

4.3 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;

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

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.

4.4 Gait pattern control

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

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

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

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

$$t_0 : \text{the moment leg } i \text{ touches the ground}$$

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

The oscillators form a dynamic system that affects each other through two types of interactions. One is continuous interaction 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. Actually, this effect is realized by resetting the phase of the oscillator from the actual value $\phi_A^{(i)}$ to the nominal value $\hat{\phi}_A^{(i)}$. Through these interactions, the oscillators generate gait patterns that satisfy the requirements of the environment.

5   VOLUNTARY MOTION CONTROLLER

In order to realize the turning motion voluntarily, the robot has to coordinate many degrees of freedom under kinematical or dynamic constraint conditions. In the turning motion, there may be considered two typical cases: One is kinematical turn and the other is dynamic turn. In the kinematical turn, locomotion velocity is slow and the dynamic influences such as centrifugal forces or other nonlinear dynamic forces can be ignorable, but geometrical and kinematical 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 is less number of the geometrical and the kinematical 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 path. Therefore, the robot needs to be compensated for the influences of several kinds of forces such as centrifugal force.

5.1   Kinematical turn

Figure 4 expresses a simple model for kinematic turn. In this model, there are several assumptions as follows;

1. Motion of the robot is restricted 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.

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 path.

4. ΔR: Distance of turning path between the front and the rear bodies.
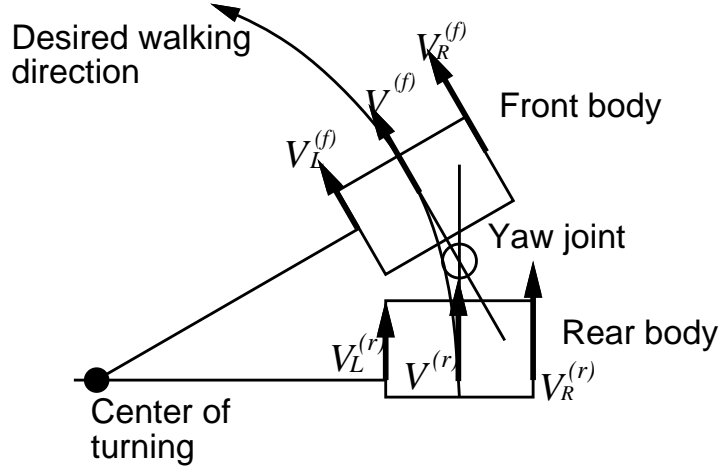
5. θ_w: Yaw angle of joint 0.

Figure 4: Kinematics of turning motion

Among these state variables, there are following constraint conditions.

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

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

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

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

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

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.

From eqs. (15) $\sim$ (19), the turning path is completely determined when two parameters are given, radius of arc for turning path $\hat{R}$ 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 path.

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

5.2   Dynamic turn

In dynamic turn, the robot needs to be compensated for the influences of several kinds of forces such as centrifugal force. This force generates a torque around the supporting point for the main body as to go outside of turning path. On the other hand, there is a gravity torque around the supporting points. In dynamic turn, the values of time period of the swinging stage for each leg deviate among outer legs and

inner legs for turning path due to the effects of the centrifugal force and the gravity torque. In general, centrifugal force moves the COP to outer side of the turning path. To the contrary, the gravity toque around the supporting points moves the average position of the COP to inner side of the turning path during curving, if the posture has an inclination to the inside of the path. Therefore, if the centrifugal force is dominant, the time period for the swinging stage becomes 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 study, 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 kinematical constraint conditions during turning motion.
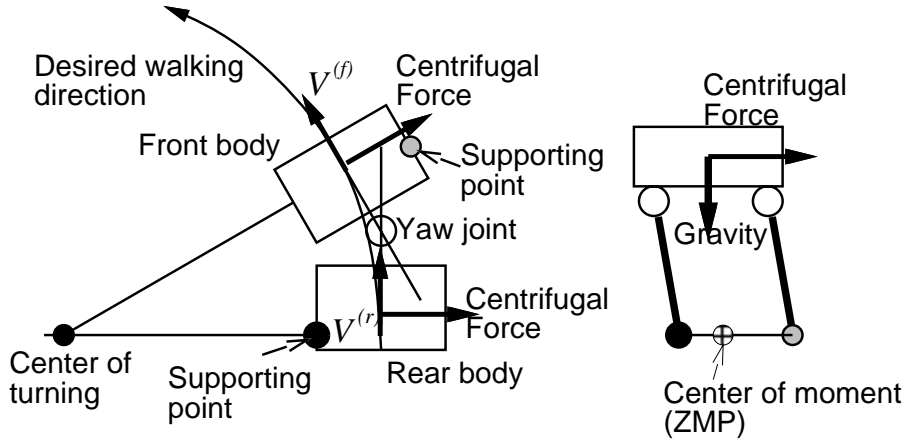

Figure 5: Dynamic property of turning motion

5.3 Controller

The controller for turning motion 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 vision system as a 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 path $\hat{R}$ is determined.

$$\hat{R} = \frac{-\Delta R \sin \frac{\theta_w}{2} + \sqrt{-\Delta R^2 \cos^2 \frac{\theta_w}{2} + \alpha}}{2 \sin \frac{\theta_w}{2}} \tag{22}$$

$$\alpha = L^{(f)2} + L^{(r)2} + 2 L^{(f)} L^{(r)} \cos \theta_w \tag{23}$$

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From Eqs.(15) $\sim$ (17), and by using nominal duty ratio $\beta^{(i)}$, the nominal stride for each leg is calculated.

$$\hat{S}^{(i)} = \frac{\beta^{(i)}T_{sw}}{1-\hat{\beta}^{(i)}}\frac{\hat{R}+\frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{24}$$

$$\hat{S}^{(j)} = \frac{\beta^{(j)}T_{sw}}{1-\hat{\beta}^{(j)}}\frac{\hat{R}+\Delta R-\frac{W^{(r)}}{2}}{\hat{R}}\hat{V} \tag{25}$$

$$(i = 1, 2, \ j = 3, 4) \tag{26}$$

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

$$\tau_0 = K_{P0}(\hat{\theta}_w - \theta_0) - K_{D0}\dot{\theta}_0 \tag{27}$$

Joint 1 of each leg

$$\dot{\hat{\theta}}_1^{(i)} = K_S(\beta^{(I)} - \beta^{(O)}) \quad O : \text{outer leg}, \ I : \text{inner leg}$$

$$\tau_1^{(i)} = K_{P1}(\hat{\theta}_1^{(i)} - \theta_1^{(i)}) - K_{D0}\dot{\theta}_1^{(i)} \tag{28}$$

6   NUMERICAL SIMULATION

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

Table 1

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

Figure 6 shows dependence of the values of adjustment for oscillator phase at AEP (i.e. $\phi_A^{(i)} - \hat{\phi}_A^{(i)}$) upon the difference of the strides among the legs(i.e. $S^{(O)} - S^{(I)}$, I: inner leg no.,O: outer leg no.) The y-axis value means the ratio of the adjusted value of the oscillator's phase at the moment of leg's contact on the ground against the total locomotion cycle. These cases are without the proposed controller. The results show that the greater the asymmetry of the stride between the left and the right becomes, the larger the difference of the values of phase adjustment becomes. The case of $\hat{\beta} = 0.55$, that is, high speed dynamic locomotion, is extremely remarkable. These results imply that the robot needs to be controlled in terms of the asymmetry of the phase adjustment of the oscillators, or the robot may cause instability during the turning motion because of its dynamic asymmetry.

Figure 7 shows the turning path of the quadruped robot with the proposed control system. Figures 7.(a) and 7.(b) show the cases of $\hat{\beta} = 0.75$ and $\hat{\beta} = 0.50$, that is, slow and high speed turning, respectively. 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]. In the figures, points and solid lines indicate the obtained path of the robot from the top view in the case of the proposed controller and no posture control, respectively. From these figures, the robot with the proposed control system can follow the desired path with small tracking errors without any external sensing such as vision system, and established steady and stable locomotion.

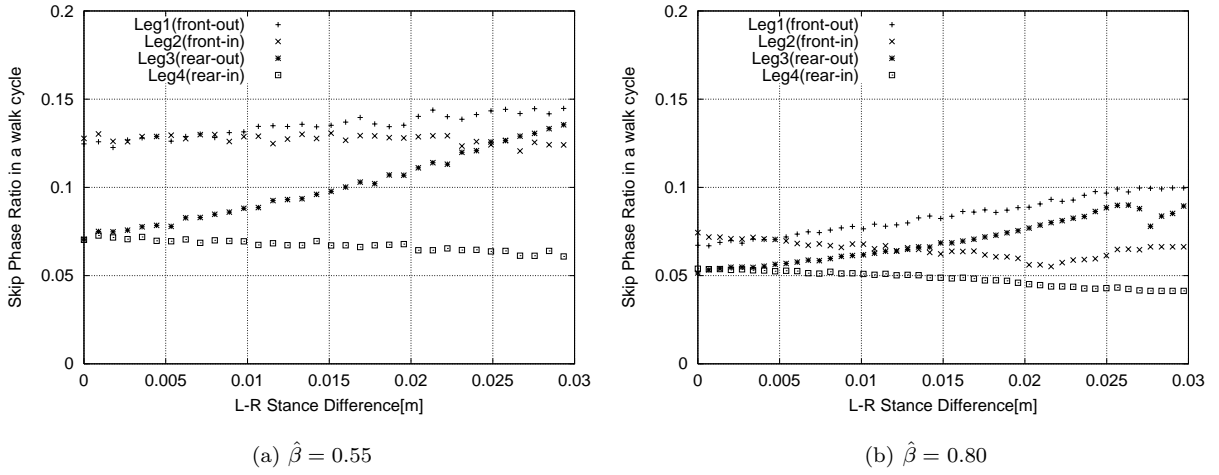The effectiveness of the proposed control system is verified through these results.

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

Figure 6: Value of adjustment for oscillator phase at AEP $(\phi_A^{(i)} - \hat{\phi}_A^{(i)})$

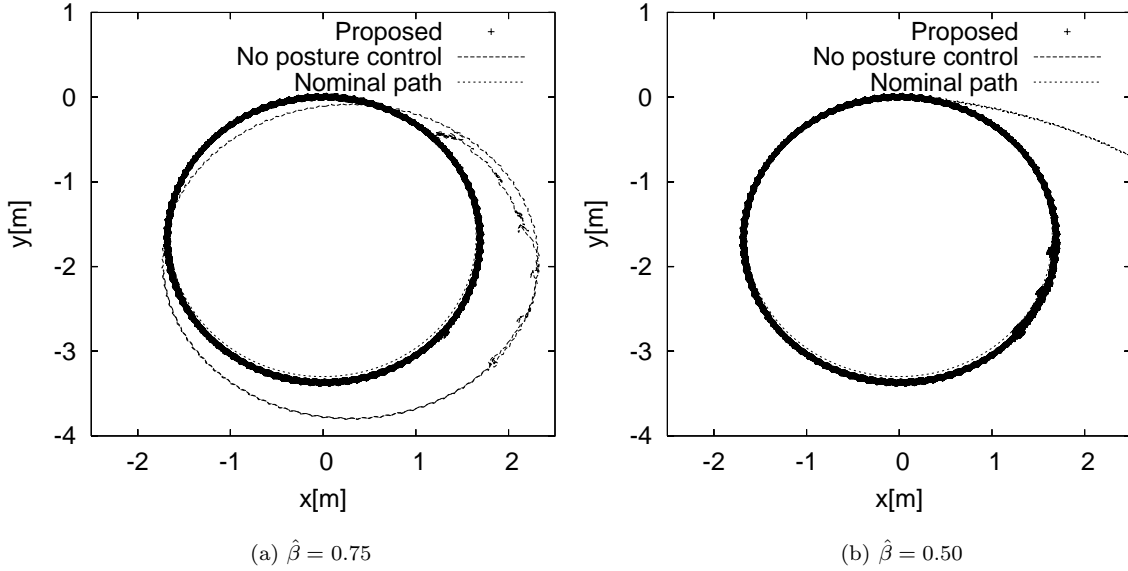(a) $\hat{\beta} = 0.75$ (b) $\hat{\beta} = 0.50$

Figure 7: Turning path of the robot (top view)

7 HARDWARE EXPERIMENTS

Performance of the proposed control system is verified through hardware experiments. The quadruped robot has three DOF for each leg and one DOF on the main body. Each joint is driven by Harmonic Drive DC actuator. Maximum actuator torque is 4.6 [Nm] and maximum rotational speed is 3.5 [rad/s]. Load cell is equipped at the tip of each leg and play roles of touch sensor and force sensor. Actuator drivers and amplifiers for force sensors are mounted on the main body.

Figure 8 shows data processing system. The controller is on-board type and its CPU is Mobile Pentium II 333[MHz]. Operating System (OS) on the controller is RT-Linux. Sampling frequency is set as 1.0 [kHz]. Personal computer as a host computer is connected to the on-board controller through Ether net and plays roles of supervisor of the controller and debugger for control program.

Figure 9 shows dependence of the values of adjustment for oscillator phase at AEP (i.e. $\phi_A^{(i)} - \hat{\phi}_A^{(i)}$) upon the difference of the strides among the legs(i.e. $S^{(O)} - S^{(I)}$, I: inner leg no.,O: outer leg no.) Figure 9.(a) and 9.(b) are the cases without the posture control and with the proposed controller, respectively. Using the proposed controller, the phases are appropriately adjusted among the oscillators, and reached the steady and stable state rapidly.

Figure 10 shows a sequence of snapshots of a hardware experiment. In the photographs, solid line on the floor is the nominal turning path. The locomotion speed is given as 0.5 [m/s]. It is found that the robot, which has no visual information about the nominal turning path, established the stable turning locomotion with a slight deviation of the turning path from the nominal path.

From these results, it is also verified as well as numerical simulations that the robot using the proposed control system has a capability of dynamic turning locomotion by adaptively changing the posture of the main body and the duty ratio among the legs.
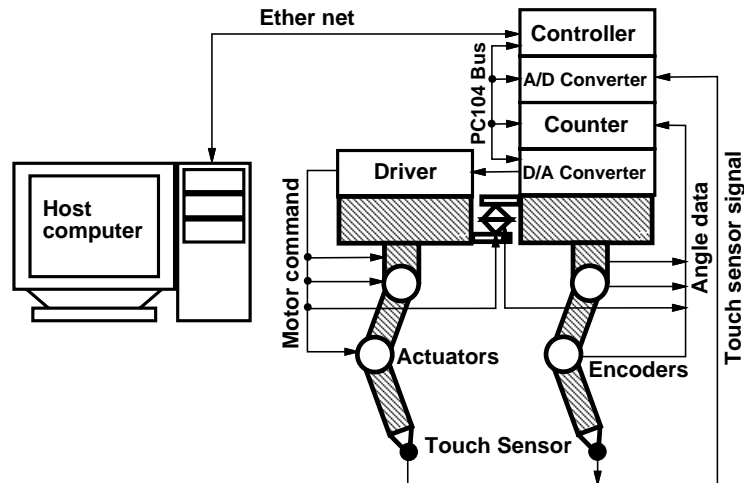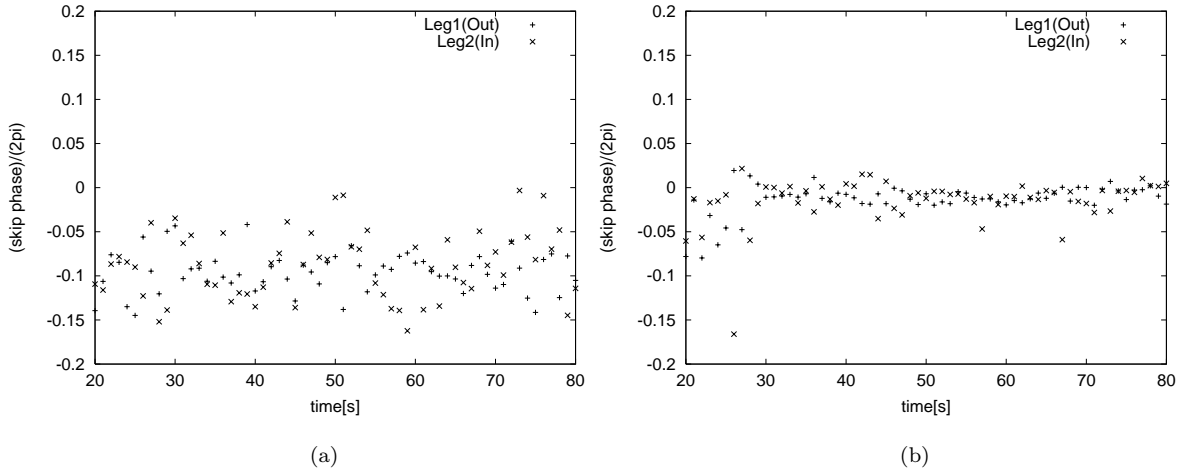

Figure 8: The data processing system

Figure 9: Value of adjustment for oscillator phase at AEP $(\phi_A^{(i)} - \hat{\phi}_A^{(i)})$, (a) without (b) with the proposed control system

8 CONCLUSIONS

A dynamic turning control system 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.

Acknowledgment

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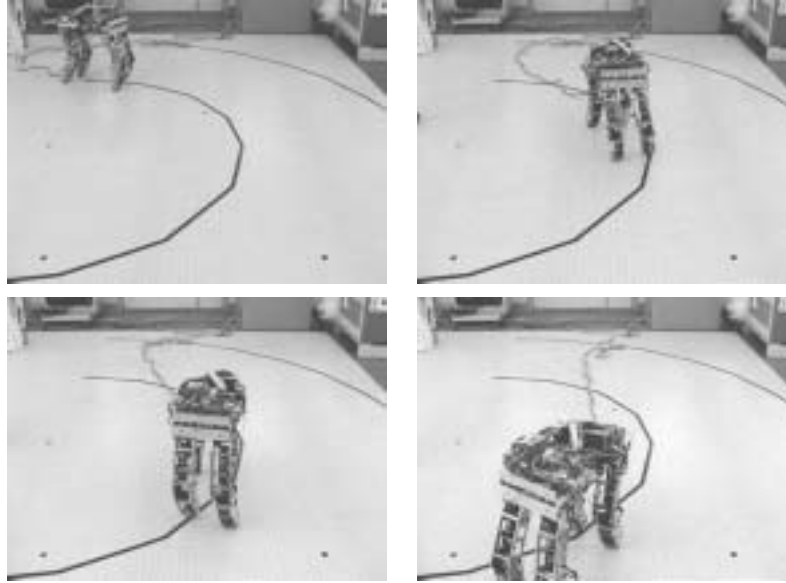
Figure 10: Snapshots of the robot during dynamic turning locomotion

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