A Study on Adaptive Generation of Motion Pattern of a Quadruped Locomotion Robot

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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: In the slow speed turning, the robot has strong geometrical constraints. Whereas in the high speed turning, the robot has great influences of dynamic forces. These constraint conditions 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, Motion pattern, Nonlinear oscillators

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) model[2)–6)].

However, not so many researches treat the generation of voluntary motion patterns such as turning locomotion for quadruped robots. One of such voluntary motion patterns is turning locomotion at various locomotion speed or various turning orientation. 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 follows; a nonlinear oscillator is assigned to each leg. The periodic trajectory of each leg is calculated as a function of the phase of its oscillator. 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 generates an appropriate combination of phase differences according to context of the changing environment, which leads to the gait pattern.

On the other hand, the voluntary motion controller controls the posture of the main body and also tunes some locomotion parameters of the spontaneous controller according to the various locomotion speed and the various turning orientation. In the slow speed turning, the robot has strong geometrical constraints. Whereas in the high speed turning, the robot has great influences of dynamic forces. These constraint conditions make the motion of the robot asymmetry between the inner and the outer side of the curved walking path in terms of duty ratio, stride and position of center of pressure. The voluntary motion controller actively and adaptively controls the waist joint of the main body to satisfy the geometrical constraints during turning, and also controls the shoulder and the hip 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 and hardware experiments.

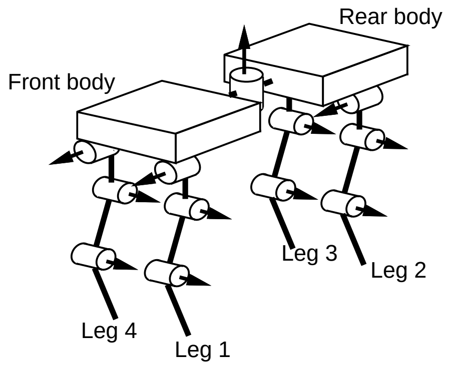


Figure 1: Schematic model of a quadruped robot

2. Model

Consider the quadruped robot shown in Fig. 1, which has four legs and a main body. Each leg consists of tree 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 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;

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

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.

3. Control system

The architecture of the proposed control system is shown in Fig. 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 controller is designed as follows[6]: The motion generator involves nonlinear oscillators corresponding to each leg. The motion generator receives the outer command of the locomotion condition, 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 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.

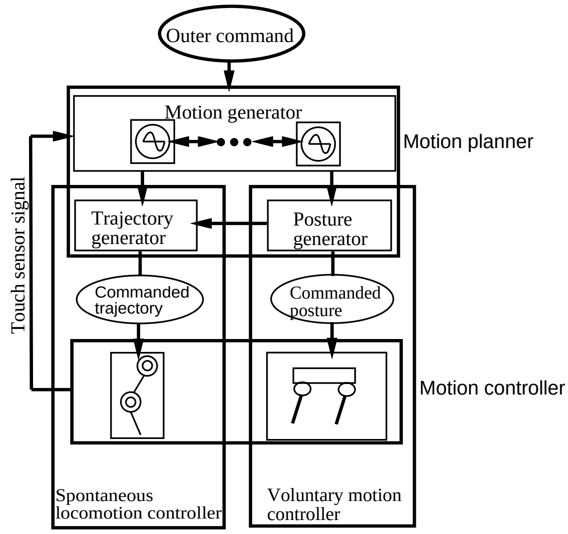


Figure 2: Architecture of the control system

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

The motion generator is composed of nonlinear oscillator network. The state of the oscillator for leg i is expressed as follows;

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

These oscillators encode the trajectories of the corresponding motions in terms of their phases. The nominal trajectory of the end of each leg is designed as follows. Two trajectories are given: One is the nominal trajectory for swinging stage, and the other is that for supporting stage. For the position of leg i's end, two typical points, $\hat{r}_A^{(i)}$, anterior extreme position (AEP) and $\hat{r}_P^{(i)}$, posterior extreme position (PEP), are defined relative to the body. 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 trajectory for the swinging stage $\hat{r}_{eF}^{(i)}$ is a closed curve involving AEP and PEP. On the other hand, the trajectory for the supporting stage $\hat{r}_{eS}^{(i)}$ is a line connecting AEP and PEP. These two trajectories are switched at AEP and PEP. This involves the swinging stage switched to the supporting stage at AEP and from the supporting stage to the swinging stage at PEP. 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.

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

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.

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

In the trajectory generator, the angle of each joint is calculated from these nominal trajectories by means of the inverse kinematics. The values of the joint angles are given to the motion controller as the commanded signals, and motion controller drives joint actuators by using high gain feedback control corresponding to the commanded signals.

The dynamics of the oscillators in the motion generator is designed as follows. A phase dynamics is used for the design of the oscillator network.

$$\dot{\phi}^{(i)} = \omega + g_1^{(i)} + g_2^{(i)} \qquad (i = 1,\ \cdots,\ 4) \tag{7}$$

$$g_1^{(i)} = -K\left(\phi^{(i)} - \phi^{(j)} - \Gamma_{ij}^{(m)}\right) \tag{8}$$

$$g_2^{(i)} = (\hat{\phi}^{(i)} - \phi_A^{(i)})\delta(t - t_0) \tag{9}$$

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 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. 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 are 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

In the kinematical turn, locomotion velocity is slow in general and three-legs supporting gaits, such as walk gait, crawl gait, etc., are mostly observed. These gait patterns 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 kinematical constraint conditions are dominant and determines the turning trajectory. Figure 3 expresses a simple model for kinematical 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. Every leg 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.
   $(i = f\ (front),\ r\ (rear),\ j = L\ (Left),\ R\ (Right))$

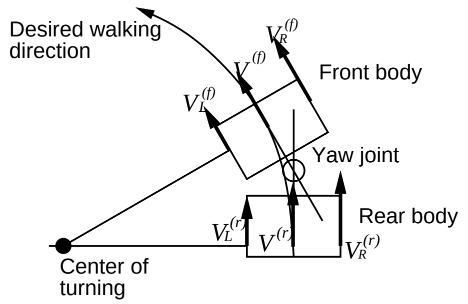


Figure 3: Kinematics of turning motion

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.

$$\frac{v_R^{(f)}}{\hat{R} + \frac{W^{(f)}}{2}} = \frac{v^{(f)}}{\hat{R}} = \frac{v_L^{(f)}}{\hat{R} - \frac{W^{(f)}}{2}} \tag{10}$$

$$\frac{v_R^{(r)}}{\hat{R}\Delta R + \frac{W^{(f)}}{2}} = \frac{v^{(r)}}{\hat{R}} = \frac{v_L^{(r)}}{\hat{R} + \Delta R - \frac{W^{(f)}}{2}} \tag{11}$$

$$\frac{v^{(f)}}{\hat{R}} = \frac{v^{(r)}}{\hat{R} + \Delta R} \tag{12}$$

$$\hat{R}^2 + L^{(f)2} = (\hat{R} + \Delta R)^2 + L^{(r)2} \tag{13}$$

$$\theta_w = \tan^{-1}\left(\frac{L^{(f)}}{\hat{R}}\right) + \tan^{-1}\left(\frac{L^{(r)}}{\hat{R} + \Delta R}\right) \tag{14}$$

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 (10),(11) 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 part of the main body are not independent. If one is given, the other is determined from Eq.(12).

3. Equation (13) expresses the geometrical relationship among the center of arc for turning path, two parts of the main body and joint 0.

4. Equation (14) determines yaw angle of joint 0 if radius of arc for turning path is given.

From eqs. (10) $\sim$ (14), the turning trajectory 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 article, 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, 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 kinematical constraints than the case of 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 path. This force generates a torque around the supporting points for the main body as to goes 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 because of centrifugal force. Time period for the 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 kinematical constraint conditions during turning motion.

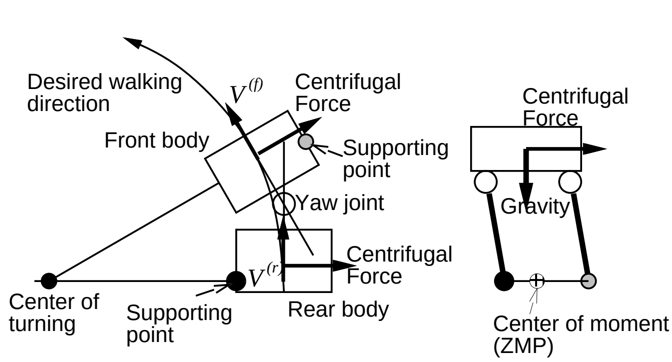


Figure 4: Dynamic property of turning motion

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.

$$\hat{\theta}_w = \hat{\theta}_{turn} \tag{15}$$

$$\hat{v}^{(f)} = \hat{V} \tag{16}$$

From Eq.(14), nominal radius of arc of turning trajectory $\hat{R}$ is determined.

$$\hat{R} = \frac{-\Delta R \sin\frac{\theta_w}{2} + \sqrt{-\Delta R^2 \cos^2\frac{\theta_w}{2} + \alpha}}{2\sin\frac{\theta_w}{2}} \tag{17}$$

$$\alpha = L^{(f)2} + L^{(r)2} + 2L^{(f)}L^{(r)}\cos\theta_w \tag{18}$$

The nominal stride for each leg is calculated from eqs.(10) $\sim$ (12) by using nominal duty ratio $\beta^{(i)}$.

$$\hat{S}^{(1)} = \frac{\beta^{(1)}T_{sw}}{1-\hat{\beta}^{(1)}}\frac{\hat{R}+\frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{19}$$

$$\hat{S}^{(2)} = \frac{\beta^{(2)}T_{sw}}{1-\hat{\beta}^{(2)}}\frac{\hat{R}+\frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{20}$$

$$\hat{S}^{(3)} = \frac{\beta^{(3)}T_{sw}}{1-\hat{\beta}^{(3)}}\frac{\hat{R}+\Delta R-\frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{21}$$

$$\hat{S}^{(4)} = \frac{\beta^{(4)}T_{sw}}{1-\hat{\beta}^{(4)}}\frac{\hat{R}+\Delta R+\frac{W^{(f)}}{2}}{\hat{R}}\hat{V} \tag{22}$$

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

$$\tau_0 = K_{P0}(\hat{\theta}_w - \theta_0) - K_{D0}\dot{\theta}_0 \tag{23}$$

Joint 1 of each leg

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

$$\tau_1^{(i)} = K_{P1}(\hat{\theta}_1^{(i)} - \theta_1^{(i)}) - K_{D0}\dot{\theta}_1^{(i)} \tag{24}$$

6. Numerical simulations and Hardware experiments

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	0.46	[m]	Mass of link 1	0.92	[kg]
Total Mass	8.4	[kg]	Mass of link 2	0.60	[kg]

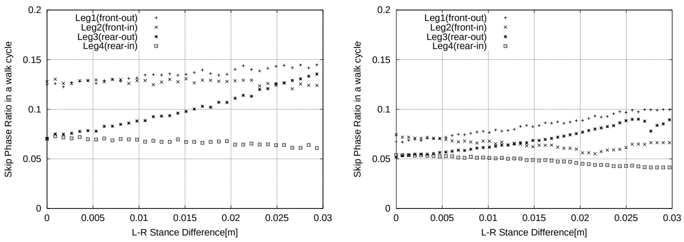
The nominal time period of the swinging stage is chosen as 0.20 [sec]. First, asymmetry of duty ratio during motion is investigated.

Figure 5 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 6 shows the turning path of the quadruped robot with the proposed control system. Figures 6.(a) and 6.(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 trajectory with small tracking errors without any external sensing such as vision system, and established steady and stable locomotion.

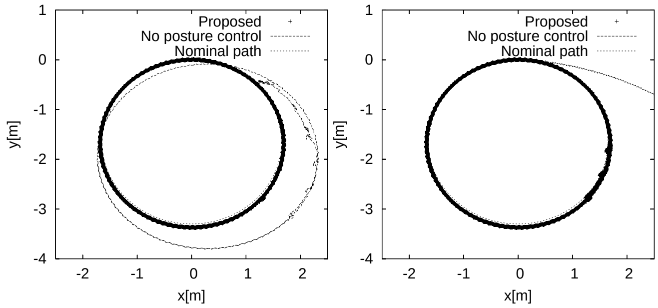
Figure 7 shows a sequence of snapshots of a hardware experiment. In the photographs, solid line on the floor is the nominal turning path. The locomotion speed is given as 0.5 [m/s]. It is found that the robot, which has no visual information about the nominal turning path, established the stable turning locomotion with a slight deviation of the turning path from the nominal path.

From these results, the effectiveness of the proposed control system is verified not only by numerical simulations but also by hardware experiments.



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

Figure 5: 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 6: Turning path of the robot (top view)

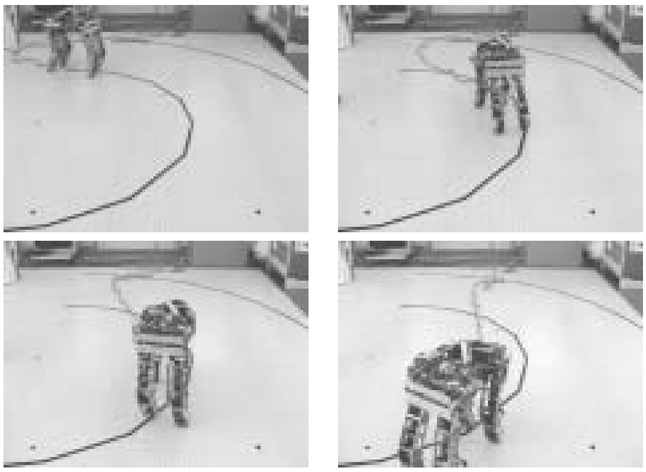


Figure 7: Snapshots of the robot during dynamic turning locomotion

7. Conclusion

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 constraint conditions make 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.

References

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

[2] 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

[3] 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

[4] 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

[5] 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

[6] K.Tsuchiya, S.Aoi and K. Tsujita, Locomotion Control of a Biped Locomotion Robot using Nonlinear Oscillators, Proc. IEEE/RSJ Int Conf on Intelligent Robots and Systems (IROS 2003), pp.1745–1750, 2003

[7] K.Tsujita, H.Toui and K. Tsuchiya, Dynamic Turning Control of a Quadruped Robot using Oscillator Network, Proc. IEEE Int Conf on Robotics and Automation (ICRA 2004), pp.2613–2618, 2004

[8] A.E.Patla, S.D.Prentice, C.Robinson and J.Neufeld, Visual control of locomotion: strategies for changing direction and for going over obstacles, Journal of Experimental Psychology: Human Perception and Performance, 17, pp.603–634, 1991

[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

[11] E.Iwase, S.Kato, T.Yasuda and I.Shimoyama, A Turning Gait Generating Network for a Hexapod Robot, Journal of Robotics Society of Japan, Vol.22, No.4, pp.492–498, 2004 (in Japanese)