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A consideration on biped lateral motion planning with robot experiment of adaptive frontal-plane stepping

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Abstract: In this paper, an method for biped lateral motion control is discussed, taking into consideration that the main purpose of frontal-plane is the stabilization of the inverted pendulum. Usually, the ZMP criterion is adopted to the biped control. However, the joint or the CoG reference trajectories generated based on the ZMP criterion sometimes have to be modified in relation to environmental changes. From this point of view, a control method without their reference trajectories is proposed for the biped frontal-plane motion. This control method using ground reaction force information is equivalent to the ZMP feedback control. The experiments of a biped robot whose degrees of freedom of motion is limited in the frontal plane demonstrate the effectiveness of this control method.

Keywords: Biped robot, motion planning, zero moment point, ground reaction force, center of pressure

1. INTRODUCTION

Biped locomotion consists of two types of motions: a sagittal and a frontal plane motion. Although the stability of the locomotion must be ensured in both planes, the nature of the stability is different between them. In the sagittal plane, the main purpose is to make a progression to change from one place to another. The nature of its stability is dynamic: losing static balance is essence of the sagittal plane motion, which causes the tumble to travel. In the frontal plane, on the other hand, to keep the upright posture is crucial. In this sense, the stability is static, and thus to stabilize an saddle point in the phase plane of the inverted pendulum motion is essential.

Generally speaking, for biped motion controls, so-called zero moment point (ZMP) criterion is utilized (Yamaguchi and Takanishi (1997); Nagasaka et al. (1999); Mitobe et al. (2001); Kagami et al. (2002)). Although this method is effective and useful, the planed motion using this method may be unsuitable when the environmental conditions change from the ones at the moment of the motion planning. The modification of the planned motion (Hirai et al. (1998); Huang et al. (2000); Napoleon and Sampei (2002); Wollherr and Buss (2004); Lee et al. (2005); Prahlad et al. (2007)), or on-line motion generation (Kajita and Tani (1996); Nishiwaki et al. (2002); Sugihara et al. (2002); Behnke (2006)) are excellent works to solve this problem. Normally, the motion planning based on the ZMP criterion is applied to both the sagittal and frontal plane. An idea of this paper is: the motion planning in the frontal plane can be removed according to the difference of stability nature. In the sagittal plane, the motion planning are certainly unavoidable: the motion is the principal object to control, e.g., the motion of the swing or support leg as well as the torso motion in concert with the legs. The ZMP method is, in origin, created to design such motions. But, in the frontal plane, the balance is the sole object to control, and thus the motion is the secondary problem. Nonetheless, as mention below, in the ZMP method in the frontal plane, the motion plan is planned at first, and the balance maintenance is the result of the motion control. In our opinion, it should be reversed: the balance control is first, and the motion emerges as a result of the balance control. From this point of view, the motion planning in the frontal plane should be removed by setting the balance control as the main task.

As a method to maintain the balance without motion planning, we introduced the direct ZMP control (Ito et al. (2003, 2007, 2008)). In the conventional method, the motion or posture that never disturbs the balance is firstly determined as the reference trajectory or position, and then the positional feedback control is applied to follow it. Instead of this indirect method, we select the ZMP directly as the control valuable.

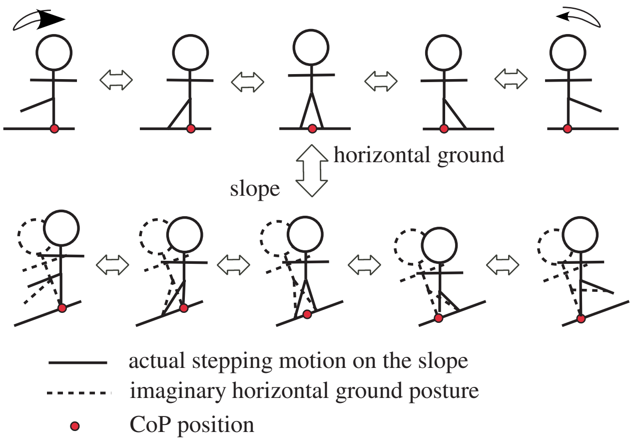


Fig. 1. Lateral stepping motion.

As an effect of this method, the adaptive behavior of the lateral motion is expected to be produced without adjusting controllers nor motion pattern generators. This effect originates from the invariance of the ZMP trajectory in the biped lateral motion. Only the lateral motion on the flat and sloped floor are drawn in the Fig. 1. To maintain the balance, the motion trajectories of the torso as well as the legs must be adaptively changed in relation to the slope angle. On the other hand, the ZMP trajectory indicating time stamp of the weight shift is invariable. Therefore, the balance control based on the direct ZMP control can naturally produce the adapted motion without designing motion trajectories. Such a control method has been proposed in our previous papers (Ito et al. (2007, 2008)), but the experimental evidences were imperfect. Accordingly, new experimental result with robot modification will be reported in this paper.

This paper is organized as follows: in the next section, we describe a control method based on the direct ZMP control for the frontal plane stepping. In the section III, the robot experiment as well as its experimental equipment are shown. Finally, the conclude this paper in the section IV.

2. CONTROL OF BIPED LATERAL MOTION

2.1 Strategy

In order to focus on the lateral motion of the biped locomotion, its analysis is restricted within the frontal plane throughout this paper. In the frontal-plane motion, the biped locomotion is also divided into the two phases: single and double support phase. The control law is defined separately in theses two phases.

Despite the separate definitions of the control law, the fundamental idea is common: The ZMP is directly controlled based on the information of the ground reaction forces. The ZMP is equivalent to the center of pressure (CoP) (Goswami (1999)), implying that the ZMP position is detected from the information of the ground reaction force. This is a reason why the control law is defined as it depends on the ZMP position or ground reaction forces.

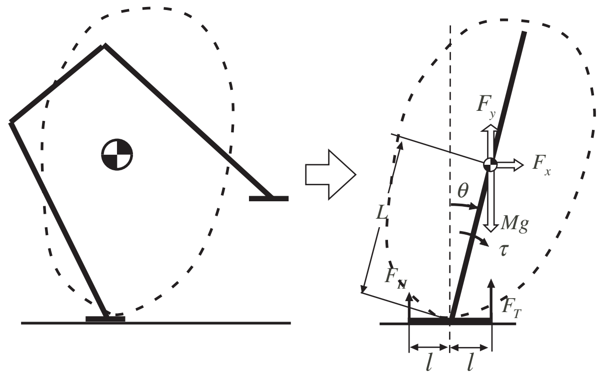


Fig. 2. A link model in single support phase.

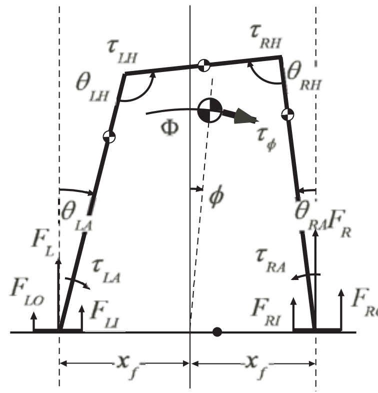


Fig. 3. A link model in double support phase .

2.2 Control in single support phase

On the slope, the entire body is wholly slanted at the ankle joint of the supporting leg as shown in Fig. 1, implying that the ankle joint plays a main role. Thus, the dynamics of the single support phase can be approximated by a inverted pendulum with a foot support, as shown in Fig. 2.

The effect of the slope as well as the swing leg dynamics are represented here by unknown external force F_x and F_y. The ground reaction forces are assumed to be detectable at the both end of the symmetrical foot support, denoted by F_H and F_T.

To main the balance, the F_H and F_T should be kept equal, indicating that the CoP, in other words, ZMP, is regulated at the center of the symmetrical foot support. To achieve this object, the control law is defined as

$$\tau = -K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f \int (F_H - F_T)dt \qquad (1)$$

where, θ denotes the sway angle, $\dot{\theta}$ is its velocity and K_d, K_p and K_f are feedback gains. It can be ensured that a stationary state where the $F_T = F_H$ is stabilized if the feedback gains are set adequately (Ito and Kawasaki (2005)). This control law is applied to the ankle joint of the support leg.

To lift the swing leg, the trajectory tracking control is compelled to be applied. Here, the reference trajectory must be set so that the it adaptively change with the slope. As a way to achieve it, the trajectory set based on the initial posture of the single support phase.

2.3 Switching to double support phase

Although the motion of the torso and swing leg will disturb the balance, the control law (1) is expect to compensate it. If the reference trajectory is designed adequately, the posture is recovered to a similar one to the initial state of the single support phase. Around this moment, the swing leg takes on the ground. Thus, the control mode is switched when the initial posture is recovered.

2.4 Control in double support phase

In order to exchange the support leg, the CoP, i.e., ZMP position must be moved from the current supporting leg to the other. Therefore, the reference ZMP trajectory is set in this way, and the control law is defined to track it. To achieve the ZMP tracking, the control law (1) is extended.

By normalizing the total ground reaction force $F_T + F_H$, the difference between F_T and F_H is equivalent to the position of the CoP, implying that the control law (1) has the same object to the CoP, i.e., ZMP position control. From this point of view, (1) can be rewritten as follows:

$$\tau_\phi = -K_d\dot{\phi} + K_p(\phi_d - \phi) + K_f\int(P_d - P_{ZMP})dt \quad (2)$$

Here, P_{ZMP} is the actual position of the ZMP, P_d is the reference trajectories of ZMP, ϕ is a sway angle at the midpoint of two ankle joints, τ_ϕ is a generalized force defined in the coordinate frame of the CoG orbit Φ, as shown in Fig. 3. P_{ZMP} can be calculated from the information of the ground reaction forces, where the two contact points are assumed at each foot.

$$P_{ZMP} = -\frac{F_{RO}}{F_{all}}(x_f + \ell_f) - \frac{F_{RI}}{F_{all}}(x_f - \ell_f) + \frac{F_{LI}}{F_{all}}(x_f - \ell_f) + \frac{F_{LO}}{F_{all}}(x_f + \ell_f) \quad (3)$$

$$F_{all} = F_{RO} + F_{RI} + F_{LI} + F_{LO}. \quad (4)$$

Here, the subscript $_{RO}$, $_{RI}$, $_{LI}$ and $_{LO}$ respectively represent the position of contact point, which are, the right outside, the right inside, the left inside and the left outside. ℓ_f is the length from the ankle joint to the side of the foot link. x_f is the distance to the ankle joint form the origin of the coordinates set at the midpoint of both ankle joints.

From the generalized force τ_ϕ, each joint torque is calculated using Jacobi matrix, which is based on the principle of virtual work. The stability was discussed in our previous papers (Ito et al. (2007, 2008))

2.5 Switching to single support phase

According to the control law (2), the ZMP position is shifted to the side of the next supporting legs by following the reference trajectory P_d. The control law is switched when the ZMP position get into the area of the next supporting foot.

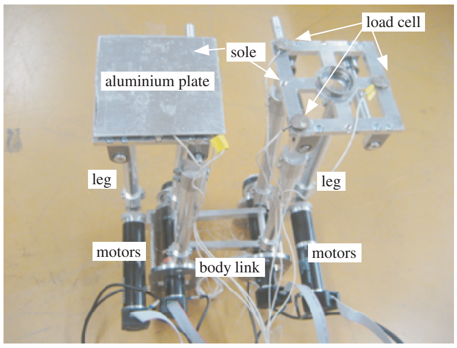


Fig. 4. Load cells attached on the sole.

3. ROBOT EXPERIMENT

3.1 Object

The control law is free from the motion planning, i.e., the reference trajectory generation of joint angles in the frontal-plane motion. Instead, the ZMP is directly controlled, which allows the robot to naturally change their motion according to the slope. The object of this experiment is to confirm this effect. In order to focus on this issue, the reduced degrees of freedom of motion is used, whose details are described in the next section.

3.2 Equipments

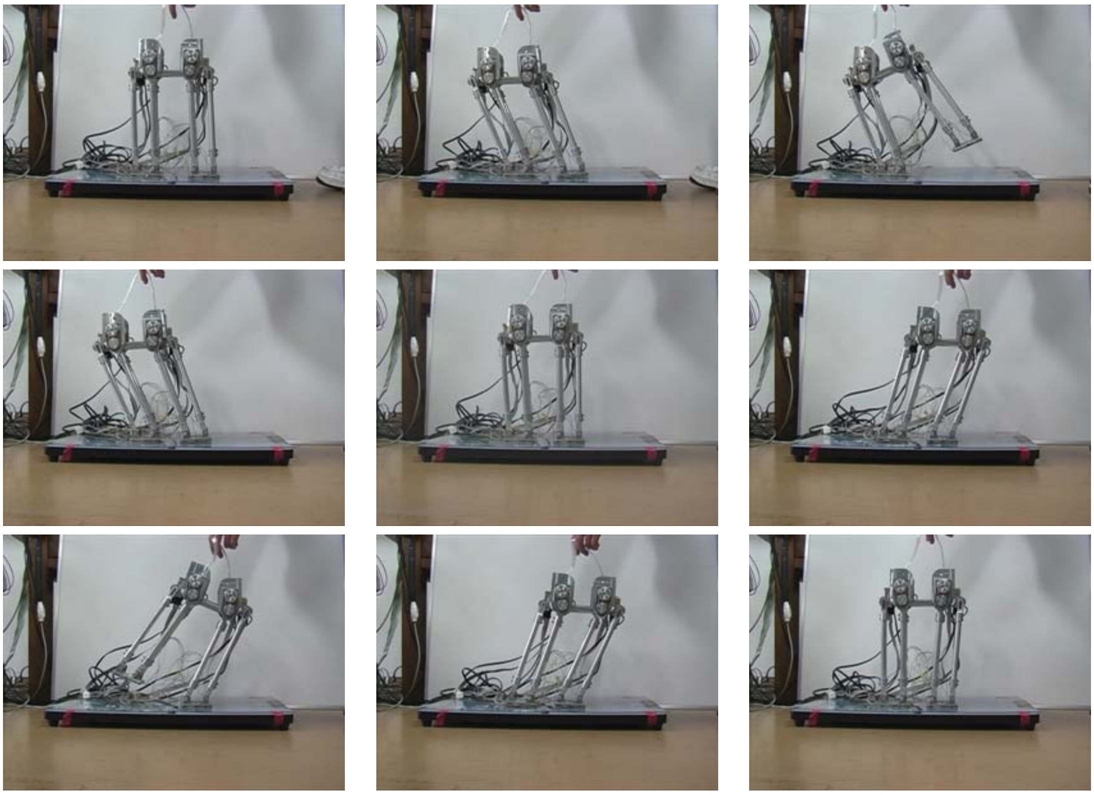
The biped robot with four degrees of freedom (DoF) of motion is used in the experiment. This robot has no DoFs other than in the frontal plane. It is about 35 cm in height and is about 2.4 kg in weight. The sole is 8.6 cm in length and the horizontal distance between right to left ankle is 13.4 cm. Four motors are installed: two are used to drive hip joints, while the other two does for ankle joints. The robot has been reconstructed from the one in the previous paper (Ito et al. (2007, 2008)) that is originally proposed by Yoneda et al. (2003).

The rotary encoder is installed in each motor, which provides the information on the joint angles of the robot. Furthermore, threes train-gage load cells are attached on each sole which allow for the ZMP detection. The photo of the soles are shown in Fig. 4. As shown by the right sole, two load cells are attached on each inside corner, whereas the other one is on the middle of the outside of the sole. In order not only for the ground reaction force to act exactly to the load cells but also to prevent the sole from slipping, they are covered by a shin aluminum plate, as shown by the left sole. The rated capacity of the load cells is 50 N.

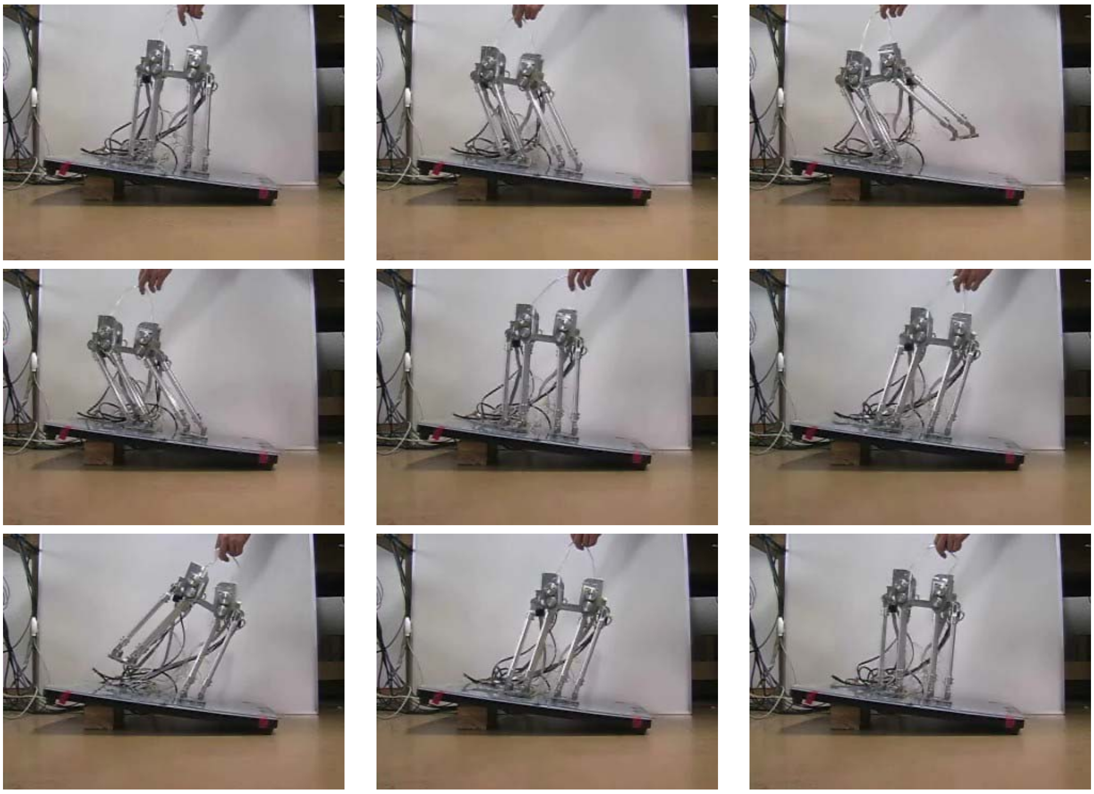
The robot controller operated by ART-LINUX acquire these sensory information via pulse counter and A/D converter boards. Then it calculate joint torque that should be applied at each joint, which are sent via D/A converter to the motor driver to drive each joint. The operating rate of the controller is 1 ms in the experiment

3.3 Methods

In the single support phase, the control law (1) is applied for the ankle joint of the supporting leg with the feedback gains: $K_d = 0.001$, $K_p = 0.005$ and $K_f = 0.0018$. Note



(a) On the flat surface.



(b) On the sloped surface.

Fig. 5. Snapshot of biped robot experiments.

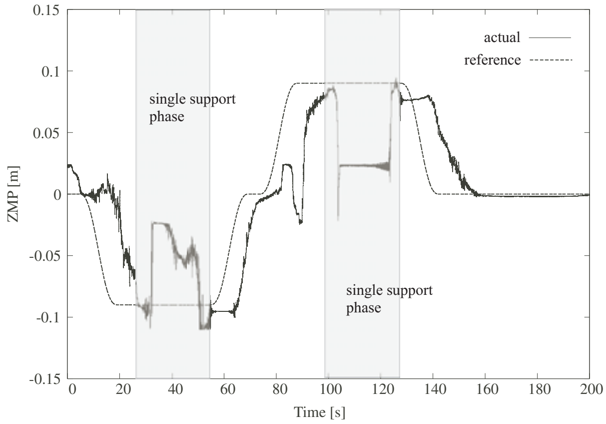
here that the unit of the angle is set to degree so as to easily check the robot motion in the experiment, and so the gains are given in the degree unit system. As the variable θ in (1), the CoG angle ϕ is approximately used instead. The θ_d in (1) is set to the angle ϕ at the initial state of the single support phase. The other joint angles are controlled, by the PD control, to their reference trajectories that are set as follows. The ankle joint of the swing leg is positionally controlled so that its sole becomes parallel to the the ground at the end of the single support phase. The hip joint of the swing leg is made to kept its neutral position. The one of the support leg is, on the other hand, made to extend 30 deg from its neutral position in 15 s, and then to return the neutral position again in 15 s. This trajectory is represented using the fifth-order polynomial equation of the time. The control mode is switched when the hip joint angle reaches neutral position. The feedback gains of PD control are: 0.0009 for derivative gain and 0.009 for proportional gain. They are the same in the three joints.

In the double support phase, the control law (2) is used. The feedback gains are set $K_d = 0.001$, $K_p = 0.002$ and $K_f = 0.07$. The reference trajectory is given using the fifth-order polynomial equation. It is set in two stage. In the first stage, it is set so as to return the midpoint of two ankle joint, actually, from 9 cm away to 0 cm in the coordinate frame whose origin is set to the midpoint. The transition time is 15 s. In the second stage, the reference trajectory is set to move away, actually, from 0 cm to 9 cm, to the reverse direction. In order to promote the ZMP movement, the distance of the ZMP shift is set slightly larger than the natural width between two ankle joint (x_f=6.7 [cm]). The control mode is switched based on the ZMP position. The threshold is set 0.5 cm before than the exact final values.

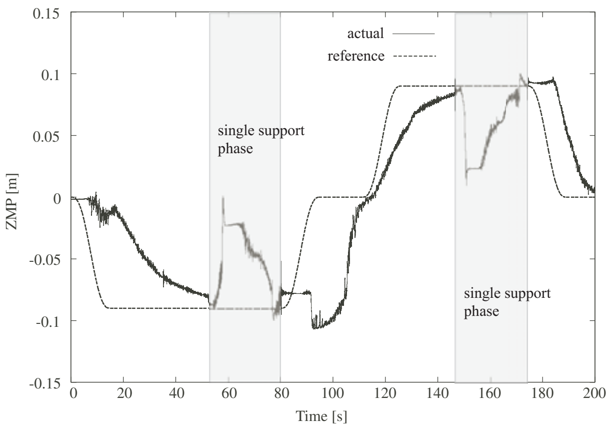
The lateral stepping experiments were executed in two conditions: on the flat ground and on 8 deg slope.

3.4 Results and discussion

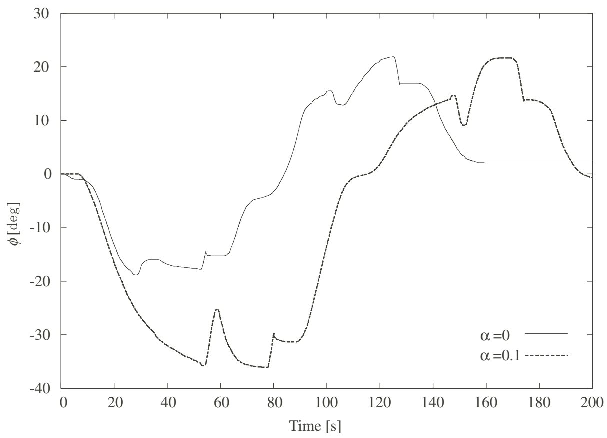
The snapshots of the robot motion on the slope are shown in Fig. 5. Figure 6(a) shows the time based plot of the ZMP position on the flat ground while (b) does the one on the sloped ground. In the graph of the Fig. 6, the positive direction of the vertical axes denote the right side in the photo of the Fig. 5. Although the robot motion was normal in these snapshots as well as in the replay of the movie, the trajectory of the ZMP was partially fluctuated in the flat ground experiment. The fluctuation is observed around 90 s. The analysis of the data on the ground reaction forces allows us to infer the following behavior of the robot: Initially, the robot slanted to the left side. Then, the weight was put in the left in both feet. Around 90 s, the total weight shifted to the left side of the right foot. To slant to the right more, the robot utilized the ground reaction force at the right side of the left foot. In this instance, the ZMP position temporally became negative once. Finally, the ZMP moved to the right side. Then, the weight is put in the right in both feet. Such a tendency is often observed in other experiments. We consider the one reason is the high sensitivity of the zero-output adjustment of the motor drivers.



(a) Reference and actual trajectory of ZMP on flat floor.



(b) Reference and actual trajectory of ZMP on slope.



(c) Horizontal position of CoM.

Fig. 6. Experimental results.

Here, note that, in the single support phase, the ZMP reference is meaningless in these graph: the balance is controlled to reduce the difference of ground reaction forces at the both ends of the supporting foot using (1). Therefore, the ZMP trajectories in the double support phase are not quantitatively different so match in both experiments besides this fluctuating term: they certainly follow the reference regardless of the variation of the ground slope. However, their response is not so good even the motion is slow. In the computer simulations, better results are shown because of the high gain feedback.

However, high gain controller vibrates the actual robot. At the low feedback gains, the effect of integration term, which is essential for the adaptive motion to the sloped ground, delays too much to achieve the rapid motion. The mechanical backlash is one reason to prevent us from increasing the gains.

The similar ZMP profiles imply the accomplishment of the lateral stepping motion. The time based plot of the sway angle ϕ is shown in Fig. 6(c). The profile of the lateral sway angle is shifted down from that of the flat condition. It indicates that the lateral motion is achieved by tilting the whole body adaptively against the slope.

In summary, these experiment revealed that the controller using the feedback of the ZMP or ground reaction forces enables the lateral stepping motion without the effect from the ground slope.

4. CONCLUSIONS

The generation of the joint reference trajectories is a causal problem in biped robot. Restricting problems to the balance control in the frontal plane motion, a control method without the joint reference trajectories was proposed. This control method makes the most use of the information on the ground reaction forces, and is equivalent to the feedback control of the ZMP position. Although the reference trajectories of the ZMP position is required, any other reference trajectories of the joints nor CoG of the body, which usually change with environmental conditions such as the slope, are unnecessary. Thanks to this property, the natural adaptive change of the lateral motion is accomplished. Applying it to the control of a biped robot whose degrees of freedom of motion is restricted within the frontal plane, its effectiveness has been experimentally confirmed. However, the achieved motion is slow. The repair of the mechanical problem such as backlash at the joints will somewhat improve the motion speed.

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