

A ZMP Feedback Control for Biped Balance and its Application to In-Place Lateral Stepping Motion

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Abstract— Many biped robot control schemes adopt a zero moment point (ZMP) criterion, where the motion is initially planned as the positional trajectories such that ZMP stays within the support polygon, while the feedback control of each joint is later applied to follow the planned reference motion. Although this method is powerful, the ZMP is not always controlled in a feedback manner. Namely, when the environment such as the gradient of the ground varies, the planned motion may cause the tumble and so replanning or modification is sometimes required in order to avoid it. With respect to the environmental variations, the ZMP trajectory is invariant in the lateral plane of the biped robot, in which the ZMP moves from the one side to the other and vice versa. From this point of view, we propose a biped control method for the frontal plane motion based on the ZMP position feedback. It does not require the reference motion of the upper body and the motion replanning or modification of the reference motion are free against environmental variation. This method is applied in the in-place stepping motion and the stability of this method is examined analytically as well as by computer simulations. Finally, the effectiveness of this method is demonstrated by the robot experiment with some improvement points.

Index Terms— biped robot, stepping motion, Center of pressure, motion planning, adaptive behavior

I. INTRODUCTION

The main problem of a biped control is maintaining balance. The tendency to fall can be determined based on the zero moment point (ZMP) [1] obtained as a cross point of the inertial and gravitational force resultant vector and the ground. Many studies of biped walking utilized the so-called ZMP criterion [2]–[5]: the reference trajectories of each joint angle, or the center of mass (CoM) of the body, are initially planned to force the computed ZMP based on the planned motion to stay inside the foot support. The joint angles, or the CoM of the body, are then controlled in a feedback manner to follow these reference trajectories. However, this strategy does not directly control the ZMP since the actual position of the ZMP is not measured

during the locomotion. In other words, the ZMP position is ensured only by the accurate realization of the reference trajectories, implying that the modeling error such as irregularities of the ground surface may disturb the ZMP trajectory from the planned one. Although some studies introduced the concept of the ZMP feedback [6]–[9], or on-line trajectory planning based on ZMP position [10]–[13], however, the stability is not discussed except in a few papers [14], [15]. In addition, some of them require accurate model of the links system, which contains complex calculations as well as the utilization of dynamic parameters such as the moment of the inertia which are usually difficult to obtain.

The control of the lateral motion during biped walk is a good candidate for the ZMP feedback control, where the ZMP is selected as a control variable. A complete walking motion is composed of sagittal plane motion characterized as an inverted pendulum motion and lateral plane motion. The control principles are different between the two. The purpose of the sagittal plane motion is the spatial migration by transferring the support legs, indicating that the forward-falling motion of the inverted pendulum is essential. On the other hand, for the lateral plane motion, the body weight shifts to make one leg lifted up without falling. Focusing on this nature of balance keeping, our scope is restricted here to the motion control in the lateral direction throughout this paper. The weight shift is represented as the lateral movement of the CoP (center of pressure) that is equivalent to the point where total body weight is placed. Thus, it is natural to select the CoP as a control variable. Goswami [16] states that the ZMP is identical to the CoP. This implies that our method is equivalent to the ZMP feedback control.

The advantage of selecting CoP as a control variable in the lateral motion control is that the reference trajectory of the CoP is invariant even if the environmental conditions change. As shown in Fig. 1, the trajectories of the body movement, i.e., joint angle or center of mass (CoM) of the body, must be modified in accordance with the environmental conditions such as a gradient of the ground. However, the trajectory of CoP does not change since it directly describes the purpose of the weight shift motion.

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Therefore, we aim here at controlling the position of the CoP to follow the reference trajectory. From the viewpoint of static balance, a method that utilizes feedback of the position of the CoP was proposed by [17] and [18]. Now this method is applied to a weight shift motion by making the reference position of CoP time-varying [19] and extended a motion control method for lateral in-place stepping [20]. Because the CoP and ZMP are identical [16], it is equivalent to the balance control based on the ZMP feedback. This method requires no reference trajectory of the body motion. Furthermore, this control law can be constructed without dynamical parameters of the biped link model. Such body's trajectory-free and dynamical parameter-free feature gives the contribution to the biped control in the aspect of the robustness as well as the reduction of the computational cost.

Summing up the mathematical analyses and robot experiments in our previous works [19], [20], this paper is structured as follows. In section II, the fundamental theory of the CoP, i.e., ZMP feedback control, is described. This theory is extended first to the weight shift movement in double support phase in section III. Based on these two sections, a new control strategy for stepping motion is proposed, and computer simulation results are shown in section IV. In section V, the details of our experimental apparatus are introduced and experiment results of the in-place lateral stepping motion are presented. The concluding remarks are given in section VI.

II. BALANCE CONTROL BY COP REGULATION

Ground reaction forces include significant information necessary for balancing control. A model-free control law effectively utilizing them such that a static balance can be maintained by changing the posture adaptively with respect to the unknown constant external forces [18].

Assumptions of the control law are as follows. The body link and the foot link are connected at the ankle joint as illustrated in the left figure of Fig. 2. The motion occurs only in the sagittal plane. The ankle joint angle θ and its velocity $\dot{\theta}$ are detectable, while appropriate torque τ is actively generated at the ankle joint. The foot link has two ground contact points at the heel and the toe, where the vertical component of the ground reaction force F_H and F_T , are measurable. The foot does not slip on the ground and its shape is symmetrical in the anterior-posterior direction. The ankle joint is located at the midpoint of the foot link with zero height.

Suppose an unknown constant external force is exerted at the center of mass (as shown in Fig. 2), whose horizontal and vertical component is F_x and F_y , respectively. If balance is kept, only the body link has dynamics which is described in the following equation of motion.

$$\begin{aligned} I\ddot{\theta} &= MLg \sin \theta + F_x L \cos \theta - F_y L \sin \theta + \tau \\ &= AL \sin(\theta - \theta_f) + \tau \end{aligned} \quad (1)$$

where

$$A = \sqrt{(Mg - F_y)^2 + F_x^2} \quad (2)$$

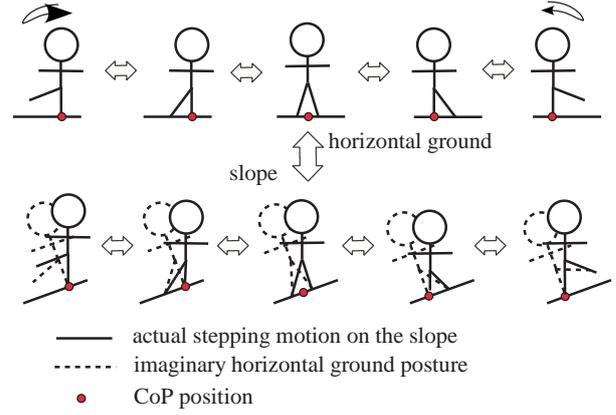


Fig. 1. Lateral stepping motion on different gradient condition.

and θ_f is a constant satisfying

$$\sin \theta_f = -\frac{F_x}{A}, \quad \cos \theta_f = \frac{Mg - F_y}{A}. \quad (3)$$

And, M is a mass of the body link, I is its moment of inertia about the ankle joint, L is the length between the ankle joint and the center of mass (CoM) of the body link and g is the gravitational acceleration.

The goal of the control is to keep the postural balance regardless of the constant external force F_x and F_y . It is most effectively achieved by making F_T and F_H equal from the aspect of the stability margin. One of the solutions can be stated by the following theorem.

Theorem 1: For the dynamical system (1), consider the torque input τ as follows:

$$\tau = -K_d \dot{\theta} + K_p(\theta_d - \theta) + K_f \int (F_H - F_T) dt. \quad (4)$$

If feedback gain K_d , K_p and K_f satisfy the conditions

$$K_p > AL > 0 \quad (5)$$

$$\frac{\ell}{I} K_d > K_f > 0 \quad (6)$$

$$(K_d \ell - K_f I) K_p > K_d \ell AL, \quad (7)$$

then, $F_H = F_T$ holds at the stationary state and $\theta = \theta_f$ becomes a locally asymptotically stable posture.

Proof: First, we define a new state variable τ_f by the following equation,

$$\tau_f = \int (F_H - F_T) dt. \quad (8)$$

Substituting (4), (1) turns to

$$\begin{aligned} I\ddot{\theta} &= AL \sin(\theta - \theta_f) \\ &\quad - K_d \dot{\theta} + K_p(\theta_d - \theta) + K_f \tau_f, \end{aligned} \quad (9)$$

On the other hand, the ground reaction forces are described with ankle joint torque as,

$$F_T = -\frac{1}{2\ell} \tau + \frac{1}{2} mg + \frac{1}{2} f_y, \quad (10)$$

$$F_H = \frac{1}{2\ell} \tau + \frac{1}{2} mg + \frac{1}{2} f_y, \quad (11)$$

zero height. At the end of both sides, the foot comes into contact with the ground, and the ground reaction forces are detectable. Furthermore, angular positions and angular velocities are measurable at the ankle and the hip joints. Every joints are actively actuated.

B. Control law

The degree of freedom (DoF) of the link model in the normal double support phase where the foot links keep contact with the ground, as shown in Fig. 3, is one, since the body link and two leg links construct a close mechanism. Because the control law (4) is also derived for stabilizing 1 DoF inverted pendulum motion, it could be extended to the bilateral balancing by addressing the following three points. First, there are two more contact points than the previous case. Second, the orbit of the CoG motion is not an exact circle. Third, the actuation is redundant. To solve these three problems, the control law is extended as follows.

1) *Description of CoP*: The added number of the contact points is an obvious difference. This problem is solved by introducing the concept of CoP. The control law (17) is available regardless of the number of the contact points. In the double support phase, the position of CoP, P_{CoP} , is calculated from the vertical component of ground reaction forces at four contact points, i.e., F_{RO} , F_{RI} , F_{LO} , and F_{LI} .

$$P_{CoP} = -\frac{F_{RO}}{F_{all}}(x_f + \ell_f) - \frac{F_{RI}}{F_{all}}(x_f - \ell_f) + \frac{F_{LI}}{F_{all}}(x_f - \ell_f) + \frac{F_{LO}}{F_{all}}(x_f + \ell_f) \quad (18)$$

$$F_{all} = F_{RO} + F_{RI} + F_{LI} + F_{LO}. \quad (19)$$

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 from the origin of the coordinates set at the midpoint of both ankle joints.

2) *Coordinate frame for CoG motion*: Although the CoG motion draws a circular arc in the biped upright model in Fig. 2, it generally does an elliptic arc in the double support model in Fig. 3 since the length between both feet is not the same as the one between both hip joints.

To solve this problem, the new coordinate frame is introduced. Here, the coordinate of CoG on this frame is presented by ϕ . It is preferable that this coordinate frame is naturally extended from the one for the single support phase. From this point of view, we define ϕ as the sway angle of CoG from the vertical direction.

$$\phi = \arctan \frac{x_G}{y_G}. \quad (20)$$

Here, (x_G, y_G) denotes the coordinate of CoG whose origin is set at the midpoint between both foot. Using

the ankle joint angle in both side, θ_{RA} and θ_{LA} , the coordination of CoG can be described as

$$x_G = 2\rho \cos \frac{\theta_{RA} + \theta_{LA}}{2} \sin \frac{\theta_{RA} - \theta_{LA}}{2} \quad (21)$$

$$y_G = 2\rho \cos \frac{\theta_{RA} + \theta_{LA}}{2} \cos \frac{\theta_{RA} - \theta_{LA}}{2} \quad (22)$$

Here,

$$\rho = \frac{2m\ell + ML}{2(2m + M)}. \quad (23)$$

Using this relation, we obtain

$$\frac{x_G}{y_G} = \tan \frac{\theta_{RA} - \theta_{LA}}{2} \quad (24)$$

According to the definition of the generalized coordinate (20), ϕ is expressed as

$$\phi = \frac{\theta_{RA} - \theta_{LA}}{2}. \quad (25)$$

The generalized force τ_ϕ is also defined as the torque exerted in the tangential direction of the orbit. Based on (4) and the relation $P_{CoP} = P_{ZMP}$, here P_{ZMP} is the position of the ZMP, τ_ϕ is determined as follows:

$$\tau_\phi = -K_d \dot{\phi} + K_p(\phi_d - \phi) + K_f \int (P_d - P_{ZMP}) dt \quad (26)$$

Since this equation takes the same form as (4), the COP (ZMP) is expected to converge to the desired value.

3) *Joint torque calculation*: Next, we calculate the joint torque which produce the generalized force τ_ϕ . When CoG moves $\Delta\phi$ along the orbit, the hip and ankle joints also changes, the amount of which is put to $\Delta\theta$ ($\theta = [\theta_{RA}, \theta_{RH}, \theta_{LH}, \theta_{LA}]$). The subscript RA , RH , LH and LA represent the joint position, which are, the right ankle, the right hip, the left hip, and the left ankle, respectively. The relation between $\Delta\theta$ and $\Delta\phi$ is described using the Jacobian matrix $\mathbf{J}(\theta)$ as

$$\Delta\theta = \mathbf{J}(\theta)\Delta\phi. \quad (27)$$

In the coordinate frame defined in this section, the $\mathbf{J}(\theta)$ is calculated as follows. From (25)

$$\dot{\phi} = \frac{\dot{\theta}_{RA} - \dot{\theta}_{LA}}{2} \quad (28)$$

is satisfied. In addition, a kinematical relation among the joint angle are given as

$$-\theta_{RA} + \theta_{RH} + \theta_{LH} - \theta_{LA} = \pi \quad (29)$$

Its differentiation becomes

$$-\dot{\theta}_{RA} + \dot{\theta}_{RH} + \dot{\theta}_{LH} - \dot{\theta}_{LA} = 0 \quad (30)$$

Now, the coordinate of the left hip joint (x_{RH}, y_{RH}) can be described as two ways:

$$\begin{aligned} \begin{bmatrix} x_{RH} \\ y_{RH} \end{bmatrix} &= \begin{bmatrix} -x_f + L \sin \theta_{RA} \\ L \cos \theta_{RA} \end{bmatrix} \\ &= \begin{bmatrix} x_f - L \sin \theta_{LA} - 2\ell_B \sin(\theta_{LH} - \theta_{LA}) \\ L \cos \theta_{LA} - 2\ell_B \cos(\theta_{LH} - \theta_{LA}) \end{bmatrix} \end{aligned} \quad (31)$$

Differentiating them, the following two equations are obtained.

$$\begin{bmatrix} -L\dot{\theta}_{LA} \cos \theta_{LA} - 2\ell_B(\dot{\theta}_{LH} - \dot{\theta}_{LA}) \cos(\theta_{LH} - \theta_{LA}) \\ -L\dot{\theta}_{LA} \sin \theta_{LA} + 2\ell_B(\dot{\theta}_{LH} - \dot{\theta}_{LA}) \sin(\theta_{LH} - \theta_{LA}) \end{bmatrix} = \begin{bmatrix} L\dot{\theta}_{RA} \cos \theta_{RA} \\ -L\dot{\theta}_{RA} \sin \theta_{RA} \end{bmatrix} \quad (32)$$

Solve the three equations (28), (30), (32) as four variables $\dot{\theta} = [\dot{\theta}_{RA}, \dot{\theta}_{RH}, \dot{\theta}_{LH}, \dot{\theta}_{LA}]^T$, and the relation between $\dot{\theta}$ and $\dot{\phi}$ is represented by

$$\dot{\theta} = \frac{2}{J_1 + J_3} \begin{bmatrix} J_1 \\ J_1 - J_2 \\ J_2 - J_3 \\ -J_3 \end{bmatrix} \dot{\phi} = \mathbf{J}(\theta) \dot{\phi} \quad (33)$$

$$J_1 = 2\ell_B \sin \theta_{LH} \quad (34)$$

$$J_2 = L \sin(\theta_{LH} + \theta_{RH}) \quad (35)$$

$$J_3 = 2\ell_B \sin \theta_{RH}. \quad (36)$$

From the principle of virtual work, the next relation holds between the generalized force τ_ϕ and the joint torques $\tau = [\tau_{RA}, \tau_{RH}, \tau_{LH}, \tau_{LA}]$,

$$\tau_\phi = \mathbf{J}^T(\theta) \tau \quad (37)$$

Solving this equation, the joint torques are given by

$$\tau = (\mathbf{J}^T(\theta))^* \tau_\phi + (I - \mathbf{J}^T(\theta)(\mathbf{J}^T(\theta))^*) \mathbf{p} \quad (38)$$

Here, * denoted its generalized inverse matrix, and \mathbf{p} is an arbitrary 4-dimensional vector.

C. Stationary state

Let us discuss the stationary state that is achieved by the control law (26). Here, assume that the joint angles can be described as a function of ϕ , i.e., $\theta = \theta(\phi)$, which is possible if $0 < \theta_{RH}, \theta_{LH} < \pi$. Note that the tangent line of CoG orbit is not orthogonal to the ground in the range of the normal lateral motion. The equation of motion can be described using ϕ as

$$M(\theta)\ddot{\phi} + C(\theta, \dot{\phi}) + G(\theta, g, \mathbf{F}) = \tau_\phi. \quad (39)$$

where, G contains not only the gravity but also external force \mathbf{F} , i.e., F_x and F_y in (1). From the mechanical property, $M(\theta) > 0$ and $C(\theta, \dot{\theta})$ become the second order term of $\dot{\theta}$. On the other hand, the joint torque control the CoP through τ_ϕ , whose relation is expressed as

$$P_{CoP} = P(\theta)\tau_\phi + Q(\theta, \dot{\theta}) + R(\theta, g, \mathbf{F}) \quad (40)$$

Now, we have defined the control input τ_ϕ by (26). For the simplicity of calculation of stationary state, a new state variable τ_f is introduced

$$\tau_f = \int (P_{ZMP} - P_d) dt = \int (P_{CoP} - P_d) dt \quad (41)$$

Then, the equation of motion (39) for ϕ becomes

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta}) + G(\theta, g, \mathbf{F}) = -K_d\dot{\phi} + K_p(\phi_d - \phi) + K_f\tau_f. \quad (42)$$

On the other hand, the differentiation of τ_f provides the relation

$$\dot{\tau}_f = P_{CoP} - P_d. \quad (43)$$

Substituting (40), the above equation becomes

$$\dot{\tau}_f = P(\theta)(-K_d\dot{\phi} + K_p(\phi_d - \phi) + K_f\tau_f) + Q(\theta, \dot{\theta}) + R(\theta, g, \mathbf{F}) - P_d \quad (44)$$

Assigning $\phi, \dot{\phi}, \tau_f$ as state variables, the stationary state $\bar{\phi}$ and $\bar{\tau}$ can be obtained. Most importantly, $\dot{\tau}_f = 0$ at the stationary state, which implies that $P_{CoP} = P_d$, i.e., the ZMP is controlled to the desired position.

D. Stability

For the stability analysis, (42) and (44) are linearized around the equilibrium point $(\bar{\phi}, \bar{\tau}_f)$:

$$\bar{M}\Delta\ddot{\phi} + \frac{\partial \bar{G}}{\partial \theta} \bar{J} \Delta\phi = \Delta\tau_\phi \quad (45)$$

$$\Delta\dot{\tau}_f = -\left(\frac{\partial \bar{R}}{\partial \theta} + \frac{\partial \bar{P}}{\partial \theta} \bar{\tau}_\phi\right) \bar{J} \Delta\phi - \bar{P} \Delta\tau_\phi \quad (46)$$

Here, $\bar{M} = M(\bar{\theta})$, $\bar{J} = J(\bar{\theta})$, $\bar{P} = P(\bar{\theta})$, $\frac{\partial \bar{G}}{\partial \theta} = \frac{\partial G(\bar{\theta})}{\partial \theta}$, $\frac{\partial \bar{R}}{\partial \theta} = \frac{\partial R(\bar{\theta})}{\partial \theta}$, $\frac{\partial \bar{P}}{\partial \theta} = \frac{\partial P(\bar{\theta})}{\partial \theta}$. The controllability matrix of the above linear system is

$$\begin{bmatrix} 0 & \frac{1}{\bar{M}} & 0 \\ \frac{1}{\bar{M}} & 0 & -\frac{1}{\bar{M}^2} \frac{\partial \bar{G}}{\partial \theta} \bar{J} \\ -\bar{P} & 0 & -\frac{1}{\bar{M}} \left[\frac{\partial \bar{R}}{\partial \theta} + \frac{\partial \bar{P}}{\partial \theta} \bar{\tau}_\phi \right] \bar{J} \end{bmatrix} \quad (47)$$

If this matrix is full rank, the stationary state becomes locally stable for the suitable feedback gains K_p, K_d and K_f , which will be designed e.g., by using the solution of the Riccati equation for LQ theorem. Since $\bar{\tau}_\phi = K_p(\phi_d - \bar{\phi}) + K_f\bar{\tau}_f = \bar{G}$, the determinant of the controllability matrix becomes

$$\frac{1}{\bar{M}^3} \frac{\partial}{\partial \theta} (\bar{P}\bar{G} + \bar{R}) \bar{J} = \frac{1}{\bar{M}^3} \frac{\partial}{\partial \phi} (PG + R) \Big|_{\phi=\bar{\phi}} \quad (48)$$

Here, assume that (48) is zero. Substituting (39) into τ_ϕ of (40) and linearize (40) around the equilibrium point, the following equation is obtained,

$$\Delta P_{CoP} = PM\Delta\ddot{\phi} + \frac{\partial}{\partial \phi} (PG + R) \Big|_{\phi=\bar{\phi}} \Delta\phi \quad (49)$$

When ϕ is deviated from $\bar{\phi}$ slowly, $\Delta\ddot{\phi}$ is regarded as zero. Then, $\Delta P_{CoP} = 0$, since we assume (48) is zero. It means that CoP stays at the same position if ϕ changes slowly. That would be possible if the CoG moves vertically. However, the tangent line of CoG orbit is not generally vertical. So, the contradiction occurs and the controllability matrix should be full rank, implying that the linear system is controllable.

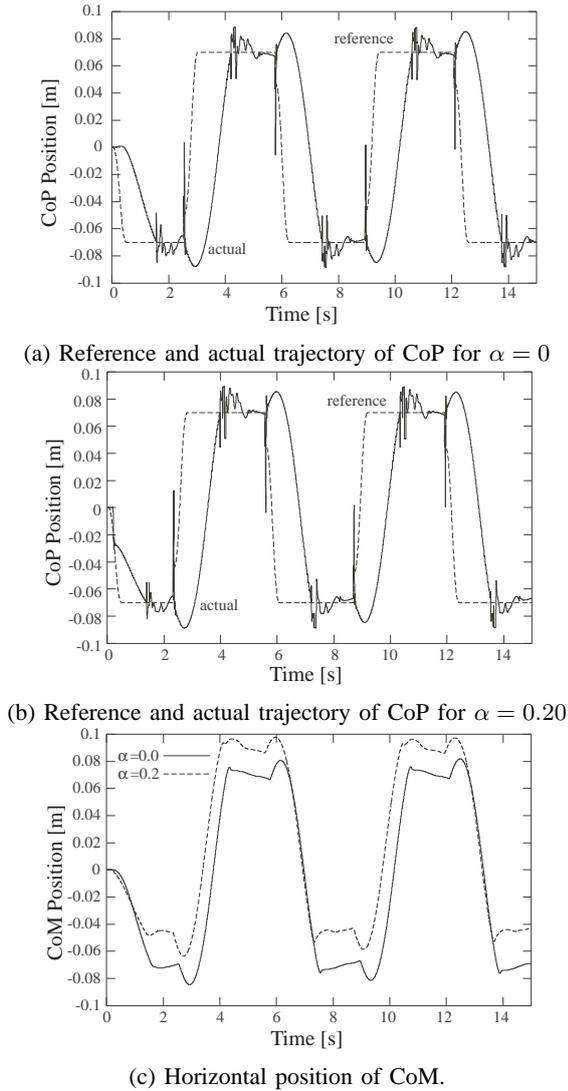


Fig. 4. Simulation results.

IV. CONTROL FOR THE STEPPING MOTION BASED ON THE ZMP FEEDBACK

In this study, a control method for stepping motion that is robust to an unknown constant external disturbance is considered. The control methods for the weight shift motion as well as the single leg static balance in the previous section can be used in combination to automatically adjust the posture or motion with respect to the unknown external force and realize stepping motion using a simple biped robot. The main problem is how to switch the control law between the two schemes. Focusing on this aspect, we propose below a control method for stepping motion based on the ZMP (COP) information.

A. Control in double support phase

At the start of walking motion, the legs are on the ground in the double support phase. To take the first step, the weight has to be shifted to the supported side to prepare the other leg to become a swing leg. In this weight shift motion, the control method that is mentioned in the

section III is used where the reference CoP trajectory is tracked in a feedback control fashion. The body motion is modified as a result of this CoP control. The robot executes a weight shift motion by tilting the whole body so as to cope with a constant external force. Note that the CoP trajectory is adequately designed in advance so that the weight shift motion can be achieved.

B. Switching from double support phase

The control in the double support phase is based on the trajectory tracking control of the CoP position. When the CoP position becomes greater than a threshold value, the weight shift motion is regarded as sufficient. At this moment, the control law is switched from that for the double support phase to that for single support phase.

C. Control for single support phase

The static balance control law (17) is adopted to the ankle joint in the single support leg. In this phase, the body as well as the swing leg moves to perform the stepping motion according to the reference trajectories, which disturb the balance in this phase. However, this disturbance will be compensated by the control law (17).

To generate the body and swing leg movements for stepping motion, the reference trajectories must be provided for the feedback control of the two hip joints. For the adaptive motion, the reference trajectories must change with respect to the environment such as the slope angle. Therefore, the initial and end posture in the reference trajectory is produced, such that, the posture of the end of the double support phase is set as both an initial posture and a final posture. These two postures are interpolated continuously to achieve the lifting-up motion of the swing leg, i.e., the hip joint in the support leg are extended and then flexed in a constant amount.

D. Switching from single support phase

When the foot of the swing leg is placed on the ground, the control law is switched back to that for the double support phase.

E. Simulation

The control method in the previous section is simulated under the influence of the constant external force expressed as the following equations.

$$F_x = -Mg \sin \alpha \quad (50)$$

$$F_y = -Mg(1 - \cos \alpha). \quad (51)$$

These external forces are equivalent to a set of external forces acting on the biped robot on the slope with slope angle α . The cases where $\alpha = 0[\text{rad}]$ (no external force) and $\alpha = 0.2[\text{rad}]$ are examined. Parameters are: $M = 2.5[\text{kg}]$, $m = 1.25[\text{kg}]$, $m_f = 0[\text{kg}]$, $L = 0.20[\text{m}]$, $\ell = 0.1[\text{m}]$, $\ell_B = 0.07[\text{m}]$, $\ell_f = 0.02[\text{m}]$. The feedback gains of (4) are set to $K_d = 30$, $K_p = 500$, and $K_f = 1$, while those of (38) are $K_d = 5$, $K_p = 10$, and $K_f = 100$.

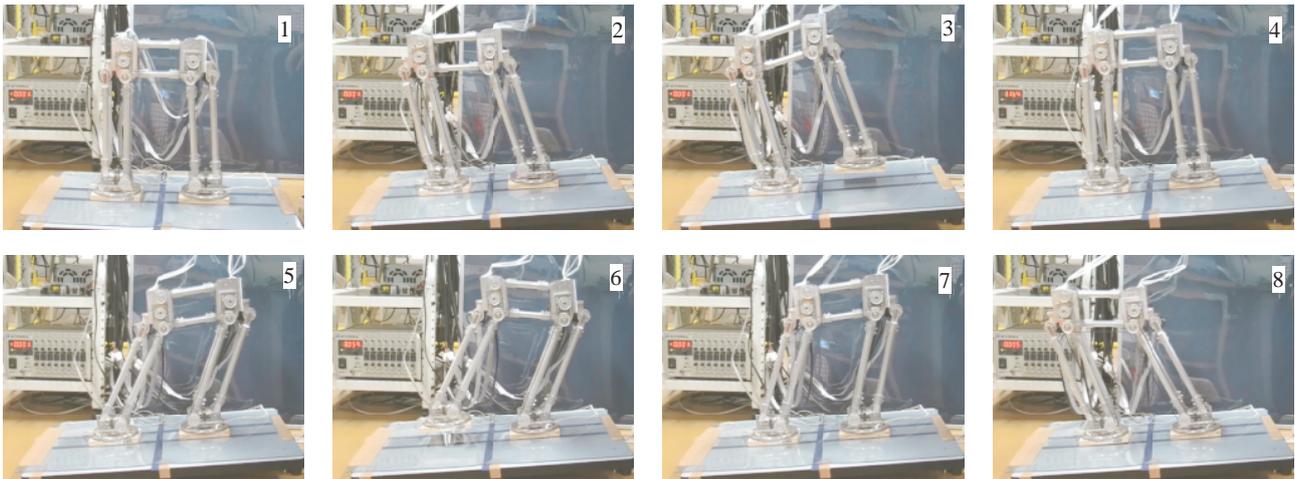


Fig. 5. In-place stepping motion experiment of the slope.

In the single support phase, the conventional PD control with nonlinear compensation is applied to the hip joints. These feedback gains are set to $K_d = 500$ and $K_p = 100$.

The graphs in Fig. 4(a) and (b) represent the time based plot of the CoP (ZMP) position. Regardless of the external forces, the similar CoP profile are obtained, implying that the weight shift is achieved as intended in both cases. The time based plot of the horizontal position of CoM is denoted in Fig. 4(c). It can be seen from the figure that when the external force is exerted, the stepping motion is performed such that the biped robot tilts the whole body against it.

V. EXPERIMENT

A. Apparatus

The reduced degree of freedom biped robot, whose design is originally proposed by Yoneda et al. [21], is used in experiments. This robot has parallel link structure in the leg parts as well as the body part, which keeps the soles parallel to each other. The biped robot is about 40[cm] in height and is about 2.9[kg] in weight. The sole is 12[cm] in length and the horizontal distance between right to left ankle is 20[cm]. Four motors are installed. One of them actuates the motion around yawing axis at ankle joints, which is not used in this experiment. The other three motors are used to achieve a stepping motion within the lateral plane.

A personal computer with RT-LINUX operating system is used to compute the torque output signal for all motors. The computed output signal is sent via D/A converter to the motor driver to make the motors generate the desired torque. A motion of the biped robot is detected by the rotary encoder installed in each motor. Three load cells are attached on each sole, from which the position of the CoP, i.e., ZMP is calculated. The controller's sampling time is 1[ms] in this experiment.

B. Control law

The control law mentioned in the section IV was adopted. However, in the preliminary experiment, the biped robot tumbled in the single support phase. Thus, the control for ankle joint in the single support phase was changed from eq. (4) to the position control of the reference trajectory. The reference trajectory was set as follows. In the first 3[s], the ankle joint was extended 0.2[rad] from its initial value. The ankle kept the current angle during next 2[s] and then flexed 0.2[rad] to return to the initial angle in the next 3[s]. For the hip joints in the single support phase, on the other hand, the reference trajectories were set as follows. The hip joint of the support leg was extended 0.9[rad] in the first 5[s] and flexed 0.9[rad] in the next 5[s]. The reference trajectory of hip joint of the swing leg was generated based on the state of the support leg so that the two legs become almost parallel.

When the swing leg contacted with the ground, the control law was switched to that for the double support phase. Here, to ensure the ground contacts, the posture at the moment of the contact was kept for 1[s] before starting the control for the double support phase.

The control in the double support phase is the tracking control of the CoP position. The reference trajectory was set so that the CoP moved from the current position to 50mm away from the midpoint of the two ankle joints in 5[s]. The threshold value for switching to the one for single support phase was selected from the experiment and set at 38[mm] away from the mid point of the two ankle joints.

C. Results

The lateral stepping experiments were executed in two conditions: on the flat ground and on 0.1 [rad] slope. As shown in (50) and (51), the slope provides the similar effect of the disturbance by constant external force. The snapshots of the robot motion on the slope are shown in Fig. 5. The time based plot of the CoP position on the flat

ground is shown in Fig. 6(a), while the one on the slope is shown in Fig. 6(b). Note here that, in the experiment, the CoP is not controlled in the shaded single support phase. Both CoP profiles of the two experimental conditions are not much different, implying that the stepping motion can be achieved regardless of the slope angle. The time based plot of the sway angle ϕ is shown in Fig. 6(c). The profile of the slope condition is shifted up about 0.1 [rad] from that of the flat condition. This means that the biped robot realizes the stepping motion on the slope by tilting the whole body in the same amount as the slope angle. These results are consistent with the simulation results as shown in Fig. 4

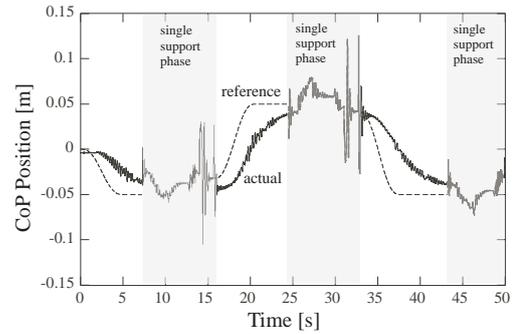
In the actual robot experiment, the control for ankle joint in the single support phase had to be changed from CoP feedback control to the conventional position feedback. One possible reason is the slow response of the control law (17) resulting in the inability to keep the balance with respect to the fast disturbances. Although the simulation results in section IV-E show that the response can be made faster with larger feedback control gains, large control gains in the actual biped robot induced mechanical vibration and the vibration impedes the control states to reach equilibrium points. The other significant reason is the mechanical problem. The slip due to wear at the set screw of the pulley is observed in the mechanical drive system of the hip joints. The slip led to control mismatch and, ultimately, loss of balance. As future works, we will fix the mechanical problem and re-examine the effectiveness of the original control law with CoP feedback in the single support phase.

VI. CONCLUSION

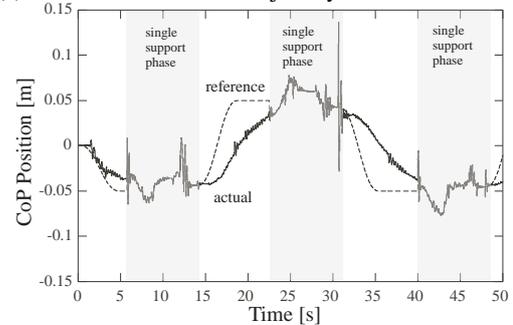
In this paper, a control method based on the ZMP feedback that allows the in-place stepping motion to be automatically adjusted according to the slope change is proposed. Using the fact that the ZMP and CoP is identical, the control method is constructed based on the CoP information detected using the force sensors on the sole. The invariance nature of the CoP reference trajectory with respect to the environmental conditions helps us construct a control law based on the CoP, i.e., ZMP feedback. This control method is basically constructed in combination with two control law: static balance control in the single support phase and weight shift movement in the double support phase. The effectiveness of the control law is confirmed by not only simulation results but also the empirical results. Consequently, the in-place lateral stepping motion is achieved on the slope as well as the flat ground without any modifications of the control law. However, the slow response in this control method as well as some mechanical matters become problems in the robot experiments, which should be improved in the future works.

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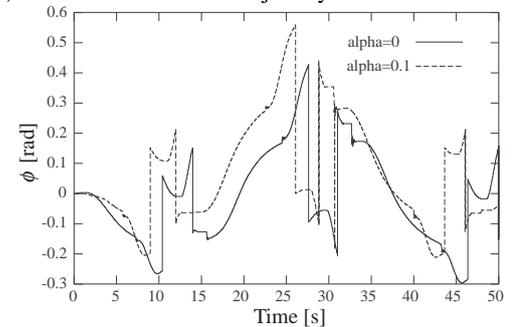
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(a) Reference and actual trajectory of CoP for $\alpha = 0$



(b) Reference and actual trajectory of CoP for $\alpha = 0.1$



(c) sway angle ϕ

Fig. 6. Experimental results.

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