Online Walking Pattern Generation for Humanoid Robot with Compliant Motion Control

Article *in* Proceedings - IEEE International Conference on Robotics and Automation · January 2019

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Abstract— **Compliant motion of humanoids is one of the most important characteristics for interaction with the human and environment in the real world. Especially during walking, the compliant motion ensures stable contact between the foot and the ground, but the walking stability is degraded due to the position tracking performance and unknown disturbance. To address this problem of possible instability of humanoid walking with compliant motion control, this paper proposes a real-time walking pattern generation considering the motion control performance of the robot. The dynamics model of the robot with the motion controller is described as a second order system approximating position tracing performance with a linear inverted pendulum model for the relation between Zero-Moment Point (ZMP) and Center of Mass (CoM). The CoM trajectory is calculated using the preview control based on the dynamics model and the current state of the robot. Therefore, even if the robot has the low tracking performance due to compliant motion control of the robot, the walking stability can be ensured. The proposed method was implemented on our humanoid robot, DYROS-JET, and its performance was demonstrated by improved stability during walking.**

I. INTRODUCTION

The recent DARPA Robotics Challenge (DRC) has shown that humanoids can perform a variety of tasks for human [1]. One of the features of humanoids is that they have more versatile mobility than other wheel-based robots on various terrains such as an uneven terrain and human-oriented environment. However, the stable walking on various terrains still remains one of the difficult tasks for legged robots [2].

The walking pattern generation methods have been proposed in order to enhance walking stability under the disturbance caused by external force. First, the Center of Mass (CoM) trajectory generation method was proposed based on the Linear Inverted Pendulum Model (LIPM), which expresses the dynamic relationship between the CoM and the Zero Moment Point (ZMP) simplifying the robot as a point mass with a constant height [3], [4]. When the desired ZMP trajectory is provided, the corresponding CoM trajectory can be calculated from the LIPM. However, this offline method cannot deal with unknown disturbance and model error. Thus, for the real-time implementation, the walking pattern generation based on preview control is implemented to minimize the ZMP error and the jerk of the CoM [5], [6]. This approach can generate the stable walking patterns with arbitrary foot placement regulating the ZMP error caused by the difference between the LIPM and multibody dynamics. Second, the trajectory generation method based on Capture Point (CP) was developed [7], [8]. The CP is the location of the ground surface where the foot is to be located to stop the CoM at the position. In [9], the CP was then extended to its 3-dimension equivalent one, Divergent Component of Motion (DCM). Several studies were conducted to change foot step using this CP or the DCM [10], [11] or to track the desired CoM trajectory indirectly by the CP control [12]. Aforementioned methods using preview control or CP control enabled biped robots to walk robustly because they can reflect robot's current states during real-time walking control.

At control level, the compliance of the humanoid robot is essential to maintain stable contact between the feet and ground. There are researches to enhance compliance capability to cope with disturbance from unexpected contacts. Impedance control [13] and damping control [14] have been proposed to adjust the position of the foot using the measured contact force for stable contact. Also, the disturbance observer based controller and torque control based walking method have been proposed to provide the robot with compliance [15], [16]. These compliant motion controls, however, have low tracking performance due to dynamics model error and force/torque sensor noise [17].

In order to achieve stable walking with disturbances, the robot must not only follow the CoM trajectory from the online walking pattern generation but also ensure the compliant motion. The previous walking pattern generation methods enabled the stable walking of the robot based on the assumption that the humanoid robot has a high trajectory tracking performance. However, the robot with compliant motion control can have low tracking performance, so this could deteriorate the walking stability. Therefore, more robust walking can be realized by considering the control performance of the robot by compliant motion control.

In this paper, we suggest an online walking generation method accounting for the control performance of the robot. Dynamic model of robot consists of LIPM which represents the relationship between CoM and ZMP, and tracking performance model of CoM. The tracking performance model approximates the motion of the CoM as spring damper system. The CoM trajectory is calculated using the preview control which is based on the dynamic model that reflects trajectory tracking performance.

*This work was supported by Industrial Strategic Technology Development Program (No. 10077538) funded by the Ministry of Trade, Industry & Energy (MI, Korea) and by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. NRF-2015R1A2A1A10055798).

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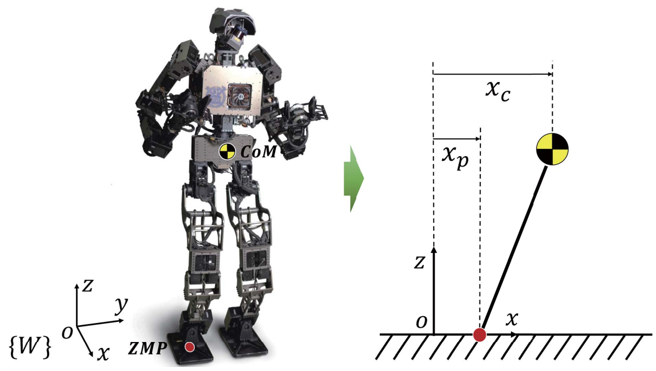


Fig. 1. Linear Inverted Pendulum Model

This paper is organized as follows. In Sec. II, we briefly introduce the LIPM as a simplified model of humanoid robot and the preview control as a walking pattern generation method. Section III proposes a new walking pattern generator considering the control performance of the robot as well as the compliant motion control based on disturbance observer. Section IV describes the experimental procedure and validates the effectiveness of the proposed method. Finally, the conclusions is presented in Sec. V.

II. BACKGROUND

In this section, we briefly introduce the LIPM and the preview control for the generation of the CoM trajectory. The LIPM has been widely used to simplify humanoid model in order to reduce the computation time to solve full dynamics of the humanoids. The preview control based on LIPM provides a way to generate a CoM trajectory for tracking a ZMP trajectory in real time. In this paper, bold upper letter $\boldsymbol{A}$, bold lower letter $\boldsymbol{a}$, and lower/upper letter a/A indicate matrix, vector, and scalar, respectively.

A. Linear Inverted Pendulum Model

The LIPM is used to derive the relationship of the CoM and the ZMP of the robot, as shown in Fig. 1. The assumptions of the LIPM are that the total mass is concentrated on one point at the CoM and the height from the ground is constant.

The ZMP can be calculated as [18]

$$x_p = x_c - \frac{z_c}{g}\ddot{x}_c, \tag{1}$$

where x_p and x_c denote the position of CoM and ZMP in x-axis, respectively. g denotes the gravitational acceleration and z_c is the height of the COM.

B. Walking Pattern Generation by Preview Control

The walking pattern generation by the preview control was proposed Kajita et al. [5]. The preview control allows a humanoid robot to obtain the CoM trajectory considering the future states of the predefined ZMP to minimize the ZMP error and jerk of the CoM.

If we define the state variable, output, and control input as $\boldsymbol{x}[k] = [x_c(k\Delta t) \quad \dot{x}_c(k\Delta t) \quad \ddot{x}_c(k\Delta t)]^T$, $y[k] = [x_p(k\Delta t)]$, and $u_c = [\frac{d}{dt}\ddot{x}_c]$, we can rewrite (1) as a state space form of discrete-time system with sampling time Δt, as below.

$$\begin{aligned} \boldsymbol{x}[k+1] &= \boldsymbol{A}\boldsymbol{x}[k] + \boldsymbol{B}\boldsymbol{u}_c[k], \\ \boldsymbol{y}[k] &= \boldsymbol{C}\boldsymbol{x}[k], \end{aligned} \tag{2}$$

where

$$\boldsymbol{A} = \begin{bmatrix} 1 & \Delta t & \frac{\Delta t^2}{2} \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} \frac{\Delta t^3}{6} \\ \frac{\Delta t^2}{2} \\ \Delta t \end{bmatrix}, \boldsymbol{C} = \begin{bmatrix} 1 & 0 & \frac{-z_c}{g} \end{bmatrix}.$$

To calculate the optimal control input $u_c[k]$, the performance index J is specified as

$$J = \sum_{i=k}^{\infty} \left\{ Q_e e^2[i] + \Delta\boldsymbol{x}^T[i]\boldsymbol{Q}_x\Delta\boldsymbol{x}[k] + R\Delta u_c^2[i] \right\}. \tag{3}$$

In the right hand side of (3), $e[k] = x_p[k] - x_p^d[k]$ is the tracking error of the ZMP and $x_p^d[k]$ is the desired ZMP position. $\boldsymbol{\Delta x}[k] = \boldsymbol{x}[k] - \boldsymbol{x}[k-1]$ is the incremental state vector and $\Delta u_c[k] = u_c[k] - u_c[k-1]$ is the incremental input. Q_e and R are positive weighting coefficients, and $\boldsymbol{Q}_x$ is a non-negative definite matrix.

Consequently, the control input that minimizes the cost function can be calculated as the following equation.

$$u_c[k] = -G_i \sum_{j=1}^{k} e[j] - G_x\boldsymbol{x}[k] - \sum_{l=1}^{N_l} G_d[l]x_p^d[k+l] \tag{4}$$

where G_i, G_x, and G_d are the gain matrices that minimize the cost J in (3). N_l is the previewable future step at every sampling time.

III. PROPOSED METHOD

This section is devoted to providing mainly the walking pattern generation method considering compliant motion and also the compliant motion control of our robot. To enhance the walking stability, we propose the walking pattern generation method that reflects the control performance of compliant motion control. Furthermore, the compliant motion control using the disturbance observer is described for stable contact between the foot and the ground. The aim of the proposed method is to enhance the walking stability by the compliant motion control and the walking pattern considering the control performance.

A. Walking Pattern with Control Performance Model

For humanoid robot with compliant motion control, we propose the walking pattern generation method considering the control performance. First, the control performance model is proposed to approximate the tracking performance between desired CoM and real CoM. Second, the dynamic model based on the LIPM with the control performance model is applied to the preview controller. Most of the previous studies [5], [6] enable the stable walking against unknown disturbance from external force and uneven terrain, assuming the high trajectory tracking performance. However,

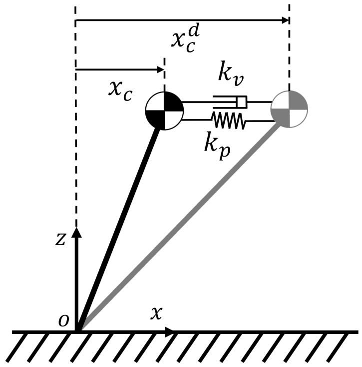


Fig. 2. The control performance model

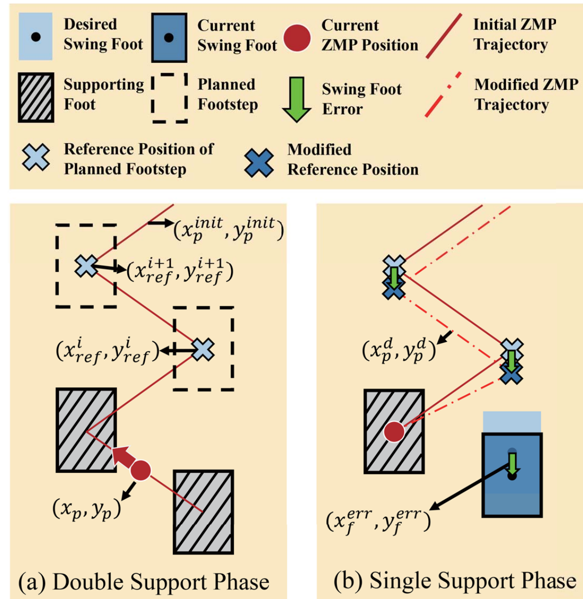


Fig. 3. Desired ZMP trajectory modification method when the swing foot position error occurred. (a) Initial ZMP trajectory generation based on the reference position (x_{ref}^i) at the start of the Double Support Phase. (b) Modification of the desired ZMP trajectory reflecting the swing foot position error during the Single Support Phase.

the proposed method can generate CoM trajectory for stable walking even if the position tracking performance is low.

The control performance model approximates the tracking performance of the CoM including the low-level controller. The model assumes that there is a spring and a damper between the desired CoM and real CoM. This assumption can be described as a second-order dynamic model, as shown in Fig. 2,

$$\ddot{x}_c = k_p(x_c^d - x_c) - k_v \dot{x}_c, \tag{5}$$

where x_d is the desired CoM position. k_p and k_v are the gains for the spring and damping coefficient, respectively.

The problem of pattern generation is then to find the CoM trajectory for a predefined ZMP trajectory based on dynamics model. The dynamic system can be written in its discretized form by combining (1) and (5), as below.

$$\begin{aligned} \bar{\boldsymbol{x}}[k+1] &= \boldsymbol{A}\bar{\boldsymbol{x}}[k] + \boldsymbol{B}\bar{u}_c[k], \\ \bar{y}[k] &= \boldsymbol{C}\bar{\boldsymbol{x}}[k] + \boldsymbol{D}\bar{u}_c[k], \end{aligned} \tag{6}$$

where

$$\bar{\boldsymbol{x}}[k] = \begin{bmatrix} x_c(k\Delta t) & \dot{x}_c(k\Delta t) \end{bmatrix}^T,$$
$$\bar{u}_c[k] = \begin{bmatrix} x_c^d(k\Delta t) \end{bmatrix}, \quad \bar{y}[k] = \begin{bmatrix} x_p(k\Delta t) \end{bmatrix},$$
$$\boldsymbol{A} = \begin{bmatrix} 1 - \frac{1}{2}k_p\Delta t^2 & \Delta t - \frac{1}{2}k_v\Delta t^2 \\ -k_p\Delta t & 1 - k_v\Delta t \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} \frac{1}{2}k_p\Delta t^2 \\ k_p\Delta t \end{bmatrix},$$
$$\boldsymbol{C} = \begin{bmatrix} 1 + \frac{z_c}{g}k_p & \frac{z_c}{g}k_v \end{bmatrix}, \quad \boldsymbol{D} = \begin{bmatrix} -\frac{z_c}{g}k_p \end{bmatrix}.$$

In (6), the state variable $\bar{\boldsymbol{x}}[k]$ is the position and velocity of the CoM, the output $\bar{y}[k]$ is the ZMP position, and control input $\bar{u}_c$ is the desired CoM for the robot to follow the desired ZMP considering the control performance.

The dynamics model with LIPM and control performance model is applied to the preview controller to find the optimal solution based on the desired ZMP. To generate the walking pattern by using the preview control, a tracking problem of ZMP trajectory is rewritten as an error system.

$$\begin{aligned} \begin{bmatrix} e[k+1] \\ \boldsymbol{\Delta}\bar{\boldsymbol{x}}[k+1] \end{bmatrix} &= \begin{bmatrix} 1 & \boldsymbol{C} \\ \boldsymbol{O} & \boldsymbol{A} \end{bmatrix} \begin{bmatrix} e[k] \\ \boldsymbol{\Delta}\bar{\boldsymbol{x}}[k] \end{bmatrix} + \begin{bmatrix} \boldsymbol{D} \\ \boldsymbol{B} \end{bmatrix} \Delta\bar{u}_c[k] \\ &+ \begin{bmatrix} -1 \\ \boldsymbol{O} \end{bmatrix} \Delta y_d[k], \end{aligned} \tag{7}$$

Here, we redefine the incremental state vector, incremental input, and incremental desired ZMP to deal with $\boldsymbol{D}$ in (6), as follows [19].

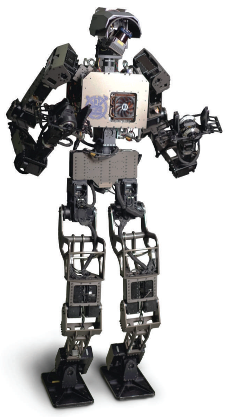
$$\begin{aligned} \boldsymbol{\Delta}\bar{\boldsymbol{x}}[k] &= \bar{\boldsymbol{x}}[k+1] - \bar{\boldsymbol{x}}[k], \\ \Delta\bar{u}_c[k] &= \bar{u}_c[k+1] - \bar{u}_c[k], \\ \Delta y_d[k] &= x_p^d[k+1] - x_p^d[k]. \end{aligned} \tag{8}$$

Finally, the control input is calculated by minimizing performance index (3) in Sec. II-B

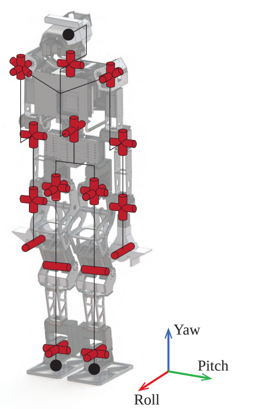
$$\begin{aligned} \bar{u}_c[k] &= \sum_{i=0}^{k-1} \Delta\bar{u}_c[i] \\ \Delta\bar{u}_c[k] &= -G_i e[k] - G_x \Delta\bar{x}[k] - \sum_{l=1}^{N_l} G_d[l]\Delta y_d[k+l]. \end{aligned} \tag{9}$$

B. Real Time ZMP Trajectory Generation

The real-time ZMP trajectory generation method are proposed to reflect the current state of the robot. The desired ZMP trajectory is generated based on the pre-planned foot step positions to be in the supporting polygon of the foot. However, in practical, the planned ZMP trajectory may locate on the edge of the support polygon due to the control error. For example, the swing foot often fails to arrive at the planned foot position due to low control performance and unexpected disturbance during Single Support Phase (SSP). However, the desired ZMP is still set to move toward the pre-planned foot step position which is not the center of the current landing foot and this can make the robot unstable or even falling off. To cope with this problem, the real-time



(a)



(b)

Fig. 4. Experimental system overview: (a) DYROS-JET, (b) configuration of joint of DYROS-JET

modification of ZMP trajectory is proposed as the following steps. First, the initial trajectory of ZMP is generated based on the reference positions which is the center of the planned footsteps. Next, the reference position is modified to reflect the tracking error of swing foot at every sampling time, as shown in Fig. 3. Finally, the desired ZMP trajectory is generated based on the modified reference position. This modification of ZMP trajectory reflects the error of swing foot on the ZMP trajectory ensuring that the desired ZMP is exactly on the center of the landing foot.

C. Compliant Motion Control with Disturbance Observer

To enhance the compliance capability, the linear feedback control with disturbance observer is implemented at each joint controller [15]. This controller provide not only to enhance compliance capability for unknown contact but also to suppress the vibration caused by joint elasticity. More precisely, the disturbance caused by external force is estimated using the disturbance observer based estimator. Furthermore, the linear quadratic regulator based trajectory tracking controller with the gravity compensator is designed to reduce vibration and deflection due to the joint elasticity.

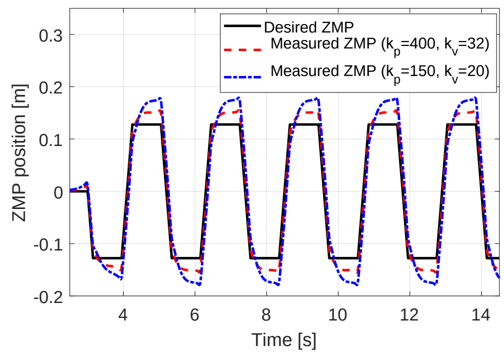
IV. EXPERIMENTS

The proposed method was verified through experiments with humanoid robot, DYROS-JET, as shown in Fig. 4. First, we performed experiments using a robotics simulator to verify that the proposed method shows better performance and stability compared to the pattern generator using a conventional preview controller. Second, the experiment with the humanoid was performed to demonstrate the effectiveness of our walking pattern generator in real robot. The subsections below describe the details of our experimental setup and experimental results.

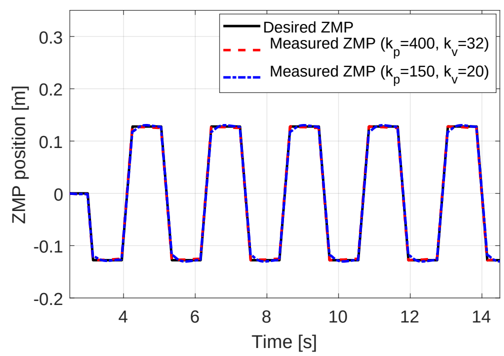
A. System Overview

The proposed method was implemented on the position-controlled humanoid robot, DYROS-JET. The robot is an upgraded THORMANG model to increase manipulability and workspace [20]. The total body weight and height are 48kg and 1.63m. JET consists of a total of 32 DoFs : 8 in each arm (including gripper), 6 in each leg, 2 in the torso, and 2 for the head, as shown in Fig. 4(b). An actuator module with an external encoder for measuring the deflection of the joint is used in the robot. The control frequency is 200Hz.

On the other hand, *V-REP (Coppelia Robotics. Co.)* with *Vortex* dynamics engine *(Cm Labs. Co.)* was used as a simulator for validation.



(a)



(b)

Fig. 5. Comparison of the desired ZMP and measured ZMP in the lateral direction during walking experiment with the simulator. (a) the conventional preview control (b) the proposed method.

B. Experiments with Simulation

Two sets of experiments with the simulator were conducted to verify that the proposed method improves the walking stability. In these experiments, we set the single support time and the double support time to 0.8 s and 0.3 s, respectively. The robot walked only forward direction on a flat surface. First, a set of experiment is conducted to compare the walking performance of the conventional preview control with the proposed method. The spring coefficient k_p and the damping coefficient k_v of the control performance model in (5) were experimentally obtained. In this experiment, we changed the robot's joint control gains in the simulation so that the robot is simulated with two different kinds of the control performance. A high control performance model ($k_p = 400$, $k_v = 32$) with larger joint control gains and a low control performance model ($k_p =$

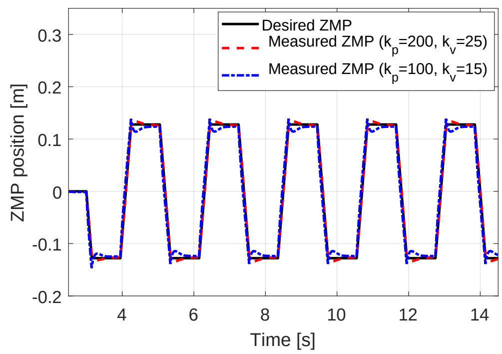


Fig. 6. Desired and measured ZMP positions according to error of the control performance model during walking experiment with the simulator.

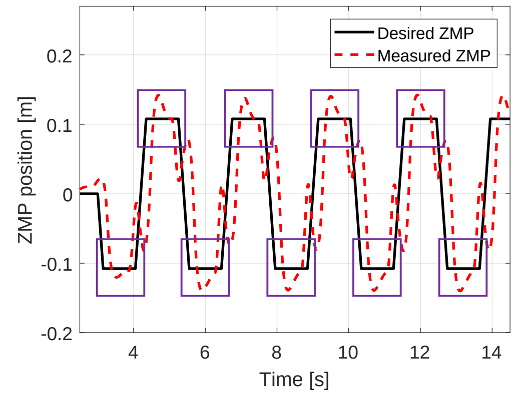


Fig. 7. Desired and measured ZMP positions during walking experiment with the real robot. The purple box denotes foot placement of the humanoid robot

150, $k_v = 20$) with smaller joint control gains are used to verify that the proposed method improves the ZMP tracking performance with various control performances. Fig. 5 shows the desired ZMP and measured ZMP in the lateral direction during the walking. The result of the proposed method shows better ZMP tracking performance than the conventional preview control. The ZMP of conventional preview control with the high control performance model shows relatively better ZMP tracking performance than that with the low control performance model. The maximum value of the ZMP error with the conventional preview control was 5.04cm. However, the maximum value of ZMP error with the proposed method was 0.95cm. This is because the proposed method based on LIPM with the control performance model compensates for the degradation of the ZMP tracking occurred from the control performance of the robot.

Next, the walking experiment was conducted to verify the effect of ZMP tracking performance when the error of the control performance model exists. The control performance model is experimentally obtained by approximating complex multibody dynamics of the robot. Thus, the ZMP tracking performance may be degraded in real hardware because of the inaccuracy of the control performance model. In order to verify the walking stability according to the modeling error, the spring and damping coefficient of control model were intentionally set to the different values from the estimated values ($k_p = 150$, $k_v = 20$). We obtained two inaccurate control models with higher control performance model ($k_p = 200$, $k_v = 25$) and lower control performance model ($k_p = 100$, $k_v = 15$). Fig. 6 shows the measured ZMP and desired ZMP depending on the different coefficient values. The ZMP tracking performance was degraded compared to the first experiment using the proposed method in Fig. 5(b), but it provides better tracking performance compared with the conventional preview control in Fig. 5(a). The maximum of ZMP error was 2.67cm. This result demonstrates the robustness of the proposed method with respect to the uncertainty in the control performance model of the robot.

C. Experiments with Humanoid Robot

The robot performed a continuous walking experiment. The k_p and k_v of the control performance model were 38.6 and 6.6. The coefficients of the real hardware were lower than those of the simulation. This is because the control performance of the robot is deteriorated due to hardware specification and unknown disturbance. As shown in Fig. 7, the ZMP was inside the supporting polygon of the feet, which means that stable walking was achieved by using the proposed method. In case of using the conventional preview control, however, the robot could not walk. This is because the CoM was unable to follow the desired CoM due to the low tracking performance, so the ZMP could not move to the supporting foot during the DSP. Therefore, the robot fell down as soon as the robot lifted the swing foot.

Next, the experiment was conducted in the case where the obstacle is present in front of the robot, as shown in Fig. 8. We set the single support time and the double support time to 0.8 s and 0.3 s, respectively, and the desired step length is 6cm. At 3.9 s, the right foot of the robot collided with the obstacle and was unable to move to the planned position. In the next step, the left foot of the robot was also obstructed by the obstacle, and the robot was unable to move to advance by the obstacle. However, the robot continued the walking motion in the same position without falling. This is because the proposed method generates the walking pattern considering the control performance and current state of the robot.

V. CONCLUSIONS

In this paper, a novel walking pattern generation method for humanoid robot with compliant motion control is proposed. The compliant motion control ensures stable contact with environment, but it can degrade motion tracking performance. Especially, the walking can be unstable due to low tracking performance of the CoM. To solve this problem, we suggest a real time walking pattern generation considering the motion control performance of the robot. The control performance model is proposed which is approximated as

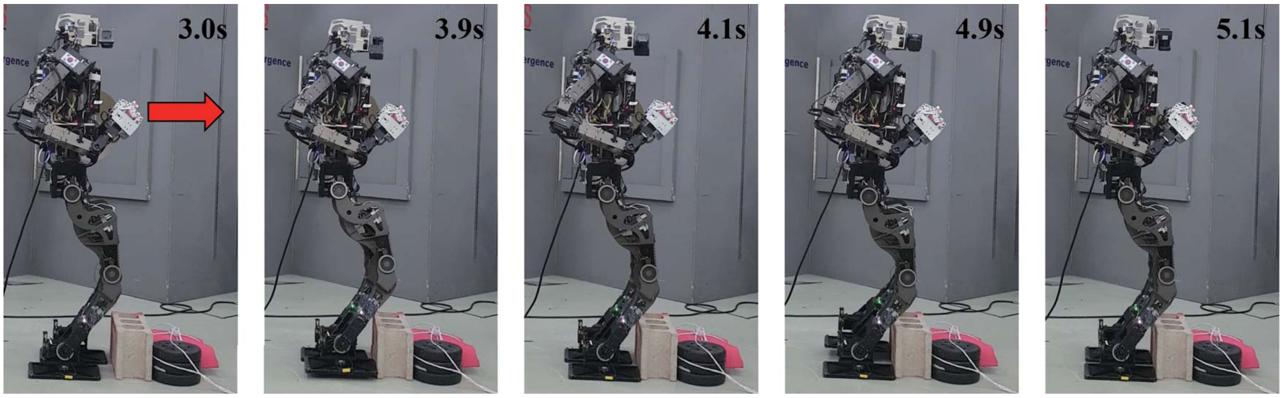


Fig. 8. Snapshots of walking experiment when the obstacle is in front of the robot.

the second order system with the spring and damper to represent the tracking performance of the CoM. Also, the preview control based on the control performance model and LIPM is designed to generate the CoM trajectory. This improves the walking stability which can be deteriorated by the tracking performance of the compliant motion control. The experimental results demonstrated that the proposed method shows improved ZMP tracking performance compared with the conventional preview control of the robot. Also, the stable walking is achieved reflecting the tracking performance and the current state of the robot when the robot is disturbed by an obstacles. On the other hand, we observed that the robot has a little bit more sluggish behavior due to the compliant motion control and the preview control that reflects the current state of the robot. This problem will be one of our future work. In addition, we will study how to effectively obtain the control performance model, and apply the proposed method in more complex behaviors.

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