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Strategies for Adjusting the ZMP Reference Trajectory for Maintaining Balance in Humanoid Walking

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Abstract— **The present paper addresses strategies of changing the reference trajectories of the future ZMP that are used for online repetitive walking pattern generation. Walking pattern generation operates with a cycle of 20 [ms], and the reference ZMP trajectory is adjusted according to the current actual motion status in order to maintain the current balance. Three different strategies are considered for adjusting the ZMP. The first strategy is to change the reference ZMP inside the sole area. The second strategy is to change the position of the next step, and the third strategy is to change the duration of the current step. The manner in which these changes affect the current balance and how to combine the three strategies are discussed. The proposed methods are implemented as part of an online walking control system with short cycle pattern generation and are evaluated using the HRP-2 full-sized humanoid robot.**

I. INTRODUCTION

Humanoid walking is commonly realized by constructing a dynamically stable trajectory using the dynamic parameters of a robot in advance and executing this trajectory with sensor feedback if necessary (e.g., [1]–[3]). This is because bipedal humanoids have a more complicated dynamic model than bipedal walking robots, which have been developed primarily to verify walking theories, and the cost of calculating the dynamics of the robot is high.

In recent years, studies that realize online generation of dynamically stable walking patterns have been published (e.g., [4]–[14]). Using an online generation system, online walking control by a tele-operating device, such as a joystick, intelligent navigation using information observed online, and emergency stop motion have been realized (e.g., [15]–[18]). Most of the online walking control systems mentioned above generate and update walking patterns in order to reflect the requested motion commands online. The sensor feedback for maintaining the balance is usually carried out independently as a lower layer of the online generation.

On the other hand, we have proposed an online walking control system, in which trajectory generation is carried out with very short cycle (10–40 [ms]), and that maintains actual walking balance [19], [20]. Actual motion in the absolute coordinate system is estimated at every generation using the attitude sensor, and a dynamically stable motion pattern that starts from the estimated motion condition is generated [20]. Moreover, we have shown that the control framework is effective for walking on previously unknown rough terrain.

We herein propose strategies by which to extend adaptivity to terrain of unknown roughness by changing the future reference ZMP trajectory. The estimated actual motion status is used to decide if and how the ZMP reference trajectory should be changed, so that dynamically feasible walking patterns starting from the current motion status will be generated.

II. APPROACH

In human walking, changing the next stepping position, changing the stepping timing, and changing the center of pressure inside the sole all help to maintain balance in walking.

These changes correspond to changing the reference trajectory of the future ZMP in a short cycle pattern generation system. As we will discuss later herein, changes in the nearer future affect the current balance more, and larger changes in position also affect the current balance more. We consider three strategies for changing the ZMP reference trajectory. The three strategies and the characteristics of each strategy are as follows.

a) Changing the reference ZMP inside the sole during a step: This strategy can change the nearest future ZMP reference. However, the changes are limited to inside the contact region, which is a relatively small region. The greatest advantage among these three strategies is that it will not change the stepping position and stepping timing, which are usually given as command parameters by an upper control layer, such as, a gait planner.

b) Changing the next stepping position: Change of reference ZMP will occur rather farther future than the previous strategy. However, the allowed changing region, which is decided by the kinematic and mechanical performance limits, will usually be larger.

c) Changing the duration of the current step: This strategy will change the timing of the transition of the reference ZMP from the current stance foot to the next stance foot. The parameter is one DOF that affects the 2D position of the ZMP. The advantage here is that the stepping position is not changed.

Kajita et al. proposed the concept of the auxiliary ZMP, and the manner in which the future ZMP reference should be modified in order to change the current ZMP was investigated based on the preview control theory [21]. We also use the same characteristics of preview control theory and develop strategies for changing the future ZMP reference in order to maintain the ZMP tracking capability of online pattern

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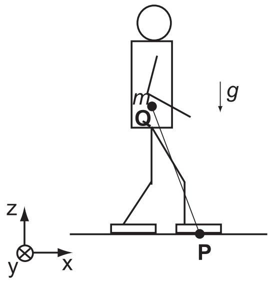

Fig. 1. Coordinate System for the Mass Concentrated Model

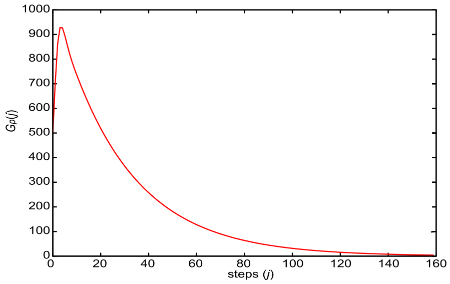

Fig. 2. Gain Parameter $G_p(j)$ ($h = 0.8[m], R_1/R_2 = 1 \times 10^6$)

generation, where the actual motion status is used for the initial conditions.

The remainder of the present paper is organized as follows. The method of generating the trajectory of the center of mass (CM) from the reference ZMP trajectory based on preview control theory is reviewed in the next section. The online walking control framework is described in Section IV. The manner in which each strategy for changing the reference ZMP affects the current balance is investigated in Section V. A method of combining the three strategies for maintaining balance in walking is explained in Section VI. Experiments using the HRP-2 full-size humanoid robot are described in Section VII. Finally, conclusions are presented in Section VIII.

III. GENERATION OF CM TRAJECTORY USING PREVIEW CONTROL

Applying preview control theory to the generation of the CM trajectory that realizes a given ZMP trajectory was proposed by [22]. We use this method to generate walking patterns online and to calculate how the change in the future ZMP reference affects the current balance. We review this method for the further explanation.

Consider a robot as a mass-concentrated model. Let the z-axis be in the vertical upward direction, and let $\mathbf{P} = [p_x, p_y, p_z]^T$ and $\mathbf{Q} = [q_x, q_y, q_z]^T$ be the ZMP and the concentrated mass position, respectively (Fig. 1). Assuming that $\ddot{q_z} = 0$, p_x can be obtained as follows:

$$p_x = q_x - \frac{h}{g}\ddot{q_x}, \tag{1}$$

where g is the gravitational acceleration, and $h = q_z - p_z$. Let u_x be the time derivative of $\ddot{q_x}$. Then, Eq. (1) can be translated into a strictly proper dynamic system as follows:

$$\frac{d}{dt}\begin{bmatrix} q_x \\ \dot{q_x} \\ \ddot{q_x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_x \\ \dot{q_x} \\ \ddot{q_x} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u_x, \tag{2}$$

$$p_x = \begin{bmatrix} 1 & 0 & -\frac{q_z - p_z}{g} \end{bmatrix} \begin{bmatrix} q_x \\ \dot{q_x} \\ \ddot{q_x} \end{bmatrix}. \tag{3}$$

The system is then discretized with sampling time T as follows:

$$\mathbf{q}_x(k+1) = \mathbf{A}\mathbf{q}_x(k) + \mathbf{B}u_x(k), \tag{4}$$

$$p_x(k) = \mathbf{C}\mathbf{q}_x(k). \tag{5}$$

In order to solve the problem in the error system, let

$$\begin{cases} \Delta u_x(k) = u_x(k) - u_x(k-1), \\ \Delta \mathbf{q}_x(k) = \mathbf{q}_x(k) - \mathbf{q}_x(k-1), \\ \Delta p_x^{ref}(k) = p_x^{ref}(k) - p_x^{ref}(k-1), \\ \mathbf{q}_x^*(k) = \begin{bmatrix} p_x(k) \\ \Delta \mathbf{q}_x(k) \end{bmatrix}, \end{cases} \tag{6}$$

where $p_x^{ref}(k)$ is the x-component of a given reference of the ZMP. Here, the performance index is given as

$$J = \sum_{i=k}^{\infty} \left\{ R_1 \left(p_x^{ref}(i) - p_x(i) \right)^2 + R_2 \Delta u_x^2(i) \right\}, \tag{7}$$

where R_1 and R_2 are positive values.

Then, when the ZMP reference is previewed for N steps, $\Delta u_x(k)$ that minimize the performance index is given by:

$$\Delta u_x(k) = -G_x q_x^*(k) - \sum_{j=1}^{N} G_p(j) \Delta p_x^{ref}(k+j). \tag{8}$$

where G_x and $G_p(j)$ are the gains that are calculated from R_1, R_2, and $(q_z - p_z)/g$ by applying preview control theory.

Here, u_y can be decided in the same manner.

Figure 2 shows $G_p(j)$ for a typical center of mass height ($h = 0.8[m]$). Here, $T = 0.01$ [s], $R_1 = 1 \times 10^6$, and $R_2 = 1$. Using reference ZMP till 1.6 [s] ahead ($N = 160$) is sufficient, from a practical standpoint, for deciding $\Delta u_x(k)$.

IV. ONLINE WALKING CONTROL SYSTEM WITH SHORT CYCLE PATTERN GENERATION

The outline of the online walking control system is explained in this section. Trajectory generation is performed with a cycle of 20 [ms]. The generated trajectory is then stored and executed by the reactive sensor feedback control with a cycle of 1 [ms] (Fig. 3).

We are using three different ZMP trajectories in the online walking control system. First one is reference input to the walking pattern generation component, which is designed using stepping positions and timings. We call it as designed reference ZMP. Second one is reference input to the reactive sensor feedback component, which is calculated using the generated trajectory in the walking pattern generation component. We call it as generated reference ZMP. Third one is the ZMP measured by force sensors at feet. This is used in the reactive sensor feedback component.

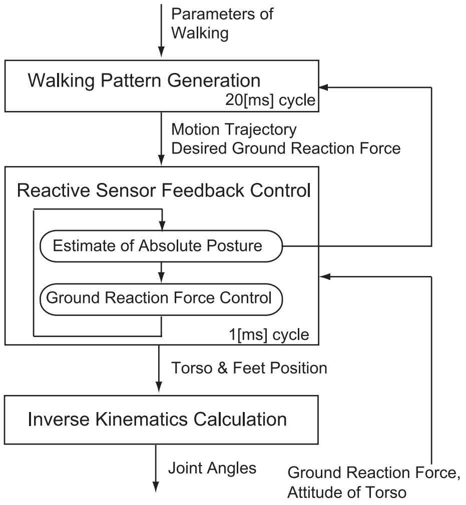

Fig. 3. Overview of the Online Walking Control System

The actual posture of the robot in the absolute coordinate system is estimated using the attitude sensor system mounted to the torso and the commanded joint angles at the moment inside the reactive sensor feedback control component. This information is used to determine the initial conditions of each generation. The balance maintenance problem considered in the present study is generating a realizable trajectory from these initial conditions by adjusting the designed reference ZMP trajectory.

The reactive sensor feedback control component serves as the ground reaction force controller so that the robot follows the generated motion in the absolute coordinate system even when the actual terrain shape is different from the assumed terrain shape. The ground reaction force required in order to realize the generated motion is calculated by the walking pattern generation component.

V. STRATEGIES FOR ADJUSTING THE FUTURE DESIGNED REFERENCE ZMP

In this section, the manner in which each method of designed reference ZMP adjustment affects the current balance is investigated. Here, we adopt 0.01 [s] and 0.8 [m] as the sampling time (T) and height of the center of mass from the ground (h), respectively.

A. Changing the Next Stepping Position

1) Effect of Changing the Future Designed Reference ZMP: When $\mathbf{q}_x(k_s)$ is given as the initial condition of trajectory generation at a moment, according to Eqs. (4) and (5), the resultant ZMP, namely, generated reference ZMP, at k_s+1 will be as follows:

$$p_x(k_s+1) = \mathbf{CA}\mathbf{q}_x(k_s) + \mathbf{CB}u_x(k_s). \tag{9}$$

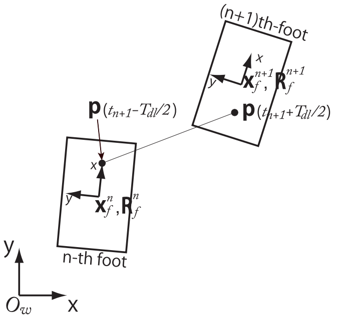

Fig. 4. Coordinate Systems for Designing the Reference ZMP

Here, $u_x(k_s)$ is determined using Eq. (8) based on preview control:

$$\begin{aligned} p_x(k_s+1) = \mathbf{CA}\mathbf{q}_x(k_s) + \mathbf{CB}u_x(k_s-1) - \mathbf{CB}G_x q_x^*(k_s) \\ -\mathbf{CB}\sum_{j=1}^{N} G_p(j)\Delta p_x^{ref}(k_s+j). \end{aligned} \tag{10}$$

The change in the designed reference ZMP at k_s+l will affect $p_x(k_s+1)$ as follows:

$$\delta p_x(k_s+1) = -\mathbf{CB}G_p(l)\delta\Delta p_x^{ref}(k_s+l). \tag{11}$$

We use this relationship to determine the degree of change that is necessary in order to maintain the current balance.

2) Design of the Reference ZMP: Let $\mathbf{x}_f^n$ and $\mathbf{R}_f^n$ be the n-th stance foot position and the rotation matrix in the global coordinate system, respectively (Fig. 4). Then, let t_n, T_n, and T_{dl} be the start time of the n-th step, the duration of the n-th step, and the duration of the dual leg support phase, respectively. Here, we defined each step as starting at the middle of the dual leg support phase.

Assuming that the designed reference ZMP trajectory is planned in the stance foot local coordinate system during the single leg support phase, the designed reference ZMP trajectory in the global coordinate system will be as follows:

$$\mathbf{p}^{ref}(t) = \mathbf{x}_f^n + \mathbf{R}_f^n\mathbf{p}_l^n(t),\ t_n + T_{dl}/2 \le t \le t_{n+1} - T_{dl}/2, \tag{12}$$

where $\mathbf{p}_l^n(t)$ is the designed reference ZMP trajectory in the stance foot local coordinate system. Then, during the dual leg support phase, we make the ZMP move at constant velocity from the previous stance foot to the next stance foot.

$$\begin{aligned} \mathbf{p}^{ref}(t) = (1-r)\left(\mathbf{x}_f^n + \mathbf{R}_f^n\mathbf{p}_l^n(t_{n+1}-T_{dl}/2)\right) \\ +r\left(\mathbf{x}_f^{n+1} + \mathbf{R}_f^{n+1}\mathbf{p}_l^{n+1}(t_{n+1}+T_{dl}/2)\right), \\ t_{n+1}-T_{dl}/2 \le t \le t_{n+1}+T_{dl}/2, \end{aligned} \tag{13}$$

where

$$r = \frac{t-(t_{n+1}-T_{dl}/2)}{T_{dl}}. \tag{14}$$

3) Effect of Stepping Position Change: Assume that the next stepping position $\mathrm{x}_f^{n+1} = (x_f^{n+1}, y_f^{n+1})$ is changed to $\mathrm{x}_f^{n+1'} = (x_f^{n+1'}, y_f^{n+1})$ at the generation of a trajectory that

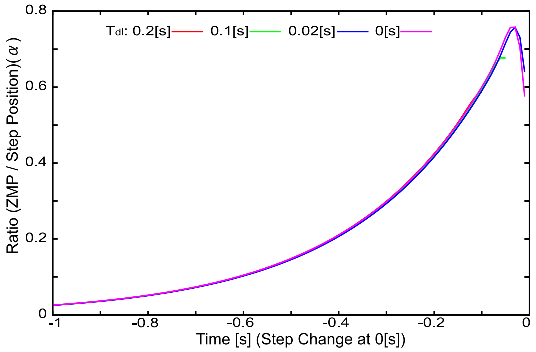

Fig. 5. Effect of Stepping Position Change on the Generated Reference ZMP

starts at time mT before the end of the n-th step. The change in Δp_x^{ref} can be calculated using Eqs. (12) and (13).

$$\begin{aligned}\delta\Delta p_x^{ref}(k) &= \Delta p_x^{ref\prime}(k) - \Delta p_x^{ref}(k)\\ &= \begin{cases} 0.0, & k \le m^- \\ \delta x_f^{n+1}/n_{dl}, & m^- < k \le m^+ \\ 0.0, & m^+ < k\ , \end{cases}\end{aligned} \tag{15}$$

where

$$\begin{aligned}\delta x_f^{n+1} = x_f^{n+1\prime} - x_f^{n+1},\quad n_{dl} = T_{dl}/T,\\ m^- = m - 0.5T_{dl}/T,\quad m^+ = m + 0.5T_{dl}/T.\end{aligned} \tag{16}$$

Here, we assumed that T_{dl} is an integer multiple of $2T$. Substituting Eq. (15) for Eq. (11), we obtain

$$\delta p_x(k_s+1) = -\mathbf{CB}\sum_{j=m^-}^{m^+} G_p(j)\delta x_f^{n+1}/n_{dl}. \tag{17}$$

The stepping position change effect α is defined as:

$$\alpha(m) = \frac{\delta p_x(k_s+1)}{\delta x_f^{n+1}} = -\mathbf{CB}\sum_{j=m^-+1}^{m^+} G_p(j)/n_{dl}. \tag{18}$$

Plots of α for multiple T_{dl} values are shown in Fig. 5. Since the change in T_{dl} does not affect α, we decide to use α of $T_{dl} = 0$ for any T_{dl}. Then, α is calculated using the following equation:

$$\alpha(m) = -\mathbf{CB}G_p(m). \tag{19}$$

Now, T_{dl} need not be an integer multiple of $2T$. The change in the stepping position can be decided by dividing the desired change in the generated reference ZMP at the next calculation step by α.

B. Changing the Duration of the Current Step

The effect of changing the duration of the current step at the generation of a trajectory that starts mT before the end of the n-th step is investigated.

Define a function $g(n_1, n_2, k)$ as follows:

$$g(n_1,n_2,k) = \begin{cases} 0, & k \le n_1 - n_2/2 \\ 1, & n_1 - n_2/2 < k \le n_1 + n_2/2 \\ 0, & n_1 + n_2/2 < k\ . \end{cases} \tag{20}$$

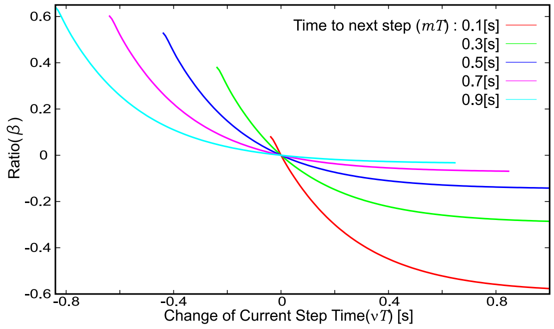

Fig. 6. Effect of Current Step Duration Change on the Generated Reference ZMP

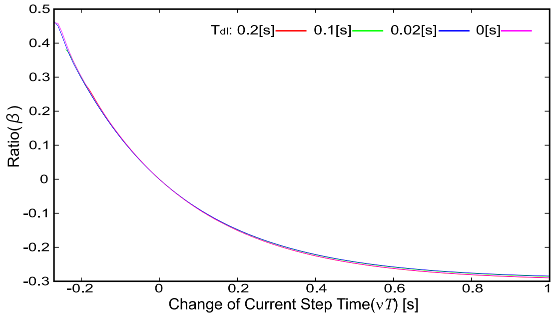

Fig. 7. Effect of Current Step Duration Change on the Generated Reference ZMP ($T_{dl} varied$)

Here, we assume that $\mathbf{p}_l^n(t)$ and $\mathbf{p}_l^{n+1}(t)$ are constant vectors and that the change in start time of the $(n+2)$-th step is negligible. When the step duration is increased by νT, $\delta\Delta p_x^{ref}(k)$ will be:

$$\begin{aligned}\delta\Delta p_x^{ref}(k) &= \Delta p_x^{ref\prime}(k) - \Delta p_x^{ref}(k)\\ &= (g(m+\nu, n_{dl}, k) - g(m, n_{dl}, k))\Delta x_f^{n+1}/n_{dl}\end{aligned} \tag{21}$$

where

$$\Delta x_f^{n+1} = x_f^{n+1} - x_f^n. \tag{22}$$

Here, T_{dl} is assumed to be an integer multiple of $2T$. Substituting Eq. (21) for Eq. (11), we obtain

$$\begin{aligned}&\delta p_x(k_s+1)\\ &= -\mathbf{CB}\sum_{j=1}^{N} G_p(j)(g(m+\nu, n_{dl}, j) - g(m, n_{dl}, j))\Delta x_f^{n+1}\\ &\quad /n_{dl}.\end{aligned} \tag{23}$$

The change in the step time duration effect β is defined as:

$$\begin{aligned}\beta(m,\nu) &= \frac{\delta\Delta p_x^{ref}(k_s)}{\Delta x_f^{n+1}}\\ &= -\mathbf{CB}\sum_{j=1}^{N} G_p(j)(g(m+\nu, n_{dl}, j) - g(m, n_{dl}, j))/n_{dl}.\end{aligned} \tag{24}$$

Plots of β for different m values are shown in Fig. 6. Plots of

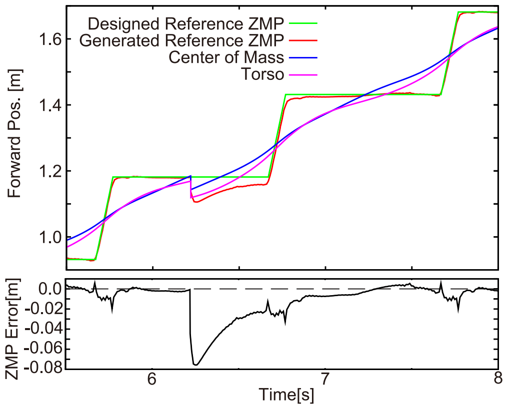

Fig. 8. Simulated Results for the Situation in which the Torso Position is Suddenly Changed

β for $mT = 0.3$ with different values of T_{dl} are also shown in Fig. 7. Since the difference in T_{dl} causes only negligible changes to β, β at $T_{dl} = 0$ is adopted in order to determine the change in the stepping duration νT for any T_{dl}. β for $T_{dl} = 0$ is

$$\beta(m, \nu) = -\mathbf{CB}(G_p(m + \nu) - G_p(m)). \tag{25}$$

Now T_{dl} need not be an integer multiple of $2T$.

Using the desired change in the generated reference ZMP $\delta\Delta p_x^{ref}(k)$ and the planned stepping position, the desired β is decided. Then, the desired $G_p(m+\nu)$ is calculated using Eq. (25). Since $G_p(k)$ decreases monotonically, except for the first few steps (Fig. 2), a linear search is carried out to find ν that realizes the given $G_p(m+\nu)$. Since $G_p(k)$ converges to 0, $G_p(m+\nu)$ cannot be less than 0. If the desired $G_p(m+\nu)$ is less than $G_p(N)(N = 160)$, then $\nu = N - m$ is adopted for the generation.

C. Changing Reference Position inside the Contact Region

If the actual motion status, which is used for the initial condition of preview-control-based trajectory generation, is unsuitable for realizing the designed reference ZMP, then the generated reference ZMP trajectory includes error to the designed reference as the result of optimal control that minimizes Eq. (7). Simulation results obtained using the online walking control system are shown in Fig. 8. The terrain was assumed to be horizontally flat as supposed, and 0.25 [m/step] forward walking was performed. A simulated disturbance suddenly changed the torso forward position by 0.05 [m] at the midpoint of a step (purple line). The generated reference ZMP trajectory (red line) diverges from the planned reference ZMP trajectory (green line) by 0.075 [m] at maximum so that the overall tracking will be realized. We decided to use this feature to change the generated reference ZMP inside the contact region. When the generated reference ZMP remains inside the contact region, the motion can be realized by controlling the ZMP at that point. The generated reference ZMP trajectory obtained by preview control is used as the reference ZMP for walking control, and, if the divergence from the designed reference is too large, the other two strategies are applied to limit the divergence.

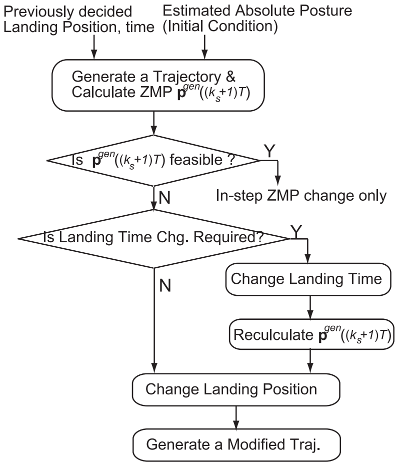

Fig. 9. Combination of 3 Modification Strateies

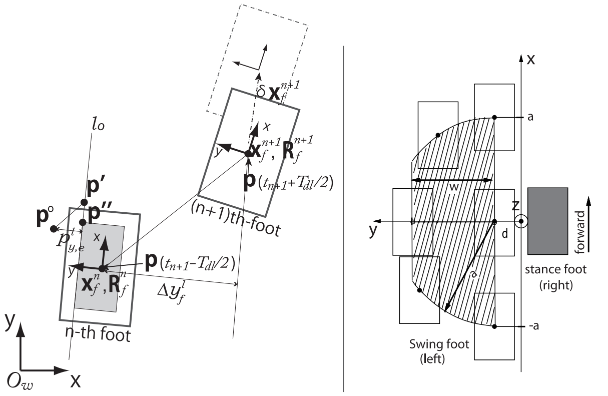

Fig. 10. Combination of Designed Reference ZMP Changing Strategies (left) and Limit of the Landing Area of the Swing Foot (right)

VI. COMBINING ZMP REFERENCE ADJUSTING STRATEGIES

In this section, the manner in which the three adjustment strategies are applied is explained. In the current implementation, modification of the stepping position and the step duration is only considered during at the trajectory generation, where the generated trajectory starts between the start of the single leg support phase and 80% of the single leg support phase. A 20% margin is arranged for designing smooth free leg trajectories. If changing the reference position inside the contact region is sufficient, maintaining the given stepping position and step duration is preferable. Figure 9 shows the flow of deciding application of the three strategies.

First, generated reference ZMP $\mathbf{p}^{gen}((k_s+1)T)$ is calculated by preview control using the actual motion status at k_sT and the currently planned stepping position and step duration. Here, the current plan includes the changes made by previous online generations. Then, $\mathbf{p}^{gen}((k_s+1)T)$ is transformed to the stance foot local coordinate system. If the calculated position is inside the sole region with some margin (gray area in Fig. 10), then the generated reference ZMP is adopted and the stepping position and step duration will not be changed. The region is currently set to be the area

0.03 [m] inside the contact region, which is approximated as a rectangle.

Secondly, when the generated reference ZMP is opposite outside of next step position (left side of l_o in Fig. 10, such as, $\mathbf{p}^o$), then the current step duration is extended so that the generated reference ZMP at $(K_s+1)T$ will be located on the line l_o. In this case, we used the step duration extension because the possible landing area relative to the stance foot position is defined as shown in Fig. 10 (right), considering the kinematical limits, and the swing foot cannot step inside the neutral position. Let $p^l_{y,e}$ and Δy^l_f be the desired movement of the generated reference ZMP along the y-axis of the local coordinate system and the y-component of the designed reference ZMP movement at the next step change, respectively, in the same coordinate system, as shown in Fig. 10. Then, β will be $p^l_{y,e}/\Delta y^l_f$, and extension time steps ν will be decided. As a result of this operation the generated reference ZMP will not move only in the local y-direction. The new generated reference ZMP at $(K_s+1)T$ will be located at $\mathbf{p}'$. Note that, in this case, ν will always be positive, which simplifies the problem of redesigning the swing foot trajectory.

Thirdly, changing the next stepping position is considered. The vector from the generated reference ZMP to the nearest point inside the permissible area is calculated as $\mathbf{p}^g_e$ ($\mathbf{p}^g_e = \mathbf{p}'' - \mathbf{p}'$ for the case shown in Fig. 10). Using α, which is decided by the time to the next step, the desired change in the stepping position is calculated according to Eq. (18) as follows:

$$\delta x^{n+1}_f = \frac{\delta p_x(k_s+1)}{\alpha(m)}. \tag{26}$$

The actual modification amount δx^{n+1}_f may be reduced by redesigning the swing foot trajectory stage in order to limit the maximum velocity and the acceleration of the foot.

VII. EXPERIMENTS

Since the proposed methods are effective for the cases in which the robot inclines during a step, experiments on stepping on the edges by the HRP-2 full-size humanoid robot [23] were carried out. Corresponding video clips of the following experiments are included in the video attachment.

A. Stepping on the Edges Aligned in the Forward Direction

An experiment was carried out to examine stepping on the edges aligned in the forward direction of the robot while walking sideways. The edge was made of stacked carpet tiles. The change in height at the edge is 14 [mm]. Plots of the experimental results are shown in Fig. 11. The gray area is the permissible sideways ZMP region for each step. At the steps marked ⓓ, the step duration is modified so that the generated reference ZMP is regulated inside the area. The stepping position is modified during a step at the steps marked ⓟ so that the generated reference ZMP will remain inside the area. Both worked successfully, and the generated reference ZMP remained inside the area throughout the walking. Snapshots of the moments when changing the duration of the step and changing the next stepping position were activated are shown in Fig. 12.

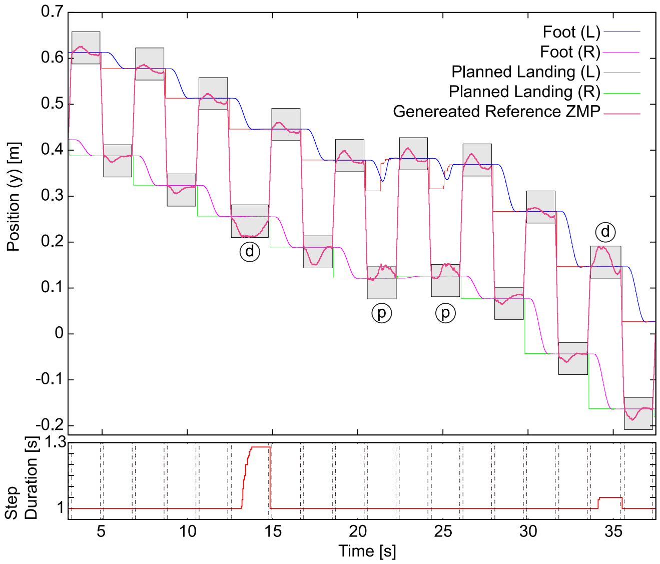

Fig. 11. Walking Sideways while Stepping on the Edges

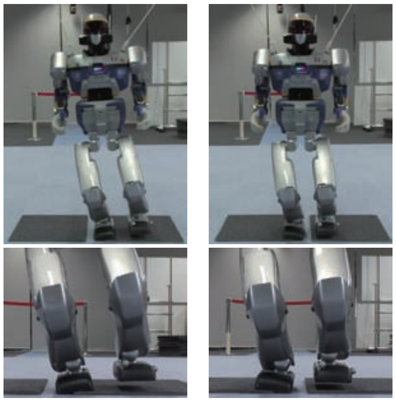
t=13.1[s] Duration Change
t=21.3[s] Position Change

Fig. 12. Snapshots of an Experiment on Walking Sideways

B. Stepping on the Edge Aligned in the Lateral Direction

An experiment on stepping on the edge aligned in the sideward direction of the robot is carried out. The robot first travels forward and then steps in place so that the edge is under the sole of the foot of the robot. The edge was made of stacked carpet tiles. The change in height at the edge is 28 [mm]. Since the permissible ZMP area is wide along the forward direction, the stepping position did not need to be changed during the steps. The reference ZMP during stepping in place is shown in Fig. 13. A snapshot taken at approximately 12 [s] is shown in Fig. 14.

C. Walking on a Complex Terrain

A complex terrain that required all three strategies during forward walking was constructed of carpet tiles. The setup is shown in Fig. 15. The robot successfully walked through the terrain using the change in duration and the change in stepping position as shown in Fig. 15.

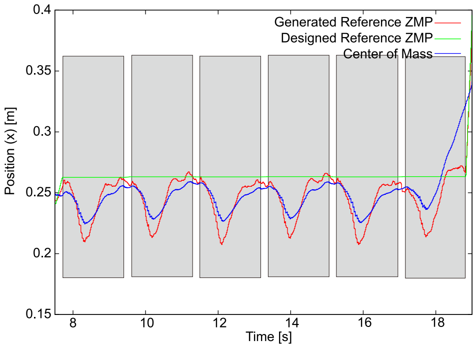

Fig. 13. Stepping on the Edge Aligned in the Sideward Direction

Fig. 14. Snapshots of an Experiment on Stepping on the Edge

VIII. CONCLUSION

Three strategies, namely, changing the reference ZMP inside the sole, changing the next stepping position, and changing the current step duration are considered as methods by which to change the future reference ZMP in order to maintain the current balance. The effect of changing the next stepping position and changing the current step duration to the current balance are investigated using the preview control theory. The method of combining the three strategies in order to maintain the balance of actual walking is then developed and implemented as a part of the online walking control system. The proposed strategies and the combination method are verified through experiments using the HRP-2 full-size humanoid robot. In the future, we intend to build combination strategies that take into consideration a given terrain map around the robot.

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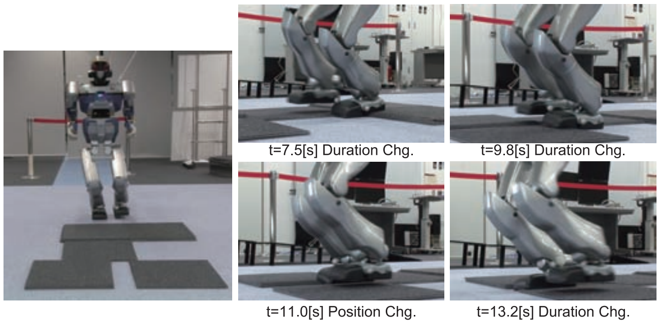
t=7.5[s] Duration Chg.
t=9.8[s] Duration Chg.
t=11.0[s] Position Chg.
t=13.2[s] Duration Chg.

Fig. 15. Walking through Complex Terrain

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