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Emergent walking stop using 3-D ZMP modification criteria map for humanoid robot

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Abstract— **Real-time emergent stop walking motion is necessary for humanoid robots. We propose a new emergent stop method using modification criteria map. The stable gait change is generated by adjusting the amount of the ZMP modification according to the timing of stop command. The modified ZMP trajectory is given so that the humanoid robot can change the current motion without falling down. The modification criteria are defined from the relation between the predicted ZMP trajectory using a preview controller and the support polygon. The preview controller employs Table-Cart model and it derives Center of Mass(CoM) trajectory from ZMP reference in real-time. We make the map of relation among the ZMP modification length, the modification timing and the timing of the stop command for stable gate modification. The robot can execute the best motion referring to the predefined map. In this method, the humanoid robot can stop immediately within one step or zero step to avoid a collision, if humans or objects appeared unexpectedly in front of the walking humanoid robot. The stop motion is typically divided two phase: single leg support phase and double leg support phase. In the single leg support phase, the next landing position and timing are decided according to command time of the stop signal. In the double leg support phase, the humanoid robot can stop anytime without changing standing position. The validity of the proposed method is confirmed by experiment using a humanoid robot HRP-2.**

I. INTRODUCTION

In recent years, the robot technology advances and it will be introduced in various fields. Especially, humanoid robots that have two arms and two legs can be smoothly substituted for the human worker and the cooperation work with man can be achieved easily by the human like motion. On the other hand, when the robots are used in human living space, the risk injuring human has to decrease. First of all, it is necessary to avoid dangerous contact since such kind of robots is near human. As for the humanoid robot, the walking motion has to be stopped flexibly according to the various situations.

In the previous study, the walking pattern as batch process has been proposed to generate the center of mass (CoM) trajectory in certain period [1]. In this method, it must be calculated to generate continuous walking pattern previously. Thus, when the robot changes the walking pattern, it has to wait next period; there is the time delay to reflect the change of the ZMP reference. Recently, some real-time control methods have been proposed [2], [3], [4]. By using these methods, the robot can change its walking pattern in real time. Morisawa [5] proposed the method of emergency stop motion generation in real-time, which can lead the robot to stop within one step. This method divides the stop motion according to the phase of ZMP based walking pattern and optimizes motion time with the initial states of the emergency. Kaneko [6] also developed a system to suspend safely motions without falling in case of emergency. This system generates the motion suspension not only by signal of suspension from operator terminal but also by judgment on suspension using some sensors of the humanoid robot. However, these methods don't show the capability of stop length and timing for the next foot hold.

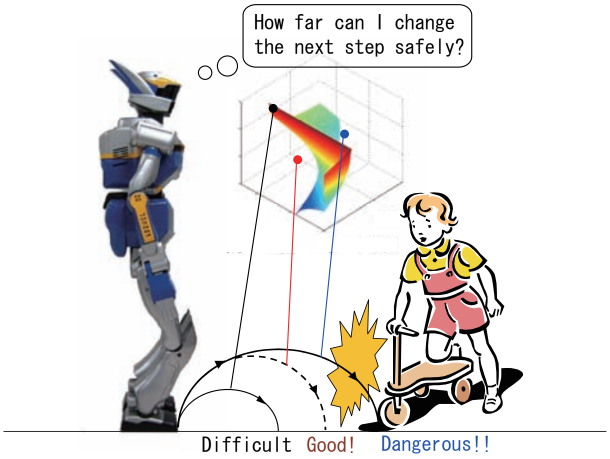


Fig. 1. Gait change for emergency

In our previous study, we proposed real-time emergent stop with preview control method[7]. This method changes CoM trajectory of the robot by modifying the pre-defined ZMP reference trajectory, when the walking humanoid robot receives a stop signal. The step length of the stop motion is reduced as much as possible according to the stop signal timing and then the robot can stop without falling down. The relation between the step length and the command timing is defined based on the ZMP modification criteria by simulations.

In this paper, we propose more flexible emergent stop method by using 3-D ZMP modification criteria map. We make the criteria map by considering the relation among the step length, the single leg support time and the stop command timing. In this method, the robot can change not only the step length but also the next step timing to avoid the dangerous foothold. The permissible adjustment is defined according to the commanded timing. The humanoid robot can estimate and choose next preferable foothold. First, we describe the method of emergent stop using a preview control in section II. In section III, we explain the emergent stop controller using the 3-D modification criteria so that the humanoid robot automatically chooses the emergent stop motion for the command time. The stop motion has two stop phases: single leg support phase and double leg support phase. In the single leg support phase, the next landing position and timing are decided as much as possible in the short stroke according to the command time of the stop signal. In the double leg support phase, the humanoid robot can stop anytime without changing standing position. Experimental results show the effectiveness of the proposed method on the real humanoid robot HRP-2 in section IV. Finally, we conclude this paper in section V.

II. EMERGENT STOP WALKING BY MODIFYING THE ZMP PREVIEW TRAJECTORY

A. *Walking pattern and ZMP preview control*

We basically use a walking pattern generator proposed by Kajita [8]. The pattern generator is composed of preview controller and a cart-table model that depicts a running cart on a pedestal table whose mass is negligible, and generates the corresponding CoM trajectory by using the ZMP trajectory of certain step future. By using the cart motion that represents the CoM trajectory of the robot and the ZMP reference of N-step future $p^{ref}_{k+i}(i = 1, 2, \ldots , N)$, the incremental input is given from the optimal preview control[9] as follows.

$$\Delta u_k = -\boldsymbol{K}\tilde{\boldsymbol{x}}_k + \sum_{i=1}^{N} f_i \Delta p^{ref}_{k+i}, \qquad (1)$$

where $\boldsymbol{K}$ is the state feedback gain, f_i is the preview gain, $\Delta p^{ref}_{k+i} \equiv p^{ref}_{k+i} - p^{ref}_{k+i-1}$ is the incremental ZMP reference of $(k+i)$-step and $\tilde{\boldsymbol{x}}_k \equiv [p_k - p^{ref}_k, \Delta \boldsymbol{x}_k]^T$ is state vector, p_k is the ZMP calculated by the cart motion $\boldsymbol{x}_k \equiv [x_k, \dot{x}_k, \ddot{x}_k]^T$, and Δt is sampling time.

As you can see from the equation, the incremental input is defined by a preview ZMP trajectory and the state of CoM at the time k. In other words, there is no relation among the incremental input at k and former inputs. Thus, we can change the preview ZMP trajectory freely without considering the predefined N-step future ZMP reference. We proposed the quick walking pattern modification method using this characteristic of the incremental input[7].

B. *Emergent stop control by modifying the ZMP preview trajectory*

The real-time ZMP preview trajectory modification method has a characteristic that the current gait can be changed without changing both the state feedback gain $\boldsymbol{K}$ and the preview gain $f_i(i = 1, 2, \ldots , N)$. When the walking robot receives the stop signal, the robot's gait can be changed to the emergent stop walking by modifying the ZMP reference trajectory as the input of ZMP preview control. Fig.2 shows concept of proposed method. The original ZMP trajectory is changed immediately to the modified ZMP reference at the time t_C by receiving the stop command.

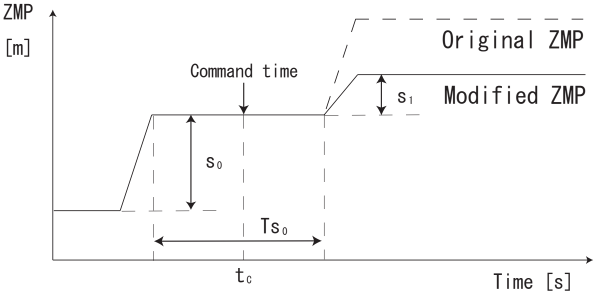
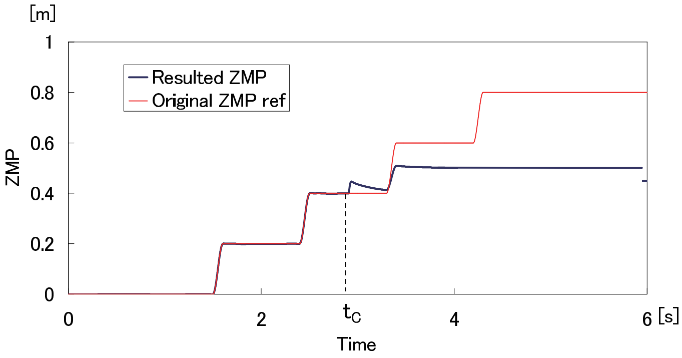
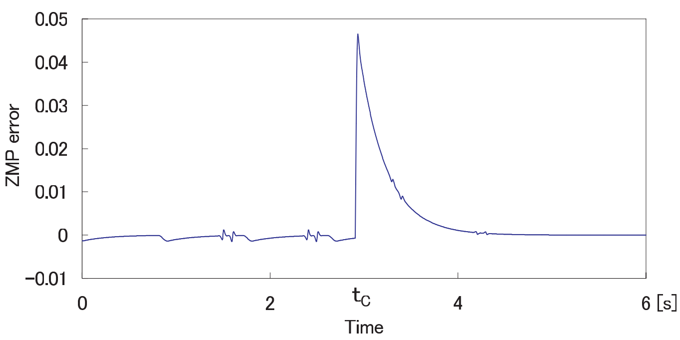


Fig. 2. ZMP reference trajectories for modifying step length(Traveling direction)



(a)ZMP trajectory



(b)ZMP error

Fig. 3. the ZMP error : the 3rd step length changes from 0.2[m] to 0.1[m]

Fig.3 shows an example of the emergency stop walking by modifying ZMP preview trajectory. In this simulation, we set that the original step length is 0.2[m], the single support term is 0.8[s] and the double support term is 0.1[s]. First, the original ZMP trajectory is given for the motion of 4 steps. After receiving the stop command, the ZMP reference changes to the modified ZMP trajectory that the 3rd step length is set 0.1[m]. The stop command timing t_c is set to 2.9[s]. In this method, because the ZMP reference within the preview period is modified suddenly, the second term of the

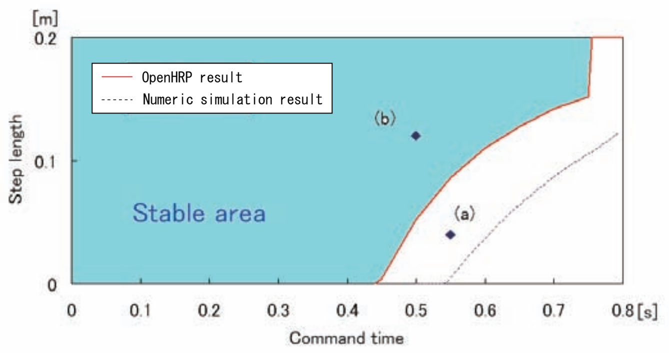


Fig. 4. Modification criteria for emergent stop

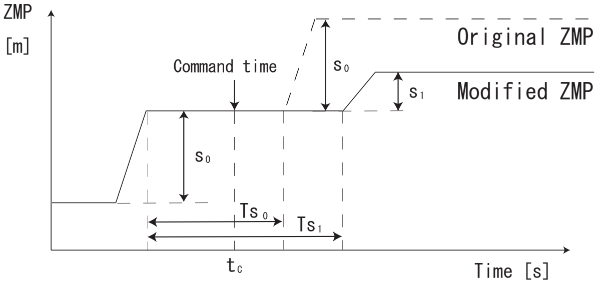
incremental input in Eq.(1) changes stepwise and the ZMP error increases gradually from the command time (Fig.3(b)). In our previous study, we focused on the maximum ZMP error value V_{max} and made the ZMP errer criteria map which indicates stable next foothold area according to the command timing without exceeding the permissible ZMP error V_L. The maximum ZMP errors for criteria map are given by numerical simulations on all possible pairs. Fig.4 shows the ZMP criteria map between next step length and stop command timing, when the permissible ZMP errer V_L is set 0.10[m]. However, on the dynamic simulator OpenHRP, the result is different from numerical simulation results, so we should consider hardware components. In the next section, we extract this 2-D criteria map into the 3-D criteria map including the step change timing.

III. EMERGENT STOP USING 3-D ZMP MODIFICATION CRITERIA MAP

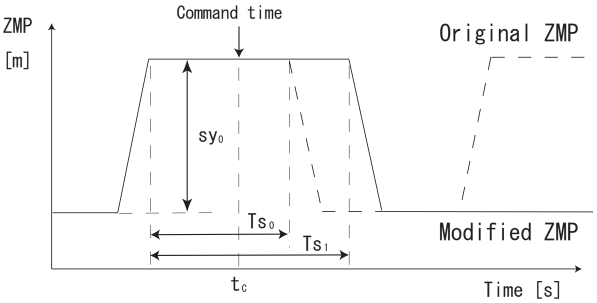
A. *Modification criteria for emergent stop*

First, we assume that the emergent stop motion is generated by the motion of the travel direction, and we fix the side step length S_{y0}. Fig.5 shows concept of modifying preview ZMP trajectory. The emergent stop ZMP preview trajectory can be controlled by the amount of step length S_1 and step change timing T_{S_1}. In this figure, x is travel direction, y is transversal direction, and these two directions are independent since the characteristic of Linear Inverted Pendulum model.

By modifying the amount of step length and step timing of ZMP preview trajectory, the gait of the robot can be changed more flexibly to the emergent stop in real time. However, when the ZMP reference within the preview period is modified suddenly, the tracking error of the ZMP increases and the resulted ZMP may move outside the support polygon. This problem is solved by selecting the preferable pair of the amount of ZMP modification and the step change timing at the command time. The criteria of the preferable pair are decided by the permissible ZMP error according to the shape of sole and its components. On our humanoid robot HRP-2[10], it has the sole which size of the former is 0.1357[m] and the latter is 0.059[m], but we can find experimentally the permissible ZMP error is 0.05[m] for numerical simulation.



(a) x-direction

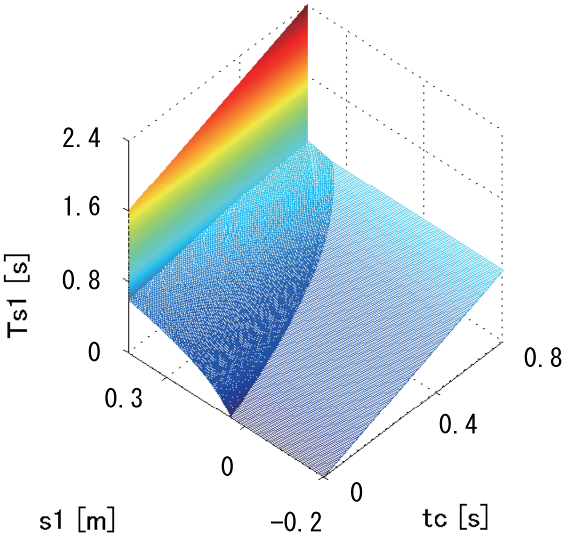


(b) y-direction

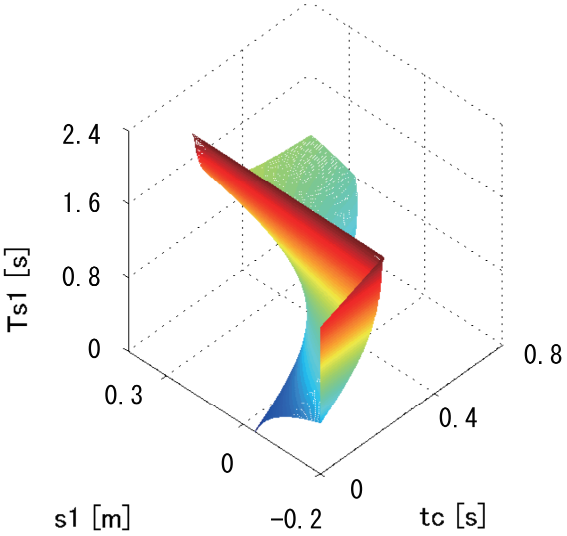
Fig. 5. ZMP trajectory for modifying step length and single support time

Fig.6 shows the 3-D modification criteria map on the changed step length and timing at the command time t_C for travel direction and Fig.7 shows the modification criteria map for transversal direction. We assume that the humanoid robot is walking on static state; step length s_0 is 0.2[m], single support term T_{s_0} is 0.8[s] and double support term is 0.1[s]. s_1 is modified step length, T_{s_1} is modified step timing. The value of the step length is a distance from the support leg. The criteria map are given by calculating all pairs of s_1 and T_{s_1} at the command time T_C. Each range of parameter is defined as follow; s_1 is set from -0.2[m] to 0.3[m] at the 0.001[m] intervals, T_{s_1} is set from t_c[s] to $t_c + 1.6$[s] at the 0.005[s] and t_c is set from 0[s](starting the single leg support phase) to 0.8[s](end of single leg support phase) at the 0.005[s]. The time slice 0.005[s] is defined since the sampling time of the HRP-2 controller. The 1.6[s] of T_{s_1} is preview time of preview control. When we want to change the next step after preview time 1.6[s], it is normal use of preview control.

Fig.6(a) shows the criteria for backward; its surface indicates the boundary of permitted ZMP error and the upper of the surface is safety area. Fig.6(b) shows the criteria for forward; the lower of the surface is safety area. Filling of these two safety areas, the humanoid robot can stop walking immediately. Fig.7 shows the criteria for transversal direction. In the transversal direction, we only modify the step timing since the step length is assumed fix. The upper of the solid line shows the limit of the left from the support origin and the lower of the solid line shows the limit of the right. The dashed line represents the minimum of the preview time at the command time. We can choose the T_{s_1} between these lines for safety stop timing at the command time T_c. Using the modification criteria, the robot can be achieved the



(a) criteria for backward ZMP error



(b) criteria for forward ZMP error

Fig. 6. Modification criteria in x-direction

emergent stop motion so that the resulted ZMP doesn't move outside the support polygon, and the walking robot can stop without falling over.

When the robot actually changes the current motion, not only the trajectory of the CoM but also the trajectory of the swing leg must be changed in real time. The trajectory of the swing leg is generated by connecting the trajectory represented by a cubic spline curve to the original trajectory, and it remains the continuity in the trajectory of the swing leg and stops after 0.1[s]. When the stop signal is received just before the landing time, the next step length is limited to the original step length of 0.2[m] since the short time by landing the swing leg to the ground needs to move the swing leg quickly and the joint angular velocity of the swing leg

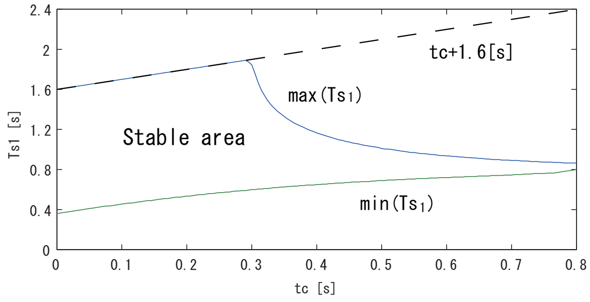


Fig. 7. Modification criteria in y-direction

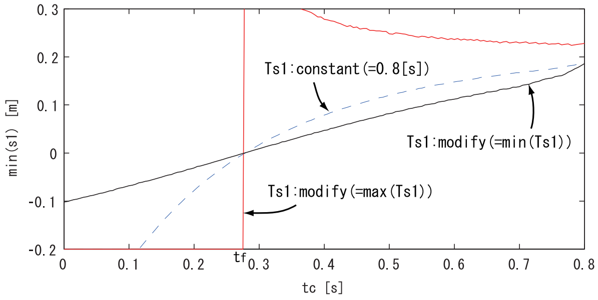


Fig. 8. Minimum of modified step length

goes over the limit.

B. Emergent stop using 3-D modification criteria map

In this section, we show an example of the stop motion system using the 3-D modification criteria map. Now, we consider stoping by the minimum step length for avoiding forward collision. To solve the problem, we can make the minimum step length map according to the command time from 3-D modification criteria map. Fig.8 shows the minimum modified step length criteria. The solid line represents the limit of the modification by using maximum modification time $max(T_{s_1})$ in Fig.7, the thin line represents the limit by using minimum modification time $min(T_{s_1})$ in Fig.7. Upper areas of the each line are permitted step length at the command time. We can see that the step length can be modified minimum by using max(T_{s_1}) before t_c=0.28[s], but we should use min(T_{s_1}) for minimum step after t_c=0.28[s]. The reason why the robot cannot change the step length

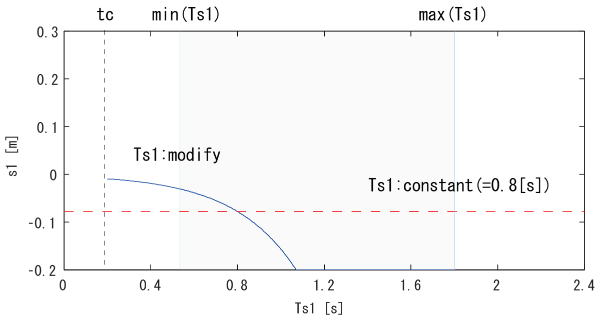


Fig. 9. Minimum of modified step length at $tc = 0.20[s]$

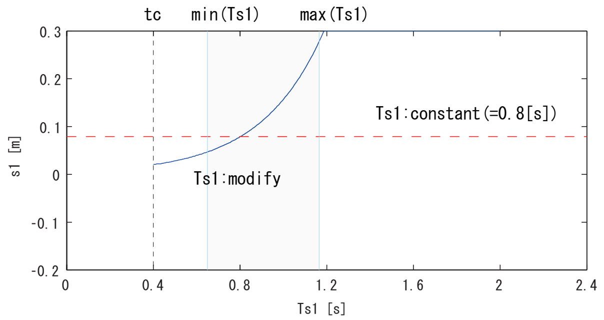


Fig. 10. Minimum of modified step length at $t_c = 0.40[s]$

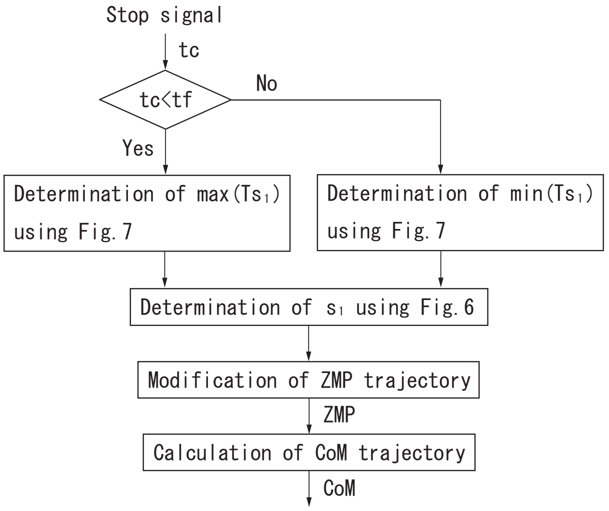


Fig. 11. Flow of gait change based on modification criteria

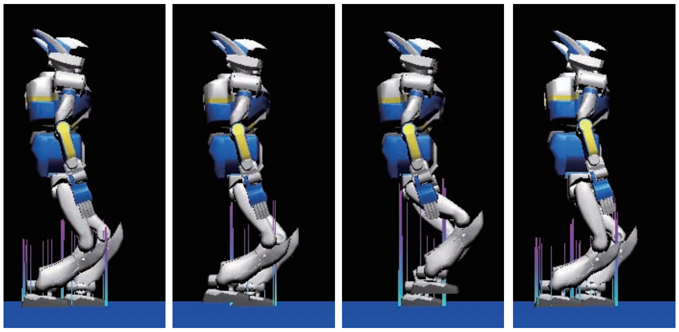


Fig. 12. Gait change from $t_c = 0.2[s]$

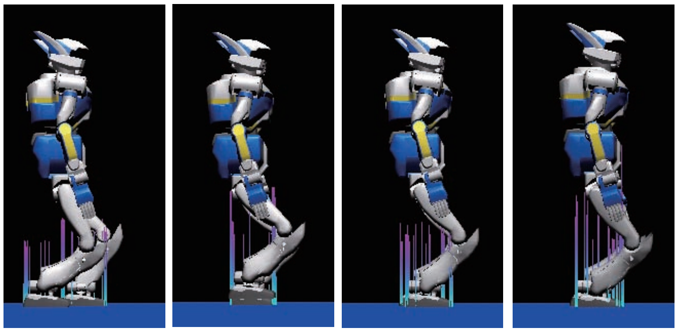


Fig. 13. Gait change from $t_c = 0.4[s]$

to shorter than 0[m] after t_c=0.28[s] is assumed that the momentum of the COM becomes too large to cancel by the single leg position. Thus, we define the timing discovered in the criteria map as the limit timing t_f for the back step. The dashed line in Fig.8 shows the limit of the our previous method; the step timing t_c is fixed 0.2[s]. Comparing the previous method, we can see the method changing the step timing enables to enlarge the modification step length.

Fig.9 and Fig.10 show the example of the minimum of the step length at t_c=0.2 and 0.4[s]. The meshed areas are permissible modification time T_{s_1} defined by Fig.8. The upper of the solid line is safety area for modification. From the Fig.9, the minimum step solution is defined at the t_{s_1} larger than about 1.1[s]. From the Fig.10, the minimum step solution is defined at the min(t_{s_1}). Comparing the constant step timing, the minimum step length becomes 0.122[m] smaller in Fig.9, and 0.032[m] smaller in Fig.10.

C. Emergent stop system

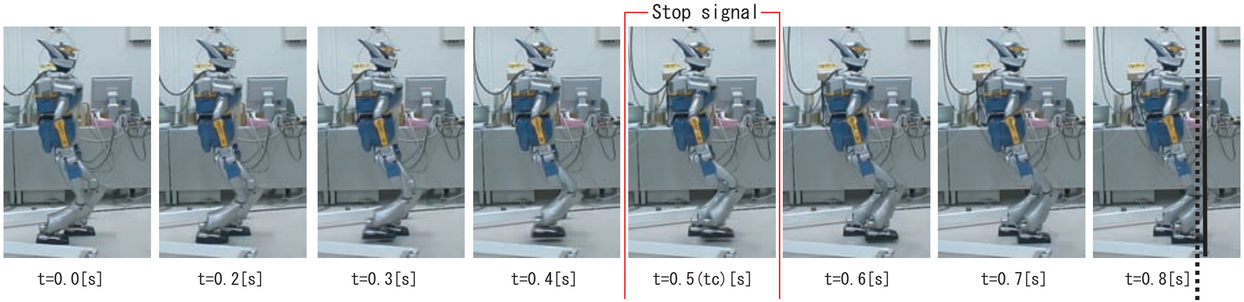
The control flow of the emergent stop system is shown in Fig.11. First, the robot checks transversal direction ZMP modification timing for fulfilling the ZMP error within 0.05[m] using Fig.8, when the stop command is received. When the command time is faster than t_f:we can find 0.28[s] from Fig.8, the T_{s_1} is defined to max(T_{s_1}). When the command time is later than t_f, the T_{s_1} is defined to min(T_{s_1}). Then, using Fig.6, the modification step length s_1 is defined by the T_{s_1} and the command time t_c. Next, the resulted modification reference implements to the ZMP preview trajectory for the control input. The position of the CoM and the velocity of the swing leg are calculated by the controller. Finally, the target joint angles are calculated by using the Resolved Momentum Control [12].

D. simulation

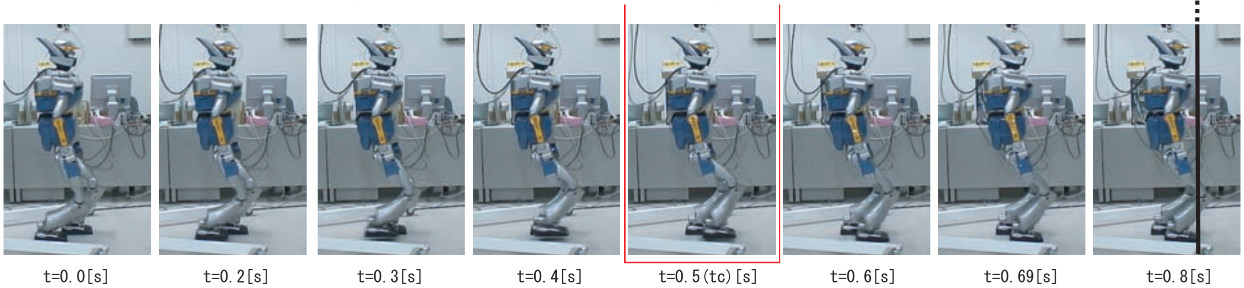
We simulate the proposed system on the dynamic simulator OpenHRP[11]. We assume that the humanoid robot is walking at the step length of 0.2[m], the single support term is 0.8[s] and the double support term is 0.1[s]. Fig.12 and Fig.13 show the simulation result at the command time 0.2[s] and 0.4[s]. We can see that the each result shows the step modification success without falling down, and the modification length becomes larger when the command timing is faster.

IV. EXPERIMENT

In this section, we describe the experiments of the stop motion by the gait change in real time using the actual humanoid robot HRP-2 [10]. The original step length before the gait change is set to 0.2[m], and the single support and the double support phases are 0.8[s] and 0.1[s] respectively. The experimental result of the gait change using the previous method is shown in Fig.14(a). The experimental result of the



(a) Experiment result by modifying only step length



(b) Experiment result by modifying step length and single support time

Fig. 14. Experiment result

gait change using the proposed method is shown in Fig.14(b). In these two case, the command time t_c was set to 0.5[s] and the robot changes 3rd step. In the proposed method, since the t_c is later than t_f(=0.28[s]), t_{s_1} is defined 0.69[s] by the min(t_{s_1}) using Fig.8. Next, the s_1 is defined 0.082[m] by the t_{s_1}=0.69[s] and t_c=0.5[s] using Fig.6. When the single leg support term is not changed, the modified step length can be changed to 0.12[m]. Thus, the proposed method can shorten the modified step length than the previous method. We can see that the humanoid robot HRP-2 determines the stop motion more flexible rather than the previous method, and safely stops without falling down.

V. CONCLUSION

We proposed emergent stop control for walking humanoid robots. The emergent stop is achieved by modifying the predefined reference ZMP trajectory when the robot receives a stop signal. The modified reference is defined according to the timing of stop command, the next step timing and the next step length. We make the 3-D modification criteria map using the relation between the predicted ZMP trajectory of the preview controller and the support polygon. The humanoid robot can safely reduce the step length as much as possible and stop without falling down using the criteria. The experimental result shows the validity of the proposed method using a real humanoid robot HRP-2.

The implement of the continuous gait change for more convenient motion and the analysis of modification criteria for the gait change are our future work.

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