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Emergency Stop Algorithm for Walking Humanoid Robots

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***Abstract*— This paper presents an emergency stop algorithm of a walking humanoid robot. There are many cases which force a walking robot to stop quickly without falling. Since an emergency occurs at unpredictable timing and at any state of robot, the stopping motion must be generated in real-time.**

To overcome these problems, our emergency stop motion is divided into four phases according to the role of the Zero-Moment Point (ZMP). In each phase, approximate analytical solutions of the Center of Gravity (COG) dynamics is used to generate the motion. During the single support phase, a landing time and position are determined by evaluating the average velocity of the swing leg and the horizontal position of the COG. During the double support phase, the travel distance of the COG and the ZMP are evaluated. The validity of the proposed method is confirmed by simulation and experiment using a humanoid robot HRP-2.

***Index Terms*— Emergency stop, Biped walking, Real-time gait planning, Walking pattern generation.**

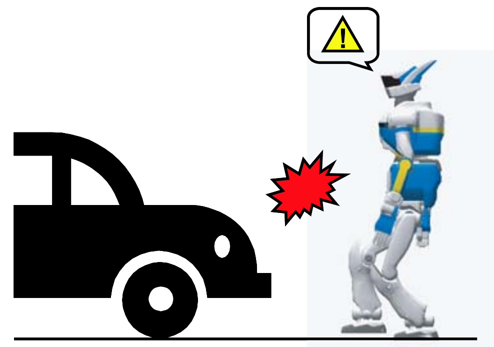

Fig. 1. Emergency stop.

I. Introduction

Recently so-called human-friendly machines have begun to spread in society, for example, pet robot, human-like robot, high performance home robot and so on. Industrial countries will need such machines due to the fast aging society. Because humanoid robots have the advantage of working in environments which is designed for human being, they are expected to assist our society in future.

From the practical point of view, it is necessary for humanoid robot to have the capability of walking where humans can. In such environment, not only unknown disturbance may hit humanoid robots, but also humanoid robots may hurt to humans or objects (Fig.1). To avoid physical damage, Fujiwara achieved to fall over without fatal damage by human-sized humanoid robot[1], [2]. However, the falling down can not necessarily avoid damages. One approach to solve this problem is that the robot stop immediately. Up to now, some real-time control methods have been proposed. Shimoyama proposed the method for improvement of stability of biped robot by changing the landing position[3]. Kajita[4] proposed the method of a real-time walking pattern generation using analytical solution. Nishiwaki developed the online method of a walking pattern generation of humanoid robot by dynamically stable mixture and connection of pre-designed motion trajectories every one step[7]. Harada[6] also realized real-time gait planning using analytical solution and the ZMP[8] trajectory which is expressed as spline function and discussed a real-time connectivity of the COG trajectory and that of the ZMP one. However, these methods require more than two steps to stop the robot. Sugihara proposed the fast online gait planning method with boundary condition relaxation[9]. In this method, because the walking cycle is constant, humanoid robots will be possible to stop by one step only in some cases especially slow walking.

In this paper, we propose a method to generate emergency stop motion in real-time which can lead the robot to stop within one step. The features of proposed method are admitting the ZMP overshoot and optimizing motion time according to the initial states of the humanoid robot.

The rest of this paper is organized as follows. The stop motion parameters are derived from the aspect of real-time gait planning in Section II. In section III, the stop motion parameters are determined by fast iterative computation. Then, the motion of the upper body joints are generated in Section IV. Furthermore, crouching down motion is introduced for avoidinf a singular configulation. Simulation results of the emergency stop motion are shown in V. Actual walking in experiment is tested using humanoid robot HRP-2[10] in Section VI. Finally, we conclude in Section VII.

II. Real-time gait planning for emergency stop

A. Strategy of emergency stop

In an original operation, stop motion generator just monitors internal states Fig.2 (a). If humanoid robots are put in abnormal circumstances, it will be preferable for robots to take a statically stable posture as soon as possible. Moreover,

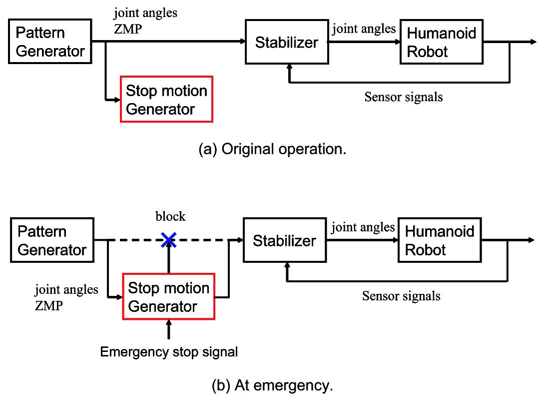

Fig. 2. Signal flow of proposed control system.

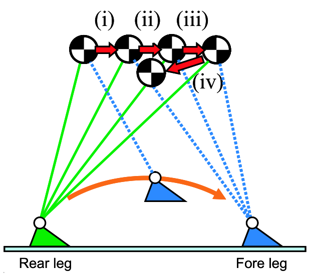

Fig. 3. Strategy of emergency stop.

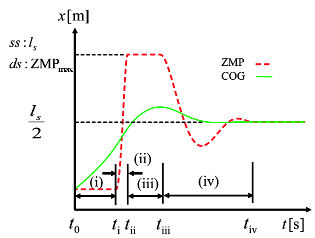

Fig. 4. The COG and the ZMP trajectories in emergency stop.

stop motion must be generated in real-time from any state of robots. The proposed control system is shown in Fig.2. If the joint angular velocity and the differentiation of the ZMP can not be obtained, the stop motion generator always estimates it. When the stop motion generator receives an emergency stop signal, the COG and the ZMP trajectories will be generated according to the internal states at the time. Thus, during the playback of off-line walking pattern, the stop motion generator can be also used to make the walking humanoid robot to stop instantly.

According to the role of the ZMP for the generation of the COG trajectory, the emergency stop motion is divided into four phases shown in Fig.3 and Fig.4, that is i.e.

- (i) Landing Phase,
- (ii) ZMP Transition Phase,
- (iii) Slowdown Phase,
- (iv) Halt Phase,

where Landing Phase is the single support phase in which swing leg moves to the target landing position. In ZMP trasition Phase, the ZMP moves from the rear leg to the fore leg. In Slowdown Phase, the velocity of the COG is adjusted to 0. Finally, the COG comes to a halt in Halt Phase. If the emergency signal is given in double support phase, the stop motion can also deal with the emergency by starting from ZMP Transition Phase.

B. Real-time gait planning[6]

A halt motion must be generated by changing the original walking pattern to stop humanoid robot suddenly. Moreover, the new motion must be connected with the original motion smoothly. The difference between the original landing position of the next step and the newly planned one will prevent humanoid robots from keeping balance. An analytical solution is used [5], [6] to calculate the motion trajectory within one sampling time, In theses generation methods, the COG and the ZMP trajectories can be generated by satisfying the boundary condition. In our approach, the COG and the ZMP trajectories are generated by setting the initial condition and the boundary conditions in every one phase, respectively to change a landing position and a landing time.

Let us consider a humanoid robot walking on a flat floor. While we focus on the motion of the humanoid robot within the sagittal (x-z) plane, the motion in the lateral (y-z) plane is accompanied by the stop motion parameter in the sagittal plane. Let us assume that the ZMP trajectory of the humanoid robot is given by a polynomial function of degree n. Let $\boldsymbol{P}^{(j)}_{\boldsymbol{zmp}} = [x^{(j)}_{zmp}\ y^{(j)}_{zmp}\ 0]^T$ be the trajectory of the ZMP of the j-th phase corresponding to four phases (i, ..., iv) in the stop motion. The trajectory of the ZMP in the sagittal plane can be expressed as

$$x^{(j)}_{zmp} = \sum_{i=0}^{n} a^{(j)}_i (t - t_{j-1})^i, \quad t_{j-1} \le t \le t_j, j = \mathrm{i}, \dots, \mathrm{iv}, \tag{1}$$

where $a^{(i)}_i (i = 0, \dots, n, j = \mathrm{i}, \dots, \mathrm{iv})$ are scalar coefficients. Let $\boldsymbol{P}^{(j)}_G = [x^{(j)}_G\ y^{(j)}_G\ z^{(j)}_G]^T$ be the trajectory of the COG corresponding to the ZMP trajectory belonging the j-th phase in the stop motion, and let $\boldsymbol{\mathcal{L}}^{(j)} = [\mathcal{L}^{(j)}_x\ \mathcal{L}^{(j)}_y\ \mathcal{L}^{(j)}_z]^T$ be the angular momentum of the robot about the COG. The relationship between the ZMP and the COG within the sagittal plane is expressed by the following equation,

$$x^{(j)}_{zmp} = \frac{-\dot{\mathcal{L}}^{(j)}_y + M\left(x^{(j)}_G(\ddot{z}^{(j)}_G + g) - z^{(j)}_G \ddot{x}^{(j)}_G\right)}{M(\ddot{z}^{(j)}_G + g)}. \tag{2}$$

The height of the COG is divided into constant part $\bar{z}_G$ and variable part $\Delta z^{(j)}_G$. By setting $z^{(j)}_G = \bar{z}_G + \Delta z^{(j)}_G$, the ZMP equation (2) can be rewritten by

$$x^{(j)}_{zmp} = \bar{x}^{(j)}_{zmp} + \Delta x^{(j)}_{zmp}, \tag{3}$$

$$\bar{x}^{(j)}_{zmp} = x^{(j)}_G - \frac{\bar{z}_G}{g}\ddot{x}^{(j)}_G, \tag{4}$$

$$\Delta x^{(j)}_{zmp} = \frac{-\dot{\mathcal{L}}_y g + M\ddot{x}^{(j)}_G(\bar{z}_G \Delta\ddot{z}^{(j)}_G - \Delta z^{(j)}_G g)}{Mg(\Delta\ddot{z}^{(j)}_G + g)}, \tag{5}$$

where we suppose that the influence of the COG motion in the vertical direction and effect of angular momentum are small enough for emergency stop ($\Delta x^{(j)}_{zmp} \approx 0$), and focus on the horizontal motion. Substituting (1) into (4) and solving with respect to $x^{(j)}_G$, an analytical solution of the position of the

COG is obtained as

$$\begin{aligned} x_G^{(j)}(t) &= V^{(j)}\cosh(\omega_c(t-t_{j-1})) \\ &+ W^{(j)}\sinh(\omega_c(t-t_{j-1})) \\ &+ \sum_{i=0}^{n} A_i^{(j)}(t-t_{j-1})^i, j=\mathrm{i},\ldots,\mathrm{iv}, \end{aligned} \tag{6}$$

$$a_i^{(j)} = A_i^{(j)} - \frac{1}{\omega_c^2}(i+1)(i+2)A_{i+2}, \quad i=0,\ldots,n-2, \tag{7}$$

$$a_i^{(j)} = A_i^{(j)}, i=n-1,n, \tag{8}$$

where $\omega_c = \sqrt{g/\bar{z}_G}$, and $V^{(j)}$ and $W^{(j)}$ $(j=\mathrm{i},\ldots,\mathrm{iv})$ donate scalar coefficients. Then, by differentiating (6) with respect to t, the velocity of the COG can also be obtained as an analytical solution,

$$\begin{aligned} \dot{x}_G^{(j)}(t) &= \omega_c V^{(j)}\sinh(\omega_c(t-t_{j-1})) \\ &+ \omega_c W^{(j)}\cosh(\omega_c(t-t_{j-1})) \\ &+ \sum_{i=1}^{n} iA_i^{(j)}(t-t_{j-1})^{i-1}, j=\mathrm{i},\ldots,\mathrm{iv}. \end{aligned} \tag{9}$$

C. Derivation of gait parameter

In the generation of emergency stop motion, the aim is to make the COG halt without falling over as soon as possible. There are $n+3$ parameters in each phase including two coefficients of the hyperbolic functions and $n+1$ coefficients of the ZMP trajectory in (6). The trajectory continuity of the COG and the ZMP are taken into account such as

$$x_G^{(j-1)}(t_j) = x_G^{(j)}(t_j), \tag{10}$$

$$\dot{x}_G^{(j-1)}(t_j) = \dot{x}_G^{(j)}(t_j), \tag{11}$$

$$x_{zmp}^{(j-1)}(t_j) = x_{zmp}^{(j)}(t_j), \tag{12}$$

$$\frac{d^{(i)}x_{zmp}^{(j-1)}(t_j)}{dt^{(i)}} = \frac{d^{(i)}x_{zmp}^{(j)}(t_j)}{dt^{(i)}}, \quad i=1,\ldots,m, \ j=\mathrm{ii},\ldots,\mathrm{iv}. \tag{13}$$

Note that the continuity of the COG trajectory in more than the second order differentiation is guaranteed by satisfying the continuity of the ZMP trajectory. Additionally, to reduce the number of unknown parameters, the boundary conditions of the higher degree derivatives of the ZMP in (13) are set to zero, that is

$$\frac{d^{(i)}x_{zmp}^{(j-1)}(t_j)}{dt^{(i)}} = \frac{d^{(i)}x_{zmp}^{(j)}(t_j)}{dt^{(i)}} = 0, \quad i=1,\ldots,m, \ j=\mathrm{ii},\ldots,\mathrm{iv}. \tag{14}$$

Therefore, the unknown coefficients of the COG trajectory are determined from the initial condition of the COG and the boundary condition of the ZMP. Then, the COG trajectory is expressed as

$$\begin{aligned} x_G^{(j)}(t) &= f_p^{(j)}\Big(t, x_G^{(j)}(t_{j-1}),\ \dot{x}_G^{(j)}(t_{j-1}), \\ &\qquad x_{zmp}^{(j)}(t_{j-1}),\ x_{zmp}^{(j)}(t_j)\Big), \\ &\qquad t_{j-1} \le t \le t_j, j=\mathrm{i},\ldots,\mathrm{iv}, \end{aligned} \tag{15}$$

where $\bigcirc^{(j)}(t_{j-1})$ and $\bigcirc^{(j)}(t_j)$ denote the beginning and the end of the phase respectively. Then, the velocity of the COG in (9) can be also expressed by

$$\begin{aligned} \dot{x}_G^{(j)}(t) &= f_v^{(j)}\Big(t, x_G^{(j)}(t_{j-1}),\ \dot{x}_G^{(j)}(t_{j-1}), \\ &\qquad x_{zmp}^{(j)}(t_{j-1}),\ x_{zmp}^{(j)}(t_j)\Big), \\ &\qquad t_{j-1} \le t \le t_j, j=\mathrm{i},\ldots,\mathrm{iv}, \end{aligned} \tag{16}$$

where the terminal time t_j and the ZMP value $x_{zmp}^{(j)}(t_j)$ in each phase are two unknowns as the gait parameters, if the initial values of the COG and the ZMP are given.

III. Determination of stop motion parameter

A. Single support phase

In ZMP Transition Phase(ii), the ZMP is moved from the rear foot to the fore foot to decelerate the COG at the next Slowdown Phase(iii). At this moment, the displacement of the ZMP can be moved according to the step length at landing. When the emergency motion begins on the landing phase, the velocity of the COG at the end of Slowdown Phase should become zero, i.e.

$$\begin{aligned} \dot{x}_G^{(\mathrm{iii})}(t_{\mathrm{iii}}) &= f_v^{(\mathrm{iii})}\Big(x_G^{(\mathrm{iii})}(t_{\mathrm{ii}}),\ \dot{x}_G^{(\mathrm{iii})}(t_{\mathrm{ii}}), \\ &\qquad x_{zmp}^{(\mathrm{iii})}(t_{\mathrm{ii}}),\ x_{zmp}^{(\mathrm{iii})}(t_{\mathrm{iii}})\Big) \\ &= 0, \end{aligned} \tag{17}$$

From the position and the velocity of the COG (15) and (16) and the conditions of the trajectory continuity (10)-(13), the stop condition (17) can be rewritten by

$$\begin{aligned} f_v^{(\mathrm{iii})}\Big(&x_G^{(\mathrm{i})}(t_0), \dot{x}_G^{(\mathrm{i})}(t_0), x_{zmp}^{(\mathrm{i})}(t_0), \ldots, x_{zmp,k}^{(\mathrm{i})}(t_0), \ldots \\ &x_{zmp}^{(\mathrm{i})}(t_{\mathrm{i}}),\ x_{zmp}^{(\mathrm{ii})}(t_{\mathrm{ii}}),\ x_{zmp}^{(\mathrm{iii})}(t_{\mathrm{iii}})\Big) = 0, \end{aligned} \tag{18}$$

where t_0 is the time of emergency stop motion and $x_{zmp,k}^{(\mathrm{i})}(t_0)$ denotes the k-th order differentiation $(= \frac{d^k x_{zmp}^{(\mathrm{i})}(t)}{dt^k}|_{t=t_0})$. The stop condition (18) contains six unknowns about the ZMP position and time period in each phase. In (18), we assume that the ZMP is not changed in Landing Phase(i) and Slowdown Phase(iii). The boundary conditions between ZMP Transition Phase(ii) and Slowdown Phase(iii) can be represented by the initial ZMP position and the step length l_s,

$$x_{zmp}^{(\mathrm{i})}(t_{\mathrm{i}}) = x_{zmp}^{(\mathrm{i})}(t_0), \tag{19}$$

$$x_{zmp}^{(\mathrm{ii})}(t_{\mathrm{ii}}) = x_{zmp}^{(\mathrm{iii})}(t_{\mathrm{iii}}) = x_{zmp}^{(\mathrm{i})}(t_0) + l_s. \tag{20}$$

Thus, the unknowns are finally reduced to four i.e. l_s, t_{i}, t_{ii} and t_{iii} and the condition of the stop motion can be given as

$$f_v^{(\mathrm{iii})}(l_s, t_{\mathrm{i}}, t_{\mathrm{ii}}, t_{\mathrm{iii}}) = 0, \tag{21}$$

where the step length in (21) can be explicitly represented by

$$l_s = f_s(t_{\mathrm{i}}, t_{\mathrm{ii}}, t_{\mathrm{iii}}). \tag{22}$$

Landing Phase(i) should be long enough to let swing leg reach to the landing position with the limited joint angle and angular

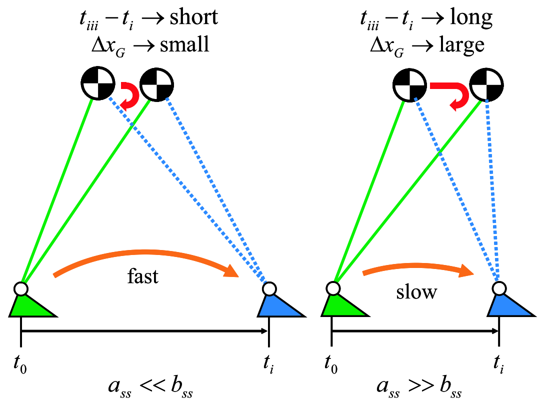

Fig. 5. The effect of stop motion parameters in the single support phase.

velocity. The stride should become exponentially long as the phase needs more time. On the other hand, shorter landing time needs to move the foot more quickly and the joint angular velocity of swing leg will exceed the limit. Moreover, a long period of the double support phase makes the displacement of the COG in the emergency stop larger. Because it is difficult to check the limitations of the joint angular velocity in real-time for all periods of the emergency stop motion, the unknown parameters are determined by evaluating the average velocity of the foot in the generalized coordinates and the period of the double support phase until the end of Slowdown Phase(iii). The determination of unknowns can be formulated as the optimization problem:

$$\min_{l_s, t_{\text{i}}, t_{\text{ii}}, t_{\text{iii}}} J_{ss}\left(l_s, t_{\text{i}}, t_{\text{ii}}, t_{\text{iii}}\right). \quad \text{subject to} \ (21) \tag{23}$$

where J_{ss} is the objective function which is defined as

$$\begin{aligned} & J_{ss}\left(l_s, t_{\text{i}}, t_{\text{ii}}, t_{\text{iii}}\right) \\ = \ & a_{ss}\left(\frac{l_s}{t_{\text{i}} - t_0}\right)^2 + b_{ss}\left(t_{\text{iii}} - t_{\text{i}}\right)^2. \end{aligned} \tag{24}$$

and a_{ss} and b_{ss} denote scalar weighting coefficients. The effect of motion parameters is shown in Fig.5. The smaller proportion of the weighting coefficient of the average velocity to that of the period of the double support phase makes the step length longer and the displacement of the COG shorter.

Substituting (22) into (24), the optimization problem in (23) is reduced to the unconstrained optimization problem:

$$\min_{t_{\text{i}}, t_{\text{ii}}, t_{\text{iii}}} J_{ss}\left(t_{\text{i}}, t_{\text{ii}}, t_{\text{iii}}\right). \tag{25}$$

The optimization problem in (25) can be solved by Newton's method. The unknowns can be obtained by iterative computation:

$$\boldsymbol{t}_{k+1} = \boldsymbol{t}_k - \left(\nabla^2 J_{ss}(\boldsymbol{t}_k)\right)^{-1} \nabla J_{ss}(\boldsymbol{t}_k), \tag{26}$$

where $\boldsymbol{t}_k = [t_{\text{i}}^{(k)} \ t_{\text{ii}}^{(k)}, t_{\text{iii}}^{(k)}]^T$ is the time vector of each phase in k-th step at the iterative computation. In (26), Hessian $\nabla^2 J_{ss}$ and gradient vector ∇J_{ss} can be obtained analytically. Thus, the solution can be derived quickly, because the iteration usually converge in several steps. Additionally, in this method, it is necessary to check if the generated step length exceeds the limit. Here, the step length can be obtained by substituting the generated time periods into (22).

Lastly, in Halt Phase, the terminal states of the COG and the ZMP are set to the center of the distance between the feet as

$$x_G^{(\text{iv})}(t_{\text{iv}}) = x_{zmp}^{(\text{iv})}(t_{\text{iv}}) = x_G^{(\text{i})}(t_0) + \frac{l_s}{2}, \tag{27}$$

$$\begin{aligned} \dot{x}_G^{(\text{iv})}(t_{\text{iv}}) &= \dot{x}_{zmp}^{(\text{iv})}(t_{\text{iv}}) = \\ & , \dots, = x_{zmp}^{(\text{iv})\ (n-2)}(t_{\text{iv}}) = 0. \end{aligned} \tag{28}$$

Therefore, the COG and the ZMP trajectories are generated simultaneously by solving two boundary condition problem[6].

B. Double support phase

The emergency stop motion in the double support phase can be generated as well as in the single support phase using ZMP Transition Phase(ii) as an initial phase. Then, the condition (17) to the stop can also be utilized as well as the single support phase. When the humanoid robots have to stop urgently during the double support phase, it is impossible to change the landing position. However, if the generated ZMP trajectory stays inside the supporting polygon, the trajectory can be used. At this time, the maximum displacement of the ZMP can be obtained by the COG position in (15) and the stop condition (17),

$$\text{ZMP}_{max} = f_{zmp}(t_{\text{ii}}, t_{\text{iii}}). \tag{29}$$

In the double support phase, the value of displacement of the ZMP is considered by the objective function to prevent from overshoot. Thus, the objective function J_{ds} is given as

$$\begin{aligned} & J_{ds}\left(\text{ZMP}_{max}, t_{\text{ii}}, t_{\text{iii}}\right) \\ = \ & a_{ds}(\text{ZMP}_{max})^2 + b_{ds}\left(t_{\text{iii}} - t_{\text{i}}\right)^2. \end{aligned} \tag{30}$$

If the weighting coefficient of the ZMP displacement a_{ds} is enough smaller than that of the COG displacement b_{ds}, the maximum ZMP becomes large and the displacement of the COG becomes short as shown in Fig. 6. In contrary, ! ! the larger weight coefficient a_{ds} will be the smaller maximum ZMP variation and the shorter COG displacement.

Substituting (29) into (30), the unconstrained optimization problem is derived as,

$$\min_{t_{\text{ii}}, t_{\text{iii}}} J_{ds}\left(t_{\text{ii}}, t_{\text{iii}}\right). \tag{31}$$

The optimization problem in (31) can be also solved by Newton's method as well as (26).

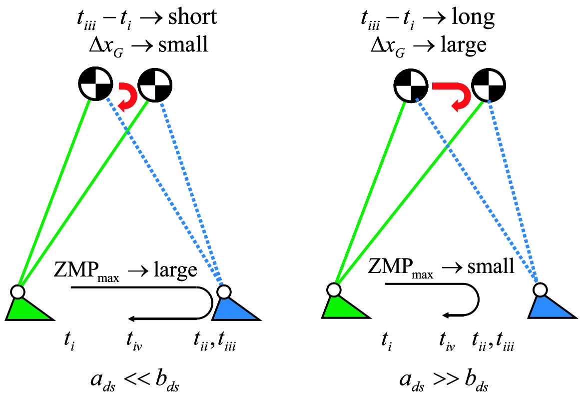

Fig. 6. The effect of stop motion parameters in the double support phase.

C. Marginal Case

When an emergency signal was triggered at close to touchdown or lefe-off, the stop motion generator calculates unrealizable trajectories of the COG and the ZMP. In other words, the landing position and the variation value of the ZMP go over the limits at the late of the single and the double support phase. In these cases, the humanoid robots will stop at next supporting phase.

IV. Generation of upper body motion

A. Crouch down motion

The crouching motion is effective for a stable stop by the following two reasons. Firstly, over extension of knee joints can be avoided. Secondly, the stability can be increased by getting down the COG. The crouching down motion can be realized by lowering the COG. The trajectory of the vertical COG is given as the fifth order polynomial function. The initial and final continuity of the acceleration are considered.

B. Halt of upper body

In emergency stop motion, it is necessary to stop the upper body joints as well as leg joints. The upper body joints are stopped through two phases:

(i) Slowdown Phase,
(ii) Halt Phase.

In Slowdown Phase, the angular velocity and acceleration of the upper body joints are set to zero. The trajectories of these joints are given as the third order polynomial function by using initial joint angle $\theta^{(\mathrm{i})}(t_0)$ and angular velocity $\dot{\theta}^{(\mathrm{i})}(t_0)$ as

$$\begin{aligned} \theta^{(\mathrm{i})}(t) &= \theta^{(\mathrm{i})}(t_0) + \dot{\theta}^{(\mathrm{i})}(t_0)(t-t_0) \\ &- \frac{\dot{\theta}^{(\mathrm{i})}(t_0)}{t_{\mathrm{i}}-t_0}(t-t_0)^2 + \frac{\dot{\theta}^{(\mathrm{i})}(t_0)}{3(t_{\mathrm{i}}-t_0)^2}(t-t_0)^3, \\ & t_0 \le t \le t_{\mathrm{i}}. \end{aligned} \quad (32)$$

Then, the maximum joint angles to check the range of joint limits are obtained,

$$\theta_{max} = \theta^{(\mathrm{i})}(t_{\mathrm{i}}) = \theta^{(\mathrm{i})}(t_0) + \frac{\dot{\theta}^{(\mathrm{i})}(t_0)(t_{\mathrm{i}}-t_0)}{3}. \quad (33)$$

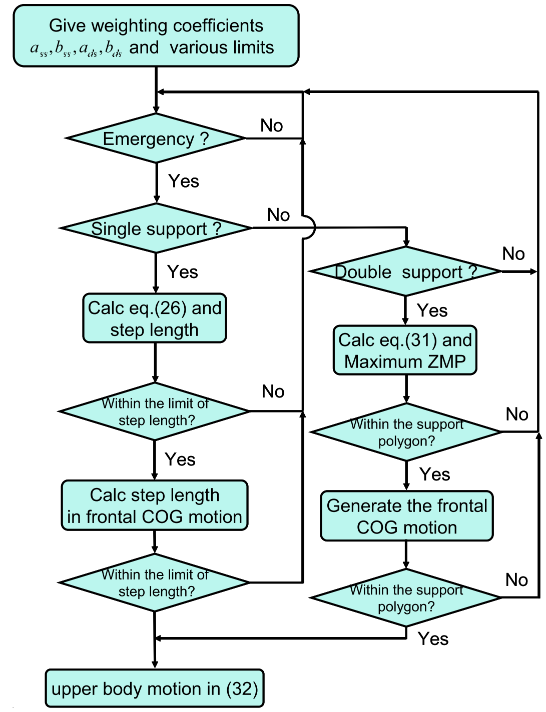

Fig. 7. Flowchart of the emergency stop.

In Halt Phase, the trajectories of the upper body joints are generated as the fifth order polynomial function. However, these upper body joints rotate independently.

Thus, overall algorithm is shown by a flowchart in Fig.7.

V. Simulation

A. Emergency stop at the single support phase

Fig.8 shows simulation result of the emergency stop motion with crouching down in the single support phase. Before the emergency stop, the robot is walking with step length of 0.3[m] and step cycle of 0.8[s]. The weighting factor a_{ss} and b_{ss} are set to 5.0 and 1000.0 respectively. In this simulation, the command of emergency stop is given at 3.4[s] at the late single support phase. Thus, in the original walking pattern, the single support phase has a little time to terminate. The stop motion generator postponed the touchdown time and extended the step length.

In Fig.9, we can see that the humanoid robot can stop within one step. Then, the knee joints in the crouching down motion are compared with the constant height of the COG in Fig.10. The left and the right legs are the rear and the fore respectively. Although the maximum knee joint angle in the rear leg increases, the rotate range of the knee joints in the fore leg can be reduced as shown in Fig.10. Thus, the crouching motion can prevent from the expanding of the knee joint.

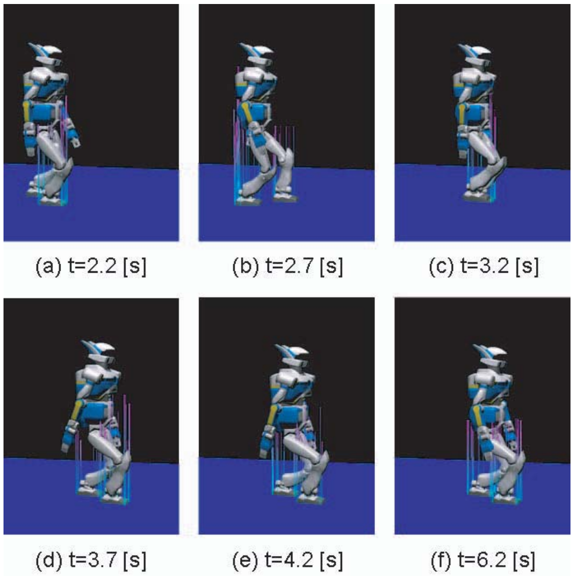

Fig. 8. Snapshot of the emergency stop with crouch down.

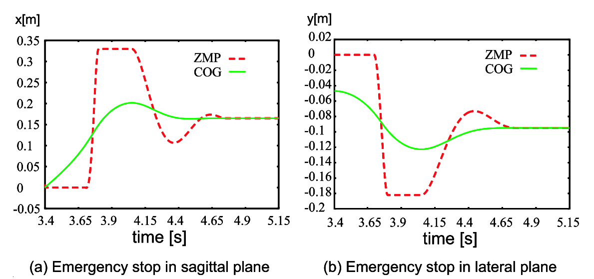

Fig. 9. The COG and the ZMP trajectories of the emergency stop.

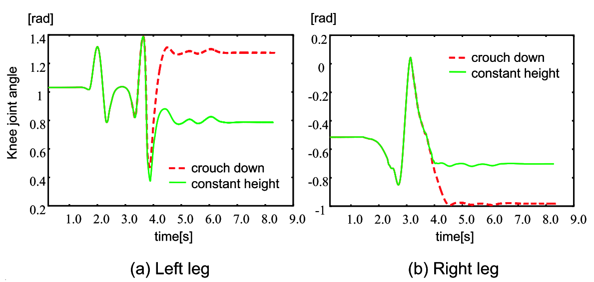

Fig. 10. Comparison of the knee joints.

B. Emergency stop at the double support phase

The simulation result of the emergency stop motion in the double support phase is shown in Fig.11. The walking pattern is used as well as the single support phase. The command of emergency stop is set as 3.5[s]. The weighting coefficients a_{ds} and b_{ds} are set to 50.0 and 1000.0 respectively. The generated trajectories of the COG and the ZMP are shown in Fig.12. We can see that the overshoot of the generated ZMP trajectory at about 4 seconds. The overshoot wa caused by quantization error of phase transition time due to the fixed servo cycle.

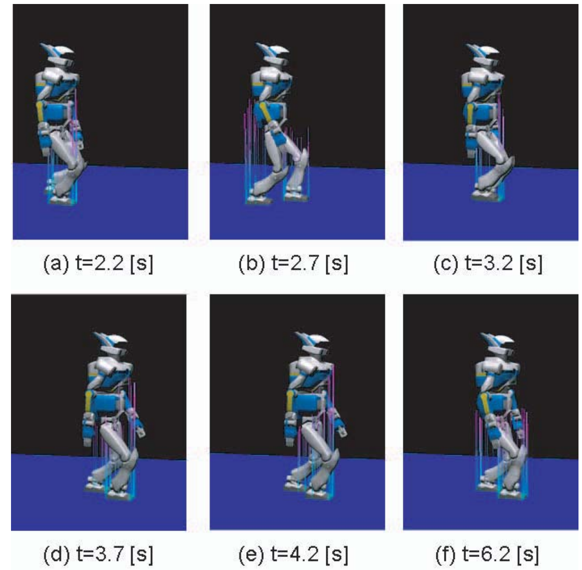

Fig. 11. Snapshot of the emergency stop in the double support phase.

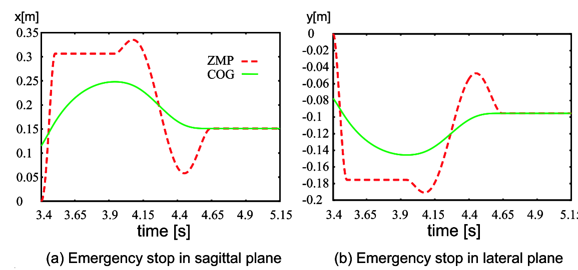

Fig. 12. The COG and the ZMP trajectories of the emergency stop.

VI. Experiment

Since it is guaranteed that the emergency stop motion can be realized, we tested it on the actual humanoid robot HRP-2[10]. The same weighting coefficients are used as the simulation. The step length and step cycle are set to 0.15[m] and 0.8[s] respectively. The timing to command the emergency stop was set to the half of the single support phase. The snapshots of the emergency stop motion are shown in Fig.13.

VII. Conclusion

This paper presented the emergency stop algorithm of a walking humanoid robot. The emergency stop motion was divided into four phases according to the role of the Zero-Moment Point (ZMP). In each phase, approximate analytical solutions of the Center of Gravity (COG) dynamics was used to generate the motion. During the single support phase, a landing time and position were determined by evaluating the average velocity of the swing leg and the horizontal position of the COG. During the double support phase, the travel distance of the COG and the ZMP were evaluated. The emergency stop to more complicate motion such as dancing and so on is an issue in our future.

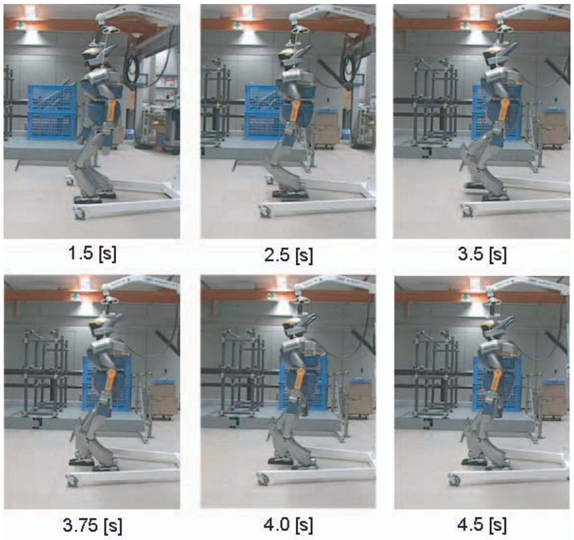

Fig. 13. Snapshot of the emergency stop in experiment.

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