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A Fast Dynamically Equilibrated Walking Trajectory Generation Method of Humanoid Robot

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Abstract. This paper describes a fast dynamically equilibrated trajectory generation method for a humanoid robot. From a given input motion and the desired ZMP trajectory, the algorithm generates a dynamically equilibrated trajectory using the relationship between the robot's center of gravity and the ZMP. Three key issues are denoted: 1) an enhanced ZMP constraint which enables the calculation of robot stability even if several limbs are contacting the environment, 2) a simplified robot model is introduced that represents the relationship between its center of gravity and ZMP, 3) a convergence method is adopted to eliminate approximation errors arising from the simplified model. Combining these three key issues together with online ZMP compensation method, humanoid robot H5 have succeeded to walk, step down and so on. Experimental results using humanoid robot H5 are described.

Keywords: bipedal walking, dynamically equilibrated walking trajectory, humanoid robots

1. Introduction

Recently research on a humanoid type robot is active field in robotics society, and many remarkable elemental functions are proposed. Especially soft skin, 3D vision, motion planning and other topics are very much progressing. However, in order to achieve a humanoid robot which works in a human world together with human being, not only these elemental functions but also dynamic walking function is required. Therefore, algorithms for maintaining dynamic stability are central to humanoid robot control. Recent advances in computing hardware have enabled increasingly sophisticated physically-based simulation techniques to be utilized for the offline generation of dynamically-equilibrated motions for complex robots, such as humanoid robots (e.g., Yamane and Nakamura, 2000).

This paper presents an offline algorithm for generating dynamically equilibrated compensation motions for humanoid robots. Given input motion and the desired ZMP trajectory, the algorithm generates a modified dynamically-equilibrated motion for a humanoid robot. The system consists of three parts: 1) enhanced ZMP constraint which enables to calculate robot equilibrium even several limbs are attaching to the environment, and it can be applied not only single/dual leg(s) motion but also limbs motion if limbs has 6 DOFs, 2) humanoid robot dynamics model by representing its center of gravity, so that differencial equation of center of gravity and ZMP can be obtained, and then this equation is solved using trinomial expression, 3) converge method is adopted to treat model error to the real robot. Combining these three key issues together with online ZMP compensation method, humanoid robot H5 have succeeded to walk, step down and so on. Experimental results by using humanoid type robot H5 are denoted.

2. Related Research

So far, there are remarkable biped robots have been proposed, and their trajectory generation method can be devided into two major schemes: 1) online simple model based trajectory generation method, and 2) offline position-based trajectory generation method. The former method has many advantages, especially calculation simpleness and adaptability for various environemnt. Remarkable issues have been proposed for biped type robots (Kajita and Tani, 1996; Pratt et al., 1997).

However, since a humanoid robot has many degrees of freedom and heavy legs & upperbody, simplified method does not work well. Therefore, position-based offline trajectory generation has been adopted mostly using a ZMP (Vukobratović et al., 1990) constraint. Currently, methods for calculating dynamically equilibrated trajectories can be categorized into three ways: a) heuristic search such as GA (genetic algorithm), b) problem optimization method such as optimal gradient method, and c) model simplification with iteration. Several remarkable issues have been proposed using these schemes mostly applying to a walking pattern generation for a real humanoid type robot (Yamaguchi et al., 1993; Hirai, 1997; Nagasaka et al., 1999b; Kagami et al., 2000).

Heuristics search method or problem optimization method for find out a dynamically equilibrated motion trajectory under ZMP constraint are considered as a general method, however these methods require huge number of iteration to find out a solution, and it requires many computation time. This is a fundamental problem of position-based trajectory method. In this paper, we propose a fast trajectory generation method by using a relationship between robot center of gravity and ZMP. This algorithm is belonging to category c) in above.

3. A Fast ZMP Tracking Trajectory Generation Method

3.1. *Dynamics Model of Humanoid Type Robot*

First, we introduce a model of humanoid type robot by represeting motion and rotation of the center of the gravity (COG). Set z axis be the vertical axis, and x and y axis be the other component of sagital and lateral plane respectively. Set m_i, $r_i = (x_i, y_i, z_i)$, w_i, $\boldsymbol{I}_i$ be weight, position, angle velocity, inertia moment of ith link respectively. Let total mass of the robot be m_{total}, and total center of the gravity be $\boldsymbol{r}_{cog} = (r_{cog_x}, r_{cog_y}, r_{cog_z})$. Then they are represented as follows:

$$m_{total} = \sum m_i \tag{1}$$

$$r_{cog_x} = \frac{\sum m_i r_{x_i}}{m_{total}} \tag{2}$$

$$r_{cog_y} = \frac{\sum m_i r_{y_i}}{m_{total}} \tag{3}$$

$$r_{cog_z} = \frac{\sum m_i r_{z_i}}{m_{total}} \tag{4}$$

Let moment around its center of gravity be $\boldsymbol{M}_{cog}$, total force that robot obtains be $\boldsymbol{f} = (f_x, f_y, f_z)$ and total moment around a point $\boldsymbol{p} = (p_x, p_y, p_z)$ be $\boldsymbol{T}$, then dynamic equation around a point $\boldsymbol{p}$ is approximately represented as follows:

$$\begin{aligned} m_{total}(\boldsymbol{r}_{cog} - \boldsymbol{p}) \times (\ddot{\boldsymbol{r}}_{cog} + \boldsymbol{g}) + \boldsymbol{M}_{cog} - \boldsymbol{T} = 0 \\ \boldsymbol{f} = m_{total}(\ddot{\boldsymbol{r}}_{cog} + \boldsymbol{g}) \end{aligned} \tag{5}$$

ZMP $\boldsymbol{p}_{cog} = (p_{cog_x}, p_{cog_y})$ around point $\boldsymbol{p} = (p_x, p_y, h)$ on the horizontal place $z = h$ is defined as a point where moment around point $\boldsymbol{p}$ be $\boldsymbol{T} = (0, 0, Tz)$, and it can be calculated from Eq. (5).

$$\begin{aligned} p_{cog_x} &= r_{cog_x} - \frac{M_{cog_y} - m_{total}(r_{cog_z} - h)(\ddot{r}_{cog_x} + g)}{m_{total}(\ddot{r}_{cog_z} + g)} \\ p_{cog_y} &= r_{cog_y} - \frac{M_{cog_x} - m_{total}(r_{cog_z} - h)(\ddot{r}_{cog_y} + g)}{m_{total}(\ddot{r}_{cog_z} + g)} \end{aligned} \tag{6}$$

Let $h = 0$ in Eq. (6) and using Eq. (5), then ZMP can be calculated as follows when desired robot motion has been achieved (Nagasaka et al., 1998).

$$
\begin{aligned}
p_{cog_x} &= r_{cog_x} - \frac{M_{cog_y} - m_{total} r_{cog_z} (\ddot{r}_{cog_x} + g)}{f_z} \\
p_{cog_y} &= r_{cog_y} - \frac{M_{cog_x} - m_{total} r_{cog_z} (\ddot{r}_{cog_y} + g)}{f_z}
\end{aligned} \tag{7}
$$

3.2. *Equilibrum by Horizontal Center of Gravity Position Modification*

Let $p^*_{cog}(t)$ be the given ideal ZMP trajectory, and $\boldsymbol{WBT}(t)$ be the whole body trajectory (e.g., walking motion trajectory). When robot moves along given $\boldsymbol{WBT}(t) = \boldsymbol{r}^o(t)$, then resulting moment $\boldsymbol{M}^o$, force $\boldsymbol{f}^o$, ZMP p^o_{cog}, center of gravity $\boldsymbol{r}^o_{cog}$ is calculated.

Problem statement and compensation scheme are defined as follows:

Problem Statement. For given ideal ZMP trajectory $p^*_{cog}(t)$ and given input body trajectory $\boldsymbol{WBT}(t) = \boldsymbol{r}^o(t)$, calculate an approximate new trajectory $\boldsymbol{r}^*_{cog}(t)$ that causes a new ZMP trajectory $\boldsymbol{p}_{cog}(t)$ which is close enough to the given ideal ZMP trajectory $\boldsymbol{p}^*_{cog}(t)$.

From Eq. (7), following equations is obtained for both in ideal and current $\boldsymbol{p}, \boldsymbol{r}$ respectively.

$$
\begin{aligned}
p_{cog_x}(t) &= r_{cog_x}(t) \\
&\quad - \frac{M^o_{cog_x}(t) - m_{total} r_{cog_z}(t) (\ddot{r}^o_{cog_x}(t) + g)}{f^o_z(t)}
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
p^*_{cog_x}(t) &= r^*_{cog_x}(t) \\
&\quad - \frac{M^*_{cog_x}(t) - m_{total} r^*_{cog_z}(t) (\ddot{r}^*_{cog_x}(t) + g)}{f^*_z(t)}
\end{aligned}
$$

Compensation Scheme. In order to simplify Eq. (7), only horizontal modification of the body trajectory is considered.

Since only horizontal compensation motion of the body is considered, $r^o_{cog_z} = r^*_{cog_z}$. Then, two assumptions are introduced:

Assumption 1. We assume that effect to the force $\boldsymbol{f}(t)$ that robot obtains from its self motion is small enough. Therefore,

$$
f^o_z(t) = f^*_z(t) \tag{9}
$$

Assumption 2. We assume that effect to the torque around center of gravity that robot obtains $\boldsymbol{M}_{cog}(t)$ from its self motion is small enough. Therefore

$$
\boldsymbol{M}^o(t) = \boldsymbol{M}^*(t) \tag{10}
$$

With these assumptions, and let $\boldsymbol{p}^{err}_{cog}(t)$ be an error between ideal ZMP $\boldsymbol{p}^*_{cog}(t)$ and current ZMP $\boldsymbol{p}_{cog}(t)$, and $\boldsymbol{r}^{err}_{cog}(t)$ be the an error between ideal center of gravity trajectory $\boldsymbol{r}^*_{cog}(t)$ and current trajectory $\boldsymbol{r}_{cog}(t)$.

$$
\begin{aligned}
\boldsymbol{p}^{err}_{cog}(t) &= \boldsymbol{p}^*_{cog}(t) - \boldsymbol{p}_{cog}(t) \\
\boldsymbol{r}^{err}_{cog}(t) &= \boldsymbol{r}^*_{cog}(t) - \boldsymbol{r}_{cog}(t)
\end{aligned} \tag{11}
$$

Therefore following result is obtained from Eqs. (8) and (11).

$$
\boldsymbol{p}^{err}_{cog}(t) = \boldsymbol{r}^{err}_{cog}(t) - \frac{m_{total} r_{cog_z}(t) \ddot{\boldsymbol{r}}^{err}_{cog}(t)}{f^o_z(t)} \tag{12}
$$

3.3. *Solving Differential Equation*

Equation (12) can be solved as subtract approximation. By discretizing Eq. (12) with small time step Δt with iteration i $(i = 0, 1, 2, \ldots, n-1, n)$,

$$
\begin{aligned}
\boldsymbol{p}^{err}_{cog}(t) &\rightarrow \boldsymbol{p}^{err}_{cog}(i) \\
\boldsymbol{r}^{err}_{cog}(t) &\rightarrow \boldsymbol{r}^{err}_{cog}(i) \\
\ddot{\boldsymbol{r}}^{err}_{cog}(t) &\rightarrow \frac{\boldsymbol{r}^{err}_{cog}(i+1) - 2\boldsymbol{r}^{err}_{cog}(i) + \boldsymbol{r}^{err}_{cog}(i-1)}{\Delta t^2}
\end{aligned} \tag{13}
$$

Then trinomial expression which satisfies $r^{err}_{cog}(i)$ is obtained when $1 \leq i \leq n-1$.

$$
a_i r^{err}_{cog}(i-1) + b_i r^{err}_{cog}(i) + c_i r^{err}_{cog}(i+1) = d_i \tag{14}
$$

Here,

$$
\begin{aligned}
a_i &= -\frac{m_{total} r^o_{cog_z}(i)}{f^o_z(i) \Delta t^2} \\
b_i &= 1 + 2\frac{m_{total} r^o_{cog_z}(i)}{f^o_z(i) \Delta t^2} \\
c_i &= -\frac{m_{total} r^o_{cog_z}(i)}{f^o_z(i) \Delta t^2} \\
d_i &= p^{err}_{cog}(i)
\end{aligned} \tag{15}
$$

Then using boundary condition of trinomial expression, boundary condition $i = 0$, $i = n$ is calculated. In this paper, we fix terminal position. If statically stable posture is given as the terminal posture, both end of resulted trajectory will not be moving.

- Since terminal position is fixed, x_0, x_n are given.
- From position and acceleration of center of gravity relationship, number of variables is $n-1$ from $t=1$ to $t=n-1$.
- From ZMP constraint, number of variables is $n+1$ from $t=0$ to $t=n$.

As for boundary condition, terminal velocity is indefinite, we set the following boundary conditions.

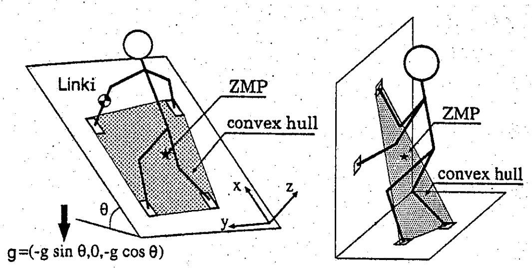
$$\begin{aligned} b_0 &= b_n = 1 \\ a_0 &= a_n = 0 \\ c_0 &= c_n = 0 \end{aligned} \tag{16}$$

Given coefficient matrix, trinomial expression is solved, and discrete r_{cog}^{err} is calculated.

3.4. Enhanced ZMP Constraint

Original ZMP constraint is designed for only one leg is supporting the body and the leg should be on a ground plane (vertical plane along to the gravity direction). For example in dual leg state on a floor, it is enhanced as a virtual sole which covers both legs sole like a convex hull, so that ZMP constraint is calculated on this virtual sole.

Since humanoid type robot has four limbs, body may be supported by many points. Therefore, we introduce a case that supporting points are placed only one plane which is slant to the ground plane (Fig. 1(a)). Introducing coordinate system shown in Fig. 1(a), let total torque around a point $\boldsymbol{p}' = (p'_x, p'_y, p'_z)$ be T', then



(a) In case of Contact Points are on one plane

(b) In case of Contact Points are not on one plane

Figure 1. Enhanced ZMP.

dynamic equation under this assumption and moment equation around a point p' is approximately represented as follows:

$$m_{total}(\boldsymbol{r}'_{cog} - \boldsymbol{p}') \times (\ddot{\boldsymbol{r}}'_{cog} - \boldsymbol{g}') - \boldsymbol{M}'_{cog} - \boldsymbol{T}' = 0 \tag{17}$$

Since $\boldsymbol{g}' = (-g\sin\theta, 0, -g\cos\theta)$, ZMP $p'_{cog} = (p'_{cog,x}, p'_{cog,y})$ around point $\boldsymbol{p}' = (p'_x, p'_y, h)$ on the place $z = h$ can be represent as follows when moment is $\boldsymbol{T}' = (0, 0, T'z)$.

$$\begin{aligned} p'_x &= \frac{m_{total}(\ddot{r}'_{z_i} + g\cos\theta)r'_{x_i} - m_{total}(r'_{z_i} - h)(\ddot{r}'_{x_i} + g\sin\theta) + \sum_i M'_{xi}}{m_{total}(\ddot{r}'_{z_i} + g\cos\theta)} \\ p'_y &= \frac{m_{total}(\ddot{r}'_{z_i} + g\cos\theta)r'_{y_i} - m_{total}(r'_{z_i} - h)\ddot{r}'_{y_i} + \sum_i M'_{yi}}{m_{total}(\ddot{r}'_{z_i} + g\cos\theta)} \end{aligned} \tag{18}$$

Then, we introduce a case that supporting points are placed on plural planes (Fig. 1(b)). In this case, there are combination of supporting points which consists of placed on one plane. When one of a ZMP constraints satisfies Eq. (18), motion trajectory will be dynamically equilibrated. Assuming that each limb supports the body only using its end-effector, there exists at most four plane, and it is not too hard to calculate these combinations.

4. Implementation

4.1. Model Error Convergence

Using approximated modelling in section above, we can calculate a error trajectory of center of gravity $r_{cog}^{err}(t)$ from given ideal ZMP trajectory $p_{cog}^*(t)$ and

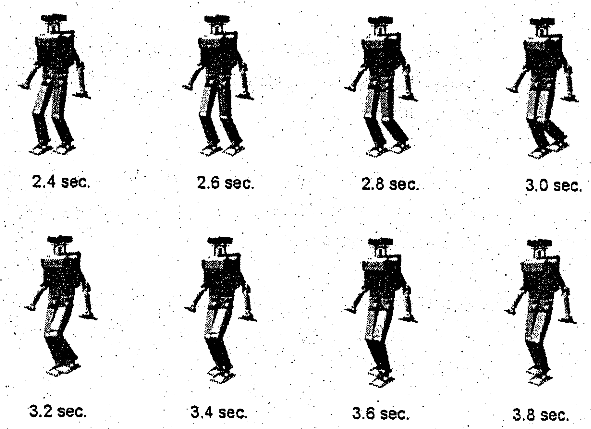


Figure 2. Walking pattern.

given whole body trajectory $\boldsymbol{WBT}(t)$. However, there exists some model error with $\boldsymbol{r}_{cog}^{err}(t)$, since it is a simplified approximation model. Furthurmore, given $\boldsymbol{WBT}(t) = \boldsymbol{r}_{cog}(t)$ is hard to control directly in a horizonatal plane. In order to solve this problem, $\boldsymbol{r}_{torso}(t)$ is selected as for a control variables of the robot by introducing a following assumption.

Assumption 3. Since horizontal motion of the torso is assumed, assume linear relationship between motion of torso $\Delta(\boldsymbol{r}_{torso}(t))$ and motion of the center of gravity $\Delta(\boldsymbol{r}_{cog}(t))$.

$$\Delta(\boldsymbol{r}_{torso}(t)) \cong k_{cog}\Delta(\boldsymbol{r}_{cog}(t)) \tag{19}$$

From this assumption, following model improvement equation is obtained using coefficient value k_{cog}.

$$\boldsymbol{r}_{cog}^{err}(t) = \boldsymbol{r}_{cog}^{*}(t) - k_{cog}\boldsymbol{r}_{torso}(t) \tag{20}$$

4.2. *Implementation*

We implemented the algorithm above by receiving torso, limbs and ZMP trajectories, then convert torso trajectory to track given ZMP. The algorithm has following iteration. We introduce a coefficient $K(0 < K < 1)$ for a trinomial expressions, in order to compensate several approximations. Then do a convergence to calculate a suitable dynamically equilibrated torso trajectory.

1. Apply inverse dynamics $INV()$ to given whole body trajectory $\boldsymbol{r}(t)$ to calculate current $\boldsymbol{p}_{cog}(t)$. Then calculate the error $\boldsymbol{p}_{cog}^{err}(t)$ between given ideal ZMP $\boldsymbol{p}_{cog}^{*}(t)$ and current ZMP $\boldsymbol{p}_{cog}(t)$.
2. Calculate torso trajectory difference $\boldsymbol{r}_{cog}^{err}(t)$, and estimate torso trajectory $\boldsymbol{r}_{torso}(t)$ using Eq. (20) by applying trinomial expressions with coefficient $K(0 < K < 1)$.

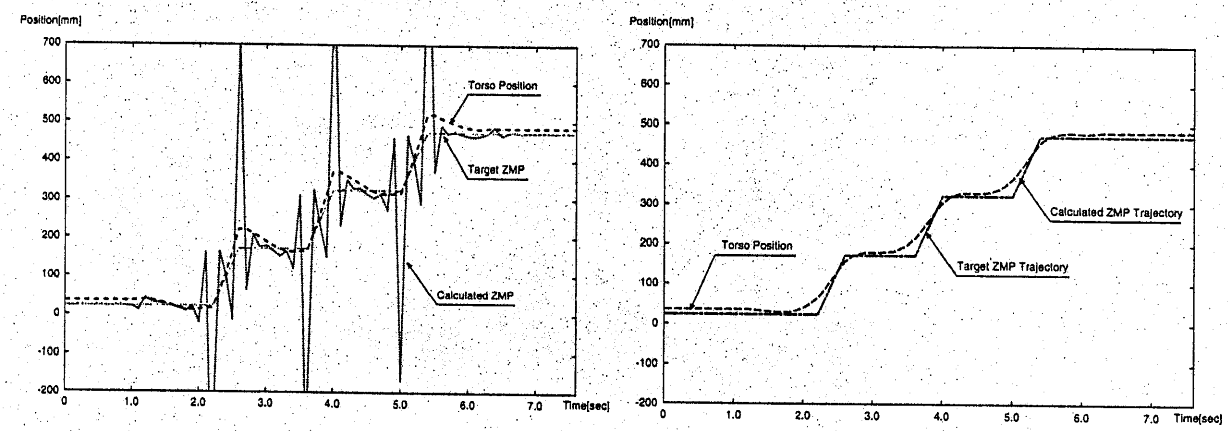


Figure 3. Input and output ZMP, torso trajectories for front (x) direction.

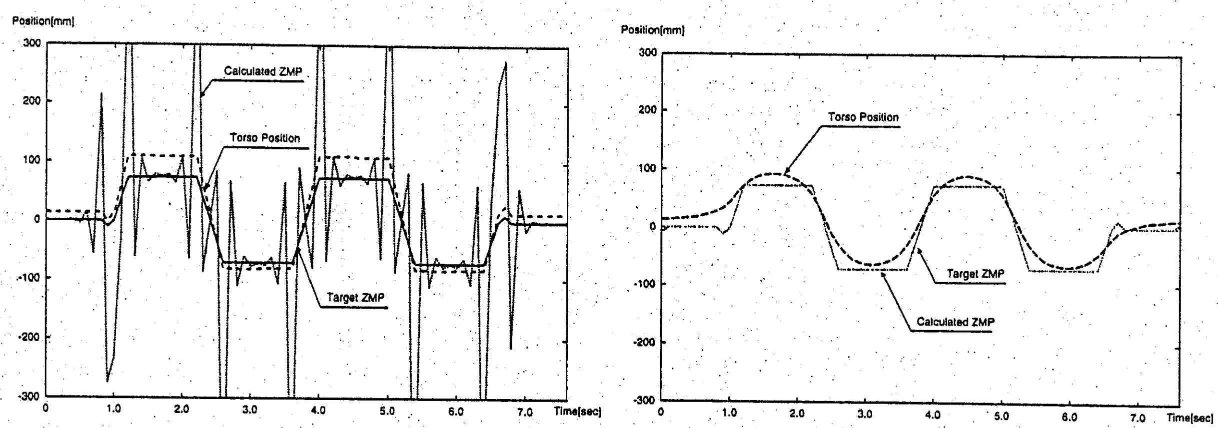


Figure 4. Input and output ZMP, torso trajectories for side (y) direction.

3. Let error E be an average from the given ZMP $p^*_{cog} * t)$, and evaluate it using following equation.

$$E = \frac{1}{step} \sum_i \|p_{error,i}\| \qquad (21)$$

4. Let error of jth iteration be Ej, and stop this algorithm when $E_j \leq CE_{j-1}$. C is a constant threshold, and in this paper $C = 0.95$.
5. Back to 1 step.

4.3. *Inverse Dynamics Calculation*

Inverse dynamics calculation is utilized to calculate $p_{cog}(t)$ from given input trajectory $\boldsymbol{WBT}(t)$. The inverse dynamics is the problem to find out a set of input torque of each joints τ with given joint angle θ, joint angle velocity $\dot{\theta}$ and joint angle acceleration $\ddot{\theta}$. Then inverse dynamics $INV()$ is represented as follows.

$$\tau = INV(\theta, \dot{\theta}, \ddot{\theta}) \qquad (22)$$

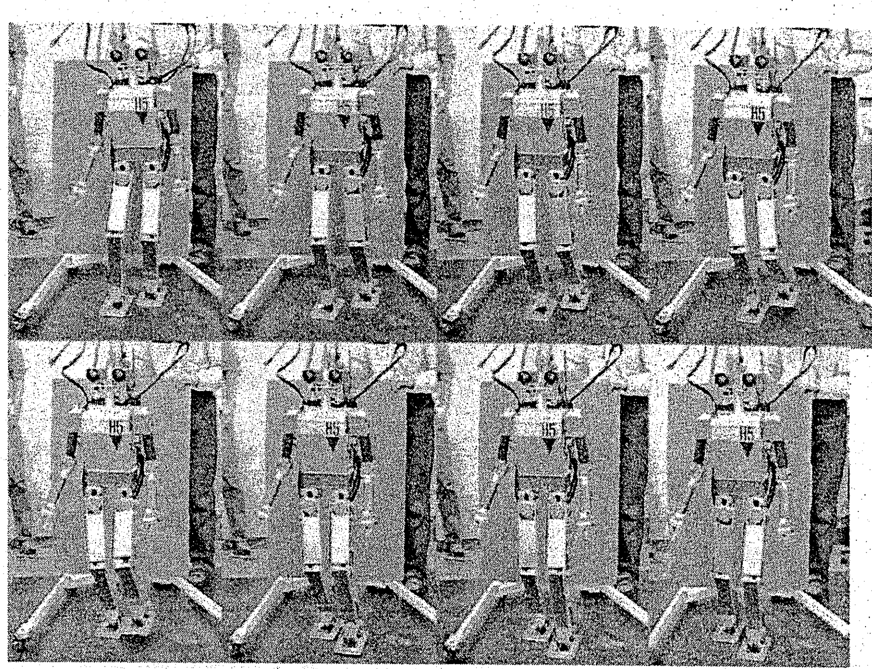


Figure 5. H5 walking experiment.

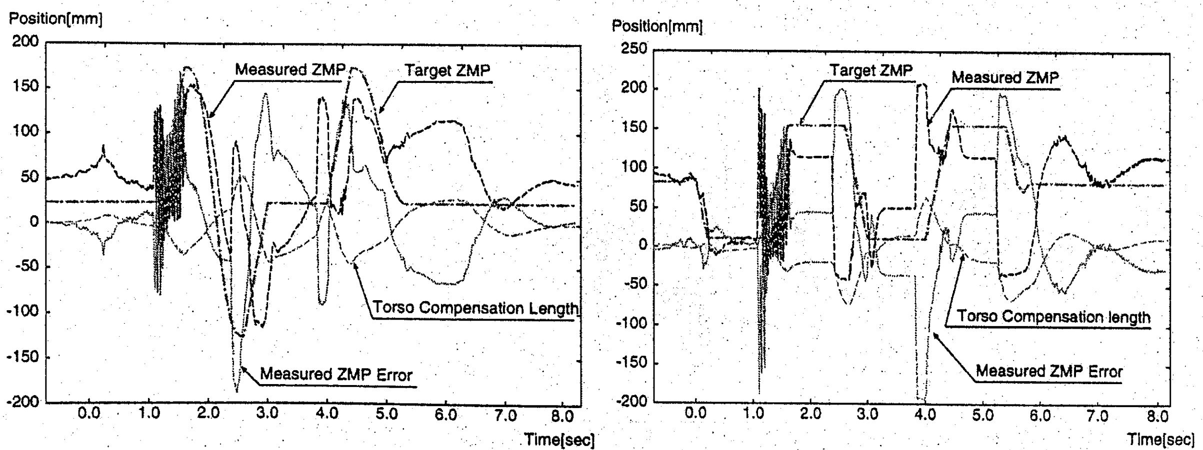


Figure 6. Desired ZMP, real ZMP, error and torso position for front x and side y direction.

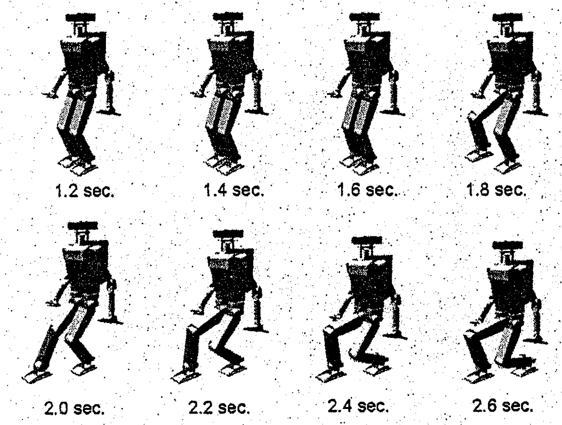


Figure 7. Squat down with stepping forward pattern.

Fast and general inverse dynamics calculation library (Sugihara et al., 2000) is adopted in order to achieve fast trajectory generation. This library is originally developed for multi-limb body and appropriate link can be fixed to the world coordinates, so that inverse dynamics of any body configuration to the environemnt can be efficiently calculated.

The procedure for calculating $p(t)$ by this algorithm is denoted as follows:

1. Set fixed link to the world as a supporting leg terminal link (foot),
2. Set robot joint angles, angle velocities, angle accelerations,
3. Recursively calculate link translation velocity acceleration, angular velocity and acceleration respectively from root link,
4. Calculate root link translation velocity, acceleration, angular velocity and acceleration respectively, from the relative motion between fixed link and root link, then re-calculate all link motion,
5. Recursively calculate link force and moment from terminal link,
6. Calculate ZMP from root link force and moment.

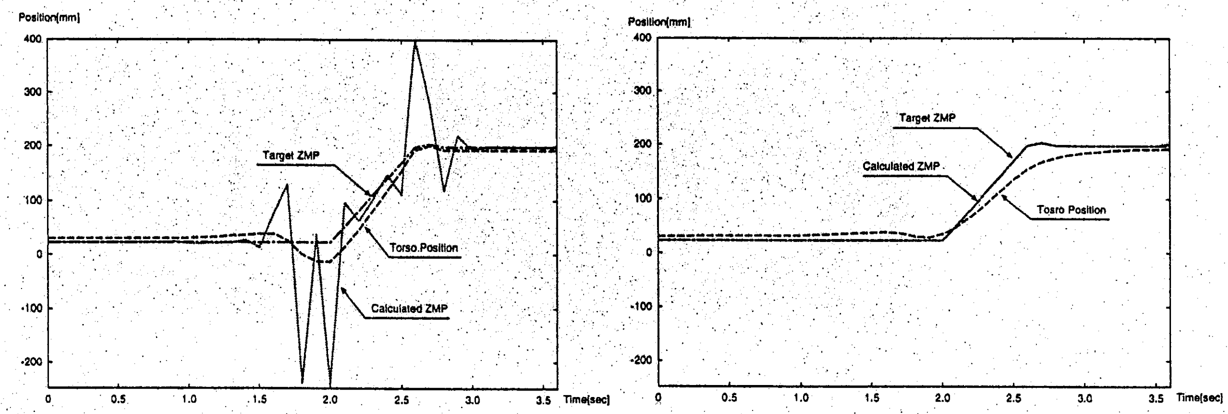


Figure 8. Input and output ZMP, torso trajectories for front (x) direction.

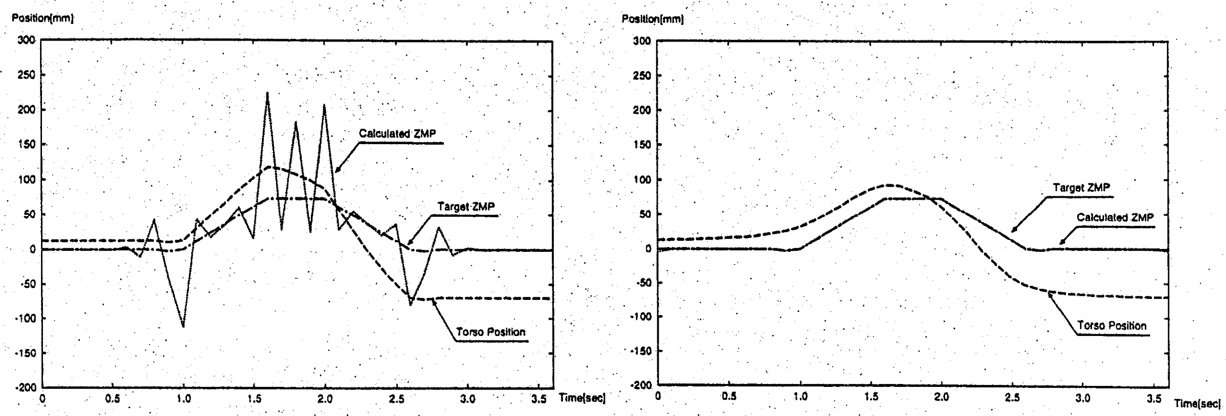


Figure 9. Input and output ZMP, torso trajectories for side y direction.

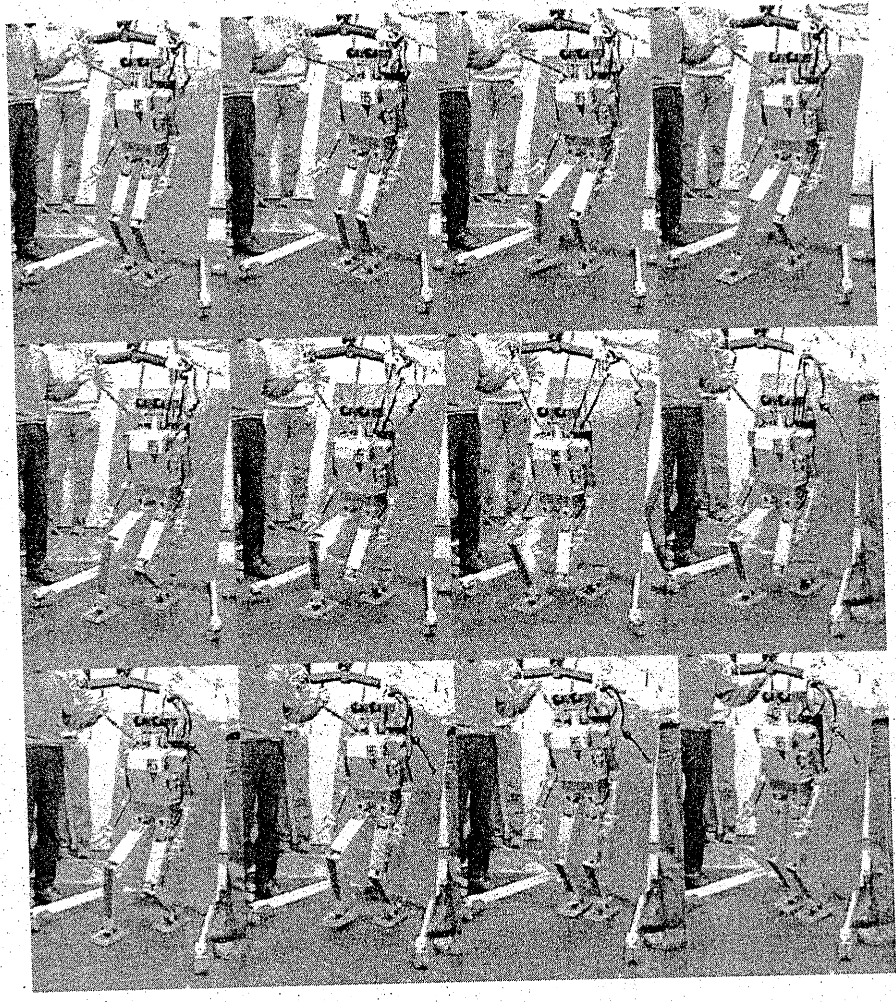


Figure 10. H5 squat down experiment.

The algorithm is based on Newton-Euler method (Luh et al., 1980), and tree-like link structure is known to be solved as follows (Walker and Orin, 1982). Computational complexity of this part is $O(n)$, where n is number of DOFs.

4.4. Online ZMP Compensation Method by Horizonatal Torso Movement

Humanoid type robot is hard to "replay" the given trajectory in openloop in real world even given trajectory satisfies the ZMP constraint. Therefore, several local compliance control methods have been proposed (Honda. Co. Ltd., 1993a, 1993b, 1998). In this paper, we adopted a torso position compliance method to track a given ZMP trajectory (Nagasaka et al., 1999a). This method tries to track a given ZMP trajectory by the horizontal motion of the torso. It consists of two parts, one is ZMP tracking mechanisms, and the other is inverse pendulum control to keep its dynamic balance.

In ZMP tracking mechanisms, process is same as in a one step of trinomial expression in Eq. (14). In inverse pendulum control, think about inverse pendulum with desired ZMP as the supporting point.

4.5. Humanoid Robot H5

The H5 has 1300 [mm] height and 33 [kg] weight. It has 6 DOFs in each leg, 6 DOFs in each arm, 1 DOF for each finger, and 4 DOFs in each neck and vergence respectively. It has 12 force sensors at the bottom of each sole and measures the ZMP. It has a

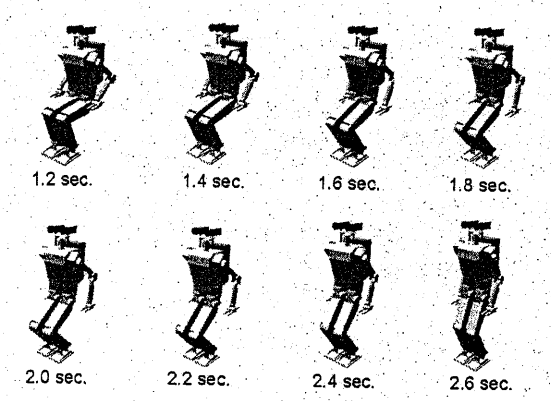


Figure 11. Stand up with arms pattern.

PC/AT clone on body which has PentiumIII-333MHz, and motor servo loop is 1msec cycle which is written as RT-Linux kernel module.

5. Trajectory Generation for Humanoid Robot H5

We apply this fast motion generation algorithm to our dynamic humanoid robot "H5", and show efficiency of the algorithm.

5.1. Walking Trajectory Generation and Experiment

Modified walking pattern is shown in Fig. 2, from statically stable trajectory as for input. Input and modified, torso and ZMP trajectories are shown in Figs. 3 and 4 for front x and side y direction respectively.

We applied output motion mentioned in the section above to humanoid robot H5, and confirm its performance (see Fig. 5).

Figure 6 shows output desired ZMP trajectory, real ZMP trajectory, error between desired and real ZMP and torso position for front x and side y direction respectively. For the first step, ZMP is mostly tracking the original trajectory. However, when changing the grounding leg, free leg is touched to the ground before its original trajectory, and since then ZMP trajectory occasionally shifted from the original one, however leg compliance feedback allows ZMP to track the original one.

5.2. Squat Down Trajectory Generation and Experiment

Output squat down motion with right leg is stepping forward pattern is shown in Fig. 7, from statically stable trajectory as for input. Input and modified, torso and ZMP trajectories for front x and side y direction respectively are shown in Figs. 8 and 9.

We applied output motion mentioned in the section above to humanoid robot H5, and confirm its performance (see Fig. 10).

5.3. Standing Up with Arms Trajectory Generation

Using enhanced ZMP constraints, not only a motion which attach to the environment with its feet, but also arm-leg cooperative motion can be generated. Output standing up with arms from sitting posture pattern is shown in Fig. 11, from statically stable trajectory as for input. Input and modified, torso and ZMP trajectories for front x direction is shown in Fig. 12.

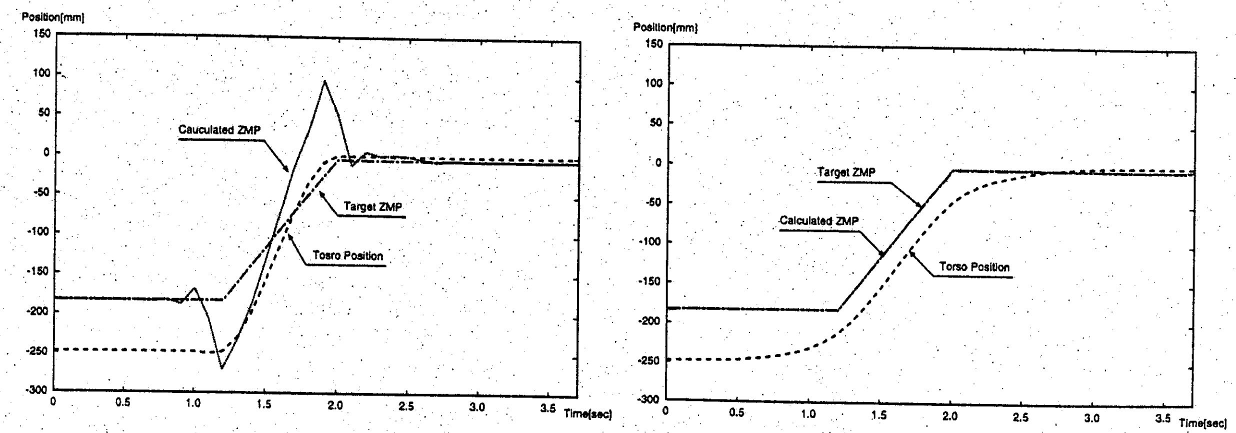


Figure 12. Input and output ZMP, torso trajectories for front (x) direction.

Table 1. Gain K and convergence.

Gain K	$K = 0.1$	$K = 0.3$	$K = 0.5$	$K = 0.7$
Walk	27	9	5	26
Squat down	18	6	4	–
Stand up with arms	29	9	5	–

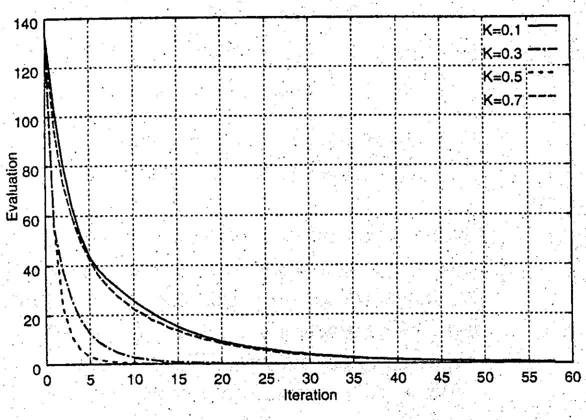


Figure 13. Error feedback gain K and convergence for walking pattern generation.

5.4. Convergence and Performance Evaluation

Iteration number for decrease average ZMP error along trajectory E to be under 5 [mm] is shown in Table 1. Figure 13 shows a relationship between iteration number and error which is calculated in Eq. (21) for generating walking pattern. Most of the calculation time is consumed by solving inverse dynamics $INV()$. Figure 14 shows a relationship between given length of the trajectory (one step is one second) and

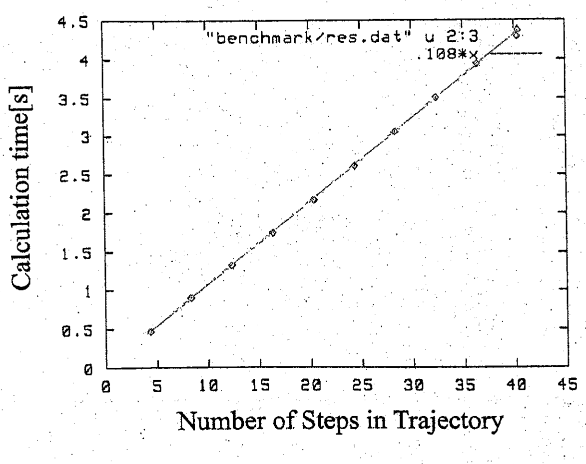


Figure 14. Calculation time and length of walking trajectory.

computational time for compensating the grajectory. Calculation time for this algorithm is about 10 times faster than real speed. For example, given walking pattern is 10 sec and calculation time to make it dynamically equilibrated is also about 1 sec. This result is remarkably fast and we believe that this algorithm can be applied for a realtime walking pattern generation in the future.

6. Concluding Remarks

In this paper, a trajectory generation method from given input to dynamically equilibrated trajectory was proposed. This algorithm can be applied not only dual legs motion but also limbs motion if limbs has 6 DOFs. Three key issues are denoted, 1) enhanced ZMP constraint which enables to calculate robot stability even several limbs are attaching to the environment, 2) simplified robot model of which mass is concentrated on its center of gravity, so that dynamic equation is solved using trinomial expression, 3) converge method is adopted to treat model error to the real robot. Furthermore, experimental results by using humanoid type robot H5 are denoted.

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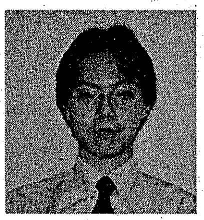

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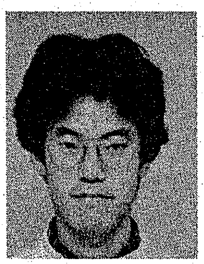

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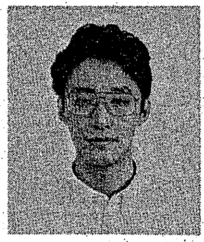

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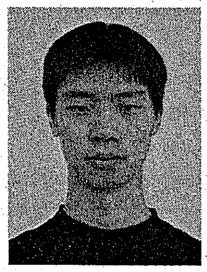

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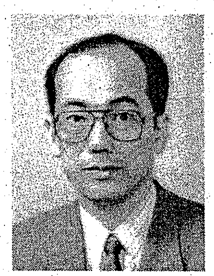

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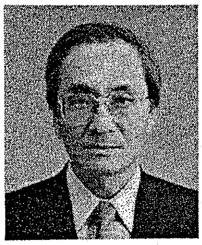

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