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Walking Pattern and Compensatory Body Motion of Biped Humanoid Robot

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Abstract

This paper presents a walking pattern generation method for biped walking. There are three walking phases such as a double support, a swing and a contact phase. In the swing phase, a leg motion pattern is produced by using a six order polynomial, while a leg motion pattern is generated by using a quintic polynomial in the contact and double support phase. When a biped humanoid robot dynamically walks on the ground, moments are produced by the motion of the lower-limbs. So, a moment compensation method is also discussed in this paper. Based on the motion of the lower-limbs and ZMP (Zero Moment Point), the motion of the trunk and the waist is calculated to cancel the moments. Through simulation, the effectiveness of the moment compensation methods is verified.

1. Introduction

Biped or multi-legged robots will be more useful than caterpillar robots for moving over uneven terrain or through narrow spaces. Especially, biped humanoid robots will be able to adapt well to a human living and working environments, and give affinity to a human because they have the same shape as a human. So, I have studied biped-walking motion with the aims to apply the biped robots to industrial and non-industrial areas. One thrust has been toward realizing complete dynamic walking on not only even or uneven terrain but also hard or soft terrain. The other thrust has been toward exploring robot-environment interaction and robot application.

Recently, many biped-walking robots have been developed. Humanoid Robotics Institute of Wasea University has developed a human-like biped robot, WABIAN since 1996 [1]. It consists of a total of 35 DOF; two 3-DOF legs, two 10-DOF arms, a 2-DOF neck, two 2-DOF eyes and a torso with a 3-DOF waist (see Figure 1). Its height is 1.66 m and its weight is 107.4 kg. ASIMO developed by Honda Motor Corporation in 2000, which has 28 DOF such as 6 DOF in each leg, 5 DOF in each arm, 1 DOF in each hand and 2 DOF in the head [2]. Its height is 1.2 m and its weight is 52 kg (see Figure 2). Ministry of Economy, Trade and Industry of Japan lunched 5-year Humanoid Robotics Project (from 1998 to 2002) and developed HRP-2P that can lie down and get up on a floor in 2003 [3, 4]. It consists of 30 DOF such as 6 DOF in each leg, 6 DOF in each arm, 1 DOF in each hand, 2 DOF in the neck and 2 DOF in the waist. Its height is 1.58 m and its weight is 58 kg (see Figure 3). Sony developed a small size humanoid robot, SDR-4X II [5]. It height is 0.58 m and its weight is 7 kg. It consists of 38 DOF such as 6 DOF in each leg, 5 DOF in each arm, 5 DOF in each hand, 4 DOF in the head and 2 DOF in the waist (see Figure 4). A compact size humanoid robot, MK-5, was developed by Aoyama Gakuin University [6]. It has 24 DOF such as 6 DOF in each leg, 5 DOF in each arm and 2 DOF in the head. Its weight is 1.9 kg and its height is 3.56 m. H7 was developed by University of Tokyo in 2001 [7]. Its weight is 55 kg and its height is 1.47 m. It has 30 DOF such as 6 DOF in each leg, 6 DOF in each arm, 1 DOF in each hand, 1 DOF in each foot and 2 DOF in the head. However, biped robots with serial links have many problems such as rigidity and energy consumption problem and position errors. Thus, Humanoid Robotics Institute of Waseda University has developed biped-walking robots having a parallel mechanism, WL-16, in 2002 [8]. The robots consist of twelve 1-DOF active linear actuators, six 2-DOF and 3-DOF passive joints.

Other researchers have studied the analysis, design and control of biped robots. Vukobratovic and his co-workers modeled the walking biped robot that was balanced by manipulating the projected center of gravity and the support area provided by the feet [9]. A sequence control method and a program control method were presented for continuous dynamic biped walking [10, 11]. A hierarchical control strategy was proposed to realize dynamic walking [12]. A virtual model control method was developed to control a pla-

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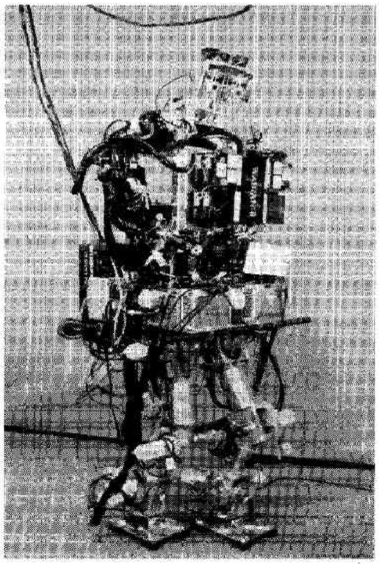

Figure 1: Photo of WABIAN-RI.

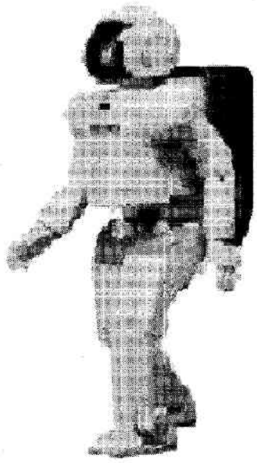

Figure 2: Photo of ASIMO.

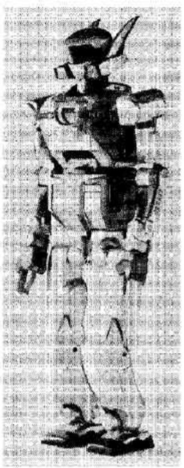

Figure 3: Photo of HRP-2P.

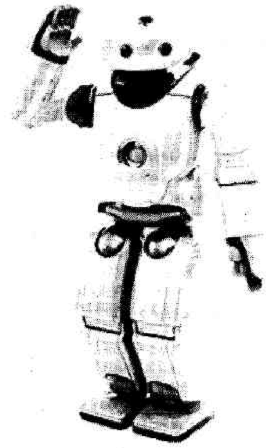

Figure 4: Photo of SDR-4X II.

nar biped robot [13]. A control method to deal with sloped terrain was studied [14]. A linear inverted pendulum mode that is based on massless leg model was discussed to control a biped walking robot [15].

The adaptability of terrain can be regarded as one of the crucial abilities for biped walking robots to deal with rough terrain. In the case of a biped humanoid robot that consists of only lower-limbs, the lower-limbs have to perform two functions at the same time. One is a path control of the lower-limbs according to the surface of terrain. The other is a balance control not to fall down. In order to achieve the dynamic biped walking, the function for the stability should take priority over the function for the path control of the lower-limbs. Therefore, the terrain adaptability of this kind of biped robot is severely limited. If the biped robot has a trunk, the functions can be separated. Its trunk carries out the function for stability, while its lower-limbs work out the function for the path control.

In this paper, a pattern generation for biped locomotion is described. In a swing phase, a leg motion pattern is produced by using a six order polynomial, while a leg motion pattern is generated by using a quintic polynomial in a contact and double support phase. Also, a moment compensation method capable of canceling moments generated by the leg motion is discussed. In this moment compensation method, the motion of the trunk and the waist is employed.

This paper is organized as follows. Section 2 describes how to obtain a walking pattern of the lower-limbs. Section 3 illustrates a moment compensation method. Section 4 describes simulation of compensatory motion of the trunk. Finally, conclusion is discussed in Section 5.

2. Pattern Generation

In order to set a walking pattern of the lower-limbs of a biped humanoid robot, three walking phases are considered, which consists of a double support, a swing and a contact phase. During the swing phase, one foot is not constrained from the ground while the other foot is on the ground. As soon as the heel of the swing leg reaches the ground, the swing phase is changed to the contact phase. If both toe and heel of the swing leg contact on the ground, the phase becomes the double support phase. Figure. 5 shows three walking phases. In the contact and double support phase, a foot motion pattern on even or uneven terrain is made by using a quintic polynomial considering angle, angular velocity, angular acceleration. In the swing phase, a foot motion pattern $\boldsymbol{x}$ is generated by using the sixth order polynomial considering angle, angular velocity, angular acceleration, angle at a half point of the swing phase.

In making a smooth motion of the foot in the swing phase, at least seven constraints on $\boldsymbol{x}$ are evident. Three constraints on the function's value come from the selection of initial, intermediate and final values:

$$\boldsymbol{x}(t_0) = \boldsymbol{x}_0, \;\; \boldsymbol{x}(t_m) = \boldsymbol{x}_m, \;\; \boldsymbol{x}(t_f) = \boldsymbol{x}_f. \qquad (1)$$

An additional four constrains are the zero initial and final velocity and acceleration:

$$\dot{\boldsymbol{x}}(t_0) = \boldsymbol{0}, \;\; \dot{\boldsymbol{x}}(t_f) = \boldsymbol{0}, \;\; \ddot{\boldsymbol{x}}(t_0) = \boldsymbol{0}, \;\; \ddot{\boldsymbol{x}}(t_f) = \boldsymbol{0}. \qquad (2)$$

These seven constrains can be satisfied by a polynomial of at least sixth degree. Since the sixth order polynomial has seven coefficients, it can be made to satisfy the seven constraints given by Equation (1) and (2). These constraints uniquely specify the following equation:

$$\boldsymbol{x}(t) = \boldsymbol{a}_0 + \boldsymbol{a}_1 t + \boldsymbol{a}_2 t^2 + \boldsymbol{a}_3 t^3 + \boldsymbol{a}_4 t^4 + \boldsymbol{a}_5 t^5 + \boldsymbol{a}_6 t^6. \quad (3)$$

Also, the velocity and acceleration along this trajectory are as follows:

$$\begin{aligned} \dot{\boldsymbol{x}}(t) &= \boldsymbol{a}_1 + 2\boldsymbol{a}_2 t + 3\boldsymbol{a}_3 t^2 + 4\boldsymbol{a}_4 t^3 + 5\boldsymbol{a}_5 t^4 + 6\boldsymbol{a}_6 t^5, \\ \ddot{\boldsymbol{x}}(t) &= 2\boldsymbol{a}_2 + 6\boldsymbol{a}_3 t + 12\boldsymbol{a}_4 t^2 + 20\boldsymbol{a}_5 t^3 + 30\boldsymbol{a}_6 t^4. \quad (4) \end{aligned}$$

Combining Equation (3) and (4) with the seven constraints, the seven coefficients can be obtained. Then, substituting these coefficients for Equation (3), the foot pattern will be obtained. Also, a waist pattern will be produced by a quintic polynomial, considering the movable range of the legs. Considering the foot and the waist pattern and DOF of the leg, a preset complete walking pattern of the leg can be set by using inverse kinematics.

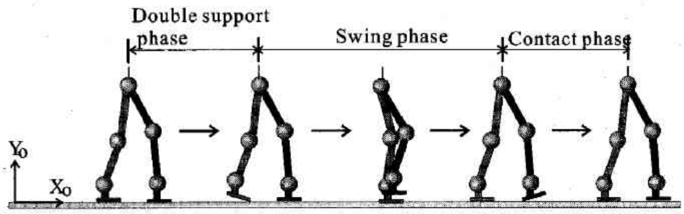

Figure 5: Three walking phases.

3. Moment Compensation

In this study, ZMP (Zero Moment Point) is employed as a stability criterion, which can indicate the gait balance during dynamic walking and provide a quantitative measure for reaction forces on the supporting foot. ZMP is a certain point around which the sum of all moments is equal to zero. For a biped humanoid robot to walk stably, the gravity and the inertial force of the robot must act to the direction of the ground, and the resultant force must act on a point in support polygon formed by the support foot.

Consider a 43 DOF biped humanoid model with rotational joints. The biped humanoid robot consists of two 6 DOF legs, two 7 DOF arms, two 3 DOF hands, a 4 DOF neck, two 2 DOF eyes and a torso with a 3 DOF waist. In modeling the humanoid robot, five assumptions are defined as follows: (a) the humanoid robot consists of a set of particles, (b) the foothold of the humanoid robot is rigid and not moved by any force and moment, (c) the contact region between the foot and the ground surface is a set of contact points, (d) the coefficients of friction for rotation around the X-, Y- and Z-axes are nearly zero at the contact point between the foot and the ground, and (e) the foot of the humanoid robot does not slide on the contact surface. To define mathematical quantities, a world coordinate frame $\mathcal{F}$ is fixed on the ground where a biped humanoid robot can walk and a moving coordinate frame $\bar{\mathcal{F}}$ is attached on the center of the waist to consider the relative motion of each particle as shown in Figure 6.

The moment balance around a contact point p relative to the world coordinate frame $\mathcal{F}$ can be obtained as:

$$\begin{aligned} &\sum_{i=1}^{n} m_i(\boldsymbol{r}_i - \boldsymbol{r}_p) \times (\ddot{\boldsymbol{r}}_i + \boldsymbol{G}) + \boldsymbol{T} \\ &- \sum_{j=1}^{n} ((\boldsymbol{r}_j - \boldsymbol{r}_p) \times \boldsymbol{F}_j + \boldsymbol{M}_j) = \boldsymbol{0}, \end{aligned} \qquad (5)$$

where $\boldsymbol{r}_p$ is the position vector of point p from the

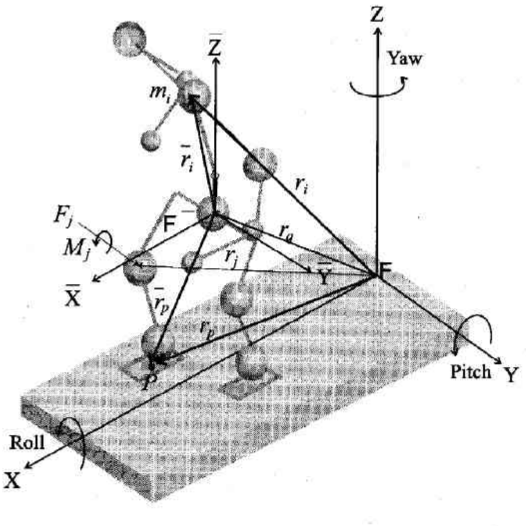

Figure 6: Coordinate frames

origin of $\mathcal{F}$. m_i is the mass of particle i. $\boldsymbol{r}_i$ and $\ddot{\boldsymbol{r}}_i$ denote the position and acceleration vectors of particle i with respect to the world coordinate frame $\mathcal{F}$, respectively. $\boldsymbol{G}$ is the gravitational acceleration vector. $\boldsymbol{T}$ is the moment vector acting on the contact point p. $\boldsymbol{r}_j$ denotes the position vector of particle j with respect to the world coordinate frame $\mathcal{F}$. $\boldsymbol{F}_j$ and $\boldsymbol{M}_j$ denote the force and the moment vectors acting on particle j relative to the frame $\mathcal{F}$, respectively. Let us consider ZMP on the point p. The moment $\boldsymbol{T}$ will be a zero vector by the ZMP concept. Equation (5) can be rewritten with respect to the moving frame $\bar{\mathcal{F}}$ as follows:

$$\begin{aligned}&\sum_{i=1}^{n} m_i(\bar{\boldsymbol{r}}_i - \bar{\boldsymbol{r}}_{zmp}) \times (\ddot{\bar{\boldsymbol{r}}}_i + \ddot{\boldsymbol{r}}_q + \boldsymbol{G}\\ &+\dot{\bar{\boldsymbol{\omega}}} \times \bar{\boldsymbol{r}}_i + 2\bar{\boldsymbol{\omega}} \times \dot{\bar{\boldsymbol{r}}}_i + \bar{\boldsymbol{\omega}} \times (\bar{\boldsymbol{\omega}} \times \bar{\boldsymbol{r}}_i))\\ &-\sum_{j=1}^{n}((\bar{\boldsymbol{r}}_j - \bar{\boldsymbol{r}}_{zmp}) \times \bar{\boldsymbol{F}}_j + \bar{\boldsymbol{M}}_j) = \boldsymbol{0},\end{aligned} \tag{6}$$

where $\bar{\boldsymbol{r}}_{zmp}$ is the position vector of ZMP with respect to the moving frame $\bar{\mathcal{F}}$. $\boldsymbol{r}_q$ is the position vector of the origin of the moving frame $\bar{\mathcal{F}}$ from the origin of the world coordinate frame $\mathcal{F}$. $\bar{\boldsymbol{\omega}}$ and $\dot{\bar{\boldsymbol{\omega}}}$ denote the angular velocity and acceleration vectors, respectively.

If the link of the biped humanoid robot is connected by rotational joints, the motion of the pitch, roll and yaw trunk is interferential each other and has the same virtual motion. Because Equation (6) is a non-linear differential equation, it is difficult to derive analytically the waist and trunk motion. So, we assume that: (1) the external forces are not considered in the approximate model, (2) the upper body is modeled as a four-mass model as shown in Figure 7, (3) the moving frame does not rotate, and (d) the trunk and waist does not move vertically. Considering four-mass model of the upper body, Equation (6) can be rewritten as:

$$\begin{aligned}&m_s\bar{\boldsymbol{r}}_s \times (\ddot{\bar{\boldsymbol{r}}}_s + \dot{\bar{\boldsymbol{\omega}}} \times \bar{\boldsymbol{r}}_s + 2\bar{\boldsymbol{\omega}} \times \dot{\bar{\boldsymbol{r}}}_s + \bar{\boldsymbol{\omega}}\\ &\times(\bar{\boldsymbol{\omega}} \times \bar{\boldsymbol{r}}_s)) + m_t(\bar{\boldsymbol{r}}_t - \bar{\boldsymbol{r}}_{zmp}) \times (\ddot{\bar{\boldsymbol{r}}}_t\\ &+\ddot{\boldsymbol{r}}_q + \boldsymbol{G} + \dot{\bar{\boldsymbol{\omega}}} \times \bar{\boldsymbol{r}}_t + 2\bar{\boldsymbol{\omega}} \times \dot{\bar{\boldsymbol{r}}}_t + \bar{\boldsymbol{\omega}}\\ &\times(\bar{\boldsymbol{\omega}} \times \bar{\boldsymbol{r}}_t)) + m_w(\bar{\boldsymbol{r}}_w - \bar{\boldsymbol{r}}_{zmp}) \times (\ddot{\bar{\boldsymbol{r}}}_w\\ &+\ddot{\boldsymbol{r}}_q + \boldsymbol{G} + \dot{\bar{\boldsymbol{\omega}}} \times \bar{\boldsymbol{r}}_w + 2\bar{\boldsymbol{\omega}} \times \dot{\bar{\boldsymbol{r}}}_w\\ &+\bar{\boldsymbol{\omega}} \times (\bar{\boldsymbol{\omega}} \times \bar{\boldsymbol{r}}_w)) = -\boldsymbol{M},\end{aligned} \tag{7}$$

where $\boldsymbol{M} = [M_x\ M_y\ M_z]^T$ is the moment generated by the motion of lower-limbs. m_s denotes the mass of both shoulders including the mass of the arms. m_t is the mass of the torso including the head, shoulders and arms, and m_w is the mass of the waist. $\bar{\boldsymbol{r}}_t$ and $\bar{\boldsymbol{r}}_w$ are the position vectors of the neck and the waist with respect to $\bar{\mathcal{F}}$, respectively. $\bar{\boldsymbol{r}}_s$ is the shoulder position vector with respect to the neck frame.

In case that the moments are not generated by the fictitious forces, the moment $\boldsymbol{M}$ can be divided as three moment components such as pitch, roll and yaw moments as follows:

$$\begin{aligned}&m_s(\bar{z}_s\ddot{\bar{x}}_s - \bar{x}_s\ddot{\bar{z}}_s) + m_t(\bar{z}_t - \bar{z}_{zmp})(\ddot{\bar{x}}_t + \ddot{x}_q + g_x)\\ &-m_t(\bar{x}_t - \bar{x}_{zmp})(\ddot{\bar{z}}_t + \ddot{z}_q + g_z) + m_w(\bar{z}_w\\ &-\bar{z}_{zmp})(\ddot{\bar{x}}_w + \ddot{x}_q + g_x) - m_w(\bar{x}_w\\ &-\bar{x}_{zmp})(\ddot{\bar{z}}_w + \ddot{z}_q + g_z) = -M_y(t),\end{aligned} \tag{8}$$

$$\begin{aligned}&m_s(\bar{y}_s\ddot{\bar{z}}_s - \bar{z}_s\ddot{\bar{y}}_s) + m_t(\bar{y}_t - \bar{y}_{zmp})(\ddot{\bar{z}}_t + \ddot{z}_q + g_z)\\ &-m_t(\bar{z}_t - \bar{z}_{zmp})(\ddot{\bar{y}}_t + \ddot{y}_q + g_y) + m_w(\bar{y}_w\\ &-\bar{y}_{zmp})(\ddot{\bar{z}}_w + \ddot{z}_q + g_z) - m_w(\bar{z}_w\\ &-\bar{z}_{zmp})(\ddot{\bar{y}}_w + \ddot{y}_q + g_y) = -M_x(t),\end{aligned} \tag{9}$$

$$\begin{aligned}&m_s(\bar{x}_s\ddot{\bar{y}}_s - \bar{y}_s\ddot{\bar{x}}_s + 2(\bar{x}_s\dot{\bar{x}}_s + \bar{y}_s\dot{\bar{y}}_s)\bar{\omega}_z + (\dot{\bar{x}}_s^2 + \dot{\bar{y}}_s^2)\dot{\bar{\omega}}_z)\\ &+m_t(\bar{x}_t - \bar{x}_{zmp})(\ddot{\bar{y}}_t + \ddot{y}_q + g_y) - m_t(\bar{y}_t - \bar{y}_{zmp})(\ddot{\bar{x}}_t\\ &+\ddot{x}_q + g_x) + m_w(\bar{x}_w - \bar{x}_{zmp})(\ddot{\bar{y}}_w + \ddot{y}_q + g_y)\\ &-m_w(\bar{y}_w - \bar{y}_{zmp})(\ddot{\bar{x}}_w + \ddot{x}_q + g_x) = -M_z(t).\end{aligned} \tag{10}$$

Equation (8), (9) and (10) have the same vertical variables, $\bar{z}_w$ and $\bar{z}_t$. Also, the lower-limbs and the upper body of the humanoid robot are connected with rotational joints. So, these equations are interferential and non-linear. We assume that neither the waist nor the trunk particles move vertically, and the trunk arm rotates on the horizontal plane only as follows:

$$\ddot{\bar{z}}_t = 0,\ \ddot{\bar{z}}_w = 0,\ \ddot{z}_q = 0,\ \bar{z}_t - \bar{z}_{zmp} = const.,\quad \bar{z}_w - \bar{z}_{zmp} = const. \tag{11}$$

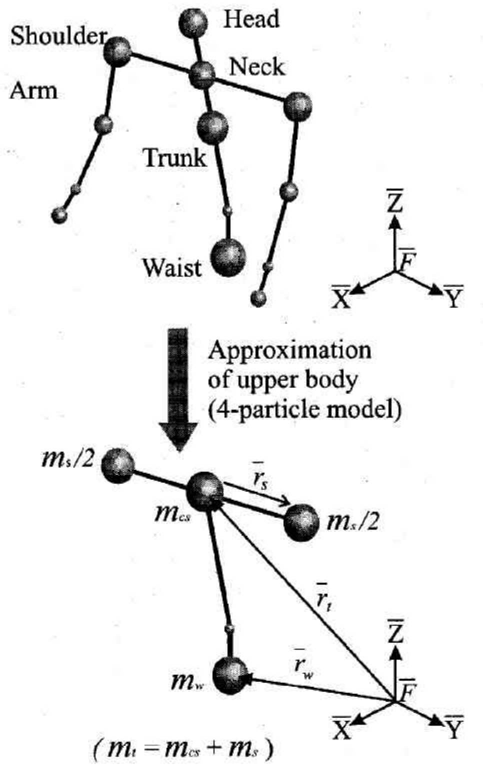

Figure 7: Approximate model of the upper body.

We put the terms relating to the motion of the upper-body on the left-hand side as unknown variables, and the terms relating to the moments generated by the lower-limbs particles on the right-hand side as known parameters. Equation (8), (9) and (10) can be decoupled and linearized as follows:

$$\begin{aligned} m_t(\bar{z}_t - \bar{z}_{zmp})(\ddot{\bar{x}}_t + \ddot{x}_q) - m_t g_z(\bar{x}_t - \bar{x}_{zmp}) \\ +m_w(\bar{z}_w - \bar{z}_{zmp})(\ddot{\bar{x}}_w + \ddot{x}_q) - m_w g_z(\bar{x}_w - \bar{x}_{zmp}) \\ = -M_y(t), \end{aligned} \quad (12)$$

$$\begin{aligned} +m_t g_z(\bar{y}_t - \bar{y}_{zmp}) - m_t(\bar{z}_t - \bar{z}_{zmp})(\ddot{\bar{y}}_t + \ddot{y}_q) \\ +m_w g_z(\bar{y}_w - \bar{y}_{zmp}) - m_w(\bar{z}_w - \bar{z}_{zmp})(\ddot{\bar{y}}_w + \ddot{y}_q) \\ = -M_x(t), \end{aligned} \quad (13)$$

$$\begin{aligned} m_t l^2(\ddot{\theta}_t + \dot{\omega}_z) + m_t(\bar{x}_t - \bar{x}_{zmp})(\ddot{\bar{y}}_t + \ddot{y}_q) \\ -m_t(\bar{y}_t - \bar{y}_{zmp})(\ddot{\bar{x}}_t + \ddot{x}_q) + m_w(\bar{x}_w - \bar{x}_{zmp})(\ddot{\bar{y}}_w \\ +\ddot{y}_q) - m_w(\bar{y}_w - \bar{y}_{zmp})(\ddot{\bar{x}}_w + \ddot{x}_q) \\ = -M_z(t), \end{aligned} \quad (14)$$

where θ_t is the vertical angle of the trunk. l is the length between the neck and the shoulder. If all known variables of Equation (12), (13) and (14) move to the right-hand side respectively, these equations can be written as follows:

$$\begin{aligned} m_t(\bar{z}_t - \bar{z}_{zmp})\ddot{\bar{x}}_t - m_t g_z \bar{x}_t + m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{\bar{x}}_w \\ -m_w g_z \bar{x}_w = \hat{M}_y(t), \end{aligned} \quad (15)$$

$$\begin{aligned} -m_t(\bar{z}_t - \bar{z}_{zmp})\ddot{\bar{y}}_t + m_t g_z \bar{y}_t - m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{\bar{y}}_w \\ +m_w g_z \bar{y}_w = \hat{M}_x(t), \end{aligned} \quad (16)$$

$$m_t l^2 \ddot{\theta}_t = \hat{M}_z(t), \quad (17)$$

where moment $\hat{\boldsymbol{M}} = \left[\hat{M}_x \; \hat{M}_y \; \hat{M}_z\right]^T$ consist of only known variables as follows:

$$\begin{aligned} \hat{M}_y(t) = -M_y - (m_t(\bar{z}_t - \bar{z}_{zmp})\ddot{x}_q + m_t g_z \bar{x}_{zmp} \\ +m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{x}_q + m_w g_z \bar{x}_{zmp}), \end{aligned} \quad (18)$$

$$\begin{aligned} \hat{M}_x(t) = -M_x - (-m_t(\bar{z}_t - \bar{z}_{zmp})\ddot{y}_q - m_t g_z \bar{y}_{zmp} \\ -m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{y}_q - m_w g_z \bar{y}_{zmp}), \end{aligned} \quad (19)$$

$$\begin{aligned} \hat{M}_z(t) = -M_z - (m_t(\bar{x}_t - \bar{x}_{zmp})(\ddot{\bar{y}}_t + \ddot{y}_q) \\ -m_t(\bar{y}_t - \bar{y}_{zmp})(\ddot{\bar{x}}_t + \ddot{x}_q) \\ +m_w(\bar{x}_w - \bar{z}_{zmp})(\ddot{\bar{y}}_w + \ddot{y}_q) \\ -m_w(\bar{y}_w - \bar{y}_{zmp})(\ddot{\bar{x}}_w + \ddot{x}_q)). \end{aligned} \quad (20)$$

To calculate four compensatory motions, $\bar{x}_t$, $\bar{y}_t$, $\bar{x}_w$ and $\bar{y}_w$, the moment components of Equation (15), (16) and (17) can be distributed to the waist and the trunk as:

$$m_t(\bar{z}_t - \bar{z}_{zmp})\ddot{\bar{x}}_t - m_t g_z \bar{x}_t = \hat{M}_{yTRUNK}, \quad (21)$$

$$m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{\bar{x}}_w - m_w g_z \bar{x}_w = \hat{M}_{yWAIST}, \quad (22)$$

$$-m_t(\bar{z}_t - \bar{z}_{zmp})\ddot{\bar{y}}_t + m_t g_z \bar{y}_t = \hat{M}_{xTRUNK}, \quad (23)$$

$$-m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{\bar{y}}_w + m_w g_z \bar{y}_w = \hat{M}_{xWAIST}, \quad (24)$$

$$\hat{M}_{yTRUNK} + \hat{M}_{yWAIST} = \hat{M}_y(t), \quad (25)$$

$$\hat{M}_{xTRUNK} + \hat{M}_{xWAIST} = \hat{M}_x(t). \quad (26)$$

$\hat{M}_{xTRUNK}$, $\hat{M}_{yTRUNK}$, $\hat{M}_{xWAIST}$ and $\hat{M}_{yWAIST}$ become the known functions because they are calculated by the motion of the lower-limbs and the time trajectory of ZMP. In steady walking, they are periodic functions because each particle of the biped humanoid robot and ZMP move periodically with respect to the moving frame $\bar{\mathcal{F}}$. Also, the components on the left-hand side of Equation (25) and (26) are periodic functions. So, the motion of the trunk and the waist can be easily computed by using Fourier transforms. Comparing the Fourier coefficients of both sides of each equation, Fourier coefficients are obtained. Moreover, the approximate periodic solutions of the pitch and roll trunk and the waist, $\bar{x}_t$, $\bar{y}_t$, $\bar{x}_w$ and $\bar{y}_w$, are obtained by inverse Fourier transforms. The vertical motion of the trunk, θ_t, is also obtained, comparing the Fourier coefficients of both sides of Equation (17).

In order to obtain the strict solutions of the trunk and the waist motion, a recursive method is used. First, the approximate periodic solutions of the linearized equation (17), (25) and (26) are calculated. Second, the approximate periodic solutions are substituted into the moment equation (6) of the strict biped model, and the errors of moments, generated by the trunk and the waist motion are calculated according to the planned ZMP. These errors are accumulated to the right-hand side of Equation (17), (25) and (26). The approximate solutions are computed again. Finally, these computations are repeated until the errors fall below a certain tolerance level.

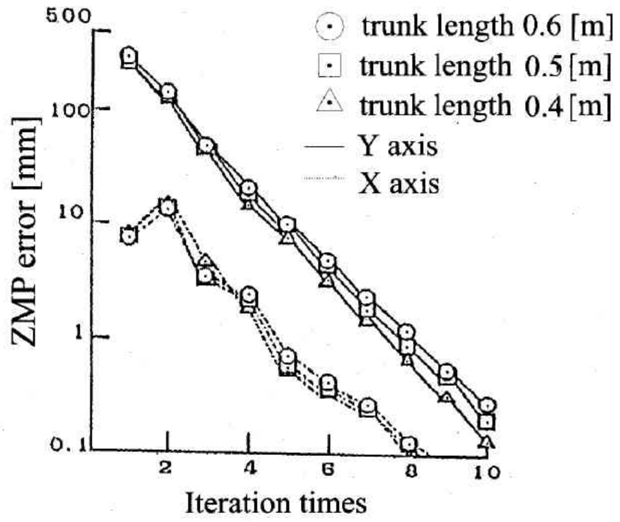

Figure 8: ZMP errors to three different parameters.

4. Simulation of the Trunk Motion

The convergence of solutions of the trunk and the waist motion is numerically verified. Walking simulation is conducted using the recursive method. Then, the length of the trunk and the walking speed are considered as parameters. The errors of ZMP are dropped below 1.0 mm after 10 iteration times as shown in Figure 8 and Figure 9. So, the method is useful for the calculation of compensatory motion.

Consider the motion of the trunk capable of canceling moments generated by the motion of the head, the shoulders, the legs and the arms, when the waist is immovable. The moment components of the pitch and roll trunk of Equation (25) and (26) can be written as follows:

$$(\bar{z}_t - \bar{z}_{zmp})\ddot{\bar{x}}_t - g_z\bar{x}_t = -A(t), \tag{27}$$

$$(\bar{z}_t - \bar{z}_{zmp})\ddot{\bar{y}}_t + g_z\bar{y}_t = B(t), \tag{28}$$

where

$$A(t) = \frac{M_y(t) + m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{\bar{x}}_w - m_w g_z \bar{x}_w}{m_t}, \tag{29}$$

$$B(t) = \frac{M_x(t) - m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{\bar{y}}_w - m_w g_z \bar{y}_w}{m_t} \tag{30}$$

Consider only the motion of the pitch trunk to investigate how the trunk moves during dynamic walking. The transfer function, $\bar{y}_t(\omega)$, of Equation (28) in

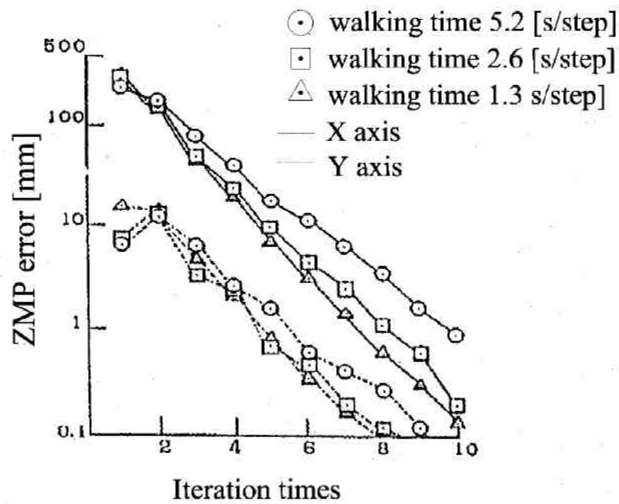

Figure 9: ZMP errors to three different parameters.

the frequency domain can be expressed as:

$$\bar{y}_t(\omega) = \frac{2p}{\omega^2 + p^2} q = (\frac{1}{p - j\omega} + \frac{1}{p + j\omega}) q, \qquad (31)$$

where

$$p = \sqrt{\frac{g_z}{\bar{z}_t - \bar{z}_{zmp}}}, \quad q = -\frac{1}{2g_z}\sqrt{\frac{g_z}{\bar{z}_t - \bar{z}_{zmp}}}. \qquad (32)$$

According to the ZMP concept, $\bar{z}_{zmp}$ in Equation (32) is zero. Equation (31) is generally known as Lorentz function, and its primitive function is written as:

$$\bar{y}_t(t) = q e^{-p|t|}. \qquad (33)$$

We can imagine from (33) that the casual law may not be applied anymore. If the walking speed of the biped robot is increased, it goes without saying that $\bar{y}_t(t)$ affects stability more badly. The trunk, therefore, should be in motion earlier than the shift of ZMP to cancel the produced moments.

5. Conclusion

For a biped humanoid robot to stably walk on the ground, its locomotion and stability should be considered at the same time. How to make a walking pattern for locomotion was proposed in this paper. Also, a compensation method was discussed, which can cancel moments generated by the motion of the head, the shoulders, the arms and the legs. Using Fourier transforms and a recursive method, the motion of the trunk and the waist is computed. This method is applicable to not only the steady walk but also the complete walk including transient walk. Through trunk motion simulations based on the walking pattern generated, the effectiveness of the proposed moment compensation method was verified.

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