BALANCE CONTROL OF HUMANOID ROBOT FOR HUROSOT

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Abstract: This paper presents balance control of humanoid robot for HuroSot using its upper body motion and swinging two arms. The upper body is modeled as an inverted pendulum for an on-line compensation. By using the upper body motion it compensates ZMP (Zero Moment Point) error, obtained by FSR (Force Sensitive Resistor) sensors attached on the sole of the foot. Also by swinging the arms it can cancel the yawing moment such that it can walk properly by keeping its overall balance. Experimental results of balance control of HSR-V, a small sized humanoid robot for HuroSot designed and developed in the RIT laboratory at KAIST, are described to demonstrate the effectiveness and applicability of the proposed method.

Keywords: Balance Control, Humanoid Robot, HuroSot

1. INTRODUCTION

A humanoid robot is a biped intelligent robot and is expected to eventually evolve into one with a human-like body. Recently, many researches have been focused on a development of humanoid robot which is similar to human beings(Hirai *et al.*, 1998)(Yamaguchi *et al.*, 1993)(Sakagami *et al.*, 2002)(Nishiwaki *et al.*, 2000)(Kim *et al.*, 2004). Since a biped robot inherently suffers from instability and always risks falling down, ensuring stability is the most important goal from the perspective of locomotion.

Most papers dealing with humanoid robots are concerned with this control problem. For a gait generation and its optimization for biped robot, there are two approaches. The first approach is to generate a gait in off-line (Huang *et al.*, 2001)(Mombaur *et al.*, 2001). However, these methods cannot cope with a humanoid robot in a dynamically changing environment. The second approach is to generate a proper gait periodically and determine the desired angles of every joint in on-line (Kajita *et al.*, 2003)(Azevedo *et al.*, 2002)(Reil and Husbands, 2002). Though it is considered that it can react against a dynamic environment, there are still many problems in real implementation. It needs a lot of computation to solve robot's dynamics and inverse dynamics, and it suffers from dynamic error which is caused by simplified dynamic models and inaccurate kinematic parameters.

This paper focuses on control problem, in particular, of balancing control of humanoid robot. A gait is generated in off-line and it is compensated in on-line control. The off-line gait generation is consisted of 2 phases. Firstly, a gait is generated using a spline method which is used generally. Because the gait satisfies the ZMP criterion(Vukobratovic and Juricic, 1969), roll and pitch moments of a robot are, of course, zeros. However, a robot can slip along with a vertical axis because a yawing moment is not considered. Therefore the method for canceling yawing moment is proposed in this paper. Moreover, the on-line balance control should be needed for a stable walking, because there are dynamic parameters which are not considered in the gait generation. It is accomplished by swing its upper body to keep the stability. To derive an on-line compensation algorithm based on ZMP (Zero Moment Point), its upper body is modeled as an inverted pendulum. The ZMP is obtained from the FSR (Force Sensitive Resistor) sensors attached on the sole. Experimental results using HSR-V, a humanoid robot developed in the Robot Intelligence Technology (RIT) Laboratory at KAIST, demonstrate the effectiveness and applicability of the proposed method.

The remainder of this paper is organized as follows: Section 2 presents the gait generation to cancel the yawing moment. Section 3 presents balance control, where overall algorithm is presented and compensation algorithm is derived. Section 4 shows experimental results. Finally, concluding remarks follow in Section 5.

2. GAIT GENERATION

2.1 First phase: Gait generation

In the first phase, off-line gait is generated to satisfy the ZMP condition using a cubic spline while a upper body is not moving. First of all, representative points are selected from the walking condition such as a walking period, a step size, a maximum foot height, etc. Then a whole trajectory is made using a cubic spline interpolation. A cubic spline interpolation method approximates the trajectory between two adjacent via points to the third polynomial. The method can make a smooth trajectory because both a velocity and an acceleration are continuous at via points. Moreover, another via points can be inserted easily.

2.2 Second phase: Yawing moment cancellation

A general ZMP equation is as follows:

$$\sum_i^n m_i(r_i - r_p) \times \ddot{r}_i = \sum m_i(r_i - r_p) \times G + T \tag{1}$$

where m_i is a mass of ith link, r_i is a vector between the origin and a COM of ith link and r_p is a vector from the origin to the ZMP. G is a gravity vector and T is a torque vector applied to the ZMP. From (1), ZMP equation which is widely known is obtained as follows:

$$\begin{aligned} X_{ZMP} &= \frac{\sum_i^n m_i(\ddot{z}_i + g)x_i - \sum_i^n m_i z_i \ddot{x}_i}{\sum_i^n m_i(\ddot{z}_i + g)} \\ Y_{ZMP} &= \frac{\sum_i^n m_i(\ddot{z}_i + g)y_i - \sum_i^n m_i z_i \ddot{y}_i}{\sum_i^n m_i(\ddot{z}_i + g)} \end{aligned} \tag{2}$$

Moreover, a yawing moment equation is also obtained as follows:

$$T_Z = \sum_i^n m_i(x_i - x_{ZMP})\ddot{y}_i - (y_i - y_{ZMP})\ddot{x}_i \tag{3}$$

To cancel yawing moment, three assumptions are considered as shown in Fig. 1.

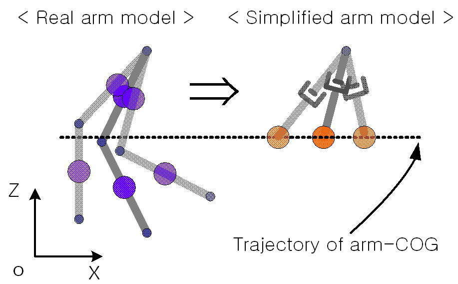


Fig. 1. Simplified arm model

(1) The robot's arms move only in the pitching direction.
(2) The robot's arms are modelled as a pendulum which has the same COM.
(3) The z-coordinates of the COM is constant.

Since the arm motion is symmetric, (3) can be expressed as follows:

$$\begin{aligned} T_Z = & \sum_{i \neq a_l, a_l}^n \{m_i(x_i - x_{ZMP})\ddot{y}_i - (y_i - y_{ZMP})\ddot{x}_i\} \\ & + \frac{1}{2}m_a\{(\overline{x}_a - \Delta x - x_{ZMP})(\ddot{\overline{y}}_a + \ddot{\Delta y}) \\ & - (\overline{y}_a + \Delta y - y_{ZMP})(\ddot{\overline{x}}_a - \ddot{\Delta x})\} \\ & + \frac{1}{2}m_a\{(\overline{x}_a + \Delta x - x_{ZMP})(\ddot{\overline{y}}_a - \ddot{\Delta y}) \\ & - (\overline{y}_a - \Delta y - y_{ZMP})(\ddot{\overline{x}}_a + \ddot{\Delta x})\} \\ = & \sum_{i \neq a_l, a_l}^n \{m_i(x_i - x_{ZMP})\ddot{y}_i \\ & - (y_i - y_{ZMP})\ddot{x}_i\} \mid_{\Delta x = \Delta y = 0} + m_a \ddot{\Delta x} \Delta y \\ = & T_{Z0} + m_a \ddot{\Delta x} \Delta y \end{aligned} \tag{4}$$

where, m_a is a mass of both the arms, T_{Z0} is yawing moment generated in the first phase and it means that the robot's arms are not swinging. Δy is a half length of the shoulder.

From (4), it should be noted that yawing moment acting to the ground is divided into one which is generated when arms are not swinging (T_{z0}) and additional moment which is caused by swinging arms ($m_a \ddot{\Delta x} \Delta y$). Therefore, the arm's trajectory to make the yawing moment be zero can be obtained as follows:

$$\begin{aligned} T_Z =& T_{Z0} + m_a \ddot{\Delta x} \Delta y \\ =& 0 \\ \therefore \ddot{\Delta x} =& -\frac{T_{Z0}}{m_a \Delta y} \end{aligned} \tag{5}$$

3. BALANCE CONTROL

Considering the external disturbances, on-line compensation is necessary to keep the ZMP stability condition. To compensate the possible ZMP error in real-time, compensation algorithm should be simple enough to be executed within a sampling time. In this paper, for balance control, its upper body is modeled as an inverted pendulum to derive such a simple algorithm.

3.1 Inverted Pendulum Model

Fig. 2(a) shows the full link model of the upper body, where l_s, l_{au}, l_{al} and l_t are the shoulder length, the upper arm length, the lower arm length and the torso length, respectively and m_s, m_{au}, m_{al} and m_t are the shoulder mass, the upper arm mass, the lower arm mass and the torso mass, respectively. The full link model is simplified as an inverted pendulum of length l_u and of mass m_u (Fig. 2(b)) which has the same COM (Center Of Mass) as that of the full link model.

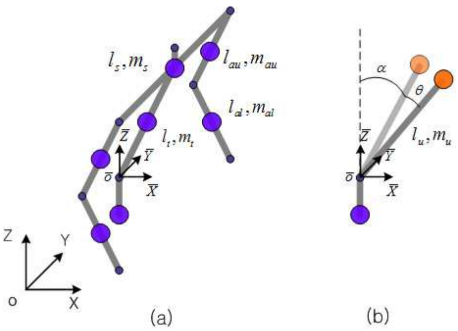


Fig. 2. Model of the upper body ($\bar{o}$: local coordinate origin attached on the waist joint). (a) Full link model. (b) Inverted pendulum model.

In Fig. 2, α is an initial tilt angle of robot's COM and θ is an incremental angle in sampling time T for balance compensation. l_u and m_u are the length and the mass of robot's COM, respectively. Since motion of the robot's COM is dominant, dynamic characteristic based on the inverted pendulum model is similar to that based on the full link model.

3.2 Compensation method

ZMP error between the pre-designed ZMP and the actual ZMP occurs while in operation. The ZMP error in the x-direction for pitching motion, e_x is defined as

$$e_x = x_{ZMPd} - x_{ZMPa} \tag{6}$$

where x_{ZMPa} is an actual (measured) ZMP value in the x-axis and x_{ZMPd} is a desired ZMP value in the x-axis.

To compensate the ZMP error, e_x, we need to calculate the compensation angle θ such that the next actual ZMP value should be satisfied.

$$x_{ZMPn} = x_{ZMPa} + e_x \tag{7}$$

Note that the ZMP error in the y-direction for rolling motion can be similarly defined.

Using the coordinate attached on the waist joint, the nominal ZMP equation for the x-direction is as follows:

$$\begin{aligned} \overline{x}_{ZMPa} =& \frac{\sum_i^n \{m_i(\ddot{\overline{z}}_i + g)\overline{x}_i\} - \sum_i^n m_i(\overline{z}_i + \overline{z}_o)\ddot{\overline{x}}_i}{\sum_i^n m_i(\ddot{\overline{z}}_i + g)} \\ =& \frac{M_A}{M_B} \end{aligned} \tag{8}$$

where $\overline{z}_o$ is a height of the waist, and M_A and M_B are a numerator term and a denominator term of the ZMP equation, respectively.

When the upper body is moving for compensation, ZMP equation varies as per its motion. If we separate the upper body terms from the ZMP equation (8), the ZMP equation becomes

$$\begin{aligned} \overline{x}_{ZMPn} =& \frac{\sum_{i\neq u}^n \{m_i(\ddot{\overline{z}}_i + g)\overline{x}_i\} - \sum_{i\neq u}^n m_i(\overline{z}_i + \overline{z}_o)\ddot{\overline{x}}_i}{\sum_{i\neq u}^n m_i(\ddot{\overline{z}}_i + g) + m_u(\ddot{\overline{z}}_u + g)} \\ &+ \frac{m_u(\ddot{\overline{z}}_u + g)\overline{x}_u - m_u(\overline{z}_u + \overline{z}_o)\ddot{\overline{x}}_u}{\sum_{i\neq u}^n m_i(\ddot{\overline{z}}_i + g) + m_u(\ddot{\overline{z}}_u + g)} \end{aligned} \tag{9}$$

where $\overline{x}_{ZMPn}$ is the ZMP value in the x axis when the upper body is in motion by control input, and the subscript u means the upper body. $\overline{z}_u$ has the following relation:

$$\overline{z}_u = \overline{z}_{u.d} + \Delta\overline{z} \tag{10}$$

where $\overline{z}_{u,d}$ is a pre-designed height of the COM of the upper body, $\Delta\overline{z}$ is a difference value between the pre-designed and the actual value during compensation. Similarly, $\overline{x}_{u,d}$ is described as follows:

$$\overline{x}_u = \overline{x}_{u.d} + \Delta\overline{x} \tag{11}$$

where $\overline{x}_{u,d}$ is a pre-designed ZMP value for the x-direction, $\Delta\overline{x}$ is a difference value between the pre-designed and the actual ZMP value during compensation.

From (10) and (11), (9) becomes

$$\begin{aligned}\overline{x}_{ZMPn} =& \frac{\sum_i^n\{m_i(\ddot{\overline{z}}_i+g)\overline{x}_i\} - \sum_i^n m_i\overline{z}_i\ddot{\overline{x}}_i}{\sum_i^n m_i(\ddot{\overline{z}}_i+g)+m_u\Delta\ddot{\overline{z}}} \\ &+ \frac{m_u\{(\ddot{\overline{z}}_{u.d}+g)\Delta\overline{x}+\Delta\ddot{\overline{z}}(\overline{x}_{u.d}+\Delta\overline{x})\}}{\sum_i^n m_i(\ddot{\overline{z}}_i+g)+m_u\Delta\ddot{\overline{z}}} \\ &- \frac{m_u\{(\overline{z}_{u.d}+\overline{z}_o)\Delta\ddot{\overline{x}}+\Delta\overline{z}(\ddot{\overline{x}}_d+\Delta\ddot{\overline{x}})\}}{\sum_i^n m_i(\ddot{\overline{z}}_i+g)+m_u\Delta\ddot{\overline{z}}}.\end{aligned} \tag{12}$$

For a simple notation, let $\overline{x}_{ZMPn}$ be as

$$\overline{x}_{ZMPn} = \frac{M_B+M_b}{M_A+M_a} \tag{13}$$

where

$$\begin{aligned}M_a =& m_u\Delta\ddot{\overline{z}} \\ M_b =& m_u\{(\ddot{\overline{z}}_{u.d}+g)\Delta\overline{x}+\Delta\ddot{\overline{z}}(\overline{x}_{u.d}+\Delta\overline{x})\} \\ &- m_u\{(\overline{z}_{u.d}+\overline{z}_o)\Delta\ddot{\overline{x}}+\Delta\overline{z}(\ddot{\overline{x}}_{u.d}+\Delta\ddot{\overline{x}})\}.\end{aligned} \tag{14}$$

The additional terms M_a and M_b are added moments by swinging the upper body. These terms are used to compensate the ZMP error. Since the upper body is pre-designed as follows:

$$\ddot{\overline{z}}_{u.d} = 0 \text{ and } \ddot{\overline{x}}_{u.d} = 0,$$

(14) becomes

$$\begin{aligned}M_a =& m_u\Delta\ddot{\overline{z}} \\ M_b =& m_u\{g\Delta\overline{x}+\Delta\ddot{\overline{z}}(\overline{x}_{u.d}+\Delta\overline{x}) \\ &- \Delta\ddot{\overline{x}}(\overline{z}_{u.d}+\overline{z}_o+\Delta\overline{z})\} \\ =& m_u\{g\Delta\overline{x}+\Delta\ddot{\overline{z}}\overline{x}_u-\Delta\ddot{\overline{x}}(\overline{z}_u+\overline{z}_o)\}.\end{aligned} \tag{15}$$

Since the upper body is modeled as an inverted pendulum, we get

$$\overline{z}_u = l_u\cos(\alpha+\theta) \text{ and } \overline{x}_u = l_u\sin(\alpha+\theta).$$

By Taylor series, above equation becomes

$$\overline{z}_u \simeq l_u\{\cos(\alpha)-\sin(\alpha)\theta-\frac{\cos(\alpha)}{2}\theta^2\} \tag{16}$$

and

$$\begin{aligned}\Delta\overline{z} =& \overline{z}_u-\overline{z}_{u.d} \\ =& \overline{z}_u - l_u \\ \simeq& l_u\{\cos(\alpha)-\sin(\alpha)\theta-\frac{\cos(\alpha)}{2}\theta^2-1\}.\end{aligned} \tag{17}$$

Similarly, we get

$$\Delta\overline{x} \simeq l_u\{\sin(\alpha)+\cos(\alpha)\theta-\frac{\sin(\alpha)}{2}\theta^2\}. \tag{18}$$

By applying (17) and (18) to (15), we obtain

$$\begin{aligned}M_a =& -m_u l_u\{\sin(\alpha)\ddot{\theta}+\cos(\alpha)\dot{\theta}^2+\cos(\alpha)\theta\ddot{\theta}\} \\ M_b =& m_u g l_u\{\sin(\alpha)+\cos(\alpha)\theta-\frac{\sin(\alpha)}{2}\theta^2\} \\ &- m_u l_u[l_u\{\ddot{\theta}+\frac{1}{2}\ddot{\theta}\theta^2+\dot{\theta}^2\theta\} \\ &+ \{\cos(\alpha)\ddot{\theta}-\sin(\alpha)\dot{\theta}^2-\sin(\alpha)\theta\ddot{\theta}\}\overline{z}_o].\end{aligned} \tag{19}$$

We can control M_a and M_b by θ. It meas that the ZMP can be controlled by a single parameter θ.

M_b can be divided into two terms as follows:

$$M_b = M_{b0} + M_{b1} \tag{20}$$

with

$$\begin{aligned}M_{b0} =& m_u g l_u\{\sin(\alpha)+\cos(\alpha)\theta-\frac{\sin(\alpha)}{2}\theta^2\} \\ M_{b1} =& -m_u l_u[l_u\{\ddot{\theta}+\frac{1}{2}\ddot{\theta}\theta^2+\dot{\theta}^2\theta\} \\ &+ \{\cos(\alpha)\ddot{\theta}-\sin(\alpha)\dot{\theta}^2-\sin(\alpha)\theta\ddot{\theta}\}\overline{z}_o]\end{aligned} \tag{21}$$

where M_{b0} is the moment due to gravity force and M_{b1} is the moment due to dynamic motion of the upper body. It means that M_{b0} is a function of position of the upper body and is only influenced by an posture of the robot. Therefore, it can be used for posture control. On the other hand, M_{b1} is a function of velocity and acceleration of the upper body and is occurred by swinging the upper body rapidly. Thus it can compensate the ZMP error instantaneously. But, when the robot stops swinging the upper body, the moment with an opposite sign is also generated. It may lead to a possibility of divergence. To avoid the possibility, weighting factors are introduced as follows:

$$\begin{aligned}M_{b.w} =& w_g M_{b0} + w_a M_{b1} \\ M_{a.w} =& w_a M_a\end{aligned} \tag{22}$$

where $0 < w_g,\ w_a < 1$. Note that w_g and w_a can be fine tuned by experiments.

Now we derive the following ZMP compensation equation from (7):

$$\frac{M_B+M_{b.w}}{M_A+M_{a.w}} = \frac{M_B}{M_A} + e_x. \tag{23}$$

By applying (19) and (22) to the above equation, we get

$$\begin{aligned}&- a w_a m_u l_u[\sin(\alpha)\ddot{\theta}+\cos(\alpha)\dot{\theta}^2+\cos(\alpha)\theta\ddot{\theta}] \\ &+ b[w_g m_u g l_u\{\sin(\alpha)+\cos(\alpha)\theta-\frac{\sin(\alpha)}{2}\theta^2\} \\ &- w_a m_u l_u[l_u\{\ddot{\theta}+\frac{1}{2}\ddot{\theta}\theta^2+\dot{\theta}^2\theta\} \\ &+ \{\cos(\alpha)\ddot{\theta}-\sin(\alpha)\dot{\theta}^2-\sin(\alpha)\theta\ddot{\theta}\}\overline{z}_o]] \\ &= c\end{aligned} \tag{24}$$

where $a = -eM_A - M_B$, $b = M_A$ and $c = e{M_A}^2$.

After changing the compensation equation to a discrete form and applying Cardano's method, the solutions can be obtained. Among the solutions, a real and minimum valued one is selected as a compensation angle value.

Similarly, we can derive a ZMP compensation algorithm to keep the balance in the y-direction by rolling the upper body.

4. EXPERIMENTS

4.1 HSR-V

In the experiments, HSR-V was used (Fig.3). HSR-V is a small sized humanoid robot designed and developed in the Robot Intelligence Technology (RIT) Laboratory at KAIST.

Height	45cm
Weight	4.5Kg (including batteries)
D.O.F.	12 (Lower body)
	16 (Upper body)
Material	Duralumin
Actuators	12 small DC motors
	16 RC Servo motors
Controllers	486 PC104 (RT-Linux)
	Atmega 128 & 32
Sensors	8 FSRs
	CCD Camera
	IR Sensors
Sampling time	1 msec (DC motos)
	20 msec (RC Servo motors)

Fig. 3. HSR-V

4.2 Yawing moment cancellation

Parameters for the proposed gait generation are listed in Table 1.

Table 1. Parameters for gait generation

T (Total step time)	1.6 (sec)
T_s (Supporting time)	0.8 (sec)
T_r (Rising time)	0.15 (sec)
T_w (Swing time)	0.5 (sec)
T_p (Landing time)	0.15 (sec)
Step size	8 (cm)
Hip height	20 (cm)

Fig. 4 shows the result generated in the first phase. In the phase, no compensation for the yawing moment is applied yet. The maximum value of the yawing moment is 1300 ($kgcm^2/sec^2$) at the rising time (0.15sec, 0.95sec). This means that the maximum yawing moment is generated at the time when the robot begins to swing its leg and it causes serious instability. To cancel the yawing moment, the arm-swing motion is added in the second phase and the result is shown in Fig. 5. It should be noted that the maximum value of the yawing moment is reduced under 250 ($kgcm^2/sec^2$).

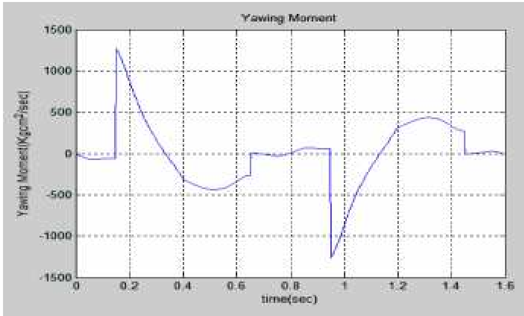


Fig. 4. Yawing moment in the first phase

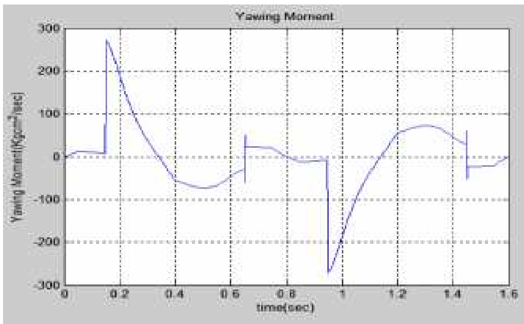


Fig. 5. Yawing moment in the second phase

4.3 Experiments of the On-line ZMP Compensation

The experiments were carried out for standing posture on the flat board. To see whether the on-line ZMP compensation algorithm operates properly, we changed the tilt angle of the board and checked if the robot would keep the balance.

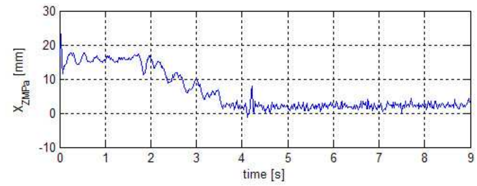
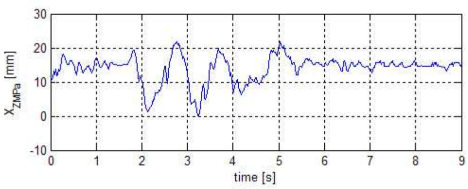


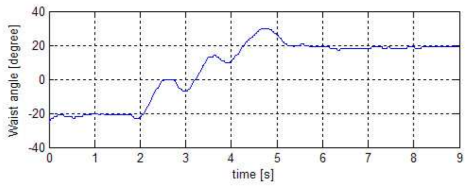
Fig. 6. Experimental results without compensation (the pre-designed ZMP trajectory is located at 15 mm).

Fig. 6 is the ZMP trajectories without compensation. In Fig. 6, we can see that the ZMP trajectory ,initially, was converging with slight oscillation. Since the pre-designed ZMP trajectory was located at 15 mm from the heel it had a constant error. After 2 second, we can see that the ZMP trajectory were moving toward the heel as the board began to tilt.

Fig. 7 is the ZMP trajectories with compensation. It shows that the ZMP trajectory converged with slight oscillation at the moment when the board began to tilt (about 2 sec).



(a) x_{ZMPa} trajectory



(b) Waist angle trajectory

Fig. 7. x-axis ZMP trajectory with compensation (the pre-designed ZMP trajectory is located at 15 mm, 5 degree tilt).

5. CONCLUSIONS

This paper presented the balance control of humanoid robot using its upper body motion. Online ZMP compensation was accomplished by moving the upper body back and forth. To investigate the performance of the proposed method, experiments were performed with a small sized humanoid robot. Experimental results for standing posture on the board demonstrated the effectiveness and applicability of the proposed compensation scheme for balance control of the humanoid robot.

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