ABSTRACT

This paper presents balance control of humanoid robot using its upper body motion. The upper body is modeled as an inverted pendulum to derive an on-line compensation algorithm. By swing the upper body it compensates ZMP (Zero Moment Point) error, obtained by FSR (Force Sensitive Resistor) sensors attached on the sole. To demonstrate the effectiveness of the proposed method, experimental results of balance control of HSR-V, a small sized humanoid robot designed and developed in the RIT laboratory at KAIST, are also described.

1. INTRODUCTION

As the development of humanoid robot is very challenging and exciting field in robotics, there are many ongoing researches. Although related technologies have been reported, however, humanoid robot is still premature to use in actual life. There are practical problems awaiting solutions. Two of them are mechanical design and control problems. Its mechanical system is likely to be damaged by the external impact when falling down. To make stronger and lighter frame, FEA (Finite Elements Analysis) was used to optimize the structure[15]. Also, magnesium cast links and new type harmonic derives (CSD type) for reduction gears were used[16]. As a control problem, inherent unstability problem of the humanoid robot should be solved, which is a main problem to make it difficult in practical application. Most papers dealing with humanoid robots are concerned with this control problem.

This paper focuses on control problem, in particular, of balancing control of humanoid robot. It is accomplished by swing its upper body to keep the stability. To derive an online compensation algorithm based on ZMP (Zero Moment Point) its upper body is modeled as an inverted pendulum. To measure the stability, ZMP is used[7]. 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.

This paper is organized as follows. Section 2 presents balance control, where overall algorithm is presented and compensation algorithm is derived. Section 3 shows experimental results. Finally, concluding remarks follow in Section 4.

2. 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.

2.1. Inverted Pendulum Model

Fig. 1(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. 1(b)) which has the same COM (Center Of Mass) as that of the full link model.

In Fig. 1 $\alpha$ is an initial tilt angle of robot’s COM and $\theta$ 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.

2.2. 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

$$e_x = x_{ZMPd} - x_{ZMPa}$$

(1)
where $xZMP_n$ is an actual (measured) ZMP value in the x-axis and $xZMP_d$ is a desired ZMP value in the x-axis.

To compensate the ZMP error, $e_x$, we need to calculate the compensation angle $\theta$ such that the next actual ZMP value should be satisfied:

$$xZMP_n = xZMP_a + e_x \quad (2)$$

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 [7]:

$$xZMP_n = \frac{\sum_i m_i (\ddot{x}_i + g) \bar{x}_i}{\sum_i m_i (\ddot{x}_i + g)} \quad (3)$$

where $\bar{x}_a$ 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 (3), the ZMP equation becomes

$$xZMP_n = \frac{\sum_{i \neq u} m_i (\ddot{x}_i + g) \bar{x}_i - \sum_{i \neq u} m_i (\ddot{x}_u + \bar{z}_u) \bar{x}_i}{\sum_{i \neq u} m_i (\ddot{x}_i + g) + m_u (\ddot{x}_u + g)} + \frac{m_u (\ddot{z}_u + g) \bar{x}_u - m_u (\ddot{z}_u + \bar{z}_u) \bar{x}_u}{\sum_{i \neq u} m_i (\ddot{x}_i + g) + m_u (\ddot{x}_u + g)}$$

(4)

where $xZMP_n$ 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. $\tau_u$ has the following relation:

$$\tau_u = \tau_{u,d} + \Delta \tau \quad (5)$$

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

$$\tau_u = \tau_{u,d} + \Delta \tau \quad (6)$$

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

From (5) and (6), (4) becomes

$$xZMP_n = \frac{\sum_i m_i (\ddot{z}_i + g) \bar{x}_i - \sum_i m_i (\ddot{z}_i + \bar{z}_i) \bar{x}_i}{\sum_i m_i (\ddot{z}_i + g) + m_u (\ddot{z}_u + g)}$$

$$+ \frac{m_u (\ddot{z}_u + g) \bar{x}_u - m_u (\ddot{z}_u + \bar{z}_u) \bar{x}_u}{\sum_{i \neq u} m_i (\ddot{z}_i + g) + m_u (\ddot{z}_u + g)}$$

$$+ \frac{m_u (\ddot{z}_u + g) \bar{x}_u - m_u (\ddot{z}_u + \bar{z}_u) \bar{x}_u}{\sum_{i \neq u} m_i (\ddot{z}_i + g) + m_u (\ddot{z}_u + g)}$$

$$+ \frac{m_u (\ddot{z}_u + g) \bar{x}_u - m_u (\ddot{z}_u + \bar{z}_u) \bar{x}_u}{\sum_{i \neq u} m_i (\ddot{z}_i + g) + m_u (\ddot{z}_u + g)}$$

(7)

For a simple notation, let $xZMP_n$ be as

$$xZMP_n = \frac{M_B + M_b}{M_A + M_u} \quad (8)$$

where

$$M_a = m_a \Delta \bar{z}$$

$$M_b = m_b \{(\bar{z}_{u,d} + g) \Delta \bar{z} + \Delta \bar{z} (\bar{z}_{u,d} + \Delta \bar{z})\}$$

$$+ m_u \{(\bar{z}_{u,d} + \bar{z}_u) \Delta \bar{z} + \Delta \bar{z} (\bar{z}_{u,d} + \Delta \bar{z})\}$$

(9)

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:

$$\ddot{z}_{u,d} = 0 \text{ and } \ddot{\bar{z}}_{u,d} = 0$$

(9) becomes

$$M_a = m_a \Delta \bar{z}$$

$$M_b = m_u \{g \Delta \bar{z} + \Delta \bar{z} (\bar{z}_{u,d} + \Delta \bar{z})\}$$

$$- (\bar{z}_{u,d} + \bar{z}_u) \Delta \bar{z} + \Delta \bar{z} (\bar{z}_{u,d} + \Delta \bar{z})\}$$

(10)

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

$$\bar{z}_u = l_u \cos(\alpha + \theta) \text{ and } \bar{x}_u = l_u \sin(\alpha + \theta).$$
By Taylor series, above equation becomes

$$\tau_u \approx l_u \{ \cos(\alpha) - \sin(\alpha)\dot{\theta} - \frac{\cos(\alpha)}{2} \dot{\theta}^2 \}$$  \hspace{1cm} (11)

and

$$\Delta \tau = \tau_u - \tau_{ud}
= \tau_u - l_u \{ \cos(\alpha) - \sin(\alpha)\dot{\theta} - \frac{\cos(\alpha)}{2} \dot{\theta}^2 - 1 \}.$$  \hspace{1cm} (12)

Similarly, we get

$$\Delta \tau \approx l_u \{ \sin(\alpha) + \cos(\alpha)\dot{\theta} - \frac{\sin(\alpha)}{2} \dot{\theta}^2 \}. \hspace{1cm} (13)$$

By applying (12) and (13) to (10), we obtain

$$M_a = - m_u l_u \{ \sin(\alpha)\dot{\theta} + \cos(\alpha)\dot{\phi}^2 + \cos(\alpha)\dot{\theta} \dot{\phi} \}
M_b = m ul_u \{ \sin(\alpha) + \cos(\alpha)\dot{\phi} - \frac{\sin(\alpha)}{2} \dot{\phi}^2 \}
- m_u l_u \{ \dot{\theta} + \frac{1}{2} \ddot{\phi} \dot{\theta}^2 + \ddot{\theta} \dot{\phi} \}
+ \{ \cos(\alpha)\ddot{\phi} - \sin(\alpha)\dot{\phi} - \sin(\alpha)\dot{\phi} \} \tau_o \}.$$  \hspace{1cm} (14)

We can control $M_a$ and $M_b$ by $\theta$. It means that the ZMP can be controlled by a single parameter $\theta$.

$M_b$ can be divided into two terms as follows:

$$M_b = M_{b0} + M_{b1} \hspace{1cm} (15)$$

with

$$M_{b0} = m ul_u \{ \sin(\alpha) + \cos(\alpha)\dot{\phi} - \frac{\sin(\alpha)}{2} \dot{\phi}^2 \}
M_{b1} = - m_u l_u \{ \dot{\theta} + \frac{1}{2} \ddot{\phi} \dot{\theta}^2 + \ddot{\theta} \dot{\phi} \}
+ \{ \cos(\alpha)\ddot{\phi} - \sin(\alpha)\dot{\phi} - \sin(\alpha)\dot{\phi} \} \tau_o \}.$$  \hspace{1cm} (16)

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:

$$M_{b,u} = w_g M_{b0} + w_a M_{b1}
M_{a,u} = w_a M_a \hspace{1cm} (17)$$

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 (2):

$$\frac{M_B + M_{b,u}}{M_A + M_{a,u}} = \frac{M_B}{M_A} + c_x.$$  \hspace{1cm} (18)

By applying (14) and (17) to the above equation, we get

$$- aw_a m_ul_u [\sin(\alpha)\dot{\phi} + \cos(\alpha)\dot{\phi}^2 + \cos(\alpha)\dot{\phi}]$$
$$+ b[w_g m_u gl_u \{ \sin(\alpha) + \cos(\alpha)\dot{\phi} - \frac{\sin(\alpha)}{2} \dot{\phi}^2 \}
- aw_a m_u l_u \{ \dot{\theta} + \frac{1}{2} \ddot{\phi} \dot{\theta}^2 + \ddot{\theta} \dot{\phi} \}
+ \{ \cos(\alpha)\ddot{\phi} - \sin(\alpha)\dot{\phi} - \sin(\alpha)\dot{\phi} \} \tau_o \}
= c$$

where $a = - e M_A - M_B$, $b = M_A$ and $c = e M_a^2$.

Above equation can be approximated by Euler’s method such that the compensation equation (19) is derived in a following discrete form:

$$[3b_{n+1}(-w_a l_u)]\theta_{n+1} = [\frac{1}{2} \cos(\alpha) + 4 \sin(\alpha)\theta_{n+1} - \sin(\alpha)\theta_{n+1}^{-1}]\theta_{n+1} + [\frac{1}{2} \cos(\alpha)\theta_{n+1} - \sin(\alpha)\theta_{n+1}^{-1}]$$
$$+ \{ \cos(\alpha)\ddot{\phi} - \sin(\alpha)\dot{\phi} - \sin(\alpha)\dot{\phi} \} \tau_o \}
- \frac{T_s^2}{m_u l_u} c_{n+1}$$
$$= 0 \hspace{1cm} (20)$$

where $a_{n+1} = - e_{n+1} M_{A,n+1} - M_{B,n+1}$, $b_{n+1} = M_{A,n+1}$ and $c_{n+1} = e_{n+1} M_{A,n+1}^2$.

Since (20) is a cubic difference equation, we can obtain the following solutions in each sampling time $T_s$ by Cardano’s method.
method:

\[ \theta_{n+1} = \sqrt{\frac{-q + \sqrt{q^2 + 4p^2}}{2}} + \sqrt{\frac{-q - \sqrt{q^2 + 4p^2}}{2}} \]

3.1. HSR-V

In the experiments, HSR-V was used (Fig.2). HSR-V is a small sized humanoid robot designed and developed in the Robot Intelligence Technology (RIT) Laboratory at KAIST.

where

\[ p = \frac{1}{3a} - \frac{b^2}{3a^2} \]

\[ q = \frac{2b^3}{27a^2} - \frac{bc}{3a^2} + \frac{d}{a} \]

\[ a = 3b_{n+1}(-w_aT_u) \]

\[ b = -4a_{n+1}w_a\cos(\alpha) - b_{n+1}\{w_ug\sin(\alpha)T_s^2 + w_au(-6\theta_n + \theta_{n-1}) - 4w_a\sin(\alpha)\tau_o \} \]

\[ c = -2a_{n+1}w_a\{\sin(\alpha) - 4\cos(\alpha)\theta_n + \cos(\alpha)\theta_{n-1} \} \]

\[ + 2b_{n+1}\{w_ug\cos(\alpha)T_s^2 - w_au(1 + \theta_n^2) \} - w_a(\cos(\alpha) + 4\sin(\alpha)\theta_n - \sin(\alpha)\theta_{n-1})\tau_o \}

\[ d = -2a_{n+1}w_a\{\sin(\alpha)(-2\theta_n + \theta_{n-1}) + \cos(\alpha)\theta_{n-2} \} \]

\[ + 2b_{n+1}\{w_ug\sin(\alpha)T_s^2 - w_au(-2\theta_n + \theta_{n-1}) \} - w_a(-2\cos(\alpha)\theta_n + 2\cos(\alpha)\theta_{n-1} - \sin(\alpha)\theta_{n-1})\tau_o \]

\[ - 2T_s^2 \]

\[ m_{au}T_u \]

Among the above three 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.

3.2. 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.

Figure 3: Experimental results without compensation (the pre-designed ZMP trajectory is located at 15 mm). (a) \( x_{ZMP_a} \) trajectory (no tilt). (b) \( x_{ZMP_a} \) trajectory (5 degree tilt).

Fig. 3 is the ZMP trajectories without compensation. In Fig. 3(a), we can see that the ZMP trajectory was converging with slight oscillation. Since the pre-designed ZMP trajectory was located at 15 mm from the heel it had a constant
error. In Fig. 3(b), we can see that the ZMP trajectory were moving toward the heel as the board began to tilt (about 2 sec).

![Graph](image1.png)

(a)

(b)

Figure 4: Experimental results with compensation (the pre-designed ZMP trajectory is located at 15 mm, no tilt). (a) $x_{ZMPa}$ trajectory. (b) Waist angle trajectory.

Figure 5: x-axis ZMP trajectory with compensation (the pre-designed ZMP trajectory is located at 15 mm, 5 degree tilt). (a) $x_{ZMPa}$ trajectory. (b) Waist angle trajectory.

Fig. 4 and 5 are the ZMP trajectories with compensation. In Fig. 4, we can see that the ZMP trajectory converged to a constant value without position error. Fig. 5 show that the ZMP trajectory also converged with slight oscillation at the moment when the board began to tilt (about 2 sec).

![Graph](image2.png)

(a)

(b)

Figure 6: Balance control (time interval = 0.33 s).

Fig. 6 is a snap shot of balance control of HSR-V. It shows that HSR-V could control its upper body to keep the balance on the board when the board was tilted. Time interval of snap shot was 0.33sec.

4. CONCLUSIONS

This paper presented the balance control of humanoid robot using its upper body motion. On-line 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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5. REFERENCES


