HUMANOID ROBOT HANSARAM: YAWING MOMENT CANCELLATION AND ZMP COMPENSATION

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ABSTRACT

This paper briefs on an overview of recent progress and development in humanoid robot, HanSaRam series. HanSaRam (HSR) is a humanoid robot undergoing continual design and development in the Robot Intelligence Technology (RIT) Laboratory at KAIST since 2,000. Currently HSR-VI, the latest version developed in 2,004, is under experiment for on-line gait generation and aperiodic motion generation. In this paper, HSR-V is used to test the control algorithm for compensating the yawing moment induced by walking and real time ZMP compensation. The experiment results of the proposed two-phase gait generation and the real-time ZMP compensation are presented. The two-phase gait generation considers the yawing moment cancellation as well as a ZMP criterion. First, a cubic spline is used to make a gait, considering a ZMP criterion. And then, the swinging trajectories of arms are calculated to cancel the yawing moment. In addition to this cancellation, the ZMP compensation is also needed to keep its balance for stable walking. The proposed ZMP compensation algorithm makes the ZMP error be zero by its torso motion.

1. INTRODUCTION

A humanoid robot is a biped (i.e.,two-legged) 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. Honda R&D's humanoid robots [1], WABIAN of Waseda University [2], ASIMO [3], H6 [4], HanSaRam of KAIST [5], Hubo of KAIST [6] and NBH-I of KIST [7] are well known humanoid robots. Humanoid robots have been developed to resemble human being, both morphologically and functionally.

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. To measure stability, ZMP (Zero Moment Point) proposed by Vukobratovic [8] is mostly used. The ZMP is defined as the point on the ground plane at which the total moments due to ground contacts becomes zero. It is important to recognize that ZMP must always reside in the convex hull of all contact points on the ground plane, since the moments on the ground plane are caused only by normal forces at the contact points which are always positive in the upper vertical direction.

For gait generation and its optimization for biped robot, there are two approaches. The first approach is to generate a gait off-line [9, 10]. However, this approach 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 on-line [11, 12, 13]. 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, or it suffers from dynamic modelling error which is caused by a simplified model or inaccurate kinematic and dynamic parameters.

This paper describes an overview of recent progress and development in humanoid robot, HanSaRam (HSR) series. Currently HSR-VI, the latest version developed in 2004, is under experiment for on-line gait generation and aperiodic motion generation. In this paper, HSR-V is used to test the balance control for compensating the yawing moment induced by walking and real time ZMP compensation, which is to improve its mobility. It has 28 DOFs and consists of 12 DC motors and Harmonic drives for the lower body and 16 servo motors for the upper body.

The proposed control method consists of two phases along with on-line ZMP compensation: first phase for an off-line gait generation and second phase for its yawing moment compensation in real-time to keep its balance. Firstly, a gait is generated off-line using a cubic spline interpolation method. Since the gait satisfies the ZMP criterion, roll and pitch moments of a robot are zero. However, a robot may slip along a vertical axis because of a yawing moment induced by its walking motion. Therefore, through the second phase the yawing moment should be compensated for stable walking. Moreover, on-line ZMP compensation is needed for stable walking, because there are unexpected external disturbances and dynamic parameters which are not considered in gait generation. The measured ZMP by FSRs (Force Sensing Resistor) on each sole of foot, is compared with the desired ZMP. The proposed ZMP compensation algorithm makes the ZMP error be zero by its torso motion, moving forward and backward or left and right. The effectiveness of the ZMP compensation is verified in the real experiment.

The remainder of this paper is organized as follows: Section 2 describes the recent HanSaRam series. Sections 3 and 4 propose the gait generation method cancelling the yawing moment and the on-line ZMP compensation using a upper body, respectively. In section 5, experimental results of HSR-V are presented. Concluding remarks follows in Section 6.

2. THE HANSARAM SERIES

This section describes an overview of recent progress and development in humanoid robot, HanSaRam series and presents a control scheme on how to improve its mobility. HanSaRam (HSR) is a humanoid robot undergoing continual design and development in the

Robot Intelligence Technology (RIT) Laboratory at KAIST since 2000. The aim for developing HanSaRam (HSR) was to participate in HuroSot competition for FIRA Cup (www.FIRA.net). However, this robot will be a good test bed to test the walking algorithm and control method because it is small and light.

2.1. HanSaRam-I, II and III

In HSR series, HSR-I, developed in 2000, has lacks of torque for proper walking and of DOFs for lower body for turning motion, as it consists of 10 RC servo motors without any sensor feedback. It was controlled by three micro-controllers. They could walk only forward and backward. The gait was a periodic one. Based on the experience of HSR-I, HSR-II was developed to have a shape of a human-like body.
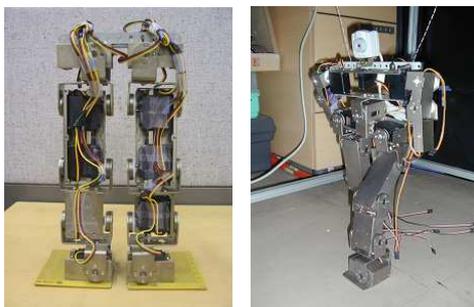
(a) HSR-I   (b) HSR-II

Figure 1: HSR I and II

HSR-III was developed in 2,001 to provide more torques and DOFs as shown in Fig. 2(a). It has 22 DOFs; 12 DOFs for a lower body using 12 geared DC motors and 10 DOFs for a upper body using 10 RC servo motors, to mimic a human body. But it has not a sensor feedback system.
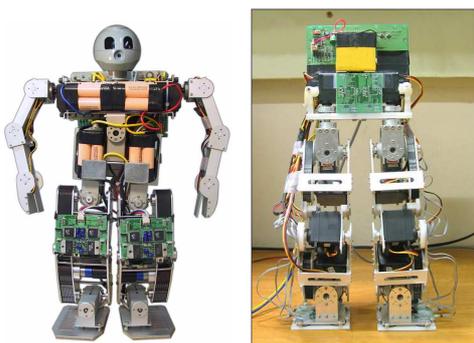
(a) HSR-III   (b) HSR-IV

Figure 2: HSR III and IV

Fig. 3 shows a walking pattern planner, which generates 3-D gait motion and motor trajectories by applying cubic spline interpolation to representative points such as feet, hip, head and hands.

The ZMP stability test, provided in the walking pattern planner, could be done for the generated gait before applying it into HSR-III. The walking patten planner is useful in generating the periodic gait. But for the aperiodic gait, aperiodic motion planner is needed, which is described in Section 2.4.
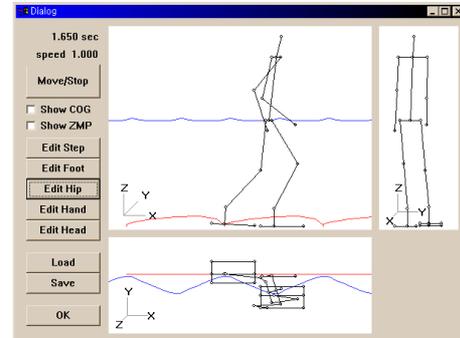

Figure 3: The simulation program

2.2. HanSaRam-IV

In the walking patter planner, the ZMP stability could be checked for the generated gait. But HSR-III did not have sensors to measure the ZMP. To test the sensor feedback mechanism HSR-IV was developed in 2002. To measure the ZMP, 4 FSRs are equipped on each foot sole of HSR-IV, as shown in Fig. 2(b).

HSR-IV consisted of 12 servo motors so that it could make a turning motion. Two micro-controllers were used. One is a master controller and the other is a slave controller. The Master controller is used for communication with the host PC and for sensor interface, and the slave controller is used for controlling the RC servo motors. The ZMP compensation algorithm is implemented in the master controller[14].

2.3. HanSaRam-V

HSR-V, developed in 2003 as shown in Fig. 4, has 28 D.O.Fs and consists of 12 DC motors for a lower body and 16 RC servo motors for a upper body. Its height and weight are 45 cm and 4.5 Kg, respectively. The design concept for the lower body was focused on sufficient torque and zero backlash. So the lower body consisted of DC motors and Harmonic drives. In a the design of the upper body, 16 RC servo motors were used to have less weight and a simple control method.

RTLinux was used in the on-board PC which contained the gait data and executed a high level logic. The gait data were provided by the walking pattern planner. The stand-alone vision board was equipped to find out three colors in real time. Six IR detectors were used to avoid the obstacle collision in walking. To measure the ZMP of the robot, 4 FSRs were equipped on each foot sole. Because HSR-V includes all computational and power parts, it has the ability for fully independent locomotion, sensing, and processing.

2.4. HanSaRam-VI

HSR-VI, developed in 2004 as shown in Fig. 5, has 25 DOFs and consisted of 12 DC motors for a lower body and 13 RC servo

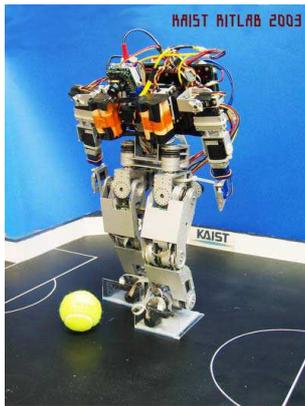Figure 4: HSR-V

motors for a upper body. Its height is 52 cm and its weight is 4.6 Kg. The design concept for its lower body was also focused on sufficient torque and zero backlash with DC motors and Harmonic drives like HSR-V. The main difference of HSR-VI compared with HSR-V is the design of lower body. It was simplified by designing the harmonic drive and DC motor as a single module. Its walking gait was generated on-line through three-dimensional linear inverted pendulum mode (3D LIPM) [11]. As the 3D LIPM effectively represents the whole dynamics of humanoid by the inverted pendulum, walking pattern can be generated on-line, and moreover turn and stop motions can be easily generated. Since the width between two z-axis of pelvis was designed to be narrow, it can walk properly with less shaking of hip compared with the previous HSRs' walking. Moreover, initial positioning of its posture is automatically set up by using a photo interrupter and a revolving disk for the DC motor control. RTLinux is also used for the control of HSR-VI, and 4 FSRs per foot sole are used to measure the ZMP. HSR-VI also has the ability for fully independent locomotion, sensing, and processing.

Figure 5: HSR-VI

Aperiodic motions can be generated by using an aperiodic motion planner as shown in Figure 6. By using the planner we could make various motions such as bowing, kicking, hand shaking, etc.

HSR-VI will participate in HuroSot for FIRA Cup and International Robot Olympiad (www.IROC.org) as well.
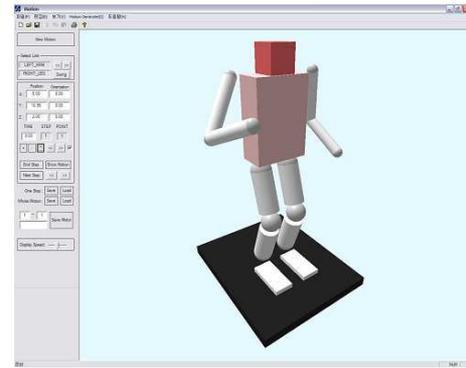

Figure 6: Aperiodic Gate Generator

3. TWO-PHASE OFF-LINE GAIT GENERATION

3.1. First phase for gait generation

In the first phase, off-line gait is generated to satisfy the ZMP stability using a cubic spline without motion of the upper body. First of all, representative data such as step time, step length. maximum foot height, etc are assigned to the walking pattern planner and via-points are selected for the foot and hip trajectories. Then a whole trajectory is made using a cubic spline interpolation. The cubic spline interpolation approximates the trajectory between two adjacent via-points to the third-order polynomial. The interpolation can make a smooth trajectory because both velocity and acceleration are continuous at via-points. Moreover, the via-point can be inserted or deleted easily.

3.2. Second phase: yawing moment cancellation

To avoid the possible slipping on the ground caused by the yawing moment, the yawing moment of the robot should be compensated by swinging its arms. In the second phase trajectories for the swinging arms are derived. A general ZMP equation is as follows:

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

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 well known, is obtained as follows:

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

Also, yawing moment equation is obtained as follows:

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

To derive an equation for cancelling the yawing moment, three assumptions are considered (Fig. 7).
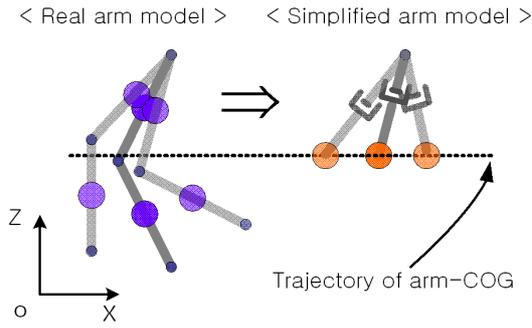
Figure 7: Simplified arm model

1. The robot's arms move only in the X (pitching)- direction.

2. The robot's arms are modelled as a pendulum which has the same COM.

3. The z-coordinate of the COM is constant.

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

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

where m_a is a mass of both arms, T_{Z0} is a yawing moment generated in the first phase, and Δy is a half of the shoulder width.

From (4), it should be noted that yawing moment consists of two components: one is generated when arms are not swinging (T_{z0}) and the other is caused by swinging its arms ($m_a \ddot{\Delta x}\Delta y$). To make the yawing moment zero to avoid the possible slipping over on the ground, the trajectories of the swinging arms can be obtained as follows:

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

By employing double integration to the above equation, we can get the trajectories of the swinging arms.

Here only sagittal motion has been considered, but the lateral motion can be analyzed similarly.

4. ON-LINE ZMP COMPENSATION

In this section on-line balance control is considered based on the ZMP. To make the problem easy, a upper body is modelled as an inverted pendulum (Fig. 8), which has the same COM as that of the original mass distribution.
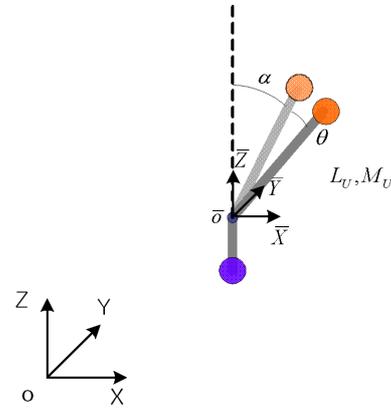

Figure 8: Simplified model of upper body

In Fig. 8 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, 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.

The ZMP in x-coordinate, generated off-line, is written as:

$$
x_{ZMPa} = \frac{M_B}{M_A}.
\tag{6}
$$

If the upper body moves, (6) can be represented as

$$
x_{ZMPm} = \frac{M_B + M_b}{M_A + M_a}
\tag{7}
$$

where M_a, M_b are additional components induced by moving its upper body. M_b can be divided into two parts:

$$
M_b = M_{b0} + M_{b1}
\tag{8}
$$

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 the 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 moving the upper body rapidly. Thus it can compensate the ZMP error instantaneously. But, when the robot stops moving its 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:

$$
\begin{aligned}
x_{ZMPn} =& \frac{M_B + M_{b.w}}{M_A + M_{a.w}} \\
M_{b.w} =& w_g M_{b0} + w_a M_{b1} \\
M_{a.w} =& w_a M_a.
\end{aligned}
\tag{9}
$$

The 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

$$e_x = x_{ZMPd} - x_{ZMPa} \qquad (10)$$

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.

Now we derive the following ZMP compensation equation from (6) and (9):

$$\frac{M_B + M_{b.w}}{M_A + M_{a.w}} = \frac{M_B}{M_A} + e_x. \qquad (11)$$

M_a and M_b are functions of the COM of the upper body $((x_u, z_u)$. Since y is a constant, (11) is a function of $x_u, z_u, \dot{x}_u, \dot{z}_u, \ddot{x}_u, \ddot{z}_u$.

$$f(x_u, z_u, \dot{x}_u, \dot{z}_u, \ddot{x}_u, \ddot{z}_u) = g(M_A, M_B, e_x). \qquad (12)$$

x_u and z_u are not independent variables, moreover they are correlated with each other by θ. Therefore (12) is obtained as follows:

$$h(\theta, \dot{\theta}, \ddot{\theta}) = g(M_A, M_B, e_x). \qquad (13)$$

By solving this equation numerically, we can find θ which can make ZMP error zero.

5. EXPERIMENTAL RESULTS

5.1. 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 length	4.0 (cm)
Hip height	20.0 (cm)

Fig. 9 shows the result generated in the first phase, where no compensation for the yawing moment is applied. The maximum value of the yawing moment is 1,300 ($kgcm^2/sec^2$) at the rising time (0.15sec, 0.95sec). This means that the maximum yawing moment is generated at the moment when the robot begins to swing its leg and it causes serious instability. To cancel the yawing moment, the arm-swing motion was added in the second phase. The result is shown in Fig. 10. It should be noted that the maximum value of the yawing moment was reduced under 250 ($kgcm^2/sec^2$).

5.2. On-line ZMP compensation

To demonstrate that the on-line ZMP compensation algorithm operated properly, the robot was placed on the flat board (Fig. 14) and its tilt angle was changed to see if the robot can keep its balance. In the experiment, the tile angle was set to 5 degrees.

Fig. 12 is the ZMP trajectory without compensation. The desired ZMP position was 15 mm in the experiment. It shows that
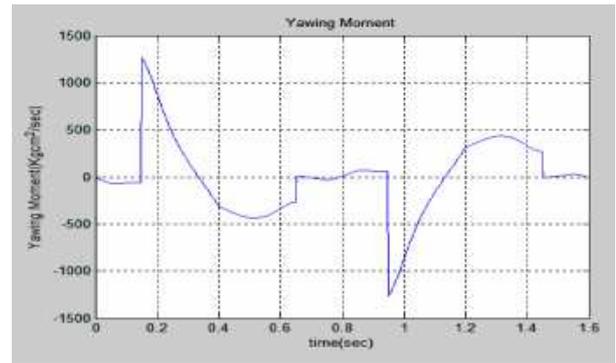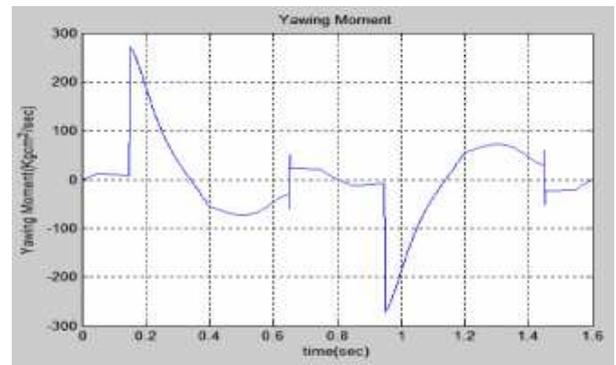

Figure 9: Yawing moment in the first phase

Figure 10: Yawing moment in the second phase

the ZMP trajectory becomes distant from the heel when the board began to tilt.

Fig. 13 is the ZMP trajectory with compensation. Fig. 13 shows that the ZMP trajectory converges to its desired ZMP position even though the board begins to tilt. To keep its balance by compensating the ZMP error, its waist was moving forward and backward.

6. CONCLUSIONS

This paper has presented an overview of research development in humanoid robot HanSaRam. The HanSaRam project was initiated in 2,000 and since then six successive versions have been designed, developed and experimentally assessed. This paper has presented the off-line gait generation method and the on-line compensation algorithm. By putting arm-swinging motion in the off-line gait generation stage, the yawing moment could be cancelled. Moreover, ZMP compensation has been accomplished by moving the upper body front and rear in on-line walking.
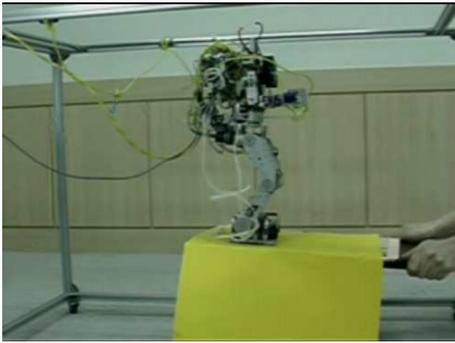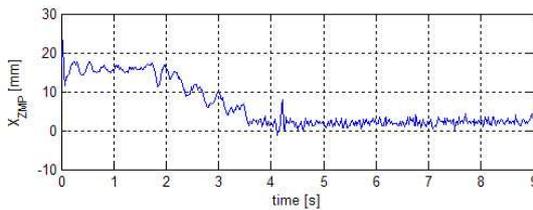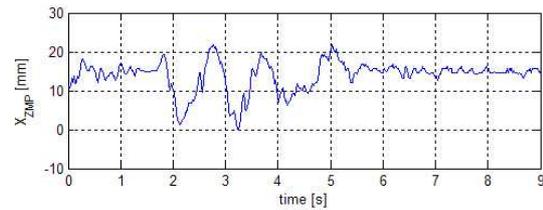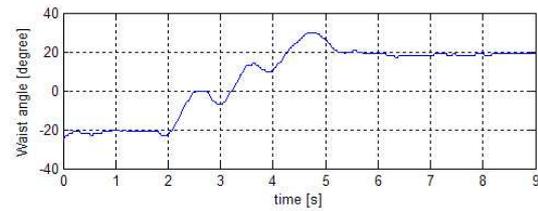
Figure 11: HSR-V on the flat board

(a) X-axis ZMP (mm)

Figure 12: x-axis ZMP trajectory when a flat board was tilted by 5 degrees and no compensation algorithm was applied

(b) Waist angle (degree)

Figure 13: x-axis ZMP trajectory and waist angle when a flat board was tilted by 5 degrees and the compensation algorithm was applied

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