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Balance Control in Whole Body Coordination Framework for Biped Humanoid Robot MAHRU-R

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***Abstract*— This paper presents balance and vibration control algorithm for bipedal humanoid robots in the motion embedded CoM Jacobian framework. The vibration control is employed during a single supporting phase, which can suppress residual vibration of the un-modelled flexibility. Because the previously proposed walking control method in the resolved momentum control framework is based on the rigid body motion, vibration control algorithm which compensates for residual vibration can make the humanoid motion into rigid body motion. The vibration control consists of the modified global planning CoM trajectory and modified ankle joint controller in the motion embedded CoM Jacobian framework. The parameters of the controller are acquired easily using MATLAB System Identification Tool box. Also, balance control algorithm which controls body orientation is applied to the whole body coordination framework. By dynamic walking experiments using a humanoid robot MAHRU-R, the validity of the proposed control methods is verified.**

I. INTRODUCTION

Human and animals use their legs to locomote with mobility. Humanoid robots like ASIMO[1], HRP[2], WABIAN[3], Johnnie[4] and HUBO[5] have been developed for humans convenience in human environment and reliable walking ability is the fundamental requirement for humanoid robots to become intelligent agents as human beings do. Particularly, the dynamical property that the center of mass (CoM), where the gravity force acts, is above the zero-moment point (ZMP), where the reaction force acts, is often modeled as the inverted pendulum; ZMP can play the role of stability criterion and become necessary to solve how to express the robot trajectory while satisfying stable walking.

In this sense, many simplified robot dynamics have been proposed: gravity compensated inverted pendulum mode (GCIPM)[6], three dimensional linear inverted pendulum mode (3D-LIPM) [7], rolling sphere model[8], etc. And they were expressed by the relation between CoM and ZMP; consequently, the CoM trajectory usually has played the key role in making robot motion. Therefore, many researchers have concentrated on the complex problem of CoM/ZMP trajectory planning: boundary condition relaxation[9], preview control of ZMP[7], etc. As CoM manipulation plays the key role in humanoid motion planning, whole body coordination (WBC) algorithms for enhanced stability and mobility could be realized with good performance [10], [11].

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Stable CoM controller which utilizes measured ZMP feedback realized stable compensation for real walking control [8].

The objective of this research is to improve a reliable humanoid robot walking algorithm based on whole body coordination(WBC) framework[8], [11]. Because stable CoM/ZMP controller in the WBC algorithm is derived from rigid body motion, un-modelled flexibility of the body motion makes the performance of CoM controller fall off. Therefore, in this paper, the vibration controller which estimates the un-modelled flexibility in the supporting leg can realize stable compensation for real walking control and improve the performance of CoM/ZMP controller. Its performance of damping out the inherent vibration is experimentally shown. Also, balance control which controls body orientation is applied. Validity and walking stability are demonstrated by the experiment on a real humanoid robot, MAHRU-R.

Fig. 1. Humanoid robot MAHRU-R

II. HUMANOID ROBOT MAHRU-R

MAHRU-R is made by modifying low level servo control algorithm in DSP, improving mechanical part design of a humanoid robot platform MAHRU[12]. Fig. 1 shows the assembled robot MAHRU-R. Its specifications are shown in Table I. MAHRU-R has 1350 mm height, 50 kg weight including batteries. It has 12-DOF in two legs and 20-DOF in two arms including hands with 4-DOF grippers. Also, it is actuated by DC servo motors through harmonic drive reduction gears that provide compactness and better controllability with reduced backlash. The body is equipped with an IMU (Inertial Measurement Unit) sensor which consists of 3-axis gyroscope and 3-axis G-force sensors. Each ankle and wrist is equipped with a force/torque sensor. A distributed

TABLE I
SPECIFICATION OF MAHRU-R

Height	1350 mm
Weight	50 kg (including battery)
Head	Neck : 2 DOF (Pitch, Yaw)
Arm	6 DOF/Arm (Shoulder 3, Elbow 1, Wrist 2)
Hands	4 DOF/Hand RS232 protocol
Legs	6 DOF/Leg (Hip 3, Knee 1, Ankle 2)
Sensors	IMU sensor in pelvis 6-axis F/T sensors in wrist and ankle
Actuators	DC servo motor + Belt-pulley Harmonic drive gear
I/O board Communication	IEEE 1394 firewire
2CH-Motor Controller	High-power PWM motor controller for legs, arms and head
Operating System	Fedora Core 5 + RTAI/Xenomai (Control Freq. 200 Hz)

system was built for humanoid using sub-controllers and IEEE 1394 protocol communication lines between the main controller and sub-controllers. The main real-time control algorithm runs on a micro-ATX CPU board in the backpack of MAHRU-R, whose operating system is real-time Linux (RTAI/Xenomai). It allows user to make timer interrupt service routine with the highest priority to control the robot in real-time.

III. KINEMATIC RESOLUTION OF COM JACOBIAN WITH AN EMBEDDED MOTION

In this section, we will explain the kinematic resolution method of CoM Jacobian with embedded motion. Let a robot have *n* limbs and the first limb be the base limb. The base limb can be any limb but it should be on the ground to support the body. Each limb of a robot is hereafter considered as an independent limb. In general, the *i*-th limb has the relation:

$$ {}^{o}\dot{\boldsymbol{x}}_i = {}^{o}\boldsymbol{J}_i \dot{\boldsymbol{q}}_i \qquad (1)$$

where ${}^{o}\dot{\boldsymbol{x}}_i$ is the velocity of the end point, $\dot{\boldsymbol{q}}_i$ is the joint velocity, and ${}^{o}\boldsymbol{J}_i$ is the usual Jacobian matrix. The leading superscript o implies that the elements are represented on the body center coordinate system, which is fixed on a humanoid robot.

In our case, the body center is floating, and thus the end point motion of the *i*-th limb about the world coordinate system is written as

$$\dot{\boldsymbol{x}}_i = \boldsymbol{X}_i^{-1}\dot{\boldsymbol{x}}_o + \boldsymbol{X}_o\,{}^{o}\boldsymbol{J}_i\dot{\boldsymbol{q}}_i \qquad (2)$$

where $\dot{\boldsymbol{x}}_o = \begin{pmatrix}\dot{\boldsymbol{r}}_o^T & \boldsymbol{\omega}_o^T\end{pmatrix}^T$ is the velocity of the body center represented on the world coordinate system, and

$$\boldsymbol{X}_i = \begin{bmatrix}\boldsymbol{I}_3 & [\boldsymbol{R}_o\,{}^{o}\boldsymbol{r}_i\times] \\ \boldsymbol{0}_3 & \boldsymbol{I}_3\end{bmatrix} \text{ and } \boldsymbol{X}_o = \begin{bmatrix}\boldsymbol{R}_o & \boldsymbol{0}_3 \\ \boldsymbol{0}_3 & \boldsymbol{R}_o\end{bmatrix} \qquad (3)$$

where $\boldsymbol{X}_i$ is a 6×6 matrix that relates the body center velocity and the *i*-th limb velocity. $\boldsymbol{I}_3$ and $\boldsymbol{0}_3$ are an 3×3 identity and zero matrix, respectively. $\boldsymbol{R}_o\,{}^{o}\boldsymbol{r}_i$ is the position vector from the body center to the endpoint of the *i*-th limb represented on the world coordinate frame and $[(\cdot)\times]$ denotes a skew-symmetric matrix for the cross product operation. Also, $\boldsymbol{X}_o$ is the transformation matrix where $\boldsymbol{R}_o$ is the orientation of the body center represented on the world coordinate frame, and hereafter, we will use the relation $\boldsymbol{J}_i = \boldsymbol{X}_o\,{}^{o}\boldsymbol{J}_i$. From Eq. (2), we can see that all the limbs should satisfy the compatibility condition that the velocity of body center is the same, and thus *i*-th limb and *j*-th limb should satisfy the following relation:

$$\dot{\boldsymbol{x}}_o = \boldsymbol{X}_i\big(\dot{\boldsymbol{x}}_i - \boldsymbol{J}_i\dot{\boldsymbol{q}}_i\big) = \boldsymbol{X}_j\big(\dot{\boldsymbol{x}}_j - \boldsymbol{J}_j\dot{\boldsymbol{q}}_j\big) \qquad (4)$$

From Eq. (4), the joint velocity of any limb can be represented by the joint velocity of the base limb and desired cartesian velocity motions of limbs. Actually, the base limb should be chosen to be the supporting leg in the single supporting phase or one of both legs in the double supporting phase. Let us express the base limb with the subscript 1, then the joint velocity of any limb is expressed as:

$$\dot{\boldsymbol{q}}_i = \boldsymbol{J}_i^{-1}\dot{\boldsymbol{x}}_i - \boldsymbol{J}_i^{-1}\boldsymbol{X}_{i1}\big(\dot{\boldsymbol{x}}_1 - \boldsymbol{J}_1\dot{\boldsymbol{q}}_1\big), \qquad (5)$$

for $i = 2, \ \cdots, \ n$. and

$$\boldsymbol{X}_{i1} \triangleq \boldsymbol{X}_i^{-1}\boldsymbol{X}_1 = \begin{bmatrix}\boldsymbol{I}_3 & \big[\boldsymbol{R}_o({}^{o}\boldsymbol{r}_1 - {}^{o}\boldsymbol{r}_i)\times\big] \\ \boldsymbol{0}_3 & \boldsymbol{I}_3\end{bmatrix} \qquad (6)$$

With this compatibility condition, the inverse kinematics of humanoid robot can be solved by using the information of base limb like Eq. (5), not by using the information of body center like Eq. (2).

Note that if a limb is a redundant system, any null space optimization scheme can be added to Eq. (5). Now, the conventional CoM Jacobian explained in [13] is obtained as

$$\dot{\boldsymbol{c}} = \dot{\boldsymbol{r}}_o + \boldsymbol{\omega}_o \times \big(\boldsymbol{c} - \boldsymbol{r}_o\big) + \sum_{i=1}^{n}\boldsymbol{R}_o\,{}^{o}\boldsymbol{J}_{ci}\dot{\boldsymbol{q}}_i \qquad (7)$$

where n is the number of limbs, $\boldsymbol{c}$ is the position vector of CoM represented on the world coordinate system, and ${}^{o}\boldsymbol{J}_{ci}$, means CoM Jacobian of *i*-th limb represented on the body center coordinate frame. The motion of the body center frame can be obtained by using Eq. (2) for the base limb as

$$\dot{\boldsymbol{x}}_o = \boldsymbol{X}_1\big(\dot{\boldsymbol{x}}_1 - \boldsymbol{X}_o\,{}^{o}\boldsymbol{J}_1\dot{\boldsymbol{q}}_1\big)$$
$$\begin{Bmatrix}\dot{\boldsymbol{r}}_o \\ \boldsymbol{\omega}_o\end{Bmatrix} = \begin{bmatrix}\boldsymbol{I}_3 & [\boldsymbol{R}_o\,{}^{o}\boldsymbol{r}_1\times] \\ \boldsymbol{0}_3 & \boldsymbol{I}_3\end{bmatrix}\left(\begin{Bmatrix}\dot{\boldsymbol{r}}_1 \\ \boldsymbol{\omega}_1\end{Bmatrix} - \begin{bmatrix}\boldsymbol{R}_o\,{}^{o}\boldsymbol{J}_{v1} \\ \boldsymbol{R}_o\,{}^{o}\boldsymbol{J}_{\omega 1}\end{bmatrix}\dot{\boldsymbol{q}}_1\right) \qquad (8)$$

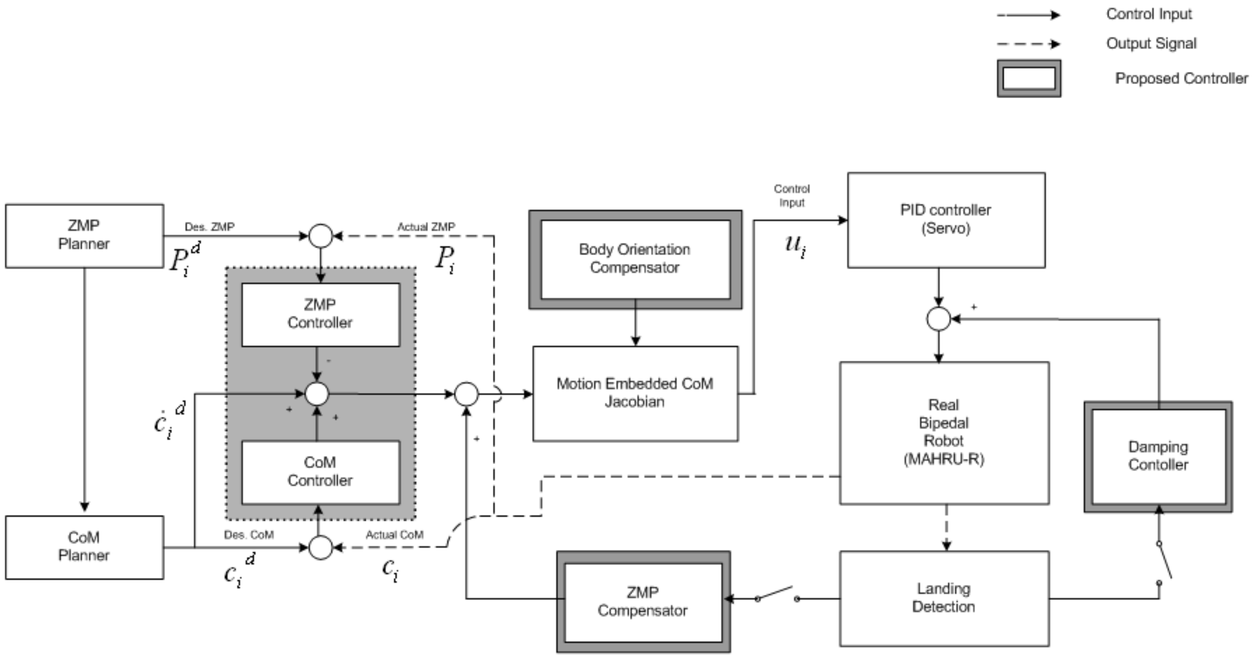

Fig. 2. Overall architecture of proposed walking control method

where ${}^{o}\boldsymbol{J}_{v1}$ and ${}^{o}\boldsymbol{J}_{\omega 1}$ are the linear and angular velocity part of the base limb Jacobian. Now, if Eq. (5) is applied to Eq. (7), the CoM motion is rearranged as follows:

$$\begin{aligned}\dot{\boldsymbol{c}} &= \dot{\boldsymbol{r}}_o + \boldsymbol{\omega}_o \times (\boldsymbol{c} - \boldsymbol{r}_o) + \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{c1}\dot{\boldsymbol{q}}_1 \\ &\quad + \sum_{i=2}^{n} \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{ci}\boldsymbol{J}_i^{-1}\big(\dot{\boldsymbol{x}}_i - \boldsymbol{X}_{i1}\dot{\boldsymbol{x}}_1\big) \\ &\quad + \sum_{i=2}^{n} \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{ci}\boldsymbol{J}_i^{-1}\boldsymbol{X}_{i1}\boldsymbol{J}_1\dot{\boldsymbol{q}}_1 \end{aligned} \tag{9}$$

Here, if Eq. (8) is applied to Eq. (9), then the CoM motion is only related with the motion of base limb:

$$\begin{aligned}\dot{\boldsymbol{c}} &= \dot{\boldsymbol{r}}_1 + \boldsymbol{\omega}_1 \times \boldsymbol{r}_{c1} - \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{v1}\dot{\boldsymbol{q}}_1 + \boldsymbol{r}_{c1} \times \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{\omega 1}\dot{\boldsymbol{q}}_1 \\ &\quad + \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{c1}\dot{\boldsymbol{q}}_1 + \sum_{i=2}^{n} \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{ci}\boldsymbol{J}_i^{-1}\big(\dot{\boldsymbol{x}}_i - \boldsymbol{X}_{i1}\dot{\boldsymbol{x}}_1\big) \\ &\quad + \sum_{i=2}^{n} \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{ci}\boldsymbol{J}_i^{-1}\boldsymbol{X}_{i1}\boldsymbol{J}_1\dot{\boldsymbol{q}}_1 \end{aligned} \tag{10}$$

where $\boldsymbol{r}_{c1} = \boldsymbol{c} - \boldsymbol{r}_1$. Also, if the base limb has the face contact with the ground (the end point of base limb represented on world coordinate frame is fixed, $\dot{\boldsymbol{x}}_1 = \boldsymbol{0}$, namely, $\dot{\boldsymbol{r}}_1 = \boldsymbol{0}$ and $\boldsymbol{\omega}_1 = \boldsymbol{0}$), then finally, all the given desired limb motions, $\dot{\boldsymbol{x}}_i$ are embedded in the CoM Jacobian. Thus the effect of the CoM movement generated by the given limb motion is compensated by the base limb. Also, the CoM Jacobian matrix with embedded limb motions can be written like the usual kinematic Jacobian of base limb as follows:

$$\dot{\boldsymbol{c}}_{emc} = \boldsymbol{J}_{emc}\dot{\boldsymbol{q}}_1 \tag{11}$$

where

$$\dot{\boldsymbol{c}}_{emc} = \dot{\boldsymbol{c}} - \sum_{i=2}^{n} \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{ci}\boldsymbol{J}_i^{-1}(\dot{\boldsymbol{x}}_i - \boldsymbol{X}_{i1}\dot{\boldsymbol{x}}_1) \tag{12}$$

$$\begin{aligned}\boldsymbol{J}_{emc} &= \boldsymbol{R}_o[-{}^{o}\boldsymbol{J}_{v1} + \boldsymbol{r}_{c1} \times {}^{o}\boldsymbol{J}_{\omega 1} + {}^{o}\boldsymbol{J}_{c1}] \\ &\quad + \sum_{i=2}^{n} \boldsymbol{R}_o\, {}^{o}\boldsymbol{J}_{ci}\boldsymbol{J}_i^{-1}\boldsymbol{X}_{i1}\boldsymbol{J}_1 \end{aligned} \tag{13}$$

The CoM motion with embedded limb motions, $\dot{\boldsymbol{c}}_{emc}$, consists of two relations: a given desired CoM motion (the first term) and the relative effect of other limbs (the second term), in which all the given desired limb motions are embedded in the relation of CoM Jacobian, thus, the effect of the CoM movement generated by the given limb motion is compensated by the base limb. Therefore, the resulting base limb motion makes a humanoid robot balanced automatically while the movement of all the other limbs is obtained by Eq. (5). The resulting motion follows the given desired motions regardless of balancing motion by base limb. In other words, the suggested kinematic resolution method of CoM Jacobian with embedded motion offers the WBC (whole body coordination) function to the humanoid robot automatically.

IV. CONTROLLER

Fig. 2 shows overall control architecture of the proposed method for walking control. An omni-directional walking pattern generation method [14] makes CoM/ZMP trajectory for the given foot prints. It proposes three step modules for generating stable walking pattern based on ZMP and linear inverted pendulum model. After we generate the walking patterns, we modify them with controllers by sensor feedback: previous walking controller which utilizes measured

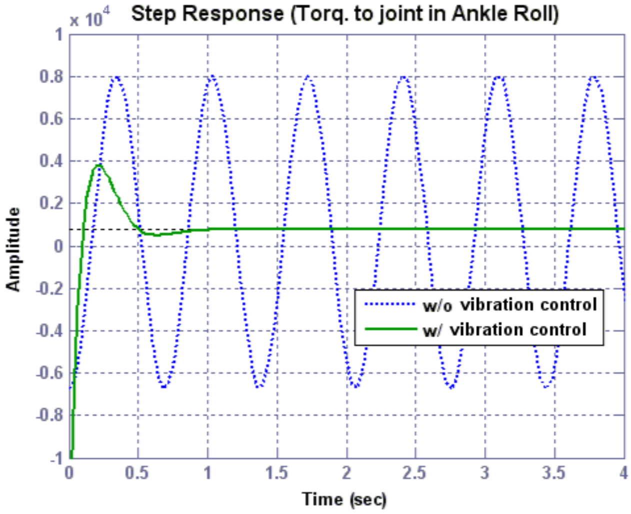

Fig. 3. Step response of vibration control (simulation result)

ZMP feedback is represented in shade region with dot line. Using the previous controller only, pelvis sags down during single supporting phase and residual vibration deteriorates the performance of the controller. Therefore, we proposed an additional control algorithm which is composed of three controllers: vibration controller, feedforward ZMP compensator, body orientation controller. Vibration controller and feedforward ZMP compensator can reduce the residual vibration in the supporting leg induced by un-modelled flexibility and improve the performance of the previous walking controller. Also, body orientation controller makes the stability better.

A. Vibration Controller

Vibration controller is designed to eliminate the sustained oscillation in the single support phase. The CoM/ZMP controller can stabilize the gross body motion[8], [11]. However, because humanoid robot consists of the harmonic drive and the leg is flexible and relatively long, an additional flexible mode induces flexible mode vibration and these un-modelled flexibilities deteriorate the performance of the CoM/ZMP controller. Hence, the vibration controller, based on damping controller[15] imposes the vibration forces at the ankle joints without any change of the steady-state value of the joint angle. In order to get the proposed model parameters in [15] from random excitation with frequency sweeping because frequency response technique is one of the simplest method utilized in system identification. Fig. 3 shows the simulation result of the proposed vibration controller during single supporting phase. The vibration controller can suppress the flexibility of humanoid. The effectiveness of the proposed controller is described in the walking experimental results. Ankle pitch mode is also designed as the same manner.

B. Feedforward ZMP Compensator

ZMP is an important measure to keep the stable motion planned by the pattern planner. The actual ZMP could be estimated by the force/torque sensor in the feet. In order to reduce the error between the desired ZMP trajectory and the actual ZMP, ZMP controller can adjust the horizontal position of the torso mainly. However, in single supporting phase, because vibration controller adjusts the body motion in order to maintain stable walking, the vibration controller makes the inevitable movement of ZMP. Consequently, feedforward ZMP compensator in a single supporting phase stabilizes additional ZMP dynamics of the simple inverted pendulum with feed forward term which adjust the horizontal position of the torso shown in Fig. 2.

In order to obtain a nominal frequency response model of a biped robot for the ZMP (taking account of its characteristic uncertainty), CoM of the biped robot is excited with a variable frequency sinusoidal signal[16]:

$$x_{\Delta c} = x_0 \sin(\omega t) \quad (14)$$

$$y_{\Delta c} = y_0 \sin(\omega t) \quad (15)$$

These excitation inputs with frequency sweeping generate other output oscillations that can be analyzed with the measured ZMP. Using the simple inverted pendulum model, $ZMP_{\Delta x}$ and $ZMP_{\Delta y}$ are in phase with these inputs $\boldsymbol{x}_{\Delta c}$ and $\boldsymbol{y}_{\Delta c}$, respectively and it is also written below:

$$ZMP_{\Delta x} = x_{0ZMP} \sin(\omega t) = x_{\Delta c} - \frac{1}{\omega_c^2}\ddot{x}_{\Delta c} \quad (16)$$

$$ZMP_{\Delta y} = y_{0ZMP} \sin(\omega t) = y_{\Delta c} - \frac{1}{\omega_c^2}\ddot{y}_{\Delta c} \quad (17)$$

where ω_c is a natural frequency of equivalent pendulum. Also, after Eq. (14) and Eq. (15) are applied to Eq. (16) and Eq. (17), it is then possible to write:

$$x_{0ZMP} = \left(1 + \frac{\omega^2}{\omega_c^2}\right) x_0 \quad (18)$$

$$y_{0ZMP} = \left(1 + \frac{\omega^2}{\omega_c^2}\right) y_0 \quad (19)$$

Because of flexibility of humanoid robots, perfect tracking of the CoM reference ($x_c(t) \rightarrow x_{cr}(t)$, $y_c(t) \rightarrow y_{cr}(t)$) is not always feasible. These tracking errors are related to uncertainties in humanoid robot mass distribution, actuator compliance, harmonic drive compliance, structure flexibilities and other un-modelled dynamics. However, this complex relationship between the actual and reference CoM could be modeled using a "harmonic balance" method[17]. Also, this technique is designed to obtain an average transfer function (analyzing the first harmonic term) and associated uncertainty function. Therefore, for low frequency signal, the average ZMP model becomes:

$$ZMP_{\Delta x} = a_x x_{\Delta cr} - b_x \ddot{x}_{\Delta cr} \quad (20)$$

$$ZMP_{\Delta y} = a_y x_{\Delta cr} - b_y \ddot{y}_{\Delta cr} \quad (21)$$

where a_x, a_y, b_x and b_y account for the un-modelled dynamic effects. The harmonic balance based algorithm is designed to obtain the parameters a_i, b_i and uncertainty transfer function[16].

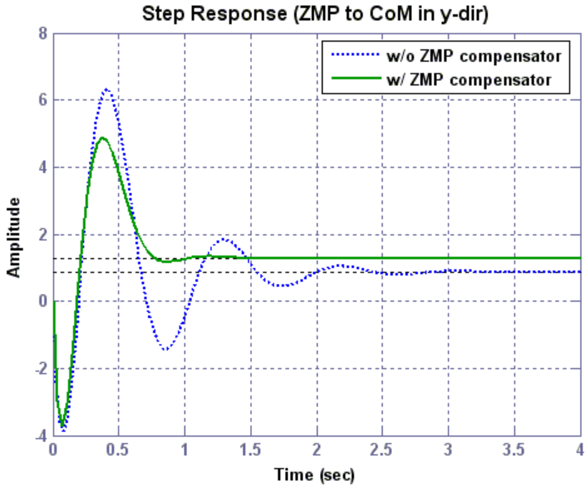

Fig. 4. Simulation result of feedforward ZMP compensator

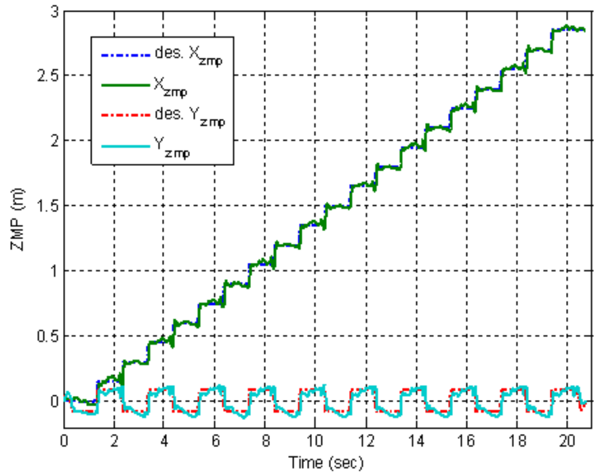

Fig. 5. Measured ZMP during straight forward walking

In this paper, we use the simple nonlinear ZMP model and a subspace method to estimate the un-modelled state-space model. Using the estimated model, we designed the compensator. Therefore, additional CoM displacement by feedforward ZMP compensator suppresses flexibility which is induced by compliance and vibration controller during single supporting phase. Fig. 4 shows damped oscillation of ZMP and the effectiveness of the proposed controller in simulation result and also described in the walking experiment results. The feedforward ZMP compensator for x-direction can be also designed as the same method.

C. Body Orientation Controller

The body orientation control reduces the difference between the desired body posture and the actual body posture which is induced by vibration controller and feedforward ZMP compensator. The controller makes the robot recover its inclination to its desired posture. Here the desired body posture is given by the motion generators. The actual body posture is calculated by kinematics with joint angles, but in near future, it will be replaced by the sensor signal which is estimated by Kalman filter with the information of the body inclination sensor which consists of gyroscope and G-force sensors. The body orientation control generates the body angular velocity as shown below:

$$\boldsymbol{\omega}_{\text{ref}} = \boldsymbol{\omega}_d + \boldsymbol{T}(\boldsymbol{\phi}) \left[\boldsymbol{K}_P(\boldsymbol{\phi}_d - \boldsymbol{\phi}) + \boldsymbol{K}_I \int (\boldsymbol{\phi}_d - \boldsymbol{\phi}) dt \right]$$

where $\boldsymbol{\phi}$ is body orientation angle expressed by RPY (Roll-Pitch-Yaw) and $\boldsymbol{T}(\boldsymbol{\phi})$ is transformation matrix from RPY.

V. Experiments

In order to verify the performance of the proposed controller in WBC framework, we did some experiments. Walking experiment was performed on a floor surface which is not perfectly flat. Fig. 5 shows the desired ZMP trajectory and the measured ZMP trajectory during straight forward walking in x and y direction. It is evident that ZMP trajectory remains in the stable region and tracks desired trajectory well. Also, Fig. 6 shows body orientation and measured normal force. Body orientation controller can compensate body orientation

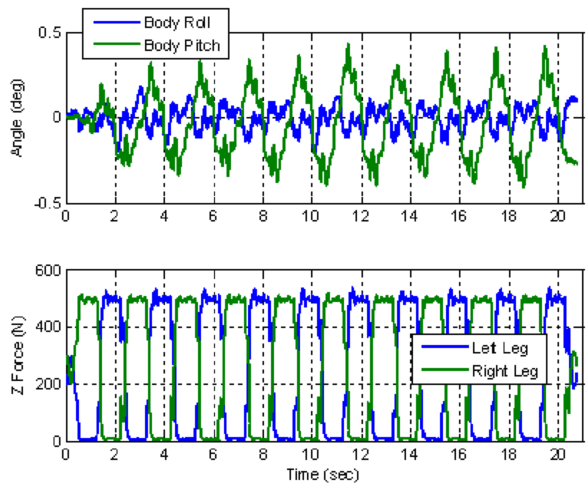

Fig. 6. Body orientation and measured normal force during straight forward walking

during walking and normal force shows flat in single support phase without large impact signal.

Fig. 7 shows the snapshot of experimental results, walking with greeting motion on the uneven floor, which is in the office building.
In this experiment, MAHRU-R can stably walk with upper body motion and WBC function can keep balance motion. Fig. 8 shows real upper body joint motion and CoM/ZMP trajectory that tracks the given CoM / ZMP trajectory very well.

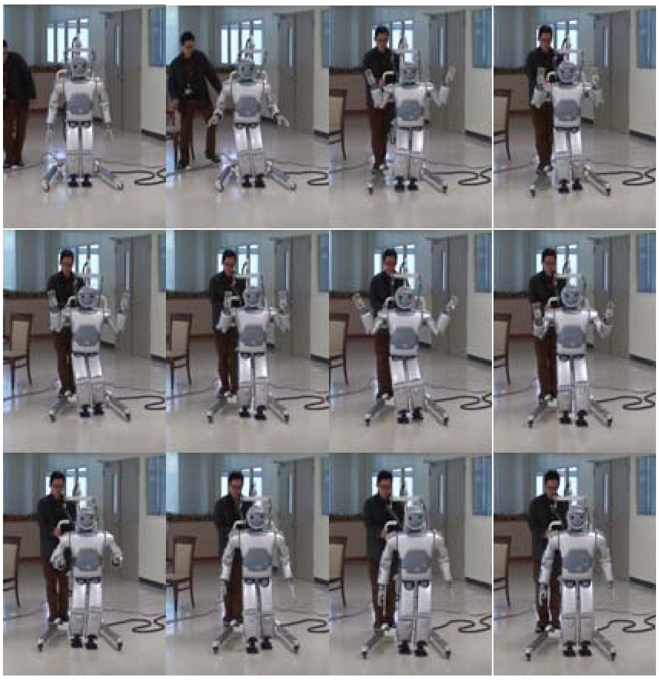

Fig. 7. Straight forward walking with greeting motion on the office floor

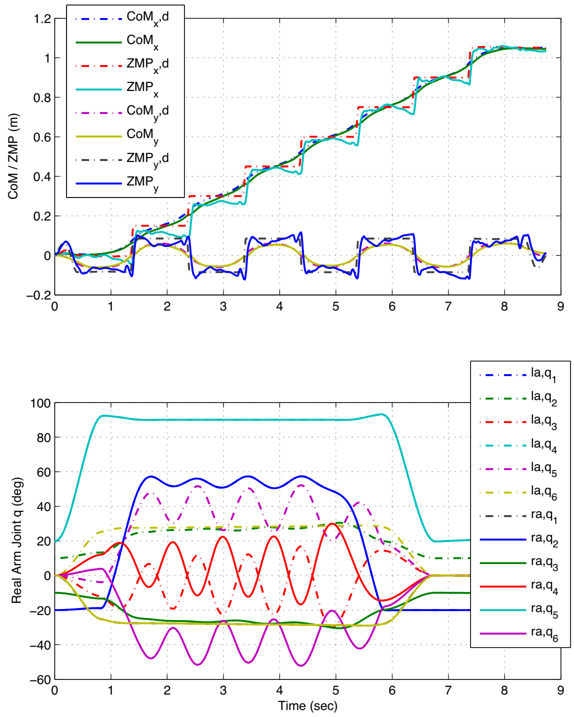

Fig. 8. Experimental results from straight forward walking with greeting motion.

VI. Conclusion

This paper presented how we improve the performance of the previous humanoid walking algorithm based on whole body coordination (WBC). We proposed vibration controller, feedforward ZMP compensator, body orientation control in the WBC framework. Also, newly developed humanoid platform MAHRU-R was introduced and experimental validation was demonstrated with new humanoid platform. Future works include the more stable balance controller to adapt more rough terrain using IMU sensor.

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