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# VIBRATION SUPPRESSION AND BALANCE CONTROL FOR BIPED HUMANOID WALKING

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**Abstract:** In this paper, we present vibration suppression and balance control algorithm for biped humanoid robots in the motion embedded CoM Jacobian. The vibration control is employed during a single supporting phase, which can suppress vibration induced by structure flexibility. Because the previously proposed walking control method in the whole body coordination (WBC) framework is based on the rigid body motion, flexible mode vibration control which suppresses the residual vibration can make the humanoid motion into rigid body motion. Also, balance control algorithm which controls body attitude is applied to the WBC framework. By dynamic walking experiments using a humanoid robot MAHRU-R, we verify the validity of the proposed control methods.

## 1. INTRODUCTION

Humanoid robot has been developed for humans convenience in the human environment; humanoid robots like ASIMO (Hirai *et al.* [1998]), HRP (Kajita *et al.* [2003a]), WABIAN (Yamaguchi *et al.* [1999]), Johnnie (L"Aofler *et al.* [2003]) and Hubo (Kim and Oh [2004a]) have reliable walking ability and can be intelligent agents as human beings do. Particularly, 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; often ZMP is used to estimate the stability criterion and became necessary to solve how to express the robot trajectory while satisfying stable walking.

In this sense, many simplified robot dynamics such as gravity compensated inverted pendulum mode (GCIPM) (Park and Kim, 1998), three dimensional linear inverted pendulum mode (3D-LIPM) (Kajita *et al.* [2003a]), rolling sphere model (Choi *et al.* [2007]) have been proposed. By expressing the relation between CoM and ZMP, we can make robot motion using the CoM trajectory. Therefore, many researchers have concentrated on the complex problem of CoM/ZMP trajectory planning: boundary condition relaxation (Sugihara and Nakamura, 2002), preview control of ZMP (Kajita *et al.* [2003a]) etc. Among these control methods, whole body coordination (WBC) algorithm for enhanced stability and mobility could be realized with good performance (Choi *et al.* [2007])(Kim *et al.* [2005]); stable CoM controller which utilizes measured ZMP feedback realized stable compensation for real walking control (Choi *et al.* [2007]).

The objective of this research is to improve a reliable humanoid robot walking algorithm based on whole body coordination (WBC) framework (Choi *et al.* [2007])(Kim *et al.* [2005]). An un-modelled flexibility of the body motion degrades the performance of CoM/ZMP controller fall off because stable CoM/ZMP controller in the WBC algorithm is based on rigid body motion. Therefore, in this paper, the flexible mode vibration controller which estimates the un-modelled flexibility in the supporting leg can suppress vibration and can improve the performance of CoM/ZMP controller. Its performance of damping out the residual vibration is experimentally shown. Also, balance control which control body attitude is applied. Validity and walking stability are demonstrated by the experiment on a real humanoid, MAHRU-R.

## 2. 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 (Choi, et al., 2007). Let a robot have n limbs and the first limb be the base limb which can be any limb but it should be on the ground to support the body. 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

$$\dot{\boldsymbol{x}}_i = \boldsymbol{X}_i^{-1}\dot{\boldsymbol{x}}_o + \boldsymbol{X}_o\,{}^o\boldsymbol{J}_i\dot{\boldsymbol{q}}_i \tag{1}$$

where $\dot{\boldsymbol{x}}_o$ is the velocity of the body center represented on the world coordinate system, and $\dot{\boldsymbol{x}}_i$ relates the body center velocity and $i$-th limb velocity. Also, $\boldsymbol{X}_o$ is the transformation matrix. From (1), we can see that all the limb 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:

$$\dot{\boldsymbol{x}}_o = \boldsymbol{X}_i(\dot{\boldsymbol{x}}_i - \boldsymbol{J}_i\dot{\boldsymbol{q}}_i) = \boldsymbol{X}_j(\dot{\boldsymbol{x}}_j - \boldsymbol{J}_j\dot{\boldsymbol{q}}_j) \tag{2}$$

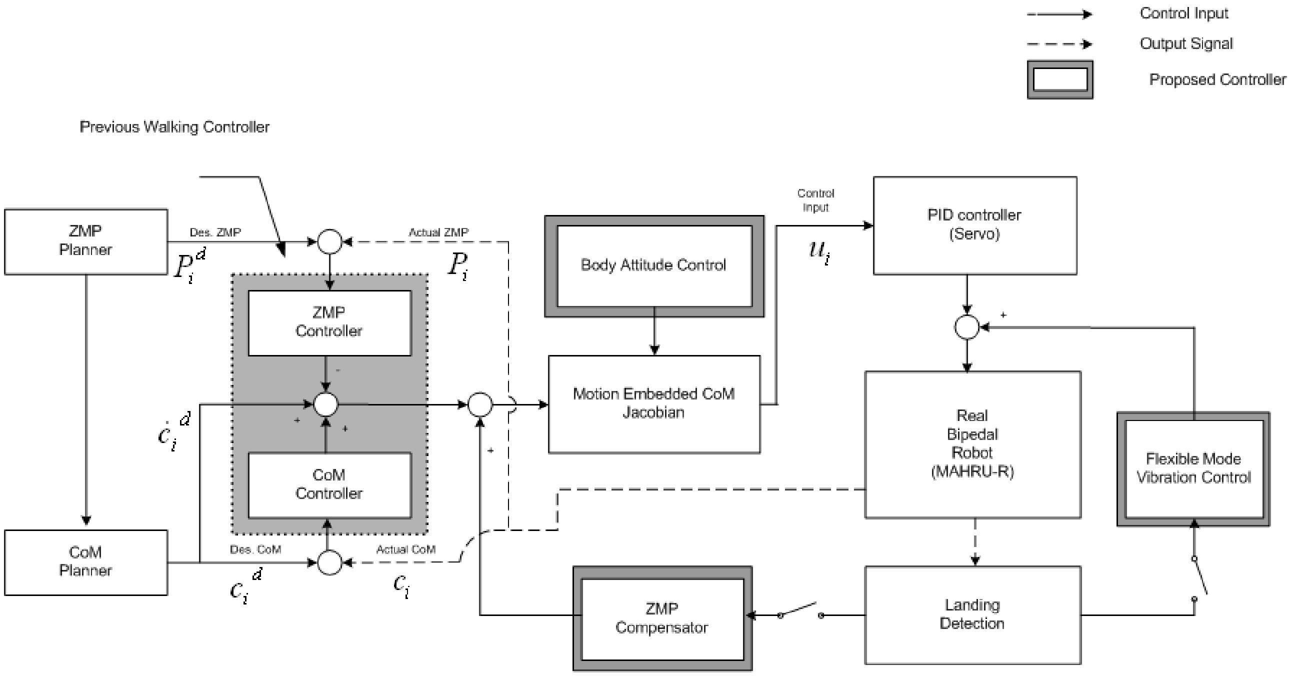


Fig. 1. Overall control architecture for walking control

From (2), the joint velocity of any limb can be represented by the joint velocity of the base limb and desired cartesian velocity motions of limbs. Also, we can express the joint velocity of any limb in terms of base limb with the subscript 1:

$$\dot{\boldsymbol{q}}_i = \boldsymbol{J}_i^{-1}\dot{\boldsymbol{x}}_i - \boldsymbol{J}_i^{-1}\boldsymbol{X}_{i1}\big(\dot{\boldsymbol{x}}_1 - \boldsymbol{J}_1\dot{\boldsymbol{q}}_1\big) \tag{3}$$

Using the compatibility condition, the inverse kinematics of humanoid robot can be solved by using the information of base limb like (3), not by using the information of body center line like (2).
Now, the conventional CoM Jacobian explained in (Sugihara and Nakamura, 2002) is obtained as

$$\dot{\boldsymbol{c}} = \dot{\boldsymbol{r}}_o + \omega_o \times \big(\boldsymbol{c} - \boldsymbol{r}_o\big) + \sum_{i=1}^{n} \boldsymbol{R}_o\, {}^o\boldsymbol{J}_{ci}\dot{\boldsymbol{q}}_i \tag{4}$$

when $n$ 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 of the body center coordinate frame. Rearanging above equations, then the CoM motion is only related with the motion of base limb:

$$\begin{aligned}\dot{\boldsymbol{c}} = {} & \dot{\boldsymbol{r}}_o + \omega_o \times (\boldsymbol{c} - \boldsymbol{r}_o) + \boldsymbol{R}_o\, {}^o\boldsymbol{J}_{c1}\dot{\boldsymbol{q}}_1 \\ & + \sum_{i=2}^{n} \boldsymbol{R}_o\, {}^o\boldsymbol{J}_{ci}\boldsymbol{J}_i^{-1}\big(\dot{\boldsymbol{x}}_i - \boldsymbol{X}_{i1}\dot{\boldsymbol{x}}_1\big) \\ & + \sum_{i=2}^{n} \boldsymbol{R}_o\, {}^o\boldsymbol{J}_{ci}\boldsymbol{J}_i^{-1}\boldsymbol{X}_{i1}\boldsymbol{J}_1\dot{\boldsymbol{q}}_1 \end{aligned} \tag{5}$$

Also, if the base limb has the face contact with the ground, finally, all the given desired limb motions 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 shown:

$$\dot{\boldsymbol{c}}_{emc} = \boldsymbol{J}_{emc}\dot{\boldsymbol{q}}_1 \tag{6}$$

The CoM motion with embedded limb motions, $\dot{\boldsymbol{c}}_{emc}$ consists of two relations: a given desired CoM motion and the relative effect of other limb. Thus, the effect of the CoM movement generated by the given limb motion is compensated by the base limb. Therefore, the resulting motion could offer the WBC (whole body coordination) function to the humanoid robot.

## 3. CONTROLLER

Overall control architecture for biped walking control is shown in Fig. 1. An omni-directional walking pattern generation method (Hong *et al.* [1998]) makes CoM/ZMP trajectory. After we generate the walking patterns, we modify them with controllers using sensor feedback: previous walking controller which utilizes measured ZMP feedback is represented in shade region with dot line. Newly proposed controller is composed of three controllers: vibration suppression control, ZMP compensator and body attitude controller. Vibration controller and ZMP compensator can reduce the structural residual vibration in the supporting leg induced by un-modelled flexibility and improve the performance of the previous walking controller. Also, body attitude controller makes the stability of the humanoid robot better.

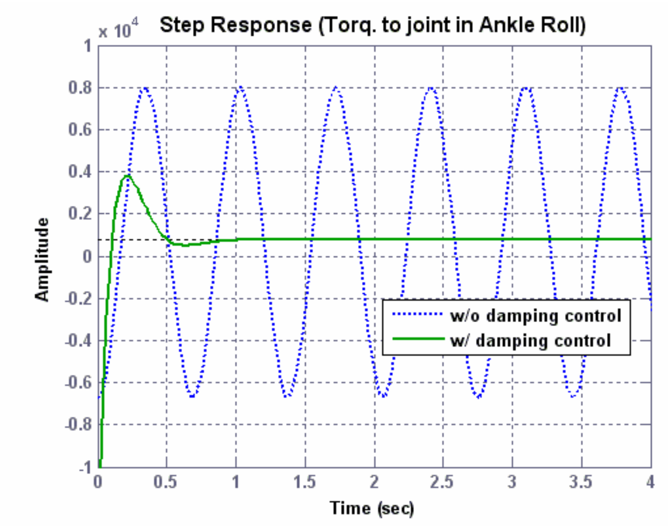


Fig. 2. Step response of vibration control (simulation result)

### 3.1 Vibration Control

Vibration controller is designed to suppress the sustained oscillation in the single supporting phase. The CoM/ZMP controller can stabilize the rigid body motion because the controller is designed by the assumption based on rigid body motion (Choi *et al.* [2007])(Kim *et al.* [2005]). However, because robot consists of the harmonic drive and the leg is relative long and flexible, an inherent flexible mode vibration induces structural vibration and this un-modelled flexibility deteriorates the performance of the CoM/ZMP controller. Hence, the controller imposes the damping forces at the ankle joints without any change of the steady-state value of the joint angle (Kim and Oh [2004b]). In order to get the proposed model parameters in (Kim and Oh [2004b]) from random excitation with frequency sweeping which is one of the simplest method utilized in system identification. Fig. 2 shows the simulation result of the proposed vibration controller during single supporting phase. The controller can suppress the flexibility of humanoid robot. The effectiveness of the proposed controller is described in the walking experimental results. Ankle pitch mode is also designed as the same manner.

### 3.2 Frequency Response Model and ZMP Compensator

ZMP is an important role of determining the stability criterion. In order to keep the stable motion planned by the pattern planner, ZMP controller can adjust the horizontal position of the torso mainly. However, in single supporting phase, because the proposed vibration controller adjusts the body motion in order to maintain stable walking and induces the inevitable movement of ZMP. Therefore, 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 in Fig. 1
In order to obtain a nominal biped robot frequency response model for the ZMP, the center of mass is excited with a variable frequency sinusoidal signal (Caballero *et al.* [2006]):

$$x_{\Delta c} = x_0 \sin(\omega t) \tag{7}$$
$$y_{\Delta c} = y_0 \sin(\omega t) \tag{8}$$

These excitation input with frequency sweeping generates other output oscillations that can be analyzed with the measured ZMP. According to 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 shown below:

$$ZMP_{\Delta x} = x_{0ZMP} \sin(\omega t) = x_{\Delta c} - \frac{1}{\omega_c^2}\ddot{x}_{\Delta c} \tag{9}$$
$$ZMP_{\Delta y} = y_{0ZMP} \sin(\omega t) = y_{\Delta c} - \frac{1}{\omega_c^2}\ddot{y}_{\Delta c} \tag{10}$$

where $\omega_c$ is a natural frequency of equivalent pendulum. Also, after (7) and (8) are applied to (9) and (10), it is then possible to write:

$$x_{0ZMP} = \left(1 + \frac{\omega^2}{\omega_c^2}\right) x_o \tag{11}$$
$$y_{0ZMP} = \left(1 + \frac{\omega^2}{\omega_c^2}\right) y_o \tag{12}$$

Because of flexibility of the robot, perfect tracking of the CoM reference trajectory is not always feasible. Uncertainties such as robot mass distribution, actuator compliance, harmonic drive compliance, structural flexibilities and other un-expected dynamics make tracking errors. However, this complex relationship between the actual and reference center of mass could be modeled using a harmonic balance method (Caballero, *et al.* [2002]). 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:

$$ZMP_{\Delta x} = a_x x_{\Delta cr} - b_x \ddot{x}_{\Delta cr} \tag{13}$$
$$ZMP_{\Delta y} = a_y x_{\Delta cr} - b_y \ddot{y}_{\Delta cr} \tag{14}$$

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(Caballero *et al.* [2006]).
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, ZMP compensator can suppress additional body motion induced flexible mode vibration controller. Fig. 3 shows damped oscillation of ZMP and the effectiveness of the proposed controller in simulation result. X-dir ZMP compensator is also designed as the same method

### 3.3 Body Attitude Control

The body attitude control reduces the difference between the desired body posture and the actual body posture

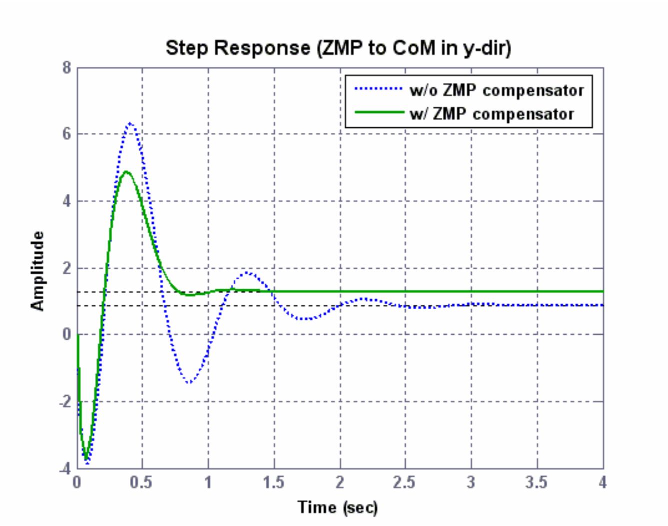


Fig. 3. Damped Oscillation of ZMP (simulation result).

which is induced by proposed controllers. The controller makes the robot recover its attitude. Here the desired body posture is given by the motion generators. The actual body posture is calculated by kinematics with joint angles. The body attitude control generated the body angular velocity as shown below:

$\omega_{\text{ref}} = \omega_d + \boldsymbol{T}(\phi)\left[\boldsymbol{K}_P(\phi_d - \phi) + \boldsymbol{K}_I \int(\phi_d - \phi)dt\right]$

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

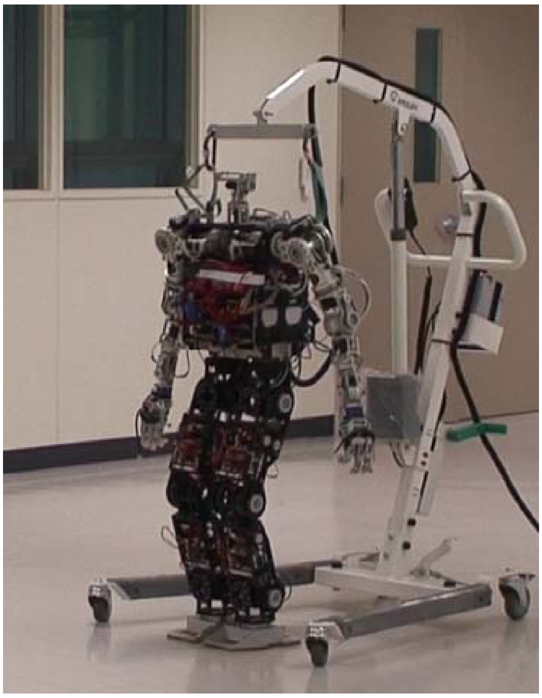

Fig. 4. Humanoid robot MAHRU-R.

## 4. EXPERIMENT

In order to show the validity of the proposed method and demonstrate its walking stability, the proposed controller was applied to MAHRU-R in Fig. 4, which is a humanoid robot developed CCRR, KIST: it is approximately

Table 1. Specification of MAHRU-R

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

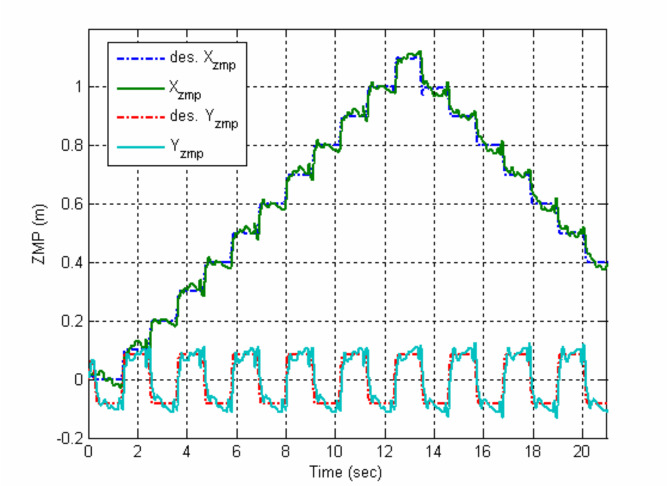


Fig. 5. Measured ZMP during straight walking with changing direction(forward to backward).

1300mm tall and weight about 50kg and its specifications are shown in Table 1.

Walking experiment was performed on a different floor surface which is not perfectly flat. Fig. 5 shows desired ZMP trajectory and measured ZMP trajectory during straight forward with changing direction forward to backward. It is evident that ZMP trajectory remains in the stable region and track desired trajectory well. Also, when the robot changed the direction of walking, it can walk stably. Also, Fig. 6 shows body orientation and measured normal force from F/T sensor. Body attitude control can compensate body attitude during walking and normal force shows flat in single support phase without large impact force. Fig. 7 shows the snap shot of experimental results walking on a common building floor based with J turn walking pattern. In this experiment, MAHRU-R can stably walk on the

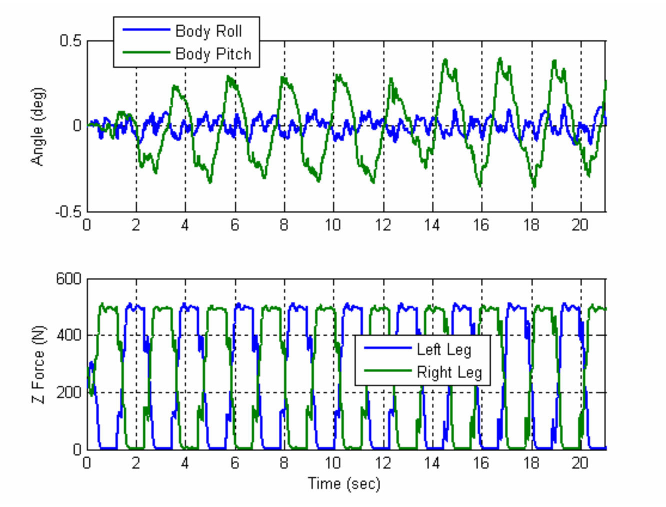


Fig. 6. Body orientation and measured normal force during straight walking with changing direction (forward to backward).

Fig. 7. J-turn walking of MAHRU-R on uneven office floor.

uneven terrain and Fig. 8 shows that it can track the given CoM / ZMP trajectory very well.

## 5. 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, ZMP compensator, body attitude control in the WBC framework. Also, newly developed humanoid platform MAHRU-R is introduced and experimental validation is 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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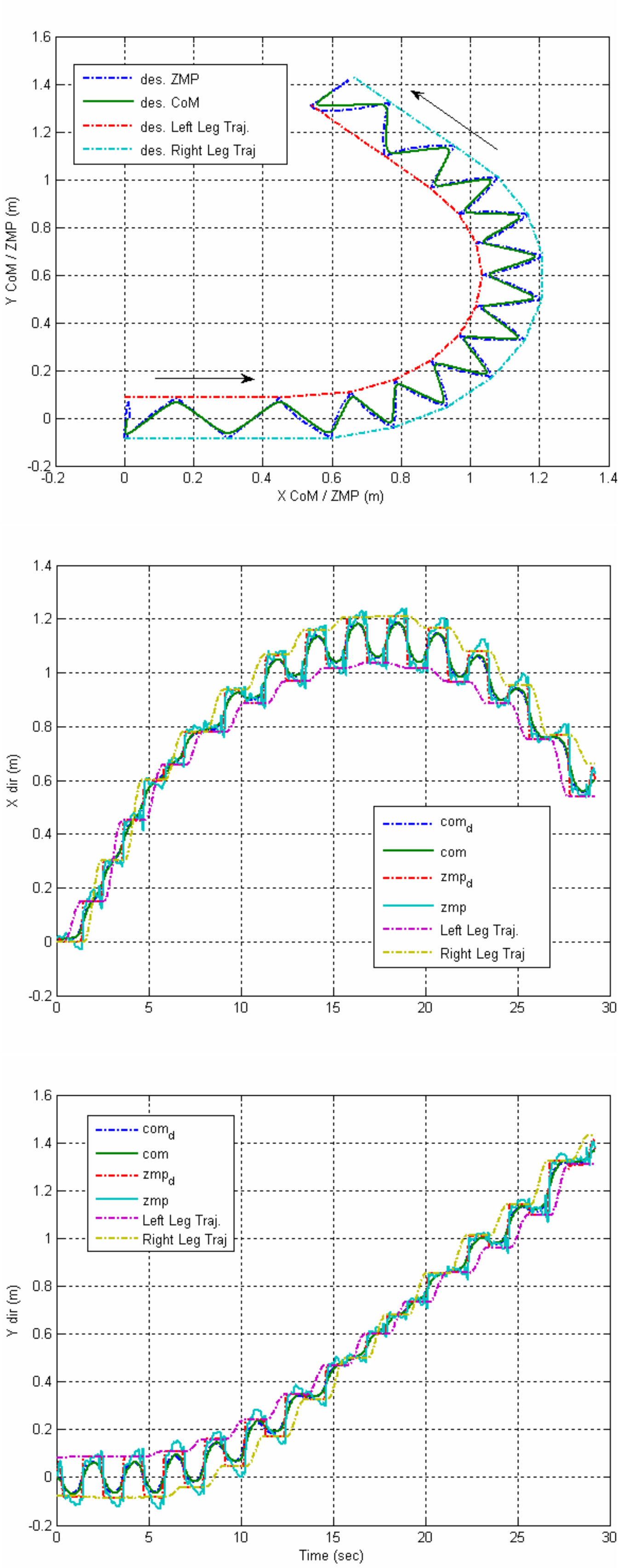


Fig. 8. Experimental results from J-turn walking of MAHRU-R on uneven office floor.