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Posture Changing Stabilization of a Humanoid Biped Robot based on Linear Regression

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***Abstract*—Stable and smooth moving is one of the most important challenge for a humanoid biped robot. In this paper, a stabilizing moving method of the humanoid biped robot is presented for the motions of a humanoid robot such as bowing and kicking motion. First, based on Zero Moment Point (ZMP) concept as the stability index, the sampled ankle angle data of a humanoid biped robot with stability are generated for the designed motions. Next, applying linear interpolation and using linear regression to obtain the complete suitable angle adjusting trajectory of the robot's ankle for the stability of the robot. The effectiveness of the proposed method was simulated by computer and experimented by a 17-degree-of-freedom (DOF) humanoid biped robot.**

***Keywords*—humanoid robot, trajectory generation, linear interpolation, linear regression, zero moment point**

I. Introduction

There have been many researches studying the moving control of humanoid biped robots. Most of their researches focused on how to keep balance and how to walk as smooth as possible. In the papers [1]-[4], the authors used Zero Moment Point (ZMP) concept to implement the balance control for the biped robot. Reference [5], [6] and [7] developed the walking pattern generator and the gravity compensation function such that the biped robot can walk and carry objects. Reference [8] described how to use fuzzy logic algorithm to reduce trunk motions of a biped robot. Reference [9] established the existence of a periodic orbit in a simple biped robot and analyzed its stability properties. A biped robot was designed in [10] to achieve a dynamically stable gait pattern allowing for high walking velocities. A walking control consisting of a feed forward dynamic pattern and a feedback sensory reflex was proposed to the biped robot in [11].

The main purpose of this paper is to propose a suitable ankle's angle changing trajectory such that the robot can achieve the posture changes from standing to other motions stably and smoothly. Based on ZMP concept as the stability index, linear interpolation and linear regression methods are applied to obtain the entire ankle adjusting angles for the robot. The final results show that the bowing and kicking motions can be simulated and realized by a real humanoid robot. Through above methods, the humanoid robot can achieve the bowing and kicking motions and keep balance at the same time.

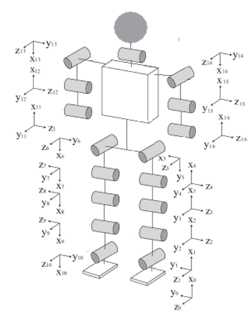


Figure 1. 17 DOF of the robot.

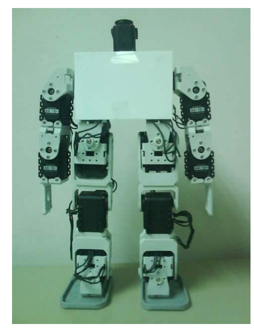


Figure 2. Photograph of the robot.

The organization of this paper is as follows. Section □ is the system descriptions including the biped humanoid robot structure. Section □ describes the trajectory establishment for postures of the robot. Simulation and practical experiment results by the humanoid biped robot are provided in Section □. The conclusion is given in the final section.

II. System Descriptions

In this paper, the considered robot is with 17 degrees of freedom (DOF) shown in Fig. 1. Fig. 2 shows the DOF configuration of the robot, each joint of which is actuated by an AX-12 motor. The maximum torque of AX-12 motor is 16.5 kg.cm under operation voltages 10 V. There is a microcontroller inside each AX-12 motor. The motor positions (feedback information) are sent to the controller system (computer) through the microcontroller by USB2 Dynamixel card. The robot's structure is modified from bioloid humanoid robot, about 30cm high, about 18cm wide and the total weight is about 3.5kg.

A. Multi-links System

The multi-links system is always applied to analyze the posture and the locomotion movement of the humanoid robot. It is also a bridge to transform a joint angle into a motor position. The multi-links system is constructed by two rotation matrices with two directions x-direction and y-direction. Fig. 3 shows the diagram of a multi-links system.

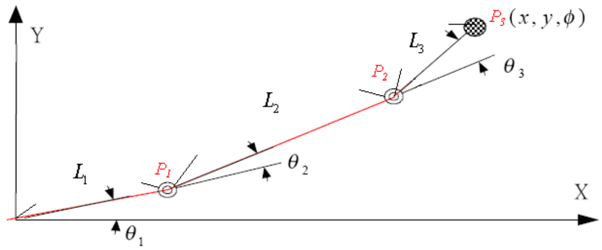


Figure 3. Multi-link system.

L_1, L_2 and L_3 are the lengths of three links respectively. θ_1, θ_2 and θ_3 are the rotated angles of three links respectively. x and y are the final positions of the multi-links system. ϕ is summation angle of θ_1, θ_2 and θ_3.

Let us define the rotation matrices as follows.

$$R_{ix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_i & -\sin\theta_i \\ 0 & \sin\theta_i & \cos\theta_i \end{bmatrix}, R_{iy} = \begin{bmatrix} \cos\theta_i & 0 & \sin\theta_i \\ 0 & 1 & 0 \\ -\sin\theta_i & 0 & \cos\theta_i \end{bmatrix}, L_i = \begin{bmatrix} 0 \\ 0 \\ l_i \end{bmatrix} \quad (1)$$

R_{ix} is the x-direction rotation matrix and R_{iy} is the y-direction rotation matrix. L_i is the length matrix and l_i is the length of link i.

Based on the definition of rotation matrices, the multi-link system in Fig. 3 can be presented as (2).

$$P_1 = R_{1x}L_1$$

$$P_2 = R_{1x}L_1 + R_{1x}R_{2x}L_2 \quad (2)$$

$$P_3 = R_{1x}L_1 + R_{1x}R_{2x}L_2 + R_{1x}R_{2x}R_{3x}L_3$$

where P_1, P_2 and P_3 are the positions of the links shown in Fig. 3. Therefore, the moving trajectories of three links can be calculated by the rotating angles θ_1, θ_2 and θ_3.

The multi-links system of a humanoid robot can be constructed in the same method. Fig.4 shows the multi-link system of the humanoid robot, in which the center of each link is defined on the mass center.

In this humanoid robot, there are 2 mass centers in each hand , 3 mass centers in each leg, and 1 mass center in the body. Therefore, the humanoid robot is made up by 11 mass centers. In Fig. 4, 11 star points are the mass centers of the links.

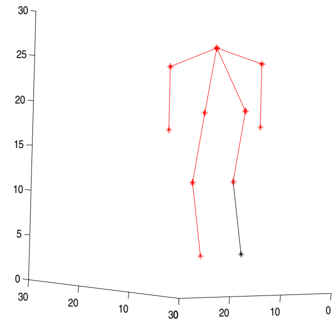


Figure 4. Humanoid robot system.

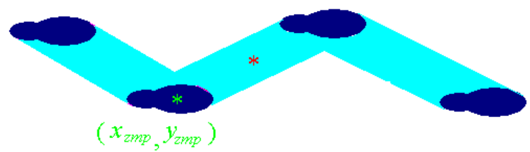


Figure 5. ZMP diagram..

B. Zero Moment Point

Zero Moment Point (ZMP) is a point where total inertial force equals zero. It is used as a stability index in the robot moving study. From [4], during signal support phase (SSP), ZMP must be located inside the support foot shown in Fig. 5 dark-blue area such as the green point. During double support phase (DSP), ZMP must be within the range surrounded by two soles shown in Fig. 5 light-blue area such as the red point. Fig. 5 shows a diagram of ZMP.

Equation (3) and (4) present the coordinates of ZMP [1].

$$x_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{p}_{iz} + g)p_{ix} + \sum_{i=1}^{n} m_i \ddot{p}_{ix} p_{iz}}{\sum_{i=1}^{n} m_i(\ddot{p}_{iz} + g)} \quad (3)$$

$$y_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{p}_{iz} + g)p_{iy} + \sum_{i=1}^{n} m_i \ddot{p}_{iy} p_{iz}}{\sum_{i=1}^{n} m_i(\ddot{p}_{iz} + g)} \quad (4)$$

where i = 0, 1, 2……n. n is the number of mass. m_i is the mass of link i. g is the acceleration of the gravity. p_{ix}, p_{iy} and p_{iz} are the coordinates of mass center i with respect to the XYZ coordinate system. $\ddot{p}_{ix}$, $\ddot{p}_{ix}$ and $\ddot{p}_{ix}$ are the accelerations of mass center i with respect to the XYZ coordinate system. Therefore, the position of ZMP (x_{zmp}, y_{zmp}) can be conculated by using (3) and (4). In order to have a stable bowing and kicking motions, the ZMP must be indise the safe region shown in Fig. 5.

III. Trajectory Generation

When the postures of the robot are changed from standing to kicking or bowing, the positions of ZMP may locate on an unstable region causing the robot to fall down. Therefore, the main goal of this paper is to propose a suitable adjusting trajectory of the ankle angles for the postures to keep ZMP inside the safe region. The method to find the suitable adjusting trajectory of the ankle angles can divide into three parts. First, sampled ankle angle data of a humanoid robot with stability are generated for bowing and kicking postures by using ankle joint controller. Second, linear interpolation is applied to get the suitable adjusting angles of the robot's ankle with the minimum ZMP errors. Finally, by using linear regression method, the complete suitable angle adjusting trajectories of the robot's ankle are approached. The flow chat of the whole proceduce is shown in Fig. 6.

A. *Ankle joint controller*

When the posture of the robot is changed from standing to kicking or bowing, the position of ZMP may locate on an unstable region. In order to keep the robot to be stable, the ankle joint is chosen as a ZMP compensator to reduce ZMP errors. By using the ZMP errors as the feedback information, ankle joint will be adjusted in x and y directions to reduce ZMP errors. Therefore, Ankle joint controller is applied to establish the sampled ankle angle trajectories of bowing and kicking motions.

It may take a lot of time to obtain the whole ankle angle trajectory of bowing and kicking motions by using ankle joint controller. Therefore, ankle joint controller is only applied to get several sampled ankle angles for bowing and kicking posture.

For example, if the robot kicks from 0 to 90 degrees. First, the kicking motion trajectory from 0 to 90 degrees is divided into 18 sample points (One sampling point is by 5 degree). ZMP error of each sampled point of kicking motion is calculated to obtain the adjusting ankle angle trajectory by using ankle joint controller.

Fig. 7 shows the block diagram of ankle joint controller. In order to maintain the upper body perpendicular to the ground, the knee angle θ_k is set as θ_a. The desired ZMP position is set as the center of the support foot. ZMP error is equal to the desire ZMP minus the present ZMP as follows:

$$error_{zmp} = ZMP_{desired} - ZMP_{present} \tag{5}$$

By using the concept of proportion controller, the adjusting angles of ankle joint can be presented as

$$\theta_a(s+1) = \theta_a(s) + K * error_{zmp}(s) \tag{6}$$

where K is a feedback gain predefined according to the expert experience.

Suppose ther are two DOF in the robot's ankle (x and y direction), the equation (6) can be rewritten as:

$$\begin{bmatrix} \theta_{a\_x}(s+1) \\ \theta_{a\_y}(s+1) \end{bmatrix} = \begin{bmatrix} \theta_{a\_x}(s) \\ \theta_{a\_y}(s) \end{bmatrix} + \begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix} * \begin{bmatrix} error_x(s) \\ error_y(s) \end{bmatrix} \tag{7}$$

where θ_{a_x} and θ_{a_y} are the adjusted ankle angles in x and y directions, respectively. K_x and K_y are the constants. Consequently, the sampled ankle angles of bowing and kicking motions can be obtain by the porposed controller.

B. *Linear interpolation*

The ZMP errors usually are not equal to zero under the ankle's angle adjustment of the ZMP compensator. In order to gets a suitable ankle adjusting angles with minimum ZMP error, linear interpolation is applied to solve this problem.

The diagram of linear interpolation is shown in Fig. 8. By using ankle joint controller, *c* and *d* can be found as the ankle adjusted angles corresponding to *b* and *a*, respectively. The ZMP error corresponding to the optimal ankle adjusted angles *x* is zero.

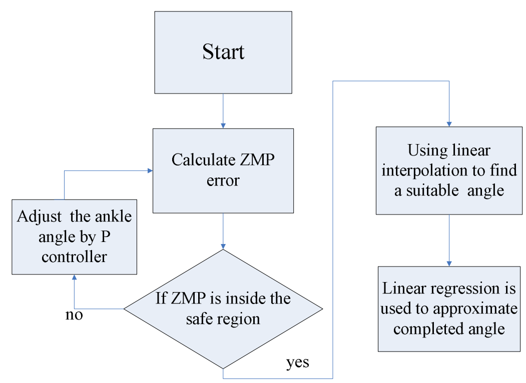


Figure 6. Flow chat of the stabilizing angle adjusted method.

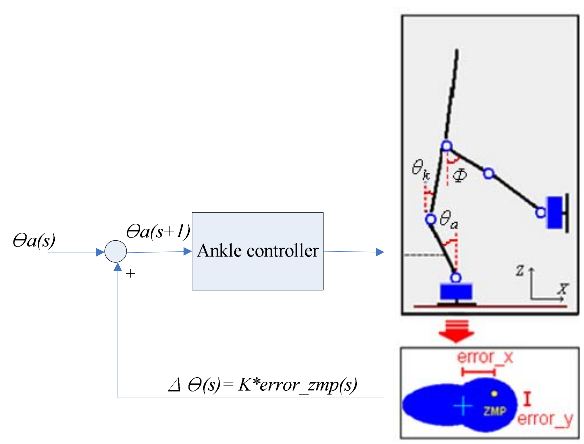


Figure 7. Block diagram of ankle joint controller.

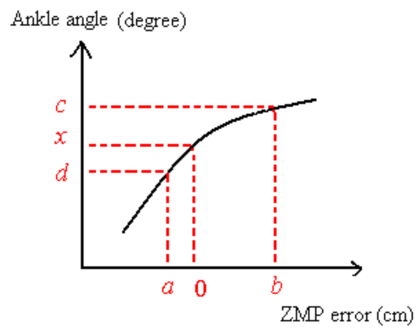


Figure 8. Diagram of linear interpolation.

By using linear interpolation method (8), the suitable angle degree can be calculated as follows:

$$x = \frac{ac - bd}{a - b} \quad (8)$$

where x is the suitable angle for sampling degree. The suitable ankle angle of several sampling points can be calculated similarly.

C. *Linear regression*

After the adjusting angle data of 18 sampled points of whole trajectory are obtained by the above methods (method A and B), the completed stabilizing trajectories of bowing and kicking motions can be approximated by using linear regression. The function of linear regression is presented as (9).

$$y = a_n x^n + a_{n-1} x^{n-1} + ... + a_1 x + 1 \quad (9)$$

where x and y are the input and output, respectively. a_n, $a_{n-1...}$ and a_1 are coefficients and n is the order.

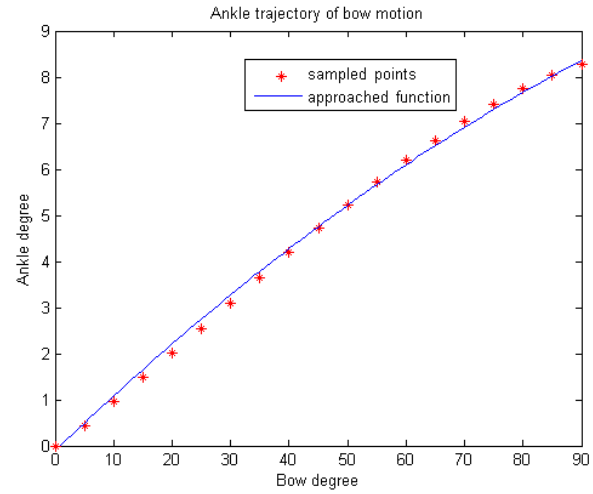
By using linear regression method, the approximated trajectory function of bowing and kicking are shown as (10) and (11), respectively.

$$y_1(x_1) = -0.00031 x_1^2 + 0.122 x_1 - 0.105 \quad (10)$$

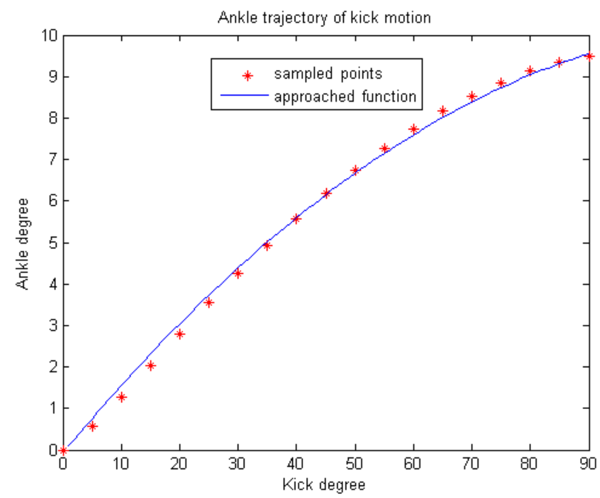
$$y_2(x_2) = -0.0007 x_2^2 + 0.17 x_2 - 0.08024 \quad (11)$$

where y_1 is the ankle angle of bow motion, x_1 is the bow degree (it is from 0 to 90 degree); y_2 is the ankle angle of kick motion and x_2 is the kick degree (it is from 0 to 90 degree).

In Fig. 9(a) and (b), the blue lines are the approximated ankle's angle trajectory of bowing and kicking motions, respectively. The red star points are the sampling points of bowing and kicking motions founded from above two methods.



(a)



(b)

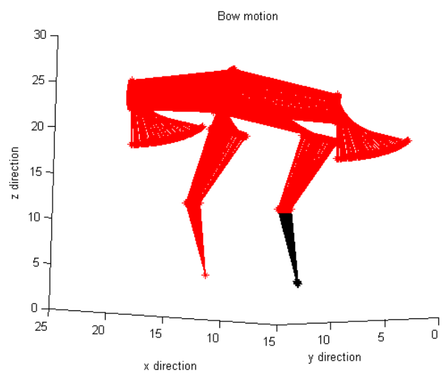
Figure 9. (a) Approximated ankle's angle trajectory of bowing motion. (b) Approximated ankle's angle trajectory of kicking motion..

IV. SIMULATION AND EXPERIMENT RESULTS

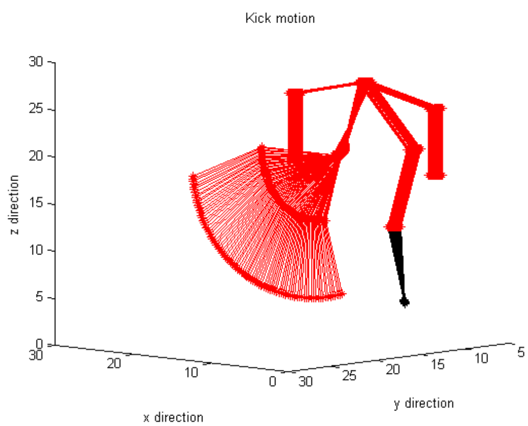
The motion simulation and experiment results for a humanoid robot are presented in this section. Part A shows simulation results of bowing and kicking motions by a humanoid robot. Part B presents experiment results by applying the simulation algorithm to a real humanoid robot. Data figures, photographs, and detail descriptions will be presented below.

A. *Simulation results*

By using the trajectory generation method introduced in Section □, the motions of bowing and kicking on a humanoid robot are simulated by the computer. Fig. 10(a) and 10(b) show the trajectories of bowing and kicking motions from 0 to 90 degrees, respectively. Fig. 11(a) and 11(b) show the ZMP errors of bowing and kicking motions from 0 to 90 degrees, respectively. The safe region of ZMP is from -2.5cm to 2.5 cm in *x* direction and -3cm to 3cm in *y* direction. The simulation results present that the ZMP errors are always inside the safe region and close to zero.

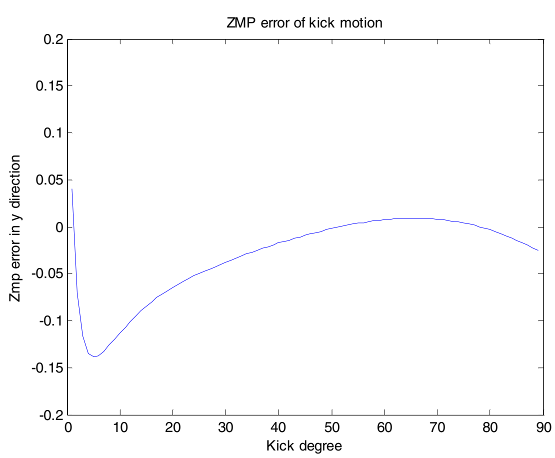


(a)

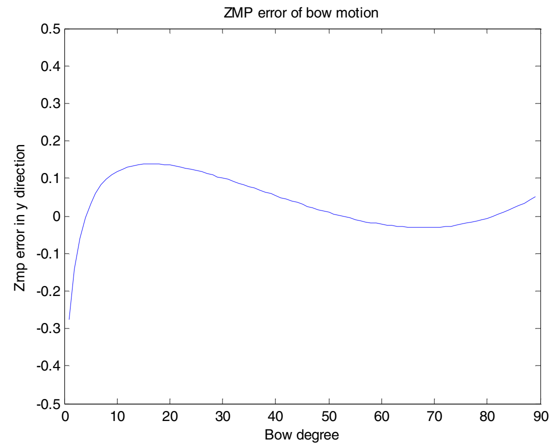


(b)

Figure 10. (a) The posture of bowing motion. (b) The posture of kicking motion.

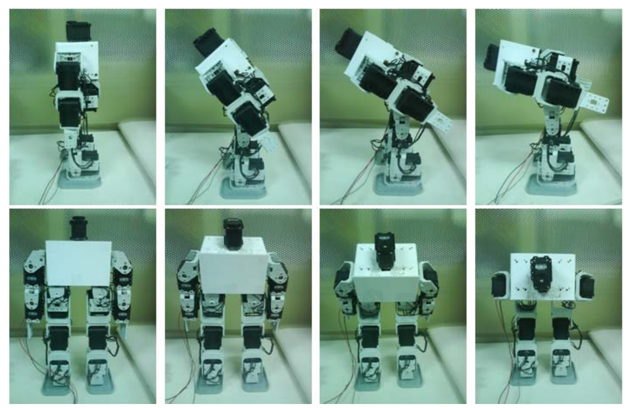


(a)

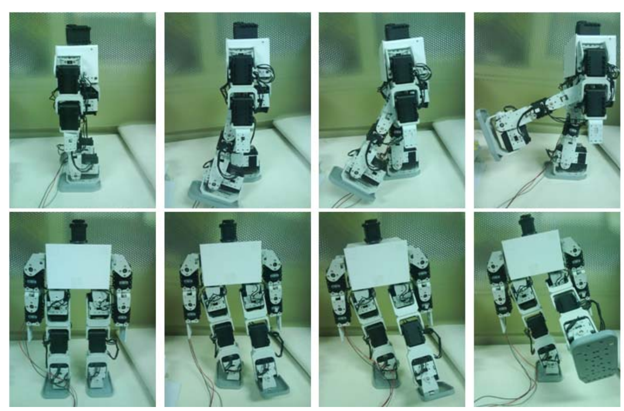


(b)

Figure 11. (a) ZMP error of bowing motion. (b) ZMP error of kicking motion.



(a)



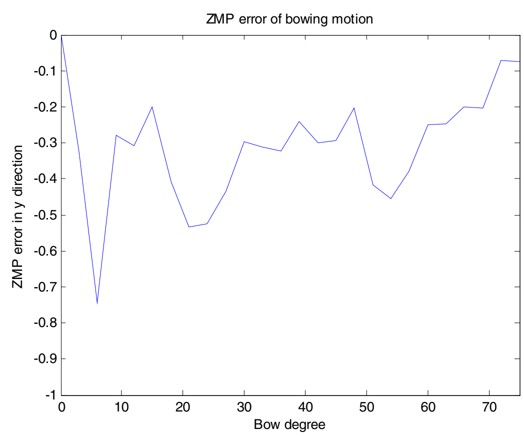
(b)

Figure 12. (a) Real experiment for bowing motion. (b) Real experiment for kicking motion.

According to the simulation and experiment results, the humanoid robot can stably change the posture from standing to bowing or kicking. The ZMP errors are close to zero and always inside the safe region. Therefore, the humanoid robot can maintain balance when changing postures.

B. Experiment results

This section presents experiment results for a humanoid robot. In order to prove the effectiveness of the proposed methods, they are realized on a real humanoid robot introduced in section . The humanoid robot practices the motions of bowing and kicking. Because of the hardware limitations of the hips, the robot can only achieve the motions of bowing and kicking from 0 to 75 degrees. Fig. 12(a) shows a series motion pictures of bowing motion. Fig. 12(b) shows the motion of kicking forward. The ZMP errors of bowing and kicking motions are calculated by the feedback information from AX-12 motors. The ZMP errors of bowing and kicking motions for a real humanoid robot are always inside the safe region from -3cm to 3cm as shown in Fig. 13(a) and 13(b), respectively. The experiment results show that the humanoid robot can smoothly and stably finish the motions of by applying the proposed methods introduced in section .



(a)

(b)

Figure 13. (a) ZMP errors of bowing motion. (b) ZMP errors of kicking motion.

V. CONCLUTIONS

In this paper, the trajectory generation method is presented to achieve continuous motions of bowing and kicking stably on a humanoid robot. Based on the stability concept of ZMP, the stable angle adjusting data of the robot's ankle are obtained to achieve bowing and kicking motions. Therefore, ankle joint controller, linear interpolation and linear regression methods are successively applied to generate the completed stable angle adjusting trajectories of motions. By the proposed methods, the humanoid robot can always keep balance from standing to bowing or kicking. The effectiveness of the proposed method has been proven by simulations and practical experiments on a humanoid robot.

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