A Stable Pose Estimation Method for the Biped Robot using Image Information

Sangbum Park and Youngjoon Han

***Abstract*—**This paper proposes a balance control scheme for a biped robot to trace an arbitrary path using image information. While moving, it estimates the zero moment point(ZMP) of the biped robot in the next step using a Kalman filter and renders an appropriate balanced pose of the robot. The ZMP can be calculated from the robot's pose, which is measured from the reference object image acquired by a CCD camera on the robot's head. For simplifying the kinematical model, the coordinates systems of individual joints of each leg are aligned and the robot motion is approximated as an inverted pendulum so that a simple linear dynamics, 3D-LIPM(3D-Linear Inverted Pendulum Mode) can be applied. The efficiency of the proposed algorithm has been proven by the experiments performed on unknown trajectory.

***Keywords*—** Biped robot, Zero moment point, Balance control, Kalman filter.

I. Introduction

THERE are high number of biped robots, generally humanoids, used within the area of service robotics, mainly in the field of exhibition and entertainment[1,2]. Especially, the kinematical structure of a humanoid robot is similar to that of a human, a humanoid robot is expected to realize such motions. For that reason, visual information can be used very effectively for maintaining balance of a walking robot. It can be proven by the fact that a human may experience difficulty in walking straight with the eyes closed. This phenomenon shows that humans depend mostly on vestibular organ, but also significantly on the visual information to keep the balance of body while walking. With this analogy, those biped robots simulating the human body may use a vision sensor to control and thus maintaining the balance of body while walking.

Applications of visual information for motion control can be easily found in industrial robots of nowadays. Such applications are mostly concentrated on visual servoing of manipulators which controls the pose of end-effecter to approach a specific trajectory by measuring the target trajectory using the visual information[3-5]. Since visual servoing is to control a manipulator based on analysis of images being provided in real-time, how to accurately and fast extract the 3D pose of the reference coordinate system becomes the major issues of visual servoing problem. To reduce the computational complexity required for solving this problem, Chesi[6] proposed a method of using 6 instead of 8 feature points which have been required for the traditional visual servoing techniques to extract the 3D pose of the reference object. It has become possible by calculating the geometrical relations among the feature points to reduce the number of variables. There are also some examples that have applied visual servoing techniques for balance control of biped robots. Differently from the visual servoing techniques used for the manipulators whose base frame is fixed to the ground, those to be used for biped robots should consider the fact that the center of mass(COM) or the zero moment point(ZMP) of robot is dynamically while a robot is walking. In order to apply the visual servoing technique used for manipulator having 6 degrees of freedom to the positioning control of a biped robot, Yamamura[7] fixed the geometrical relation between the camera frame and the robot frame to reduce the degree of freedom of each leg to 4. This approach of adapting a visual servoing technique for manipulator to the one for biped robot limits the robot's locomotion significantly. To solve the aforementioned problems merged in using visual and dynamic force sensor information for balance control with pose estimation, this paper proposes stable pose estimation method for the biped robot. For this purpose, in the first step, the motion structure of a biped robot is approximated using 3D-LIPM scheme and the reference ZMP trajectory of a biped robot is generated. The pose of the biped robot with respect to the reference image is acquired by a CCD camera on the robot's head. Since the biped robot is structured so as to have the COM concided with the center of the pelvis, the biped robot has a small error enough to ignore the position difference between them[9,10]. Therefore, the COM of the biped robot can be calculated from its pose. For the pose estimation of the biped robot, the servo controller uses the error between the reference ZMP trajectory and the current ZMP estimated by Kalman filter. The rest of this paper is constructed as follows. In section 2, the structural characteristics and the walking patterns of the walking patterns of the biped robot based on 3D-LIPM are illustrated. In section 3, the camera model is given, and the pose of robot with respect to the object frame is measured from the surround images by the camera. And the relationship between the pose and COM is explained there. In section 4, the balance control scheme is explained, which uses the error between the reference ZMP trajectory and the current ZMP estimated by Kalman filter as the input of the PID controller. The performance of the

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proposed method is evaluated by the experiments in section 5.

II. Structural Characteristics Of The Biped Robot

In this section, the structural characteristics of the biped robot to be used in this paper are illustrated first. Then, the walking pattern generation scheme is illustrated which simplifies the structural model of the robot as an inverse pendulum using the 3D-LIPM scheme and generates the symmetric and periodic walking patterns

A. Structure of the Biped Robot

Each leg of the biped robot has 6 degrees of freedom so that the foot may generate any pose in 3D space. For simplifying the kinematics analysis, the number of DH(Denavit-Hartenberg) parameters is reduced by aligning the ankle joint axis and the pelvis joint axis. The robot has no joint in the waist to align the upper body and the camera axis and each am has 3 degrees of freedom.

B. Generation of Walking Patterns of the Biped Robot

It requires complex dynamic modeling and analysis processes to analyze even a simple symmetric and periodic walking motion of a leg having six degrees of freedom. Although these processes are used, it is not guaranteed that the robot's motion can be exactly analyzed. Thus as many other researches have used eariler, this paper also uses the 3D-LIPM scheme to approximate the motion of the biped robot as that of the inverse pendulum as showing Fig. 1. The pendulum is the mass point which represents the most dominant motion of the biped robot [11,12].

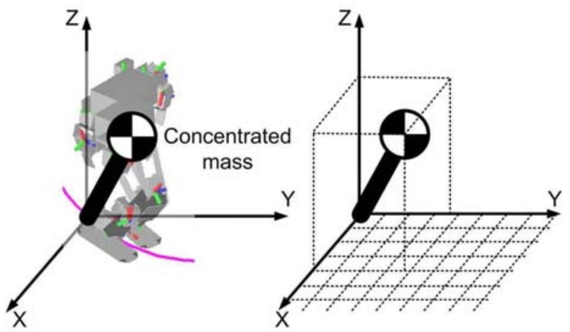


Fig. 1 Representation the motion of biped robot using the 3D-LIPM

One important feature of human walking is that the height of pelvis changes little. This feature helps simplify the complex dynamic equation by limiting the height of the motion of mass point in 3D-LIPM to a specific plane. By the dynamics analysis of the 3D-LIPM scheme, the relation between the COM and ZMP can be represented by the following equations [9].

$$-\frac{z_c}{g}\ddot{x} + x = P_x, \quad -\frac{z_c}{g}\ddot{y} + y = P_y \tag{1}$$

In Eq. (1), *(x, y)* and $(\ddot{x}, \ddot{y})$ are the differential and acceleration of the COM of biped robot in *X* and *Y* axes respectively, *g* is the gravity acceleration, (P_x, P_y) are ZMP in (*X*, *Y*) plane, and z_c is the height of the COM which does not change while the robot moves.

The principle of dynamic walking[10] tells that a biped robot may walk stable as long as the projection of the ZMP of the robot on the floor stays inside the area touched by the feet. From this principle, the trajectory of ZMP that the robot should satisfy for walking stable can be constructed from the trajectory of the feet. Fig. 2 shows an example of ZMP trajectory having a sine wave form generated with considering the symmetry and periodicity of the trajectory of the feet.

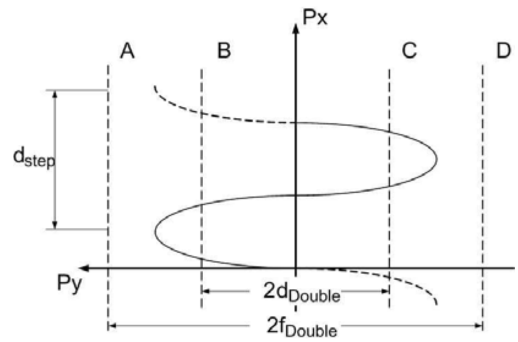


Fig. 2 ZMP trajectory of biped robot approximated as a sine wave form

To determine *y* point of the COM first, the trajectory of P_y having the angular velocity ω_y is represented as follows:Be sure that the symbols in your equation

$$P_y = A\sin\omega_y t \tag{2}$$

By applying Eq. (2), Eq. (1) is represented as the canonical non-homogeneous 2nd order differential equation as follows.

$$\ddot{y} - \frac{g}{z_c}y = -\frac{g}{z_c}A\sin\omega_y t \tag{3}$$

Since the force function P_y in the above equation is a sine wave, the steady state solution *y* will be also represented as a function of the size waves whose angular velocity is ω_y.

$$y = A_1\cos\omega_y t + B_1\sin\omega_y t \tag{4}$$

By applying this function to Eq. (4) and solving the equation with respect to *y*, Eq. (5) is obtained as the steady state solution.

$$y = \frac{g}{z_c\omega_y^2 + g}\cdot P_y \tag{5}$$

The *x* trajectory of ZMP is designed for the biped robot to have the lower speed in order to decrease the moment of inertia when the foot of the robot is touched on the floor. And the biped robot has the highest speed at the moment when the ZMP of the biped robot is entered into the center of double support area. As shown in Fig. 2, the force function P_x has the sine wave with the double angle velocity($2\omega_y$) of the P_y, and the average velocity of the biped robot according to x coordinate is the slope of the P_x function respect to time coordinate. The trajectory of P_x having the angular velocity ω_x is represented as follows:

$$P_x = \Theta_\theta \left[A \sin \omega_x t \right] \tag{6}$$

where the operator Θ_θ expresses the rotation of θ respect to time coordinate. The x position of COM can be determined as follows:

$$x = \Theta_\theta \left[\frac{g}{z_c \omega_x^2 + g} \cdot P_x \right] \tag{7}$$

Eq. (5) and (7) show that the coordinates of COM is linearly proportional to the coordinates of ZMP when the motion of COM of the biped robot is restricted to a plane where $Z=z_c$ and the trajectory of ZMP is approximated as a sine wave.

III. Estimation Of Robot's Pose From The Input Image

For simplifying the process of determining the pose of the camera with respect to the reference object, it is assumed that the feature points of the reference object are located on the same plane. This paper uses the reference object which has nine feature points equally spaced on the same plane, as shown in Fig. 3.

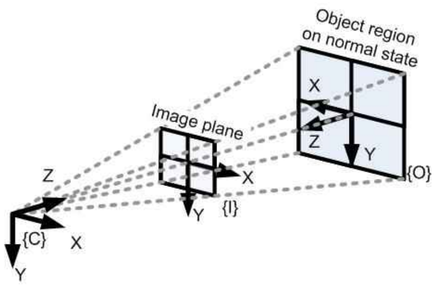


Fig. 3 Pin-hole camera model to project ${}^c\mathbf{P}_i$ on the image frame

The feature points are located in the X-Y plane in the object frame as shown in Fig. 3, their Z coordinate are zero and they can be represented as ${}^c\mathbf{P}_i=({}^cX_i, {}^cY_i, {}^cZ_i, 1)$. These points are represented as (u_i,v_i) in the computer image space and to derive inversely ${}^c\mathbf{P}_i$ from (u_i,v_i) the following parallel Eq. (8).

$$\begin{aligned} & f \cdot s_x \cdot {}^oX_i \frac{R_{11}}{T_z} + f \cdot s_x \cdot {}^oY_i \frac{R_{12}}{T_z} - (u_i - u_0) \cdot {}^oX_i \frac{R_{31}}{T_z} \\ & \qquad - (u_i - u_0) \cdot {}^oY_i \frac{R_{32}}{T_z} + f \cdot s_x \cdot \frac{T_x}{T_z} = u_i - u_0 \\ & f \cdot s_y \cdot {}^oX_i \frac{R_{21}}{T_z} + f \cdot s_y \cdot {}^oY_i \frac{R_{22}}{T_z} - (v_i - v_0) \cdot {}^oX_i \frac{R_{31}}{T_z} \\ & \qquad - (v_i - v_0) \cdot {}^oY_i \frac{R_{32}}{T_z} + f \cdot s_y \cdot \frac{T_y}{T_z} = v_i - v_0 \end{aligned} \tag{8}$$

By inserting the coordinates of the nine feature points in the object frame to Eq. (8), the following Eq. (9) is obtained which includes all the components of ${}^c\mathbf{H}_o$ the goal matrix to derive.

$$\mathbf{AK} = \mathbf{B} \tag{9}$$

To calculate T_z in Eq. (8), it is used the characteristic of the rotational matrix that the column vectors are orthogonal and also the condition that T_z is much larger than f.

$$Tz = f + \frac{1}{2}\left(\frac{1}{\sqrt{K_1^2 + K_3^2 + K_5^2}} + \frac{1}{\sqrt{K_2^2 + K_4^2 + K_6^2}} \right) \tag{10}$$

IV. Balance Control With Pose Estimation

A. Pose Estimation for a Linear Path

As shown in Fig. 4, the camera frame is fixed on the top of the biped robot so that the robot frame can be automatically determined once the pose of the camera is measured. Thus, the balance control of the biped robot becomes now a problem of determining the stable pose of the robot while walking.

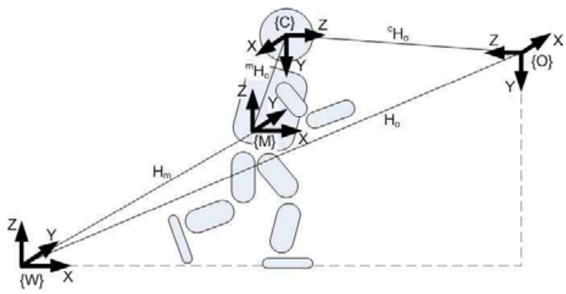


Fig 4. The relationships among the frames defined in the working environment.

For generating the stable walking pattern of the robot, this paper uses the ZMP trajectory as explained in section 2, which can calculate the COM trajectory. As the biped robot Cycloid, which is used on this paper, is structured so as to have the COM coincided with the center of the pelvis, the biped robot has the enough small error to ignore the position difference between them [9,10]. Therefore, the COM of the biped robot can be represented by Eq. (11) from the transformation relationship among the frames defined in Fig. 4.

$$\begin{aligned} \mathbf{H}_m &= \mathbf{H}_o ({}^m\mathbf{H}_c {}^c\mathbf{H}_o)^{-1} \\ &= \mathbf{H}_o {}^o\mathbf{H}_c {}^c\mathbf{H}_m \end{aligned} \tag{11}$$

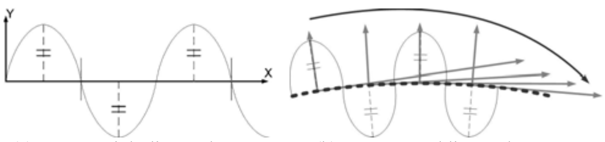
Since the COM measured from the reference object image could contain noises, the ZMP of the robot which is calculated by the Eq. (4) and Eq. (5) may be different from the reference ZMP trajectory. And the balance control of the biped robot has the general problem that it uses the error signal between the reference ZMP and the current measured ZMP as the next period control signal. As shown in Fig. 4, this paper estimates the current ZMP using Kalman filter and uses the feedback system with error signal($\mathbf{e}(k)$) between the reference ZMP trajectory and the estimation one[12].

The Kalman filter estimates the COM using the error signal input and the system noise. The COM correction in Kalman filter is performed from the measured pose of the biped robot and the measurement noise. The current period ZMP can be calculated by applying the correction one on Eq. (5) and (7).

A. Generation of Walking Patterns of the Biped Robot

In the above sections, the generation of the desired trajectory of COG for following a straight line path where the motions of the left and right legs are symmetric. However, for following a curved line path, the difference of paces (velocity) between the left and right legs is inevitable for a robot to change its motion direction. That is, the condition of symmetric motion between the left and right legs cannot be maintained and thus the generation of the trajectory of COG becomes complex problem resulting in a significant increase of computational complexity.

To estimate the trajectory of COG for following a curved line path without changing the above algorithms, this paper proposes a tangential approximation of a curved path which is illustrated in Fig.5. It finds the tangential at the present position on the curved path, and estimates the trajectory of COG along the tangential line at every step. This approach is based on the observation that the walking pace is short compared to the curvature of the curved line path so that the COG trajectory generation scheme used for a straight line path can be directly applied if it is renewed at every step along the curved line path, so shown in Fig. 5(b). Fig. 5(a) shows that the steps of the right and left legs are symmetric about the straight line path, while Fig. 5(b) also shows that they are also symmetric along the tangential of the curved line path at every step.



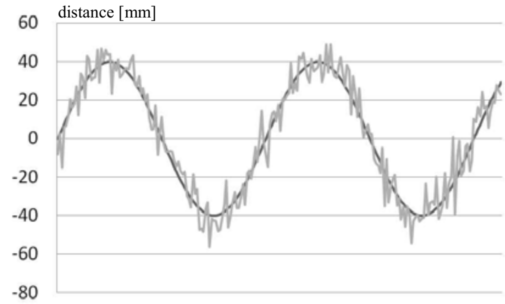
(a) For a straight line path (b) For a curved line path

Fig 5. Generation of COG trajectories

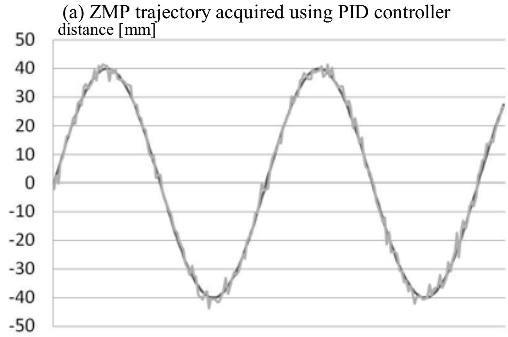
V. EXPERIMENT

The performance of the proposed scheme has been evaluated with the biped robot. The CCD camera whose image sensor size is 300 x 220 pixels and frame rate is 25[fps] is mounted on the robot's head. To visualize the process of the proposed algorithm, the GUI which is composed of three modules is implemented. The first one is to show the reference trajectory represented by that of COM of the biped robot using the 3D-LIPM, the second one is to show how the Kalman filter estimates the ZMP state in the next step from the current COM of the robot which is measured from the reference object image, and the third one is to show how similarly the actual robot trajectory follows the reference trajectory one. This GUI includes the graphic module which constructs the robot if its kinematics information is provided with. The three modules are connected by the shared memory.

For a balance control of biped robot, the proposed algorithm uses an error between the desired ZMP and the estimated ZMP by Kalman filter as the input of the PID controller. The robot initially located at (0[mm], 0[mm], 240[mm]) in the world frame walked toward the reference object along the X axis of the robot frame which coincides with the Z axis of the reference object frame. The performance of the balance control algorithm is tested by measuring how accurately the robot follows the desired ZMP trajectory. Fig. 6 shows three trajectories, acquired when the robot walked with an optimal speed of 20[mm/sec]. The first is the desired one, the second is the one obtained by using only the PID controller, and the third one is the one obtained by using the Kalman filter based PID controller that is proposed in this paper.



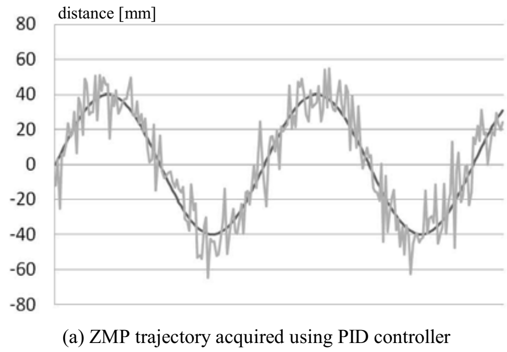
(a) ZMP trajectory acquired using PID controller



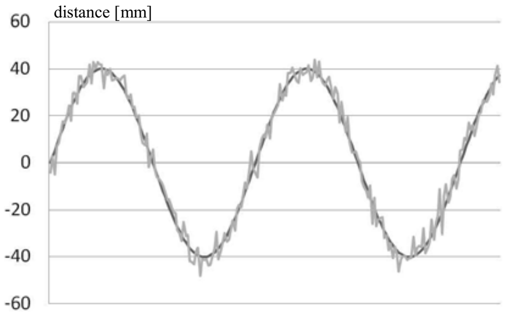
(b) ZMP trajectory acquired using Kalman filter based PID controller

Fig 6. The ZMP trajectories acquired using the proposed algorithm are compared with the reference value.

The first one and the second one are compared in Fig. 6(a) and the first one and the third one are compared in Fig. 6(b). The experimental results have shown that the balance control using only a camera is successful since the robot follows the desired ZMP trajectory within a reasonably small error boundary. The average error was 4.89[mm] when using only a PID controller and it was 1.56[mm] when using the Kalman filter based PID



(a) ZMP trajectory acquired using PID controller



(b) ZMP trajectory acquired using Kalman filter based PID controller

Fig 7. The ZMP trajectories acquired using the proposed algorithm are compared with the reference value.

controller.

With the same restrictions on the curved path, the experimental results in Fig. 7 shows that the average error was 11.87[mm] when using only a PID controller and it was 3.53[mm] when using the Kalman filter based PID controller. Fig. 8 shows the snap shots that robot follows a curved line path.

Fig. 8. The experiments for the biped robot tracking to curved path

VI. Conclusion

This paper proposed a stable pose estimation method for a biped robot which uses only the visual information in the workspace to measure the ZMP of the robot and thus to determine the pose of biped robot, with using any dynamic sensors. The pose of the robot at each sampling time was determined using a PID controller so that the current ZMP of the robot may locate at the desired ZMP which is positioned inside the stable region of the robot.

References

[1] M.Wahde and J.Pettersson, "A brief review of bipedal robotics research", Proc. Of the 8th UK Mechatronics Forum Int. Conf., pp.480-488, 2002.

[2] R.Ambrose, Y.Zheng, and B.Wilcox, "Humanoids", International Assessment of Research and Development in Robotics, World Technology Evaluation Center, Inc, pp.41-54, 2006.

[3] Wen Yu, "Stability Analysis of Visual Servoing with Sliding-mode Estimation and Neural Compensation," International Journal of Control, Automation, and Systems, Vol.4, No.5, pp.545-558, 2006..

[4] C.Taylor and J.Ostrowski, "Robust Vision-Based Pose Control," in Proceeding IEEE International Conference on Robotics and Automation, pp.2734-2740, 2000.

[5] Changhyun.C, Sungchul.K, Munsang.K and Jeabok.S, "Macro-Micro Manipulation with Visual Tracking and its Application to Wheel Assembly," International Journal of Control, Automation, and System, Vol.3, No.3, pp.461-468, 2005.

[6] J. Wang, "Fundamentals of erbium-doped fiber amplifiers arrays (Periodical style—Submitted for publication)," *IEEE J. Quantum Electron.*, submitted for publication.

[7] C. J. Kaufman, Rocky Mountain Research Lab., Boulder, CO, private communication, May 1995.

[8] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, "Electron spectroscopy studies on magneto-optical media and plastic substrate interfaces(Translation Journals style)," *IEEE Transl. J. Magn.Jpn.*, vol. 2, Aug. 1987, pp. 740–741 [*Dig. 9th Annu. Conf. Magnetics* Japan, 1982, p. 301].

[9] K.Nishiwaki, S.Kagami, Y.Kuniyoshi, M.Inaba, and H.Inoue, "Online Generation of Humanoid Walking Motion based on a Fast Generation Method of Motion Pattern that Follows Desired ZMP," IEEE/RSJ International Conference on Intelligent Robots and Systems(IROS'02), Vol.3, pp.2684-2689, 2002.

[10] K.Sorao, T.Murakami, and K.Ohnishi, "A unified approach to ZMP and gravity center control in biped dynamic stable walking," in Proceedings of Advanced intelligent Mechatronics, 1997.

[11] T.Sugihara, Y.Nakamura, and H.Inoue, "Realtime Humanoid Motion Generation through ZMP Manipulation based on Inverted Pendulum Control," IEEE International Conference on Robotics and Automation, pp.1404-1409, 2002.

[12] S.Kajita, F.Kanehiro, K.Kaneko, K.Fujiwara, K.Harada, K.Yokoi, and H.Hirukawa, "Biped Walking Pattern Generation by using Preview Control of Zero-Moment Point," Proceeding of the 2003 IEEE International Conference on Robotics and Automation, pp.1620-1626, 2003.