Proceedings of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems
September 28 - October 2, 2004, Sendai, Japan

A Novel Method of Biped Walking Pattern Generation with Predetermined Knee Joint Motion

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Abstract—**This paper describes a method of motion pattern generation for biped humanoid robot to walk like humans or walk with various kind of motions. To realize biped walking avoiding singularity at stretching leg, pattern generation uses predetermined knee joint trajectories. Reduction of DOF by predetermination is complemented by waist motion. The effectiveness of generated dynamic walking patterns is confirmed by using a 16-DOF biped robot WABIAN-2/LL.**

Keywords; Humanoid robot, Biped walking, Biped robot, Stretch Walking, Motion pattern generation

I. INTRODUCTION

The humanoid research group in Waseda University has studied about biped humanoid robots since 1966. The goal of the studies we had in the beginning and we still have today is to realize a humanoid robot which are able to be used in the same environment as humans and to clarify humans' walking mechanisms. The first biped humanoid robot WABOT-1 was developed in 1973 and realized the static walking on a horizontal plane [1]. Moreover, we realized the dynamic walking on even or uneven terrain using WL series [2] [3]. The humanoid robot WABIAN series have been developed since 1996; the emotional motion of the biped robot was presented which is expressed by the parameterization of its body motion [4]. In 2002, an online pattern generation was developed [5]. By using this method, various walking experiments with visual and auditory information were carried out [6].

Other research groups also have studied about biped humanoid robots to realize robots which are able to coexist with humans and perform a number of different tasks. For example, a research group of HONDA has developed the humanoid robot P2, P3, and ASIMO [7]. Japanese National Institute of Advanced Industrial Science and Technology and Kawada Industries, Inc. have developed HRP-2 [8] and HRP-2P [9]. University of Tokyo constructed H6 and H7 [10] [11], and Technical University of Munich also developed JOHNNIE [12]. These human-size biped robots realized stable and dynamic walking to consider Zero Moment Point (ZMP).

However, it is difficult to say that the above mentioned biped humanoid robots equal on humans in physical motion. Especially these conventional biped robots cannot realize stretch walking. The main reason why they usually walk with bended legs is a singularity problem. Considering various walking pattern generation for a biped robot, especially walking with knees stretched, it is difficult for only solving inverse kinematics based on the position and orientation of the foot and the waist to derive such a walking pattern. Actually a human has more number of redundant DOF than conventional biped humanoid robots, which enables them to achieve various motions. For a biped humanoid robot to realize a human motion, it must have a human-like mechanism in view of mechanical DOF configuration.

In advance of this study, we already have developed an algorithm which enables a biped humanoid robot to stretch its knees in steady walking avoiding singularity by using waist motion [13]. Moreover we have developed a new biped walking robot named WABIAN-2/LL (WAseda BIpedal huMAnoid-2 Lower Limb, Fig.1), which has 3-DOF in each ankle, 1-DOF in each knee, 3-DOF in each hip and 2-DOF in the waist, and carried out stretch walking experiment by using this robot [14].

In this paper, problems of previous studies and solution of that by using predetermined knee joint motions are described at first. Next, a pattern generation method for biped humanoid robot to realize various kind of walking is presented. Through software simulation and walking experiment using WABIAN-2/LL, this novel method of biped walking pattern generation is confirmed.

II. HUMAN-LIKE WALKING FOR A BIPED ROBOT

A. Probrems of Previous Stretch Walking Algorythm

To derive lower-limb joint angles of a biped robot, inverse kinematics calculation based on the position and orientation of the foot and the waist is a common and effective method. It is difficult for this method to create a stretch walking pattern because the leg has the singular point at which the joint rate approaches infinity when the knee is stretched out. However, if knee joints are fixed in advance of the calculation, they are able to be controlled

This research was supported in part by a Grant-in-Aid for the WABOT-HOUSE Project by Gifu Prefecture.

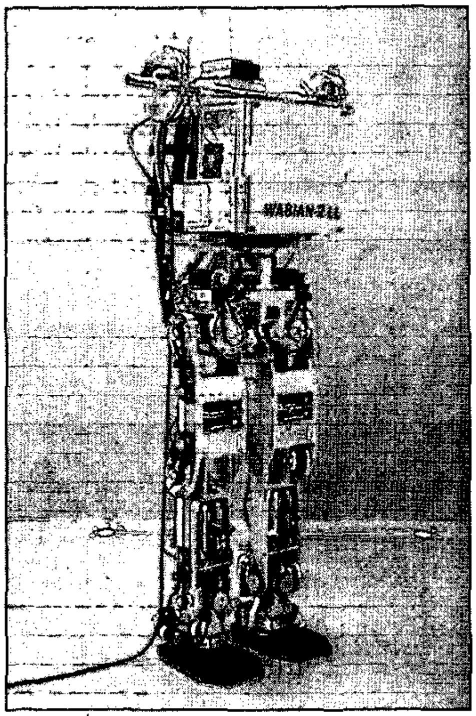


Figure 1. WABIAN-2/LL

with singular configuration or neighborhood of the configuration.

Essential features of the previous stretch walking pattern generation [13] are listed below.

- Calculation of a joint angle differs depending on whether the leg is in swinging phase or supporting phase.
- Knee angle of supporting leg is set as an initial parameter.
- Knee stretching is determined by angular velocity limitation.
- The singularity of the swinging leg can be avoided using waist rolling motion.

Fig. 2 shows the right knee patterns calculated by a pattern generator (reference) and measured by the motor encoder (response), and Fig. 3 shows the designed Y-ZMP trajectory (reference) and the Y-ZMP trajectory measured by the six axes force/torque sensors (response), in an experiment with step length of 0.20m.

However the biped robot could not realize any stable walking with a step length of more than 0.2m/step because of low stiffness of the framework and the servo driving. Also a walking pattern with rapid change in angular velocity caused unstable behavior, especially at the time when the robot changes a supporting leg to a swinging leg (marked with red circle).

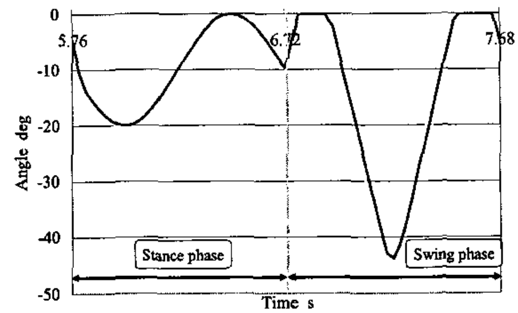


Figure 2. Knee joint pattern by previous generation

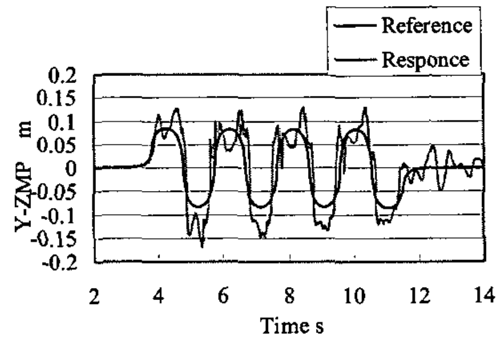


Figure 3. Stretch walking ZMP trajectory

This problem can be solved by using knee joint trajectories predetermined respectively in whole walking phase. Using specified continuous and differential trajectories as knee joint patterns in advance, a walking pattern is generated stably. Moreover, a posture with knees stretched of biped robots controlled in such way does not mean singular configuration in principle. Waist motion parameter relative to reduction of DOF with predetermined knee joint angles is described in next.

B. Waist Motion

Fig. 4 shows a popular DOF configuration for a lower limb of biped humanoid robot, which has 2-DOF in each ankle, 1-DOF in each knee and 3-DOF in each hip joint. Let a world coordinate frame $\sum_o(O-xyz)$ be defined on the ground where the robot can walk and moving frames ${}^O\sum_{R0}$, ${}^O\sum_{L0}$ and ${}^O\sum_{W0}$ be fixed on the two feet and waist respectively. If each foot trajectory has 6-DOF which is defined by position vector ${}^O\mathbf{p}_{R0\,or\,L0} \in R^3$ and orientation matrix ${}^O\mathbf{E}_{R0orL0} \in R^3$ respectively, the coordinate of the left foot relating to the right foot ${}^{R0}\sum_{L0}$ is described as six dimensional parameters, ${}^{R0}\mathbf{p}_{L0}$ and ${}^{R0}\mathbf{E}_{L0}$. The entire robot system can be regarded as a 12-DOF serial link mechanism; therefore the waist trajectory can be given as 6-DOF motion patterns, ${}^{R0}\mathbf{p}_W$ and ${}^{R0}\mathbf{E}_W$, which is also described as ${}^{O}\mathbf{p}_W=(p_{wx}, p_{wy}, p_{wz})^T$ and ${}^{O}\mathbf{E}_W=[\mathbf{e}_{wx}\ \ \mathbf{e}_{wy}\ \ \mathbf{e}_{wz}]\ \ (|\mathbf{e}|=1)$.

By using two predetermined knee motions, the robot can be regarded as a 10-DOF mechanism as shown in Fig. 5(b); the waist trajectory can be given as 4-DOF motion patterns. That is to say, two out of six parameters (position and orientation of the waist) depend on the other four parameters. By choosing those parameters respectively, a biped humanoid robot will realize various human-like walking motions.

In this study, waist horizontal motion p_{wx} and p_{wy} are used for ZMP compensation in order that the robot can walk without loosing its balance. Rotation about $\mathbf{e}_{wy}$ (defined as pitch motion in this study) and $\mathbf{e}_{wz}$ (defined as yaw motion) are definable parameters. Also knee joint trajectories are definable, so waist vertical motion p_{wz} and rotation about $\mathbf{e}_{wx}$ (defined as roll motion) depend on the other parameters.

III. Walking Pattern Generation

A. Calculation Method for Joint Angles

This motion pattern generation covers a biped robot which has the configuration in Fig.4. Although WABIAN-2 has actually 7-DOF legs which consist of 3-DOF ankles and 1-DOF knees and 3-DOF hip joints, ankle yaw joints are fixed at first in order that these redundant DOF shall be used for knee turning motion in this study.

First, according to predetermined knee joint angles, θ_{R3} in right knee and θ_{L3} in left knee, a length from ankle to hip joint, l_{RL} and l_{LL} are determined as

$$l_{RL} = \sqrt{l_{R2}^{\ 2} + l_{R3}^{\ 2} - 2l_{R2}l_{R3}\cos(\theta_{R3})} \tag{1}$$

$$l_{LL} = \sqrt{l_{L2}^{\ 2} + l_{L3}^{\ 2} - 2l_{L2}l_{L3}\cos(\theta_{L3})} \tag{2}$$

, where l_{R2} and l_{L2} are the lengths of shin link in right and left leg respectively, l_{R3} and l_{L3} are the lengths of thigh link as shown in Fig. 4. It follows that the biped robot DOF configuration can be equated with a configuration as shown in Fig. 5.

Next, according to the preset foot position $\mathbf{p}_{L0}$ and orientation $\mathbf{E}_{L0}$, position vector of center of waist $\mathbf{p}_{W(L)}$ is calculated by using the left leg as follows;

$$\mathbf{p}_{W(L)} = \mathbf{E}_{L0}\left[\begin{pmatrix}0\\0\\l_{LF}\end{pmatrix} + \mathbf{E}_{L1}\cdot\mathbf{E}_{L2}\left\{\begin{pmatrix}0\\0\\l_{LL}\end{pmatrix} + \mathbf{E}_{L3}\cdot\mathbf{E}_{L4}\cdot\mathbf{E}_{L5}\begin{pmatrix}0\\-l_H\\0\end{pmatrix}\right\}\right] + \mathbf{p}_{L0} \tag{3}$$

,

where $\mathbf{E}_{Li} = [\mathbf{e}_{Lix}\ \ \mathbf{e}_{Liy}\ \ \mathbf{e}_{Liz}] = \begin{bmatrix} e_{Lixx} & e_{Liyx} & e_{Lizx} \\ e_{Lixy} & e_{Liyy} & e_{Lizy} \\ e_{Lixz} & e_{Liyz} & e_{Lizz} \end{bmatrix}$

is orientation matrix of link (i) relative to link (i-1), l_{LF} and l_H are the length of foot link in left leg and the half

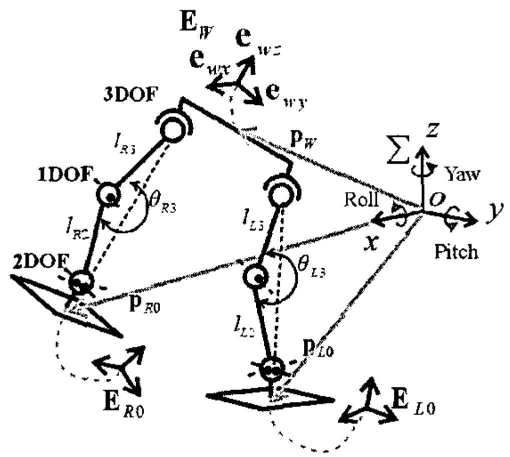


Figure 4. A popular biped humanoid robot

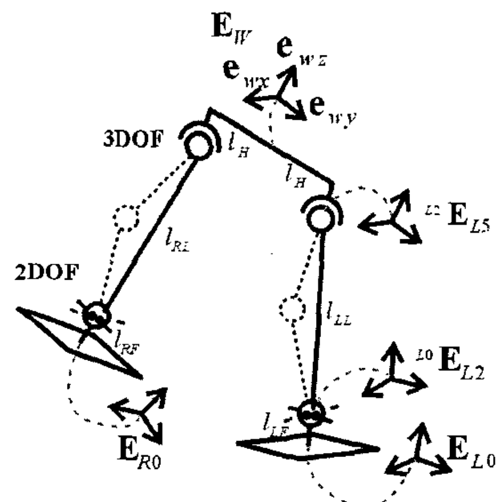


Figure 5. A cordinate flame as 10-DOF lower limb

length of waist link. $\mathbf{E}_{Li}$ is also a rotation matrix made by each joint angle θ_{Li}, which is defined as $\mathbf{E}_{Li}(\theta_{Li}) \in R^1$

Considering the orientation of waist, ${}^{O}\mathbf{E}_W$ is described as

$$\mathbf{E}_W = \mathbf{E}_{L0} \cdot \mathbf{E}_{L1} \cdot \mathbf{E}_{L2} \cdot \mathbf{E}_{L3} \cdot \mathbf{E}_{L4} \cdot \mathbf{E}_{L5} \tag{4}$$

, thus Eq. (3) can be rewritten using Eq. (4) as

$$\mathbf{p}_{W(L)} = \mathbf{E}_{L0}\left\{\begin{pmatrix} 0 \\ 0 \\ l_{LF} \end{pmatrix} + \mathbf{E}_{L1} \cdot \mathbf{E}_{L2}\begin{pmatrix} 0 \\ 0 \\ l_{LL} \end{pmatrix}\right\} + \mathbf{E}_W\begin{pmatrix} 0 \\ -l_H \\ 0 \end{pmatrix} + \mathbf{p}_{L0}. \tag{5}$$

Therefore, $\mathbf{p}_{W(L)}$ can be described as

$$\mathbf{p}_{W(L)} = l_{LF}\mathbf{e}_{L0z} + l_{LL}\mathbf{E}_{L0} \cdot \mathbf{E}_{L1} \cdot \mathbf{e}_{L2z} - l_H \mathbf{e}_{Wy} + \mathbf{p}_{L0}. \tag{6}$$

$\mathbf{p}_W$ can be described again by using the right leg according to $\mathbf{p}_{R0}$ and $\mathbf{E}_{R0}$ as

$$\mathbf{p}_{W(R)} = l_{RF}\mathbf{e}_{R0z} + l_{RL}\mathbf{E}_{R0} \cdot \mathbf{E}_{R1} \cdot \mathbf{e}_{R2z} + l_H \mathbf{e}_{Wy} + \mathbf{p}_{R0}. \tag{7}$$

$\mathbf{p}_{W(L)}$ and $\mathbf{p}_{W(R)}$ shall be the same position vector of center of waist, thus identical equation is derived as follows;

$$\begin{aligned} & l_{LF}\mathbf{e}_{L0z} + l_{LL}\mathbf{E}_{L0} \cdot \mathbf{E}_{L1} \cdot \mathbf{e}_{L2z} - l_H \mathbf{e}_{Wy} + \mathbf{p}_{L0} \\ & = l_{RF}\mathbf{e}_{R0z} + l_{RL}\mathbf{E}_{R0} \cdot \mathbf{E}_{R1} \cdot \mathbf{e}_{R2z} + l_H \mathbf{e}_{Wy} + \mathbf{p}_{R0} \end{aligned} \tag{8}$$

In Eq. (8), $\mathbf{E}_{L1}(\theta_{L1})$, $\mathbf{E}_{R1}(\theta_{R1})$, $\mathbf{e}_{L2z}(\theta_{L2})$, $\mathbf{e}_{L2z}(\theta_{L2})$ and $\mathbf{e}_{Wy} \in R^2$ are variables. If waist horizontal motion is predetermined, p_{wx-c} and p_{wy-c} are applied as follows;

$$\begin{aligned} p_{Wx(L)} &= p_{Wx(R)} = p_{Wx-c} \\ p_{Wy(L)} &= p_{Wy(R)} = p_{Wy-c} \end{aligned} \tag{9}$$

, $\mathbf{E}_{L1}(\theta_{L1})$, $\mathbf{E}_{R1}(\theta_{R1})$, $\mathbf{e}_{L2z}(\theta_{L2})$ and $\mathbf{e}_{L2z}(\theta_{L2})$ can be calculated by using Eq. (9) as variables with elements of $\mathbf{e}_{Wy}$.

As a result, Eq.(8) become a equation relative to p_{Wz} with two dimensional parameters $\mathbf{e}_{Wy}$; waist roll and yaw motion. In this study, waist yaw motion is predetermined as initial walking parameter, and then waist roll motion is calculated by solving this equation.

Finally, whole joint angles are calculated by solving inverse kinematics based on the position and orientation of the feet and the waist determined by this method. If the robot has more number of DOF than the above mentioned biped robot has, the other joint angle will also be calculated.

B. Overview of Pattern Generation

A compensatory walking pattern based on the ZMP criterion is generated as follows:

(1) The trajectories of the foot and waist are set. ZMP trajectory is planned in the support polygon formed between the contacting foot and the ground.

(2) The moments generated by the motion of the lower-limbs are computed using the ZMP criterion.

(3) The approximate compensatory motion of the linearized and decoupled biped model is computed by using FFT and IFFT.

(4) To get the strict solution, this calculation is repeated as shown in Fig. 6.

Above mentioned calculation method for joint angles is used in red lined boxes in Fig. 6. The detailed description on calculation can be found in [5].

IV. SOFTWEAR SIMULATION

A. Predetermined Knee Joint Pattern

To confirm the pattern generation method proposed in this study, Software simulations were carried out. Fig. 7 shows generated various walking patterns plotted as stick diagrams of right leg motion. Knee joint motions are predetermined by using cubic spline functions which follow continuous and differential trajectories and make

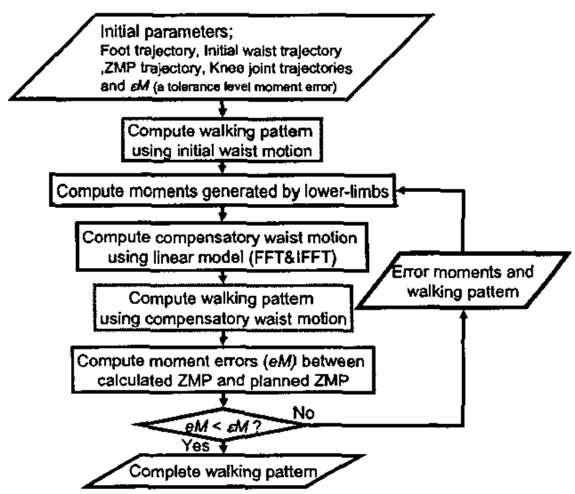
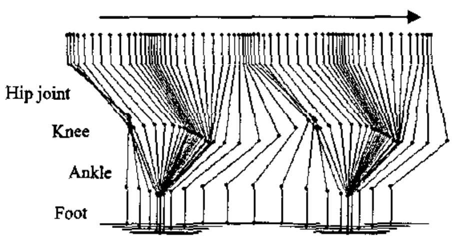
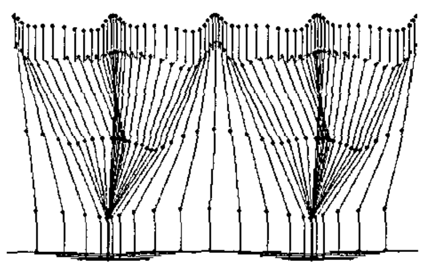


Figure 6. Pattern generation

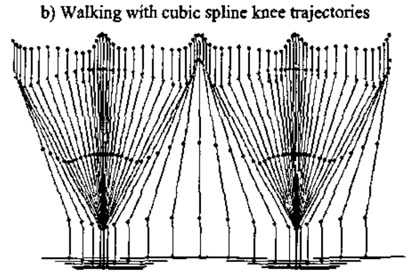
these generations easy with preset some point on the trajectory. These stick diagrams are plotted in the middle of walking with a focus on steady walking. Figure 7 a) is a walking pattern with a constant waist height, which is generated by conventional pattern generation method. Figure 7 b) is the same motion as an after-mentioned walking experiment using WABIAN-2 LL, which is walking with the step length of 0.35m and the step time of 0.96s/step (1.3km/h approximately). Also Fig. 7 c) is generated with a constant right knee joint angle set at full stretch in whole walking phase (0.35m/step, 0.96s/step). This walking may be regarded as a human walking with a handicapped leg. More over the pattern generation method can follow a walking with a long step length as Fig. 7 d) (0.50m/step, 0.96s/step).



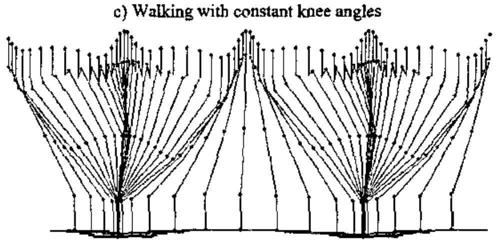
a) Conventional walking



b) Walking with cubic spline knee trajectories



c) Walking with constant knee angles



d) Walking with the step length of 0.5m

Figure 7. Stick diagrams

V. Walking Experiment

A. Stretch Walking

Stretch walking experiments were carried out on a horizontal flat plane by using WABIAN-2/LL and generated stretch walking patterns.

The experiments were done with a step cycle of 0.96s/step, a step height of 0.03m and seven different step lengths of every 0.05m from 0.00m to 0.35m. The results showed that stable walking with all step lengths can be realized. Fig. 8 shows a scene of the walking experiment with a step length of 0.35m/step. Fig. 9 shows the right knee patterns predetermined by cubic spline functions (reference) and measured by the motor encoder (response). Also Fig. 10 shows the designed X and Y-ZMP trajectories (reference) and the trajectories measured by the six axes force/torque sensors in this experiment (response).

B. Comparison of Energy Consumption

Current measurements of knee joint actuators were carried out to compare energy consumption between current bent-leg walking and stretch walking by using WABIAN-2/LL, two different walking patterns and current sensors mounted on knee joints.

The experiments were done with the same step cycle of 0.96s/step, step height of 0.03m and step length of 0.2m, respectively. A waist height of conventional walking was set as 0.63m because a maximum knee joint angular

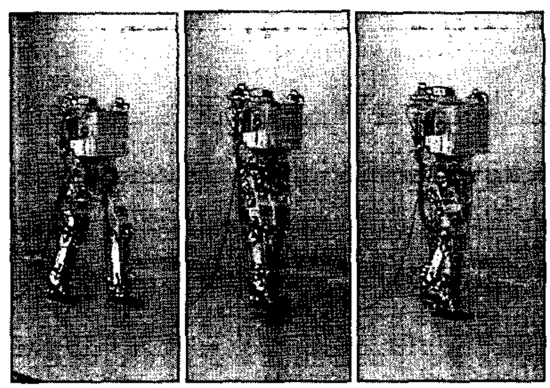


Figure 8. Walking experiment

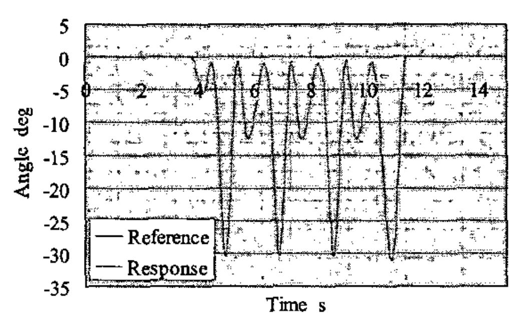


Figure 9. Right knee joint motion

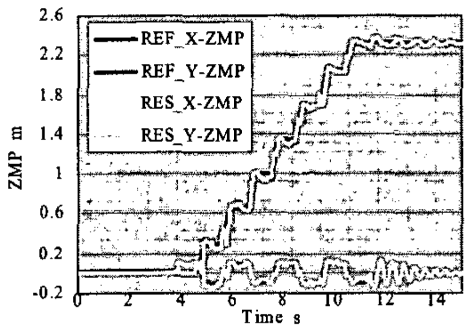


Figure 10. ZMP trajectories

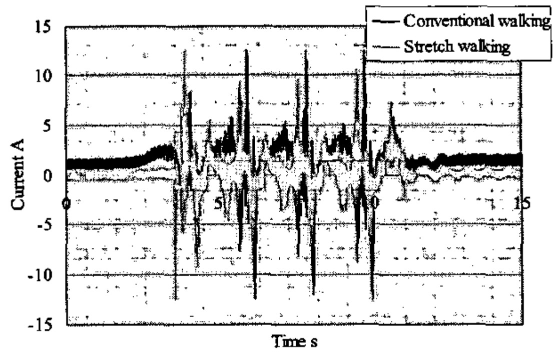


Figure 11. Mesurement of knee joint currents

velocity is about the same as stretch walking pattern. Figure 11 shows the results of measured currents from start to end of a walking. Energy consumption of conventional and stretch walking were 1295J and 697J, respectively. As a result, stretch walking realizes lower energy consumption of knee actuators than conventional walking.

VI. Conclusion and Future Work

The novel method of walking pattern generation for a biped humanoid robot to realize various kind of walking is proposed. By using predetermined knee joint motions, continuous and dynamic walking patterns with knees stretched are generated. Through software simulations and walking experiments using WABIAN-2/LL, the effectiveness of the pattern generation method was confirmed.

In spite of the result of software simulations, walking experiments with the step length more than 0.35m could not be carried out because of mechanical limitation of moveable angles. In near future, we are going to study on a method to determinate walking parameters, such as foot trajectory, ZMP trajectory and so on, for efficient walking motion using this proposed pattern generation.

Acknowledgment

A part of this research was conducted at the Humanoid Robotics Institute (HRI), Waseda University. The authors would like to express their thanks to Okino Industries LTD, Osada Electric CO., LTD, Sharp Corporation, Sony Corporation, Tomy Company, LTD and ZMP INC. for their financial support for HRI. This research was supported in part by a Grant-in-Aid for the WABOT-HOUSE Project by Gifu Prefecture and JSPS Research Fellowships for Young Scientists. We also would like to express thanks to Solid Works Japan K.K. for their supports.

References

[1] I. Kato, S. Ohteru, H. Kobayashi, K. Shirai, and A. Uchiyama, "Information-power machine with senses and limbs,"in Proc. CISM-IFToMM Symp. Theory and Practice of Robots and Manipulators, Udine, Italy, Sep. 1973, pp. 12-24.

[2] A. Takanishi, H. Lim, M. Tsuda, and I. Kato, "Realization of dynamic biped walking stabilized by trunk motion on a sagitally uneven surface," in Proc. IEEE/RSJ Int. Workshop Intelligent Robots and Systems, Tsuchiura, Japan, Jul. 1990, pp. 323-329.

[3] A. Takanishi, T. Takeya, H. Karaki, M. Kumeta, and I. Kato, "A control method for dynamic walking under unknown external force," in Proc. IEEE/RSJ Int. Workshop Intelligent Robots and Systems, Tsuchiura, Japan, Jul. 1990, pp. 795-801.

[4] H. Lim, A. Ishii and A. Takanishi, "Motion pattern generation for emotion expression," in Proc. Int. Symp. Humanoid Robots, Tokyo, Japan, Oct. 1999, pp. 36-41.

[5] H. Lim, Y. Kaneshima and A.Takanishi, "Online Walking Pattern Generation for Biped Humanoid with Trunk," in Proc. IEEE International Conference on Robotics & Automation, Washington, DC. ,USA, May. 2002, pp. 3111-3116.

[6] Y. Ogura, Y. Sugahara, Y. Kaneshima, N. Hieda, H. Lim and A. Takanishi, "Interactive Biped Locomotion Based on Visual/Auditory Information," Proceedings of the 2002 IEEE Int. Workshop on Robot and Human Interactive Communication, Berlin, Germany, Sept., 2002, pp. 253-258.

[7] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki and K. Fujimura, "The intelligent ASIMO: System overview and integration," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2478-2483, 2002.

[8] K. Kaneko, F. Kanehiro, S. Kajita, K. Yokoyama, K. Akachi, T. Kawasaki, S, Ota, and T. Isozumi, "Design of Prototype Humanoid Robotics Platform for HRP," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2431-2436, 2002.

[9] K. Fujiwara, F. Kanehiro, S. Kajita, K. Yokoi, H. Saito, K. Harada, K. Kaneko, H. Hirukawa," The First Human-size Humanoid that can Fall Over Safely and Stand-up Again," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 1920-1926, 2003.

[10] K. Nishiwaki, T. Sugihara, S. Kagami, F. Kanehiro, M. Inaba, and H. Inoue,"Design and Development of Research Platform for Perception-Action Integration in Humanoid Robot: H6," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 1559-1564, 2000.

[11] 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," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2684-2689, 2002.

[12] K. Löffler, M. Gienger, and F. Pfeiffer, "Sensor and Control Design of a Dynamically Stable Bipe Robot," Proc. IEEE Int. Conference on Robotics and Automation, pp. 484-490, 2003.

[13] Y. Ogura, H. Lim, A. Takanishi, "Stretch Walking Pattern Generation for a Biped Humanoid Robot," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 352-357, 2003.

[14] Y. Ogura, H. Aikawa, H. Lim, A. Takanishi, "Development of a Human-like Walking Robot Having Two 7-DOF Legs and a 2-DOF Waist," Proc. IEEE Int. Conference on Robotics and Automation, pp. 134-139, 2004