Proceedings of the 2000 IEEE
International Conference on Robotics & Automation
San Francisco, CA • April 2000

Balance Control of a Biped Robot Combining Off-line Pattern with Real-time Modification

Qiang HUANG[*1, *3], Kenji KANEKO[*2], Kazuhito YOKOI[*2], Shuuji KAJITA[*2], Tetsuo KOTOKU[*2]
Noriho KOYACHI[*2], Hirohiko ARAI[*2], Nobuaki IMAMURA[*4], Kiyoshi KOMORIYA[*2], and Kazuo TANIE[*2]

*1: University of Tokyo, 7-3-1 Hogo, Bunkyo-ku, 113-8656 Japan
*2: Mechanical Engineering Laboratory, 1-2 Namiki, Tsukuba, Ibaraki, 305-8564 Japan
*3: CREST Program, Japan Science and Technology Corporation, Japan
*4: Kobe City College of Technology, 8-3 Gakuen-Higashimachi Nishi-ku, Kobe, 651-21 Japan

E-mail: huang@ynl.t.u-tokyo.ac.jp, {kaneko, yokoi, kajita, kotoku, koyachi, harai, kiyoshi, tanie}@mel.go.jp, imamura@kobe-kosen.ac.jp

Abstract

Since a biped robot tends to tip over easily, stable and reliable biped walking is a very important achievement. In this paper, we propose a balance control method based on an off-line planned walking pattern with real-time modification. First, a method of generating a highly stable, smooth walking pattern is presented. Then, a method of real-time modification consisting of body posture control, actual ZMP control and landing time control based sensor information is proposed. By combining the proposed off-line walking pattern with real-time modification, the biped robot can walk smoothly and adapt to unknown environments. The effectiveness of the proposed method is confirmed by dynamic simulator such as walking on unexpected irregular rough terrain, soft ground and in environments in the presence of disturbances.

1 Introduction

Traditional industrial robots are typically used in environments that are separated from humans. However, in increasingly aging societies, the need for robots that assist human activities in human daily environments such as in offices, homes and hospitals is growing rapidly. Since wheeled mobile robots cannot easily adapt to environments designed for humans, anthropoid biped walking robots are expected to play an important role.

Since a biped robot tends to tip over easily, stable and reliable biped walking is a very important achievement. This subject has been the focus of biped robot research and has been studied mainly from two approaches.

The first approaches is to generate a stable walking pattern off-line, a method that assumes that the models of the robot and the environment are known. Some Takanishi et al. [2], Shin et al. [3], and Hirose et al. [4] have proposed methods of walking pattern synthesis based on Zero Moment Point (ZMP) [1]. Basically, these investigations first design a desired ZMP trajectory, then derive a hip or body motion that achieves the ZMP trajectory. However, since the change of the ZMP due to body motion is limited, not all desired ZMP trajectories can be achieved [7]. Furthermore, the body motion may need to vary radically to achieve the desired ZMP trajectory. To solve these problems, Huang et al. [8] have proposed a method to generate a highly stable, smooth body motion walking pattern.

Since some properties such as uneven ground surface and environmental disturbances are difficult to know in advance, it is difficult to obtain an accurate model of the actual environment. Therefore, the second approach is real-time control based on sensor information. Zheng et al. [9], Furusho et al. [10], Fujimoto et al. [11] have proposed control methods considering the interaction between the feet and the ground by using foot force sensors. Yamaguchi et al. [12] developed a foot mechanism with a shock absorbing material to adapt to uneven ground. Kajita et al. [13] achieved real-time gait control by sensing the ground profile using an ultrasonic range sensor. Kun et al. [14], Hu et al. [15] have discussed adaptive control of biped robots using neural networks.

A biped robot can walk smoothly if it has a pre-planned walking pattern, and the ability to adapt to unknown environmental factors such as disturbances and irregular terrain by the real-time control. In fact, by combining an inherent walking pattern and real-time modification, humans can walk smoothly and adapt to various unknown environments. However, previous studies have rarely considered combining the walking pattern with real-time control. Takanishi et al. [17] have proposed a method that counteracts external force by modifying the off-line walking pattern, but they only addressed changes to the gait. Hirose et al. [4] reported they had developed an anthropomorphic method using multiple sensors, however they have not yet published the details of this method.

In this paper, we propose a method of balance control consisting of an off-line walking pattern and real-time modification. The paper is organized as follows. We present the concept of the balance control in section 2, and analyze the plan of the walking pattern in section 3. In section 4, we propose a method of real-time modification using multiple sensor feedback from force sensors and body inclination sensors. Finally, we provide simulation examples such as walking on unexpected soft ground, uneven terrain and in environments in the presence of disturbances in section 5 and our conclusions in section 6.

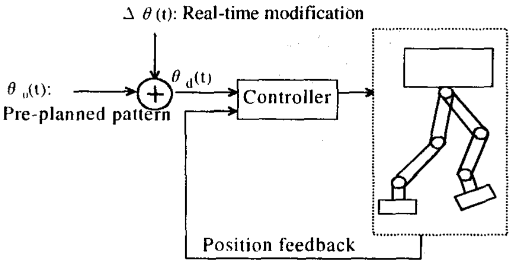


Fig. 1 Concept of balance control

2 Balance Control

Humans walk using an inherent walking pattern in normal environments such as those without disturbances and level ground, but modify their walking pattern to adapt to unexpected disturbances or irregular rough terrain. In this section, we propose the concept of such a similar method for a biped robot by combining an off-line planned walking pattern with real-time modification (Fig. 1).

To evaluate dynamic stability, we use the ZMP concept (see Appendix). The walking pattern is planned based on the ZMP off-line, assuming that the robot model and environmental conditions are known. If the actual robot model and the environmental conditions are the same as those of the planned walking pattern, the biped robot can walk stably only if follows the planned walking pattern. If there are unexpected factors in the actual environment, the planned walking pattern is modified automatically by real-time control using sensor feedback.

The object of our study is an anthropomorphic biped robot with a trunk. Each leg consists of a thigh, a lower-leg and a foot, and has 6 degrees of freedom: 3 degrees of freedom in the hip joint, 1 in the knee joint, and 2 in the ankle joint (Fig. 2).

To simplify the analysis, we will only discuss sagittal plane walking in the following. Letting $\theta_h(\mathbf{t})$, $\theta_k(\mathbf{t})$ and $\theta_a(\mathbf{t})$ be the hip, knee and ankle joints,

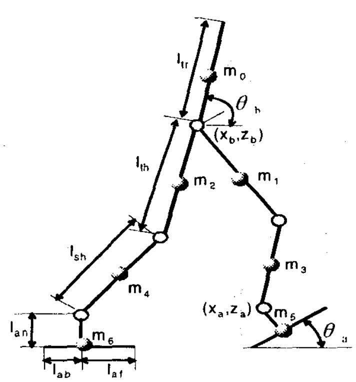


Fig. 2 Model of the biped robot

$\theta_0(\mathbf{t})=(\theta_{h0}(t),\theta_{k0}(t),\theta_{a0}(t))^T$ be the joint trajectory of off-line planned walking pattern, $\Delta\,\theta(\mathbf{t})=(\Delta\theta_h(t),\Delta\theta_k(t),\Delta\theta_a(t))^T$ be the joint increase of real-time modification (Fig. 1), the desired joint trajectory $\theta_d(\mathbf{t})=(\theta_{hd}(t),\theta_{kd}(t),\theta_{ad}(t))^T$ is given as follows:

$$\theta_d(\mathbf{t}) = \theta_0(\mathbf{t}) + \Delta\,\theta(\mathbf{t}) \tag{1}$$

3 Walking Pattern

For a biped robot to be able to walk on various ground conditions such as level ground, rough terrain and obstacle-filled environments, the robot must be capable of various types of foot motion. For example, a biped robot should be able to lift its feet high enough to negotiate obstacles, or have support feet with suitable angles that can match the roughness of the terrain. After determining the foot motion, the robot's stability should be maintained by its body motion. We have already proposed a method for planning such a walking pattern for a biped robot [8]. Here, we briefly outline this approach.

If both foot trajectories and the body trajectory are known, all joint trajectories of the biped robot will be determined by kinematic constraints. The walking pattern can therefore be denoted uniquely by both the foot trajectories and the body trajectory. For a sagittal plane, each foot trajectory can be denoted by a vector $\mathbf{X}_F=[x_f(t),z_f(t),\theta_f(t)]^T$, where $(x_f(t),z_f(t))$ is the coordinate of the ankle position, and $\theta_f(t)$ is the angle of the foot. The hip trajectory can be denoted by a vector $\mathbf{X}_B=[x_b(t),z_b(t),\theta_b(t)]^T$, where $(x_b(t),z_b(t))$ denotes the coordinate of the body position, and $\theta_b(t)$ denotes the angle of the body (Fig. 2).

3.1 Foot Trajectories

A complete walking cycle is composed of a double-support phase and a single-support phase. During the double-support phase, both feet are in contact with the ground. This phase begins with the heel of the forward foot touching the ground, and ends with the toe of the rear foot taking off the ground. During the single-support phase, while one foot is stationary on the ground, the other foot swings from the rear to the front.

Assuming that the period necessary for one walking step is T_c, the time of the kth step walking is from kT_c to $(k+1)T_c$, $k=1,2,\cdots$. We define the kth walking step to begin with the heel of the right foot leaving the ground at $t=kT_c$, and end with the heel of the right foot touching the ground at $t=(k+1)T_c$.

Let q_b and q_f be the designated slope angles of the right foot as it leaves and lands on the ground respectively (Fig. 3). Since the entire sole of the right foot is in contact with the ground at $t=kT_c$ and $t=(k+1)T_c+T_d$, the

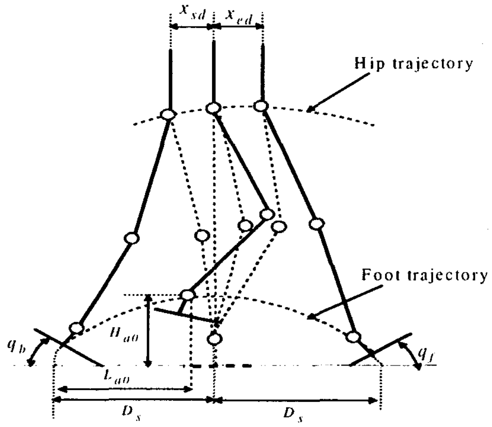


Fig. 3 Parameters of walking pattern

characteristic constraints of the right foot slope are given by the following equations:

$$\theta_f(t)=\begin{cases} q_{gs}(k) & t=kT_c \\ q_b & t=kT_c+T_d \\ q_f & t=kT_c+T_c \\ q_{ge}(k) & t=(k+1)T_c+T_d \end{cases} \tag{2}$$

where T_d is the interval of the double-support phase, $q_{gs}(k)$ and $q_{ge}(k)$ are the angles of the ground surface under the support foot, particularly $q_{gs}(k)=q_{ge}(k)=0$ on level ground.

Let (L_{ao}, H_{ao}) be the coordinate of the highest point of the swing foot (Fig. 3). From the kinematic constraints, the characteristic constraints of the right foot position are given as follows:

$$x_a(t)=\begin{cases} kD_s & t=kT_c \\ kD_s+l_{af}(1-\cos q_b)+l_{an}\sin q_b & t=kT_c+T_d \\ kD_s+L_{ao} & t=kT_c+T_m \\ (k+2)D_s-l_{ab}(1-\cos q_f)-l_{an}\sin q_f & t=kT_c+T_c \\ (k+2)D_s & t=(k+1)T_c+T_d \end{cases} \tag{3}$$

$$z_a(t)=\begin{cases} h_{gs}(k)+l_{an} & t=kT_c \\ h_{gs}(k)+l_{an}\cos q_b+l_{af}\sin q_b & t=kT_c+T_d \\ H_{ao} & t=kT_c+T_m \\ h_{ge}(k)+l_{an}\cos q_f+l_{ab}\sin q_f & t=kT_c+T_c \\ h_{ge}(k)+l_{an} & t=(k+1)T_c+T_d \end{cases} \tag{4}$$

where D_s is the length of one step, kT_c+T_m is the time when the right foot is at its highest point, l_{an} is the height of the foot, l_{af} is the length from the ankle joint to the toe, l_{ab} is the length from the ankle joint to the heel (Fig. 2).

To generate a smooth trajectory, it is necessary that second derivatives (accelerations) $\ddot{\theta}_a(t)$, $\ddot{x}_a(t)$ and $\ddot{z}_a(t)$ be continuous at all t including all breakpoints $t=kT_c$, kT_c+T_d, kT_c+T_m, $(k+1)T_c$, $(k+1)T_c+T_d$. To solve for the foot trajectory which satisfies constraints (2), (3), (4) and the constraints of second derivative continuity, we use 3rd order spline interpolation [18]. By setting the values of $q_{gs}(k)$, $q_{ge}(k)$, q_b, q_f, H_{ao} and L_{ao}, we can produce different foot trajectories.

3.2 Body Trajectory

From the viewpoint of stability, it is desirable that $\theta_b(t)$ is constant when the robot has no waist joint; in particular, $\theta_b(t)=0.5\pi$ [rad] on level ground. Body motion along the z-axis has little affect on position of the ZMP. To reduce the impact force between the sole and the ground, we can specify $z_b(t)$ to be constant, or vary within a small range. To get a smooth body motion along the x-axis with high stability, we take the following steps:

(1) Generate a series of smooth $x_b(t)$.

(2) Determine the final $x_b(t)$ with a large stability margin

$x_b(t)$ during a one-step cycle can be described by one function for the double-support phase and one function for the single-support phase. Letting x_{sd} and x_{ed} denote distances along the x-axis from the hip to the ankle of the support foot at the beginning and the end of the single-support phase, respectively (Fig. 3), we get the following equation:

$$x_b(t)=\begin{cases} kD_s+x_{ed} & t=kT_c \\ (k+1)D_s-x_{sd} & t=kT_c+T_d \\ (k+1)D_s+x_{ed} & t=(k+1)T_c \end{cases} \tag{5}$$

The initial constraints such as $x_b(t_0)=0$, and final constraints such as $x_b(t_n)=0$, are known. Using 3rd order spline interpolation, we can obtain a $x_b(t)$ trajectory that satisfies constraints (5) and second derivative continuity. We obtain a series of smooth $x_b(t)$ by setting different values of x_{sd} and x_{ed} within fixed ranges, in particular $0.0<x_{sd}<0.5D_s$, $0.0<x_{ed}<0.5D_s$. Then, the smooth trajectory $x_b(t)$ with the largest stability margin (Appendix) can be found by exhaustive search calculation.

4 Real-time Modification

Although the planned walking pattern satisfies the dynamic stability constraint, the biped robot may tip over when walking on unexpected irregular rough terrain or if affected by an external force. When the biped robot begins to tip, the body slants. If the body posture is not recovered in time, the tipping moment becomes large and slanting increases. When tipping over, in general, only one edge of the support foot is in contact with the ground. In addition, to walk continuously, the swing foot should land on the ground on time; for example, the robot will tip forward if the swing foot lands on the ground too late. To adapt to unknown environmental factors, we proposed a real-time modification consisting of body posture control, actual ZMP control and landing time control based on sensor feedback.

4.1 Body Posture Control

A biped robot tends to tip forward easily if its body leans forward from the desired posture of the planned walking pattern, or tends to tip backwards easily if its body leans backwards from the desired posture. To maintain the desired body posture, it is possible to control the hip, knee, and ankle joints. Since the hip joints are near the body, the most effective way is to control the hip joints (Fig. 4). The increase $\Delta\theta_h(t)$ of real-time modification is given as follows:

$$\Delta\theta_h(t) = \Delta\theta_{acth}(t) \tag{6}$$

where $\Delta\theta_{acth}$ is the deflection between the actual and the desired body postures. The actual body posture is measured by inclination sensors such as accelerometer and angular rate sensors.

4.2 Actual ZMP Control

Using a foot force sensor, we can measure the actual ZMP. For a sagittal plane, generally only the toe or the heel is in contact with the ground during tipping. Viewed from the concept of the ZMP, in those cases, the actual ZMP is on the toe or on the heel, that is, the actual ZMP is on the boundary of the stable region. To avoid having only one edge of the foot contacting the ground, it is necessary to have some stability margin, that is, there should be some distance between the actual ZMP and the boundary of the stable region.

If the actual ZMP is always controlled in the center of the stable region, the robot has high stability. But in that case, the robot cannot move at high speed, and the movement of the robot becomes radical even when walking at low speed. A suitable stability margin can be the same as the minimum one of the stability margins of the off-line walking pattern, or can be computed according to environmental disturbances [7]. Thereafter, the region with the stability margin is called the valid stable region (Fig. 5). Therefore, it is necessary and adequate that the actual ZMP be within the valid stable region.

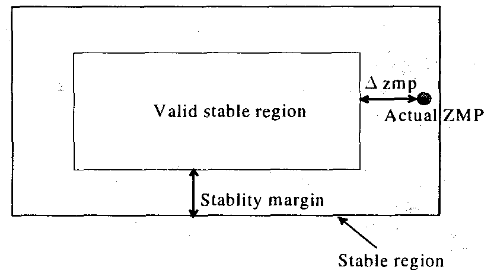


Fig. 5 Valid stable region

The most effective way of keeping the actual ZMP within the valid stable region is to control the ankle joints of the support feet. For example, suppose that the actual ZMP is on the toe, that is, only the toe is in contact with the ground. By rotating the ankle joint as shown in Fig. 5, the contact force between the toe and ground decreases, and the contact force between the heel and the ground increases relatively. The ZMP therefore moves into the valid stable region from the toe. The ankle joint increase $\Delta\theta_a(t)$ of real-time modification is calculated using the following equation.

$$\Delta\theta_a = K_a * \Delta zmp \tag{7}$$

where Δzmp is the distance between the actual ZMP and the boundary of the valid stable region (Fig. 5) and K_a is a coefficient.

4.3 Landing Time Control

To walk continuously, the transition of the swing foot to the support foot must occur at an appropriate time. If the foot lands on the ground too late, the moment of tipping forwards increases, and the robot will tip forward (Fig. 6). Conversely, if landing the ground too fast, the moment of tipping backward occurs, and the robot will tip backwards. To land on the ground on time as in the planned walking

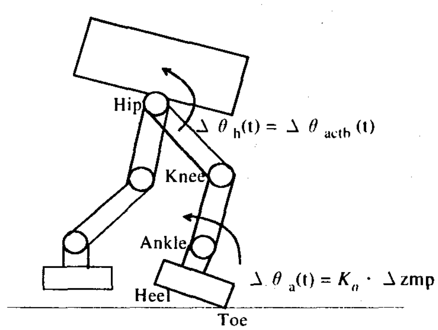


Fig. 4 Body posture control and actual ZMP control

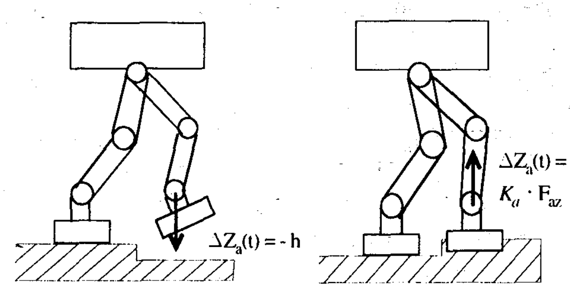


Fig. 6 Landing time control by foot position

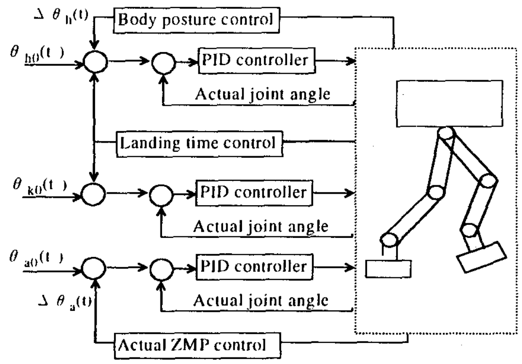


Fig. 7 Block diagram of balance control

pattern, the change $\Delta z_a(t)$ of the foot position along vertical direction is given as follows:

$$\Delta Z_a(t)=\begin{cases} k_a * F_{az} & t<T_{land}\ \&\ F_{az}>0 \\ -h & t\geq T_{land}\ \&\ F_{az}=0 \end{cases} \qquad (10)$$

where F_{az} is the ground reaction force between the landing foot and the ground which can be measured by the foot force sensor, k_a is the coefficient, and h is a constant variable, T_{land} is the landing time of the planned walking pattern. If the foot lands on the ground too fast, the robot lifts its foot in proportion to the reaction force. If the foot lands on the ground too late, the robot lowers its foot. The change of foot position from $(x_a(t), z_a(t))$ to $(x_a(t), z_a(t)+\Delta z_a(t))$ is achieved by controlling the hip and knee joints according to the kinematics. A block diagram of the entire balance control is shown in Fig. 7.

5 Simulation Examples

We constructed a biped robot simulator including dynamics, actuators, sensors and controller on an SGI workstation (Indigo2, MIPS R1000) using a dynamic software package called DADS (Dynamic Analysis and Design Systems). The PID position feedback is used as the servo controller. Using this simulator, we can simulate dynamic robot motion equivalent to an actual robot. The parameters of the biped robot (Fig. 2) were set according to Table 1.

During planning the walking pattern off-line, we

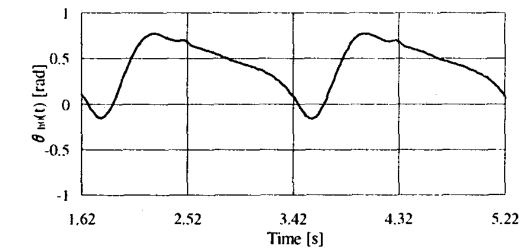
Table 1 Parameters of the biped robot

Length (cm)	l_{tr}	l_{th}	l_{sh}	l_{an}	l_{ab}	l_{af}
	60	40	40	10	10	13
Weight (kg)	m_0	m_1	m_2	m_3	m_4	m_5	m_6
	36	7.0	7.0	3.7	3.7	1.3	1.3
Inertia (kgm^2)	I_{0y}	I_{1y}	I_{2y}	I_{3y}	I_{4y}	I_{5y}	I_{6y}
	0.69	0.16	0.16	0.08	0.08	0.01	0.01

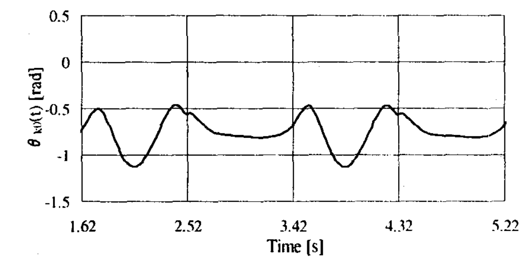
assumed that the biped robot would walk in a normal environment such as on level rigid ground and without disturbances. The step length is 0.5 [m], and the step period is 0.9 [s]. Fig. 8 shows the simulation results of the walking pattern. It is known that each joint trajectory is smooth, and that the ZMP trajectory is always near the center of the stable region.

To verify the proposed method's robust, we simulated the biped walking on unknown rough terrain, soft ground and in an environment in the presence of disturbances.

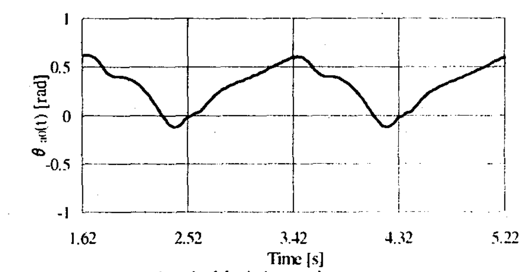
Fig. 9 shows the simulation results on unknown rigid



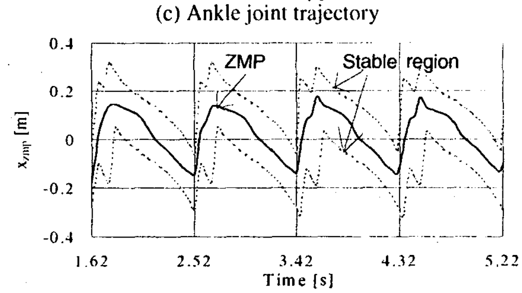
(a) Hip joint trajectory



(b) Knee joint trajectory



(c) Ankle joint trajectory



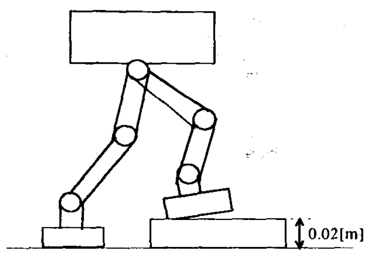
(c) ZMP trajectory

Fig. 8 Off-line planned walking pattern

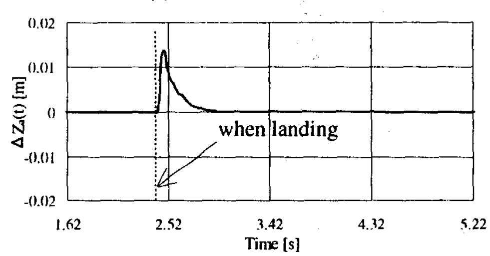
rough ground with ± 0.02 [m] height. Using our simulator, we observed that the biped robot tipped over if only it followed the off-line walking pattern, and could walk stably if the off-line walking pattern was combined with real-time modification. The change of the foot increase $\Delta Z_a(t)$ (Fig. 9 (b)) can be explained as follows. If the biped robot walks according to the off-line planned walking pattern, the depth of penetration between the landing foot and the ground is about 0.02 [m] when landing on the ground. If that were the case, a very large foot reaction force occurs, the robot will tip backwards. Therefore, the robot must lift its foot higher than the planned walking pattern, that is the $\Delta Z_a(t)$ becomes positive when landing. After the foot lands on the ground and becomes the single-support foot, the robot returns to its planned walking pattern gradually, then the $\Delta Z_a(t)$ becomes zero.

Fig. 10 shows the simulation results when the biped robot walks on soft ground. The hip increase $\Delta\theta_h(t)$ and the ankle increase $\Delta\theta_a(t)$ (Fig. 10 (b)(c)) changes are larger than on rigid ground (Fig. 9 (c)(d)). We can consider that this is because the support foot needs to adjust its hip joint and ankle joint more to keep the desired body posture and contact with the ground in the case of soft ground.

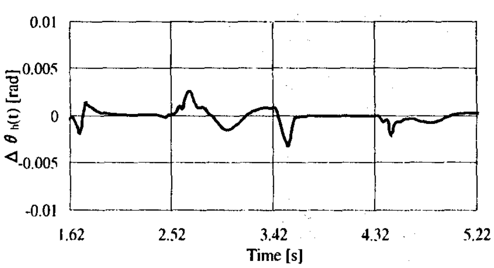
Fig.11 shows the biped robot walking in an environment in the presence of disturbance. The disturbance is assumed to be the unexpected collision force between the pendulum and the biped robot. Different collision forces add on the biped robot with different mass of the pendulum. Using our developed simulator, we can observe that the biped robot can continue walking when hit by a 3.5 [kg] pendulum.



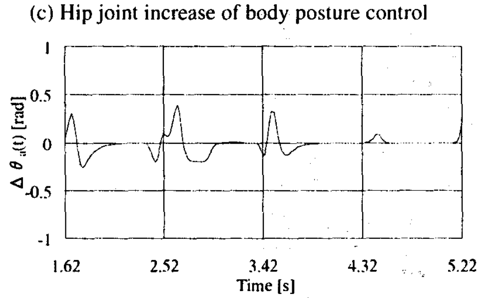
(a) unknown obstacle



(b) Foot position increase of landinf time control

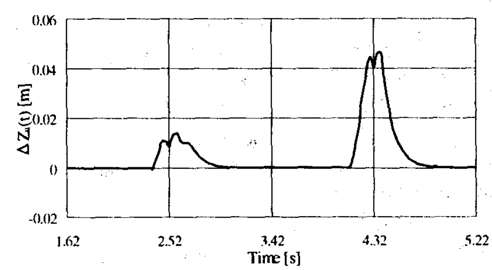


(c) Hip joint increase of body posture control

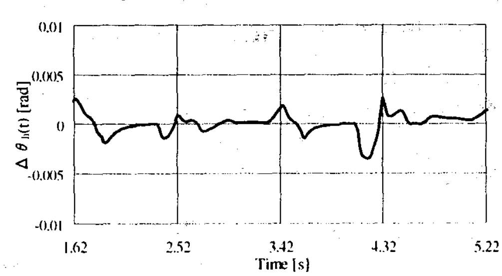


(d) Ankle joint increase of actual ZMP control

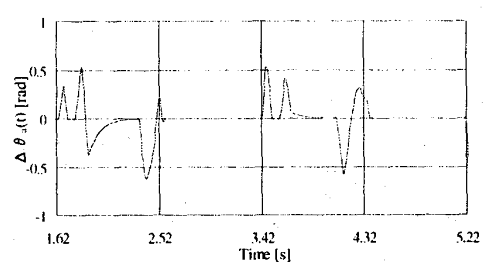
Fig. 9 Simulation results on unknown rough terrain



(a) Foot position increase of landing time control



(b) Hip joint increase of body posture control



(c) Ankle joint increase of actual ZMP control

Fig. 10 Simulation results on unexpected soft ground

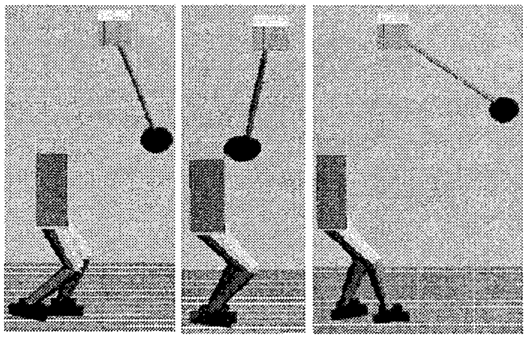


Fig. 11 Evaluation of balance control against unexpected disturbance

6 Conclusions

In this paper, we first discussed a method to plan an off-line walking pattern, and showed that various kinds of highly stable, smooth walking patterns can be obtained by setting the walking parameters. Then, real-time modification based on sensor feedback was proposed. Since this real-time control doesn't need to compute the dynamics of the biped robot, it is easy to achieve in real time. By combining the proposed off-line walking pattern with real-time modification, the robot can maintain stable walking and adapt to unknown environments. This effectiveness of our proposed method were illustrated by simulation examples such as walking on unknown irregular rough terrain, soft ground and in an environment in the presence of disturbance.

Appendix **ZMP Criterion**

The ZMP [1] is defined as the point on the ground about which the sum of all the moments of active forces equals zero. If the ZMP is within the contact polygon between the foot and the ground, the biped robot is stable. the contact polygon is called the stable region.

As it is defined, the ZMP is also equivalent to the point of the center of foot ground reaction force. For specific case, the ZMP is on the toe if only the toe is in contact with the ground. If the ZMP is near the center of the stable region, that is, the minimum distance between the ZMP and the boundary of the stable region is large, the biped robot has high stability. The minimum distance between the ZMP and the boundary of the stable region is called the stability margin (Fig. 12). The stability margin can be regarded as a measure of stability.

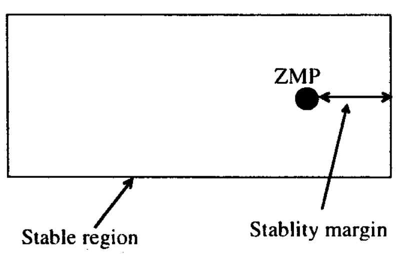


Fig. 12 Stable region and stability margin

Reference

[1] M. Vukobratovic and D. Juricic, "Contribution to the Synthesis of Biped Gait", IEEE Trans. on Bio-Medical Engineering, Vol. BME-16, No. 1, pp. 1-6 (1969)

[2] A. Takanishi, M. Ishida, Y. Yamazaki, and I. Kato, "The Realization of Dynamic Walking Robot WL-10RD", Proc. Int. Conf. Advanced Robotics, pp. 459-466 (1985)

[3] C.L. Shin, Y.Z. Li, S. Churng, T.T. Lee, and W.A. Cruver, "Trajectory Synthesis and Physical Admissibility for a Biped Robot During the Single-Support Phase", Proc. IEEE Int. Conf. Robotics and Automation, pp. 1646-1652 (1990)

[4] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The Development of Honda Humanoid Robot", Proc. IEEE Int. Conf. Robotics and Automation, pp. 1321-1326, (1998)

[5] A. Dasgupta and Y. Nakamura, "Making Feasible Walking Motion of Humanoid Robots from Human Motion Capture Data", Proc. IEEE Int. Conf. Robotics and Automation, pp. 1044-1049, (1999)

[6] T. McGeer, "Passive Walking with Knees", Proc. IEEE Int. Conf. Robotics and Automation, pp. 1640-1645 (1990)

[7] Q. Huang, S. Sugano, and K. Tanie, "Stability Compensation of a Mobile Manipulator by Manipulator Motion: Feasibility and Planning," Advanced Robotics, Vol. 13, No. 1, pp. 25-40 (1999)

[8] Q. Huang, S. Kajita, N. Koyachi, K. Kaneko, K. Yokoi, H. Arai, K. Komoriya, and K. Tanie, "A High Stability, Smooth Walking Pattern for a Biped Robot", Proc. IEEE Int. Conf. Robotics and Automation, pp. 65-71, (1999)

[9] Y. F. Zheng and J. Shen, "Gait Synthesis for the SD-2 Biped Robot to Climb Sloping Surface", IEEE Trans. on Robotics and Automation, Vol. 6, No. 1, pp. 86-96 (1990)

[10] J. Furusho and A. Sano, "Sensor-Based Control of a Nine-Link Biped", Int. J. of Robotics Research, Vol. 9, No. 2, pp. 83-98, (1990)

[11] Y. Fujimoto, S. Obata, and A. Kawamura, "Robust Biped Walking with Active Interaction Control between Foot and Ground", Proc. IEEE Int. Conf. Robotics and Automation, pp. 2030-2035, (1998)

[12] J. Yamaguchi, N. Kinoshita, A. Takanishi, and I. Kata, "Development of a Dynamic Biped Walking System for Humanoid --- Development of a Biped Walking Robot Adapting to the Humans' Living Floor ---", Proc. IEEE Int. Conf. Robotics and Automation, pp. 232-239, (1996)

[13] S. Kajita and K. Tani, "Adaptive Gait Control of a Biped Robot based on Realtime Sensing of the Ground Profile", Proc. IEEE Int. Conf. Robotics and Automation, pp. 570-577 (1996)

[14] A. Kun and W. Miller, "Adaptive Dynamic Balance of a Biped Robot Using Neural Networks", Proc. IEEE Int. Conf. Robotics and Automation, pp. 240-245 (1996)

[15] J. Hu, J. Pratt, and G. Pratt, "Adaptive Dynamic Control of a Biped Walking Robot with Radial Basis Function Neural Networks", Proc. IEEE Int. Conf. Robotics and Automation, pp. 400-405 (1998)

[16] J.K., Hodgins and M.H. Raibert, "Adjusting Step Length for Rough Terrain Locomotion", IEEE Trans. on Robotics and Automation, Vol. 7, No. 3, pp. 289-298, (1991)

[17] A. Takanishi, T. Takeya, H. Karaki, and I. Kato, "A Control Method for Dynamic Biped Walking Under Unknown External Force", Proc. IEEE int. Workshop Intelligent Robots and Systems, pp. 795-801 (1990)

[18] B.D. Bojanov, H.A. Hakopian and A.A. Sahakian, "Spline Function and Multivariate Interpolation", Kluwer Acadmedic Publishers, 1993