IEEE/RSJ International Workshop on Intelligent
Robots and Systems IROS '91, Nov. 3-5, 1991,
Osaka, Japan. IEEE Cat. No. 91TH0375-6

A Biped Walking Robot Having A ZMP Measurement System Using Universal Force-Moment Sensors

Qinghua Li, Atsuo Takanishi and Ichiro Kato

Department of Mechanical Engineering, Waseda University
3-4-1 Ookubo, Shinjuku-ku, Tokyo, 169, Japan

ABSTRACT

The authors have been using the ZMP(Zero Moment Point) as a criterion in order to distinguish the stability of walking for a biped walking robot. If the ZMP during walking can be measured, it is possible for a biped walking robot to realize stabler walking by a control method that makes use of the measured ZMP.

In this paper, a method of measuring the ZMP throughout the whole walking phase is proposed, and a newly developed biped walking robot that has a ZMP measurement system using two universal force-moment sensors is explained. The accuracy of the ZMP measurement system is experimentally confirmed, and the ZMP throughout the whole walking phase is measured. Finally the result of measured ZMP is discussed.

1. INTRODUCTION

Biped walking is essentially unstable in comparison with multi-legged walking and its control is even more difficult. Many studies of the walking control for a biped walking robot have been done from a variety of viewpoints, for example, modern control theory[1]-[2], machine mechanism[3] and biomechanism[4], etc.

The authors have been aiming the last one that human walking mechanism can be made clear in terms of biomechanism. In 1986, for achieving the walking on an uneven terrain or under external disturbance, we developed a biped walking robot WL-12 which uses a trunk for the stabilization of walking[5]. And a walking control method that we call trunk's compensative biped walking control method using the criterion of ZMP[6] was proposed. The outline of the method is as follows :

(1) We preset an arbitrary motion of the lower-limbs according to the geometry of the floor.
(2) We plan a ZMP trajectory which exists within the support polygon (stable region) created by the feet and the floor.
(3) The trunk motion is calculated for compensating the lower-limbs' motion and the ZMP trajectory.
(4) The robot's walking is executed by a program control using a set of joint motion patterns calculated by the above steps.

However, this walking control method uses only a mathematical model and a preset ZMP. The actual ZMP during walking is not measured and not reflected on the control. If the actual ZMP can be measured, it should be possible to realize stabler walking with a control method that makes use of it.

There have been many studies that focused on using force plates[7] and pylon-loads[8] to measure the ground reaction force or the ZMP in the analysis of human walking. But no example of measuring the ZMP of a biped walking robot is known so far.

Therefore, we set that the purpose of this study is to develop a biped walking robot that has a ZMP measurement system using universal force-moment sensors, and to measure the ZMP throughout the whole walking phase.

2. BIPED WALKING ROBOT WL-12RIII

The Biped walking robot WL-12RIII(Waseda Leg-12 Refined III) is shown in Fig.1. The assignment of DOFs (Degrees Of Freedom) of the robot is as follows : each of the waist, the two knees and the two ankles has one rotational DOF on pitch axis. The trunk has two DOFs, one is on pitch axis and the other is on roll axis. The total DOF is eight. The height and the total weight are about 1.7[m] and 100[kg] including the 30[kg] balancing mass on top of the trunk, respectively.

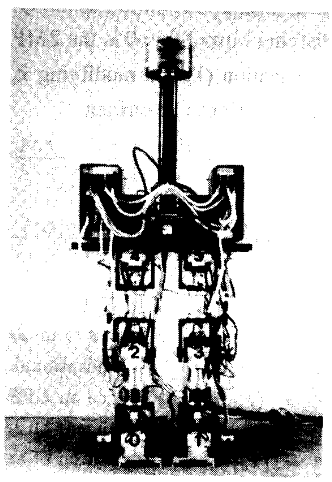


Fig.1 Photo of the biped walking robot WL-12RIII

An electro-hydro servo system, including a hydraulic RA(Rotary Actuator) and a servo valve, is employed as an actuator on each rotational joint. The angle and the angular velocity of an actuator are able to be detected simultaneously by a resolver connected directly to the actuator.

The outline of the control system of the robot is shown in Fig.2. In this control system, four 16-bit microcomputers are used. Three of the four are used to directly control the actuators of the right leg, the left leg and the trunk with a local position-feedback. The other one is located in upper control level over the other three and used as a main processor for communication with a host computer, interpolation of joint motion patterns for output and monitoring the whole robot system.

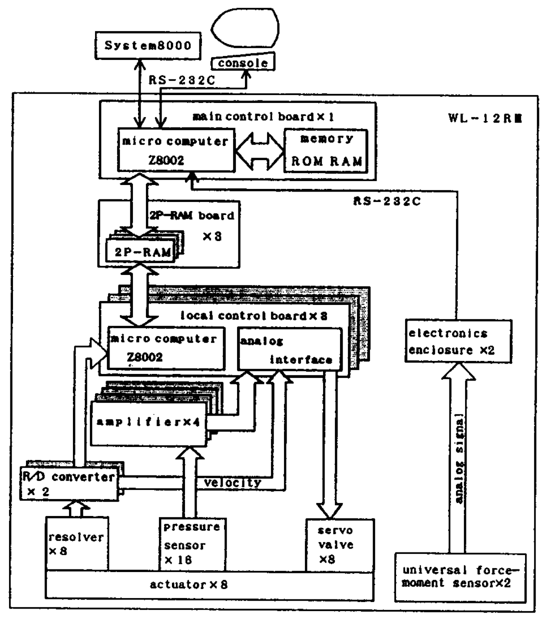


Fig.2 The control system of WL-12RIII

3. ZMP MEASUREMENT SYSTEM AND COMPUTATIONAL SCHEME OF ZMP

3.1 ZMP Measurement System

The ZMP is measured in off-line. Two sets of universal force-moment sensor (UFS) are employed for measuring the ZMP throughout the entire walking phase. The outline of measurement of the UFS is as follows : the analog signals from the sensor body are amplified, and high-frequency noise is eliminated with analog filters. Then the signals are changed into digital ones. Cross couplings are eliminated and the data are filtered with digital filters on a DSP board. As a result, highly accurate figures delivering the universal force-moment are acquired.

The sensors are installed at the both shanks of the biped walking robot (Fig.3). Through an RS-232C serial communication line, the universal force-moment data measured when the robot walks are sent to the main control computer and stored in the memories. After the walking, the stored data are loaded into a personal computer. Then the ZMP trajectories are recalculated using the following computational scheme.

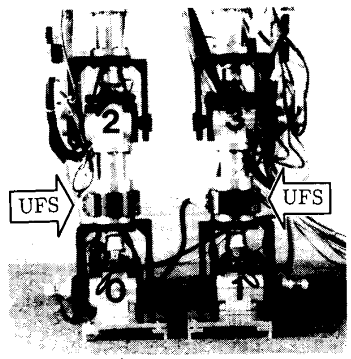


Fig.3 Photo of the lower-limbs of WL-12RIII with universal force-moment sensors (UFSs)

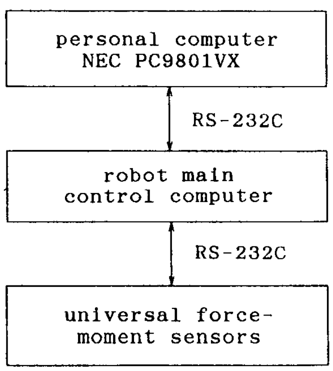


Fig.4 Flowchart of acquiring universal force-moment data from UFSs

3.2 Computation of ZMP with Force-Moment Data

The data from UFSs are composed of forces and moments. So it is necessary to compute the ZMP by using them.

While a robot is walking with one foot landing on the ground, the force and the moment caused by the parts upper than the sensor can be measured by the sensor. However, the ones caused by the part(s) lower than the sensor can not be measured. So we use a mathematical model shown in Fig.5 to compute the ZMP.

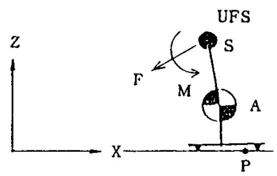


Fig.5 Model of ZMP calculation using force-moment data

A force vector F and a moment vector M caused by the motion and the gravity of the parts of the robot are assumed to act on the sensor S. At this time, the equation of motion on an arbitrary point P in the sole of a support foot is described as follows using d'Alembert's principle.

$$\overrightarrow{PS} \times F + M + \overrightarrow{PA} \times m(G + a) + M_p = 0 \qquad (1)$$

The point satisfying Mpx=Mpy=0 is the ZMP. Putting this condition into equation (1) and modifying it, formula (2) for computing the ZMP can be written.

$$X_{zmp} = \frac{x_a m(\ddot{z}_a + g) - m\ddot{x}_a z_a + x_s F_z - z_s F_x - M_y}{m(\ddot{z}_a + g) + F_z}$$
$$Y_{zmp} = \frac{y_a m(\ddot{z}_a + g) - m\ddot{y}_a z_a + y_s F_y - z_s F_y + M_x}{m(\ddot{z}_a + g) + F_z} \qquad (2)$$

where,

m : mass of ankle A
$G = (0, 0, g)$: gravitational acceleration
$F = (F_x, F_y, F_z)$: force on UFS S
$M = (M_x, M_y, M_z)$: moment on UFS S
$A = (x_a, y_a, z_a)$: position of ankle A
$S = (x_s, y_s, z_s)$: position of UFS S
$a = (\ddot{x}_a, \ddot{y}_a, \ddot{z}_a)$: acceleration of ankle A

On the basis of this formula, the ZMP of a support leg is able to be calculated using the force and moment acting on the UFS of the leg.

However, in usual biped walking, two kinds of phase appear alternately. One is called single support phase when the robot is supported with only one leg and the other is called double support phase with two legs. So the calculation of the ZMP throughout the whole walking phase is taken by the following schemes, in the single support phase and in the double support phase, respectively.

(1) Single Support Phase

In this phase, the foot of the swing leg does not directly affect any force on the ground. So the robot is considered to be an open serial link mechanism, and the ZMP calculated with formula (2) using the force–moment data of the support leg is the ZMP of the whole robot.

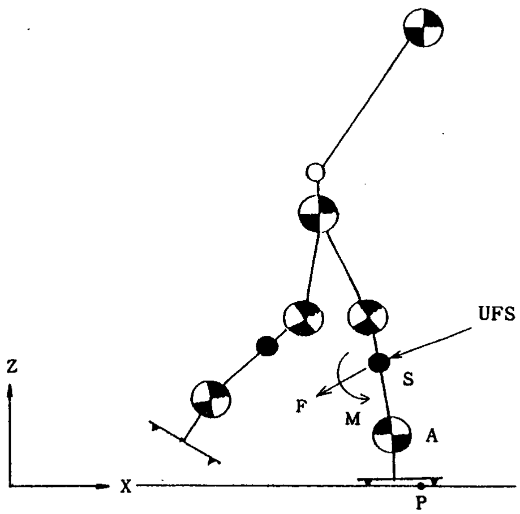


Fig.6 Calculation of ZMP in a single support phase

(2) Double Support Phase

In this phase, the double legs directly act force on the ground through their feet. So, first the ZMP of each leg is computed by formula (2) using the force–moment data measured on the leg. Then the ZMP of the whole robot is derived by composing the ZMPs of the left and the right legs. The composition method is as follows: the ground reaction force vectors at the location of the ZMP of each foot are composed shown in Fig.7, and the intersection point of the composed vector and the ground is the ZMP of the robot under the double support phase. This point can be calculated using formula (3) as follows:

$$X_p = \frac{F_{z1}X_1 + F_{z2}X_2}{F_{z1} + F_{z2}}$$

$$Y_p = \frac{F_{z1}Y_1 + F_{z2}Y_2}{F_{z1} + F_{z2}} \quad (3)$$

where,

$ZMP = (X_p, Y_p, Z_p)$: ZMP of the whole robot
$ZMP_1 = (X_1, Y_1, Z_1)$: ZMP of the right foot
$ZMP_2 = (X_2, Y_2, Z_2)$: ZMP of the left foot
$F_1 = (F_{x1}, F_{y1}, F_{z1})$: ground reaction force at ZMP_1
$F_2 = (F_{x2}, F_{y2}, F_{z2})$: ground reaction force at ZMP_2

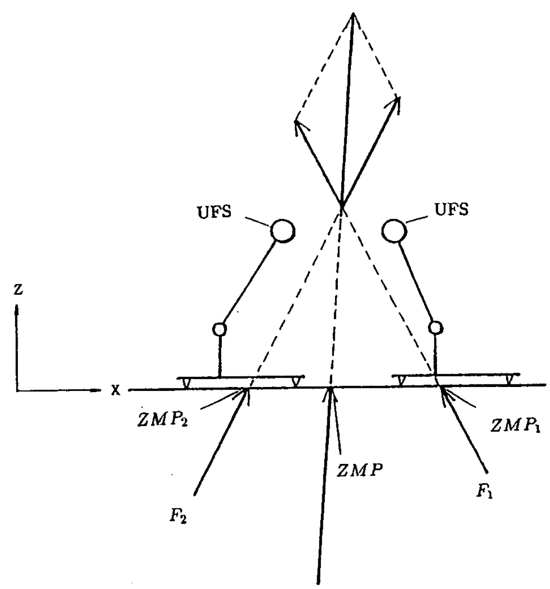


Fig.7 Calculation of ZMP in a double support phase

4. EXPERIMENTS OF ZMP MEASUREMENT

We executed the following two kinds of experiments of ZMP measurement using the biped walking robot WL–12RIII that has the ZMP measurement system.

4.1 Experiment in Single Full–support with One–point–ground–touch State

To confirm the fundamental accuracy of the ZMP measurement system, the ZMP is measured at the state that the foot of one leg is firmly touching the ground (full–support leg) and the other is touching the ground with only one point (one–point–ground–touch leg) on X axis, and an external force acts on the robot (shown in Fig.8). At this state, the ground reaction force acting on the foot of the one–point–ground–touch leg is restricted on the same point. So it can be considered that the ZMP of that leg is restrained on the contacting point.

To confirm that consideration, the experiment was performed that the ZMP was measured when the robot stood still at the state described above, and an external force was added to it by stretching a wire connected to the waist by a human.

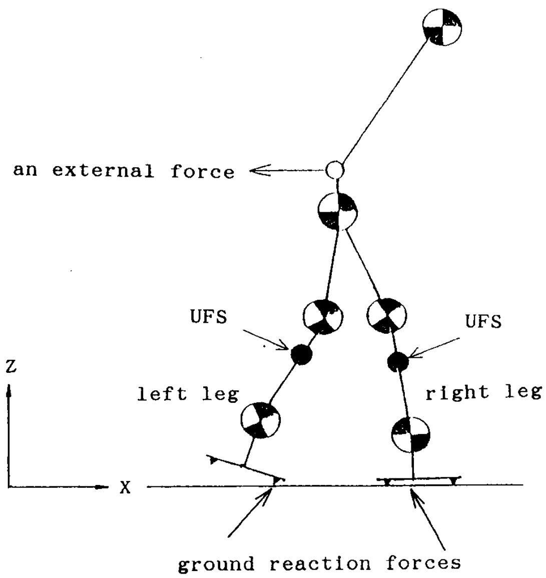


Fig.8 State of single full-support with one-point-ground-touch

The result (Fig.9) shows that with the external force changed, the ZMP of the full-support leg changed on X axis, but even if an arbitrary external force is added, the ZMP of the one-point-ground-touch leg is bound on the touching point, as long as the robot does not fall down. This result agrees with the consideration and confirms the accuracy of the ZMP measurement system.

4.2 Experiment throughout the Whole Walking Phase

We made the experiment measuring the ZMP when the biped walking robot WL-12RIII walks with the step length of 30[cm] and the speed of 1.7, 3.4 and 4.7[s/step]. The walking is realized by applying the trunk's compensative biped walking control method described in chapter 1. The results are shown in Fig.10.

5. DISCUSSION AND CONCLUSION

The followings are able to be considered from the measured ZMP trajectories shown in Fig.10.

(1) We see that the actual (measured) ZMP of the robot is within the stable region. This agrees with the ZMP criterion that the ZMP must exist within the stable region for a robot to walk.

(2) There is a trend that the faster the robot walks, the larger vibration appears in the measured ZMP. According to this, it can be considered that the faster a robot walks, the more unstable the walking becomes. Actually, there is a fact that the realization of the dynamic walking at higher speed is more difficult than that of the static walking at lower speed in biped walking. It can be considered that the trend proves the fact.

(3) The error between the measured ZMP and the preset ZMP is rather large. The reason for the error is as follows : (a) the deviations of the physical parameters between the mathematical model and the real machine, (b) bending due to the elasticity of the robot limbs, and (c) the impact force caused by the foot landing on the ground.

In conclusion, we proposed a method of measuring and computing the ZMP throughout the whole walking phase using UFSs, and developed a robot that has a ZMP measuring system. Then we succeeded in measuring the actual ZMP of the robot throughout the entire walking phase. In the future, we will try to control the motion of a biped walking robot and realize stabler walking using a measured ZMP.

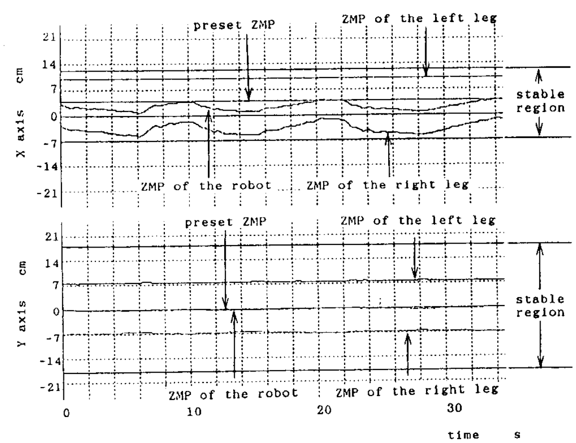
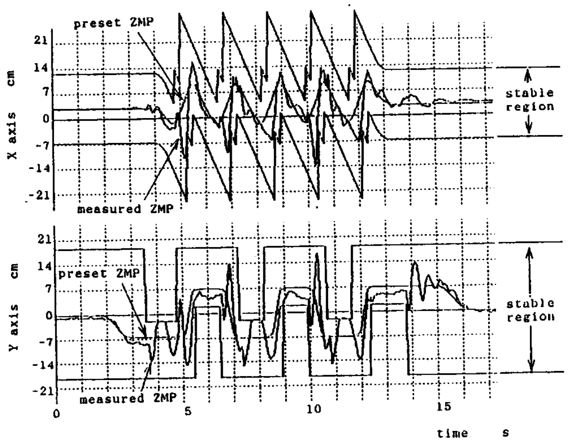
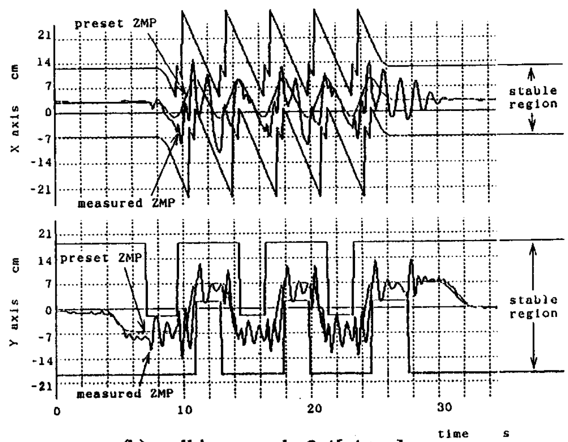


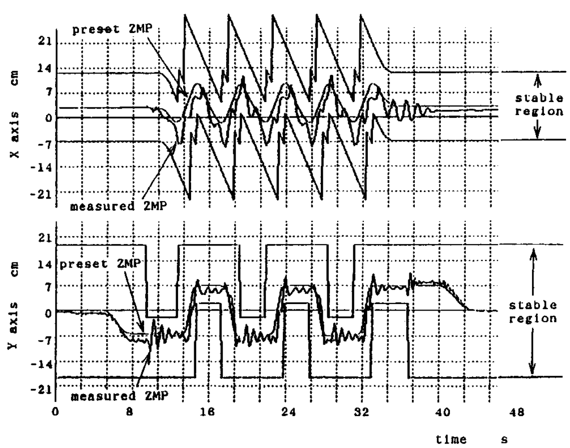
Fig.9 ZMP trajectories in the state of single full-support with one-point-ground-touch



(a) walking speed : 1.7[s/step]



(b) walking speed : 3.4[s/step]



(c) walking speed : 4.7[s/step]

Fig.10 ZMP trajectories throughout the whole walking phase with step length 30[cm] and various walking speeds

REFERENCES

[1] T. Mita, et al., "Realization of a high speed biped using modern control theory", Int. J. Control, Vol.40, No.1, p.107–119, 1984.

[2] J. Furusho and A. Sano, "Sensor–based control of a nine–link biped", Int. J. Robotics Research, Vol.9, No.2, p.83–98, 1990.

[3] H. Funabashi, et al., "Synthesis of leg–mechanisms of biped walking machines(part 1:synthesis of ankle–path–generator)", Bull. JSME, Vol. 28, No.237, p.537–543, 1985.

[4] A. Takanishi, et al., "The realization of dynamic walking by the biped walking robot WL–10RD", Proc. of the 1985 ICAR, p.459–466, 1985.

[5] M. Vukobratovic, et al., "On the stability of biped locomotion", IEEE Trans. on Biomedical Engineering, Vol. BME–17, No.1, 1970.

[6] A. Takanishi, et al., "Realization of dynamic biped walking stabilized with trunk motion", Proc. of ROMANSY'88, 1988.

[7] H.D. Eberhart, et al., "Human limbs and their substitutes", National Academy of Sciences, 1954.

[8] D.M. Cunningham and G.W.Brown, "Two devices for measuring the forces acting on the human body during walking", Proc. Soc. Exp. Stress Analysis, Vol. 9, No.2, p.75–90, 1952.