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Development of a Bipedal Humanoid Robot
- Control Method of Whole Body Cooperative Dynamic Biped Walking -

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***Abstract:** The authors have focused on the bipedal humanoid robot expected to play an active role in human living space, through studies on an anthropomorphic biped walking robot. As the first stage of developing a bipedal humanoid robot, the authors developed the human-size 35 active DOF bipedal humanoid robot "WABIAN" and the human-size 41 active DOF bipedal humanoid robot "WABIAN-R". The authors also proposed a basic control method of whole body cooperative dynamic biped walking that uses trunk or trunk-waist cooperative motion to compensate for three-axis (pitch, roll and yaw-axis) moment generated not only by the motion of the lower-limbs planned arbitrarily but by the time trajectory of the hands planned arbitrarily. Using these systems and the control method, normal biped walking (forward and backward), dynamic dance waving arms and hip, dynamic carrying of a load using its arms, and trunk-waist cooperative dynamic walking are achieved.*

1. Introduction

Many studies about biped walking robots and control methods for biped walking have been conducted in recent years[1]-[5]. At Waseda University, studies about biped walking robots have been done since 1966, and biped walking robots that have anthropomorphic forms have been pursued. As a result, dynamic complete walking[6], dynamic walking under an unknown external force[7], dynamic turn[8], and dynamic walking adapting to an unknown uneven surface[9] etc. were realized. Through pursuit of a biped walking robot that have an anthropomorphic form, the authors aimed to clarify the human walking mechanism and to apply it to the humanoid, the anthropomorphic robot.

Such a robot is expected to shares the same working space as well as common thinking and behavior patterns with humans in the 21st century. Therefore, it is demanded of the robot to do various work in human living space.

On the other hands, humans flexibly handle variable activities including locomotive activity like carrying of a load in living space by cooperatively using the whole body (lower-limbs, upper-limbs and trunk) in order of priority. Thus, to apply existing biped walking control methods to bipedal humanoid robots, whole body cooperative dynamic biped walking presupposing locomotive activities in human living space should be studied.

However, there has been no study about whole body (lower-limbs, upper-limbs and trunk) cooperative dynamic biped walking of a bipedal humanoid robot. Studies thus far have focused on robots having non-bipedal moving systems like crawlers, wheels[10], and quadruped walking machines etc.. Therefore, this project is the first step in studying whole body cooperative motion of a bipedal humanoid robot.

The objective of this study was to develop a bipedal humanoid robot which has trunk joints, to work out a whole body cooperative dynamic walking control method of the robot, and to realize dynamic walking stabilized by the trunk motion if not only the motion of the lower-limbs but also the time trajectory of the hands is planned arbitrarily.

2. Bipedal humanoid robot "WABIAN"

2.1 Machine model

The bipedal humanoid robot WABIAN (WAseda BIpedal humANoid) is shown in **Fig. 1**. The total weight is 107 kg and the height is about 1.66 m. It is made of extra-super-duralumin mainly and of GIGAS™(YKK CORPRATION). An assembly drawing and a link structure of this robot are shown in **Fig. 2** and **Fig. 3**. As Fig. 3 indicates, the lower-limbs have 6 DOF on the pitch-axis; the trunk has 3 DOF on the pitch-axis, roll-axis and yaw-axis; the upper-limbs have 14 DOF; the eyes and neck each have 2 DOF on the pitch-axis and yaw-axis; and the hands each have 3 DOF. The total active DOF is 35. In particular, the hip joint is an antagonistic driven joint using nonlinear spring mechanisms[11]. By using this mechanism, it is possible to control the stiffness of the joint across a wide range.

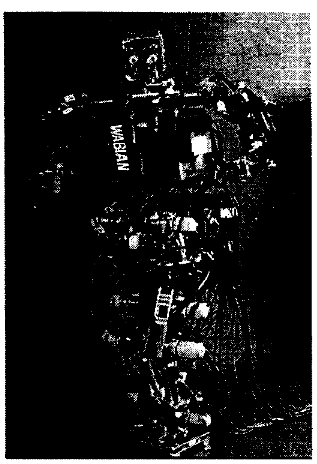


Fig. 1 WABIAN

To achieve the biped walking adapting to an un-

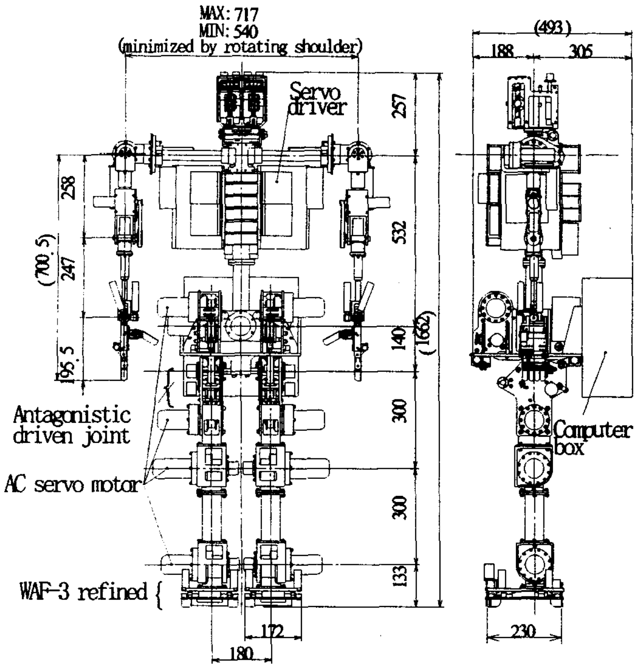


Fig. 2 Assembly drawing of WABIAN

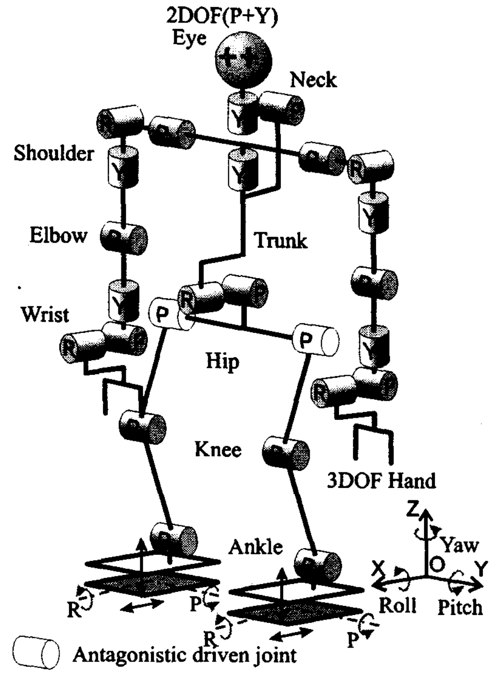


Fig. 3 Link structure of WABIAN

known uneven surface in the same way as WL-12RVII[9], the foot mechanism WAF-3R are installed to detect and compensate for modeling deviation. Modeling deviation indicates deviation between the simulation model of the walking system and the real world walking system. The feet each have 4 passive DOF.

As for the control system , 15 AC servo motors and 16 DC servo motors are centrally controlled through I/O boards(D/A, A/D, and counter) by the control computer(PC/AT compatible CPU board). The control computer is installed at the back of the waist and motor drive circuits at the top of the trunk. Thus, the only external connection of the robot is the power supply.

2.2 Trunk mechanism

The trunk of this machine model is able to generate three-axis moment by using three DOF link mechanisms. This trunk generates three-axis moment as follows: The yaw-axis moment is generated by swinging the upper-limbs around the yaw-axis using the yaw-axis actuator. The upper-limbs are linked to the yaw-axis actuator, which is installed at the top of the trunk. The pitch-axis and the roll-axis moments are generated by swinging the upper-limbs, the yaw-axis actuator, and the motor drive circuits around the pitch-axis and the roll-axis. By installing the yaw-axis actuator and motor drive circuits at the top of the trunk and using its own weight to compensate for the pitch-axis and the roll-axis moments, the authors were able to generate the three-axis moment by the trunk without adding to the total weight of the robot.

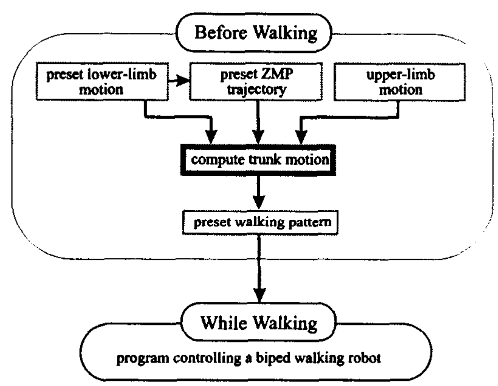


Fig. 4 Outline of the basic control method

3. Walking control method

3.1 Outline of the walking control method

The authors previously developed the control method of dynamic biped walking for biped walking robots as follows.

(1) Model based walking control (ZMP and yaw axis moment control)[12]
(2) Robust walking using the compensation mechanism of the model deviation[9]
(3) Model deviation compensative control[9]
(4) Real-time control of ZMP and yaw axis moment (external force compensative control)

In this paper, the authors introduce the basic walking control method for a biped walking robot having a trunk and upper limbs (bipedal humanoid robot) which is an improved version of [12].

this control method consists of two main components as shown in **Fig. 4** . One is an algorithm to compute the motion of the trunk which compensates for not only pitch-axis and roll-axis moments but also the yaw-axis moment on the preset ZMP before the robot begins walking. This algorithm automatically computes the compensatory trunk motion from the motion of the lower-limbs planned arbitrarily, the time trajectory of ZMP, and the time trajectory of the hands planned arbitrarily. This algorithm consists of the following four main parts.

(1) Modeling of the robot
(2) Derivation of the ZMP [13] equations
(3) Computation of approximate trunk motion
(4) Computation of strict trunk motion by iteratively computing the approximate trunk motion

The other component of the control method is a program control for walking using preset walking patterns transformed from the motion of the lower-limbs, the trunk, and the upper-limbs.

In this section, the algorithm to compute the compensatory trunk motion is described.

3.2 Modeling of the robot

Let the walking system be assumed as follows :

(1) The robot is a system of particles.
(2) The floor for walking is rigid and can not be moved by any force or moment.
(3) A Cartesian coordinate system O-XYZ is set, where the Z-axis is vertical, while the X-axis and Y-axis form a plane which is the same as that of the floor (**Fig. 5**).
(4) The contact region between the foot and the floor is a set of contact points.
(5) The coefficient of friction for rotation around the X, Y and Z-axis is zero at the contact point.

In (1), the machine model is regarded as a model composed of n particles as shown in **Fig. 6**.

3.3 Derivation of the ZMP equations

On the O-XYZ, let each vector to be established as shown in Fig. 5. The equation for three-axis moments is obtained :

$$\sum_{i}^{all\_particles} m_i(\mathrm{r}_i - p)\times(\ddot{\mathrm{r}}_i + \mathrm{G}) + \mathrm{T} = 0 \qquad (1)$$

To consider the relative motion of each part, a moving coordinate $\overline{\mathrm{W}}$-$\overline{\mathrm{XYZ}}$ is established on the waist of the robot on a parallel with the fixed coordinate O-XYZ (shown in Fig. 5). $\mathrm{Q}(x_q, y_q, z_q)$ is defined as the origin of $\overline{\mathrm{W}}$-$\overline{\mathrm{XYZ}}$ on the O-XYZ . Using the coordinate $\overline{\mathrm{W}}$-$\overline{\mathrm{XYZ}}$, equation (1) is modified into (2).

$$\sum_{i}^{all\_particles} m_i(\bar{\mathrm{r}}_i - \bar{p})\times(\ddot{\bar{\mathrm{r}}}_i + \ddot{\mathrm{Q}} + \mathrm{G}) + \mathrm{T} = 0 \qquad (2)$$

Point P is defined as ZMP(Zero Moment Point), so we denote the position vector of P as $P_{zmp}(x_{zmp}, y_{zmp}, 0)$. Equation

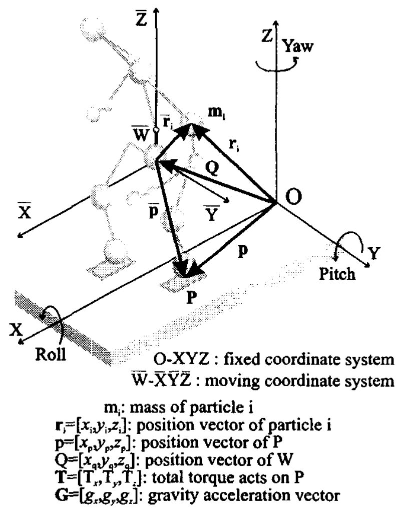


Fig. 5 Definition of coordinate system and vector

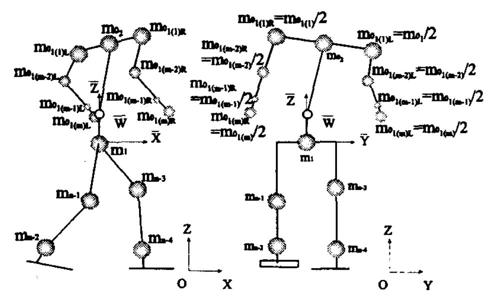


Fig. 6 Modeling of WABIAN

(2) is modified into (3) by putting the terms about the motion of the upper-limb particles on the left-hand side as unknown variables, and the terms about the moment generated by the lower-limb particles on the right-hand side as known parameters, named $M(Mx, My, Mz)$ respectively.

$$\sum_{j=1}^{m} m_{01(j)R}(\bar{r}_{01(j)R} - \overline{P_{zmp}})\times(\ddot{\bar{r}}_{01(j)R} + \ddot{\mathrm{Q}} + \mathrm{G})$$
$$+\sum_{j=1}^{m} m_{01(j)L}(\bar{r}_{01(j)L} - \overline{P_{zmp}})\times(\ddot{\bar{r}}_{01(j)L} + \ddot{\mathrm{Q}} + \mathrm{G}) \qquad (3)$$
$$+ m_{02}(\bar{r}_{02} - \overline{P_{zmp}})\times(\ddot{\bar{r}}_{02} + \ddot{\mathrm{Q}} + \mathrm{G}) = -M$$

3.4 Computation of approximate trunk motion [12]

In this section the authors introduce the method to compute approximate solutions of the compensatory trunk motion. In order to compute approximate solutions, the machine model of the robot should be modified into an approximate model in two stages. In the first stage, the upper limbs are modified into an approximation model as shown in **Fig. 7**. Moment generated by upper-limbs (left-hand side of (3)) are modified into (4) by using vectors redefined in Fig. 7.

(Moment generated by trunk and upper limbs motion)

$$= m_{01}\mathrm{r}_{0'}\times\ddot{\mathrm{r}}_{0'} + \left(\sum_{j=1}^{2} m_{0j}\right)(\bar{\mathrm{r}}_0 - \overline{P_{zmp}})\times(\ddot{\bar{\mathrm{r}}}_0 + \ddot{\mathrm{Q}} + \mathrm{G}) \quad (4)$$

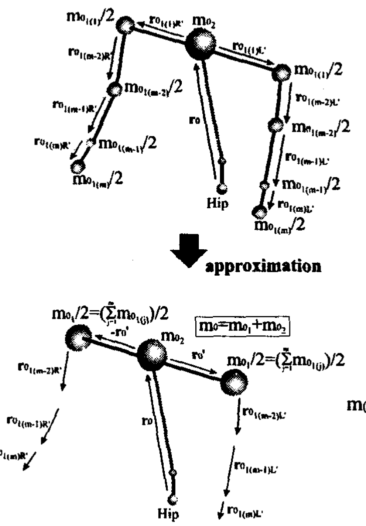


Fig. 7 Approximate model of upper part

By the first approximation, equation (3) is modified into (5), (6), and (7).The yaw-axis moment generated by the trunk motion for the pitch and roll-axis is named Mz_0.

$$m_{01}(z_{0'}\ddot{x}_{0'} - x_{0'}\ddot{z}_{0'}) + m_0(\bar{z}_0+z_q)(\ddot{\bar{x}}_0+\ddot{x}_q) - m_0(\ddot{\bar{z}}_0+\ddot{z}_q+g)(\bar{x}_0-\bar{X}_{zmp}) = -My \quad (5)$$

$$m_{01}(y_{0'}\ddot{z}_{0'} - z_{0'}\ddot{y}_{0'}) - m_0(\bar{z}_0+z_q)(\ddot{\bar{y}}_0+\ddot{y}_q) + m_0(\ddot{\bar{z}}_0+\ddot{z}_q+g)(\bar{y}_0-\bar{Y}_{zmp}) = -Mx \quad (6)$$

$$m_{01}(x_{0'}\ddot{y}_{0'} - y_{0'}\ddot{x}_{0'}) + Mz_0 = -Mz \quad (7)$$

$$Mz_0 = -m_0(\ddot{\bar{x}}_0+\ddot{x}_q)(\bar{y}_0-\bar{Y}_{zmp}) + m_0(\ddot{\bar{y}}_0+\ddot{y}_q)(\bar{x}_0-\bar{X}_{zmp})$$

However, these equations are interferential and nonlinear, because each equation has the same variable z_0 and the trunk is connected to the lower-limbs through rotational joints. Therefore, it is difficult to derive analytic solutions from them. Thus the second stage of approximation is needed. By assuming that neither the waist nor the trunk particles move vertically, i.e., the trunk arm rotates on the horizontal plane only(shown in **Fig. 8**), the equations are decoupled and linearized. The yaw-axis moment generated by the yaw-axis actuator is described by the rotational angle of the yaw-axis actuator θ_y and the radius of the trunk's arm R, and the linearized equations (8), (9) and (10) are obtained.

$$m_0(\bar{z}_0+z_q)(\ddot{\bar{x}}_0+\ddot{x}_q) - m_0 g(\bar{x}_0-\bar{X}_{zmp}) = -My \quad (8)$$

$$-m_0(\bar{z}_0+z_q)(\ddot{\bar{y}}_0+\ddot{y}_q) - m_0 g(\bar{y}_0-\bar{Y}_{zmp}) = -Mx \quad (9)$$

$$m_{01}R^2\theta_y = -Mz_0 - Mz \quad (10)$$

In these equations, My, Mx, Mz are known, because they are derived from the lower-limbs' motion and the time trajectory of ZMP. Also Mz_0 is known when the trunk motion of the pitch and roll-axis motion is derived. In the case of steady walking, My, Mx, Mz are periodic functions, because each particle of the lower-limbs and the time trajectory of ZMP move periodically for the moving coordinate $\overline{W}$ - $\overline{XYZ}$. Thus, each equation can be represented as a Fourier series. By using the Fourier Transform and by comparing the coefficients of both sides of each equation, the authors easily acquired the approximate periodic solution of the trunk motion. By the way, an offset term in the equation of the yaw-axis moment cannot be determined. In the equations of the pitch and roll-axis moment, the gravitational term determines the initial value of the offset terms, but in the equation of the yaw-axis moment, nothing determines the initial value. Therefore, the offset term in the equation of the yaw-axis moment is determined to let the yaw angle be in the rotatable region of the yaw-axis actuator.

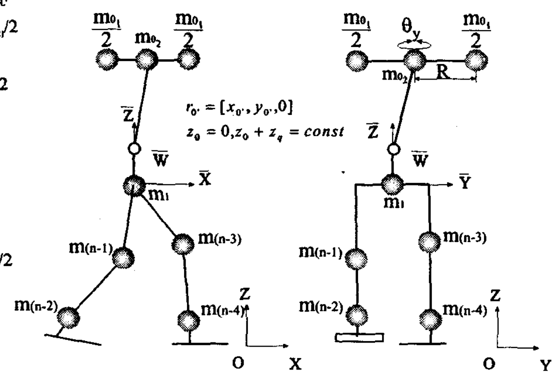


Fig. 8 Linearized model

The above computation has been applied to the case of steady walking, but the computation is applicable to complete walking, too. By regarding complete walking as one walking cycle and making the static standing states before and after walking long enough, the computation is also applicable. Thus approximate solutions of the compensatory trunk motion for complete walking can be obtained.

3.5 Computation of strict trunk motion [12]

In order to compute strict solutions, the authors propose an algorithm by iteratively computing approximate solutions of linearized equations. The iterative algorithm to compute strict

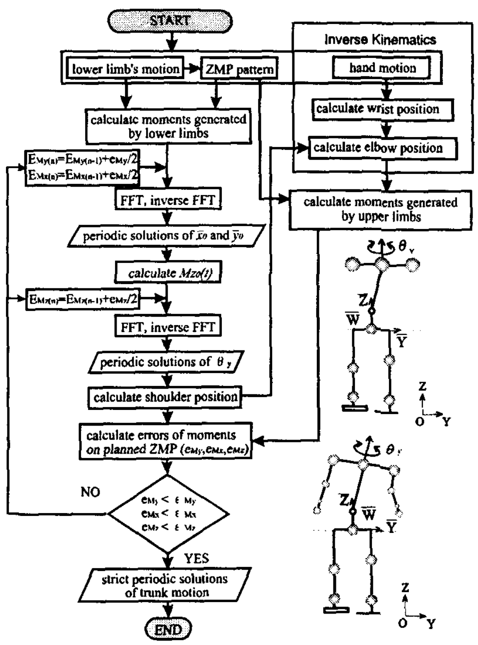


Fig. 9 Flow Chart to Compute Trunk Motion

solution of trunk motion is as follows (shown in **Fig. 9**). At first, the approximate periodic solutions of the linearized model's equations (8), (9) and (10) are computed (described in section 3.4). By applying them to the strict model's equation (3), the errors of the moments generated by the trunk $e(e_{My}, e_{Mx}, e_{Mz})$ on the preset ZMP are calculated. Then, the errors are negated on their signs and are accumulated to the right-hand side of (8), (9) and (10). The approximate solutions are computed again. Finally, by iterating the computation until the errors fall within a certain tolerance level $\varepsilon(\varepsilon_{My}, \varepsilon_{Mx}, \varepsilon_{Mz})$, strict periodic solutions of nonlinear equations are obtained. However, this method needs a huge number of iterations in computation. So, through the use of computation regularity, the authors discovered that (11) estimates the limit value of an accumulated moment error on each axis. As a consequence, the authors realized about a 90 percent decrease in the number of iteration times.

$$E_n = \frac{2E_{(n-1)} + e_{(n-1)}}{2} \quad n = 3,4,5, \cdots, \quad where\, E_1 = 0, E_2 = e_1 \quad (11)$$

$E_n(E_{My(t)}, E_{Mx(t)}, E_{Mz(t)})$ is the accumulated moment error in the n-th iteration, and e_n is the calculated moment error after n times of iterations.

To improve the generality of the above algorithm, the authors added the computation module of inverse kinematics to the part dealing with upper-limb motion setting. This module computes the position of the elbow from the geometrical relation between the position of the shoulder (calculated approximately) and the position of the hand. The computation of the elbow position is done on condition that upper-limbs do not clash against the robot's own body.

The method of calculating the trunk motion by which dynamic walking was stabilized even if an arbitrary lower limbs motion and an arbitrary hand motion were set was described above. In addition, the whole body cooperative dynamic walking pattern in various aspects can be calculated by changing an unknown variable. For instance, an arbitrary trunk motion can be set by calculating the waist motion as an unknown variable. Moreover, the whole body cooperative dynamic motion can be calculated by using and calculating the relational expression of the waist and the trunk.

The first author, Dr. J. Yamaguchi and the second author, Eiji Soga developed the GUI pattern generation software "MotionMaker97 for Windows95/NT"(**Fig. 10**) which supported a relative position, the generation moment ratio, and the quadratic performance function as a relational expression of the trunk and the waist in 1997.

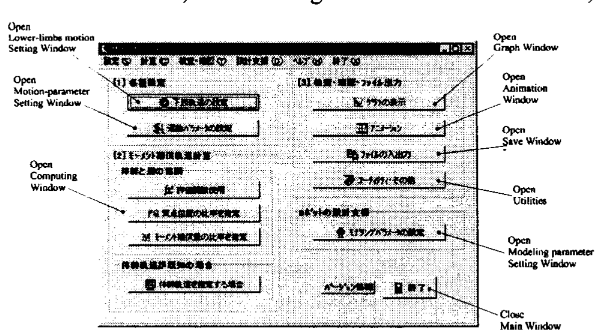


Fig. 10 MotionMaker97

4. Walking simulations

The authors performed walking simulations altering the weight of the upper-limbs (6 kg under normal conditions) into 12 kg and 30 kg. Walking conditions are as follows: The posture is shown in Fig. 1. The walking speed is 1.28 s/step. Step length is 0.15 m/step. The relation between the number of iterations and errors of the three-axis moment is shown in **Fig. 11**. It can be seen from these figures that the error of each moment falls within 0.1 Nm after 7 or 8 iterations. Then the algorithm proposed in this paper can be applied to increase of the weight of the upper-limbs while carrying a heavy load, and the generality of the algorithm is confirmed.

The stick diagrams of the walking simulations are shown in **Fig. 12**. It can be seen that the heavier the upper-limbs become, the smaller the trunk motion becomes. That is because the increase of the upper-limbs leads to an increase in the three-axis moment generated by trunk motion.

Fig.13 shows the simulation examples, which use the 49DOF-machine model that there are active roll DOF on the hip joints and foot joints. The walking condition is the same as Fig. 12.

First of all, the simulation shown in **a)** has stabilized dynamic walking by using both motions of the hip and the trunk. Next, the simulation shown in **b)** has stabilized dynamic walking by using only the hip motion. Finally, the simulation shown in **c)** has stabilized dynamic walking while sideways avoiding the obstacle in front of the robot face.

Thus, changing how to take an unknown variable can generate various whole body motion patterns. Details of this technique are described at another chance because of space.

Moreover, when MotionMaker97 for Microsoft Windows95 and Pentium II(266MHz) system are used for the generation of these motion patterns, it takes the time of about 1.0 s.

5. Walking experiments

The authors performed walking experiments with the bipedal humanoid robot WABIAN. As a result of the experiments, normal dynamic biped walking by arm fixation (forward and backward, 0.10-0.15 m/step, 8.00-1.28 s/step), dynamic dancing (step forward, step backward, and shaking hip), and dynamic carrying of a load with both arms (0.10-0.15 m/step, 1.28 s/step, a 1.5 kg load) were achieved.

By the way, the authors developed the 49DOF-machine model "WABIAN-R" under the cooperation of YKK CORPORATION and Harmonic Drive Systems, Inc. in January 1998. This machine model has roll axis active DOF for foot joint and the hip joint and yaw axis active DOF for the femur

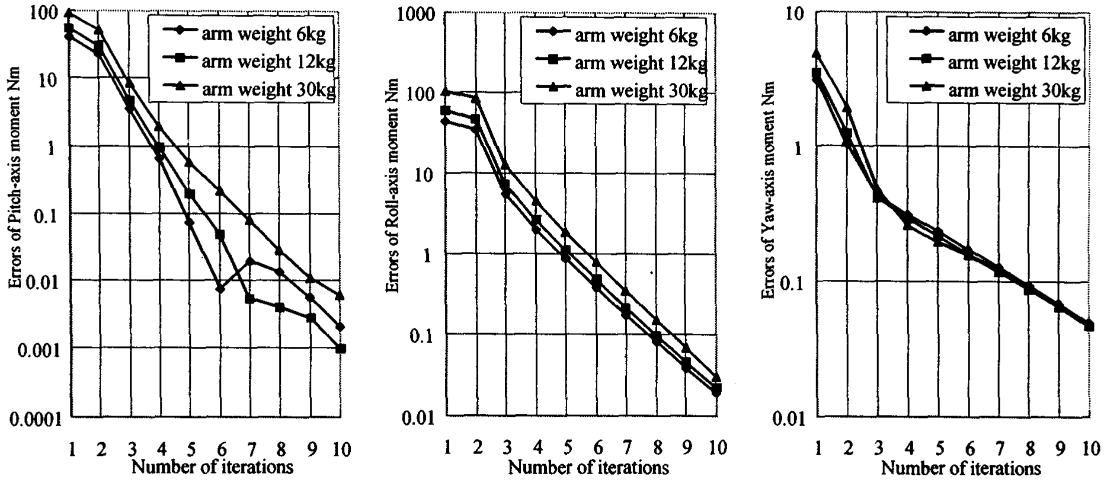
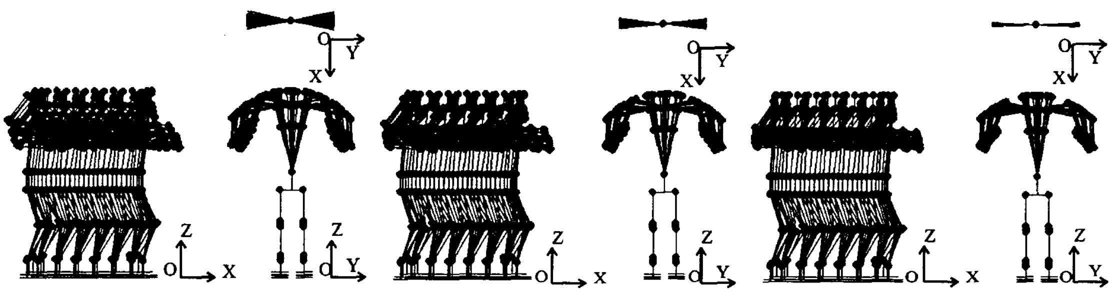
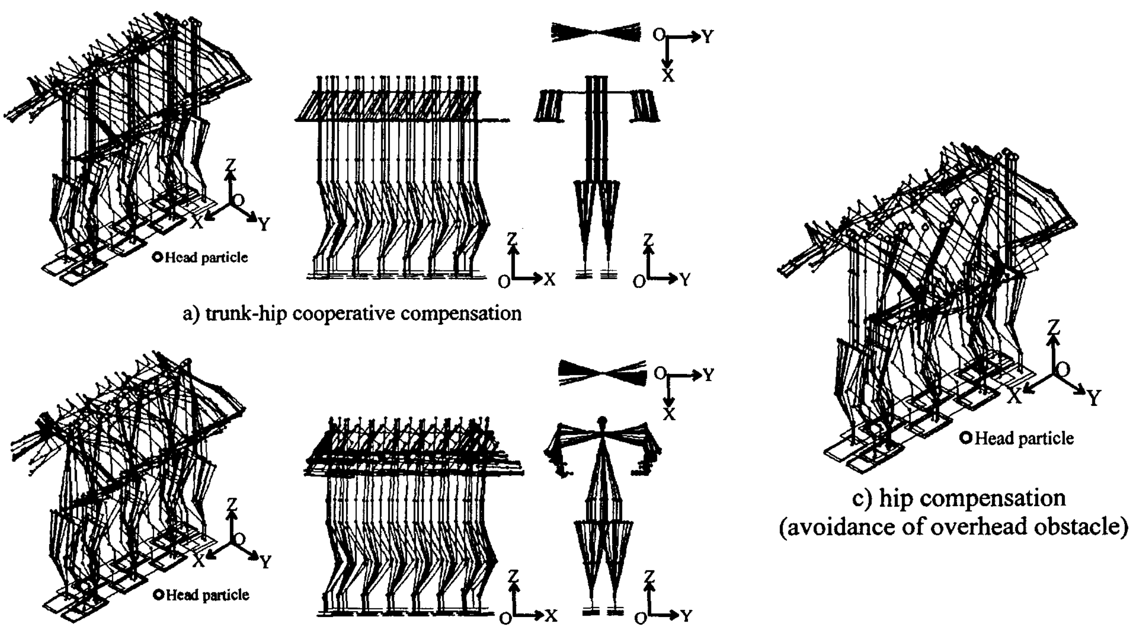


Fig. 11 Relation between error and number of iterations



a) arm weight 6kg   b) arm weight 12kg   c) arm weight 30kg

Fig. 12 Walking simulations I



a) trunk-hip cooperative compensation

b) hip compensation

c) hip compensation (avoidance of overhead obstacle)

Fig. 13 Walking simulations II

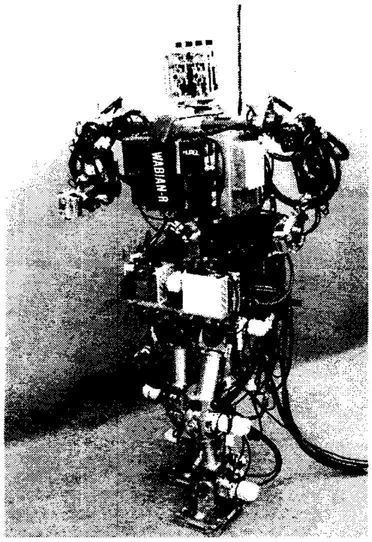


Fig.14 WABIAN-R

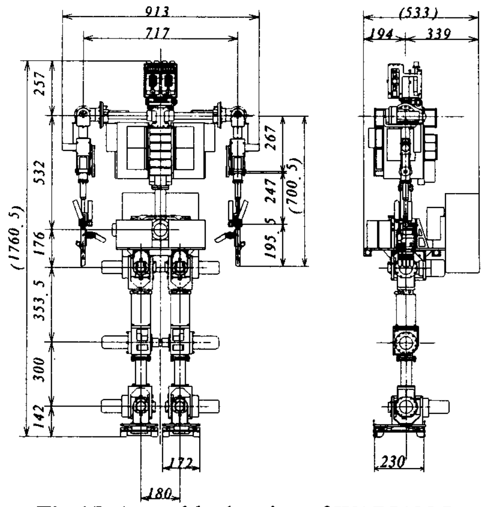


Fig.15 Assembly drawing of WABIAN-R

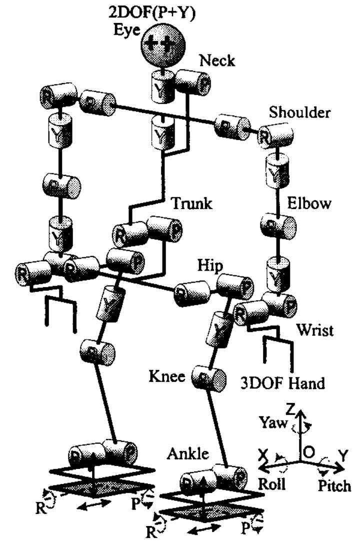


Fig. 16 Link structure of WABIAN-R

in addition to the DOF composition of WABIAN. The Total weight of WABIAN-R (**Fig.14**) is 120kg, and the height is 1.76m. GIGAS™ developed by the YKK CORPORATION is used for the lower limb mechanism. The assembly drawing and the DOF arrangement drawing are shown in **Fig.15** and **Fig.16**.

Therefore, about the case with the active DOF in the hip joint and foot joint, the authors attempted to prove the effectiveness of the proposal algorithm by using WABIAN-R. The whole body cooperative dynamic walking (0.00-0.25 m/step and 8.00-1.28s/step) shown in Fig.13 as a result of the walking experiment was achieved.

6. Conclusion

The objective of this study was to develop a whole body cooperative dynamic walking control method that can stabilize walking by using the trunk or the trunk-hip cooperative motion if not only by the motion of the lower-limbs but also the time trajectory of the hands is planned arbitrarily.

The authors first developed a control method of whole body cooperative dynamic biped walking for a bipedal humanoid robot. On the other hand, we also developed the bipedal humanoid robot WABIAN and WABIAN-R.

Next, we performed walking experiments using the control method and the bipedal humanoid robots. For example, WABIAN and WABIAN-R was able to execute normal dynamic biped walking, dynamic dancing with human, dynamic carrying of a load, and whole body cooperative dynamic walking.

In conclusion, the effectiveness of the walking control method proposed in this paper and the walking systems are experimentally supported.

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