Biped Humanoid Robots in Human Environments: Adaptability and Emotion

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Abstract

To explore issue of human-like motion, we have constructed a human-like biped robot called WABIAN-RII (WAseda BIped humANoid robot-Revised II) that has a total of forty-three mechanical degrees of freedom (DOF); two six DOF legs, two ten DOF arms, a four DOF neck, four DOF in the eyes and a torso with a three DOF waist. We present a follow-walking control with a switching pattern technique for the biped robot to follow human motion. Also, emotional walking of the biped robot is described, which expresses emotions by parameterizing its motion. The follow walking and emotion expression can be realized by the compensation of moment by the combined motion of the waist and trunk.

1. Introduction

To date, the issue of stable biped walking has been addressed by many researchers [1, 2, 3, 4, 5]. A Waseda's biped-robot group has been engaged in studies of biped robots with human configuration from two viewpoints. One is an engineering viewpoint to elucidate the walking mechanism of humans. The other viewpoint is the development of anthropomorphic robots that become human partners in the next century.

The Waseda group succeeded in achieving a dynamic biped walking with a hydraulic biped robot WL-10RD in 1984 [6]. A hydraulic biped robot WL-12 having an upper body and a two-degrees-of-freedom waist was constructed to realize more human-like motion in 1986. Also, the new control algorithm was developed to improve walking stability, which compensates for moment generated by the motion of the lower-limbs using the trunk motion. The dynamic biped walking was realized under external forces of unknown environment and on unknown walking surfaces [7, 8]. To adapt to human's living environments, the control method based on a virtual surface was introduced, which could deal with even and uneven terrain [9].

In 1992, the new project "humanoid" was founded by the late Ichiro Kato at HUREL(Humanoid Research Laboratory), Advanced Research Institute for Science and Engineering, Waseda University. This project aims at the development of an anthropomorphic robot that can share the same walking space with humans. In developing a biped humanoid robot, five things are considered as follow: (1) the size of the biped robot should be the average size of an adult Japanese woman to do a collaborative work with humans: (2) the robot could walk at approximate human speed: (3) the robot should have 3 DOF trunk and 6 DOF arm: (4) the joints of the robot should use electric servomotors: (5) a control computer and motor drives except power supply should be installed.

In this paper, we describe a biped humanoid robot WABIAN-RII to realize human-like motion that has forty-three mechanical degrees of freedom and control systems. A picture of the WABIAN-RII is shown in Figure 1. We describe a human-follow walking to cooperate with a human. The follow walking is achieved by using a pattern switching method. Also, we describe a matter of emotion expressed by the walking and the body motion. The walking of emotion is created by a set of motion parameters that consists of the lower-limb, upper-limb, waist, trunk and head parameters.

2. Development of WABIAN-RII

In this section, the hardware and software of the WABIAN-RII are described.

2.1 Hardware

Duralumin, GIGAS (YKK Corporation) and CFRP (Carbon Fiber Reinforced Plastic) are mainly employed as structural materials of the WABIAN-RII. The height of the WABIAN-RII is about 1.84[m] and its total weight is 127[kg]. The body and legs are driven by AC servomotors with reduction gears. The neck, hands and arms are actuated by DC servomotors with reduction gears, but the eyes by DC servo motors

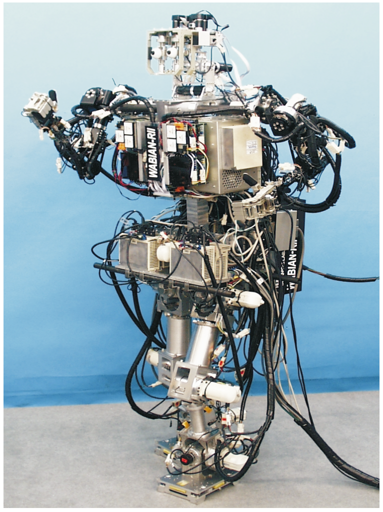

Figure 1: The photo of WABIAN-RII.

without reduction gears. The trunk having three degrees of freedom can bend front-to-back (40 degrees) and side-to-side (50 degrees), and twist left-to-right (90 degrees). The neck having four degrees of freedom can tilt front-to-back by two pitch axes (70 degrees each), tilt side-to-side (90 degrees) and twist left-to-right (90 degrees). The eyes having four degrees of freedom can look up-to-down (100 degrees) and rotate right-to-left (90 degrees). A human-like range of motion is given by mechanical stoppers and software on the waist and by only software on the neck and eyes. The arms and legs are equipped with mechanical stoppers including software to realize human-like range of motion (knee bend is 90 degrees, hip twist 180 degrees, hip and ankle rolls 40 degrees, hip pitch 80 degrees, ankle pitch 75 degrees).

2.2 Software

The WABIAN-RII is controlled by a PC/AT compatible computer PEAK-530 (an Intel MMX Pentium 200[MHz] CPU processor) which are govern by a OS, MS-DOS 6.2/V (16-bit). TNT DOS-Extender SDK (Ver.6.1) is employed to extend the OS to a 32-bit. It has three counter boards with each 24-bit 24 channels, three D/A converter boards with each 12-bit 16 channels and a A/D converter board with differential 12-bit 16 channels to interface with sensors. The joint angles are sensed by incremental encoders attached at the joints, and the data are taken to the computer through the counters. All the computations to control the WABIAN-RII are carried out by the control computer and the control program that are written in C language. The servo rate is 1[kHz]. The computer system is mounted on the back of the waist and the servo driver modules are mounted on the upper part of the trunk. The external connection is only an electric power source.

3. Compensatory Motion

We have already proposed the control method for the dynamic walking of biped walking robots as follows: (a) a model-based walking control (ZMP and yaw axis moment control), (b) a model deviation compensatory-control, and (c) a real-time control of ZMP and yaw axis moment (external force compensatory control).

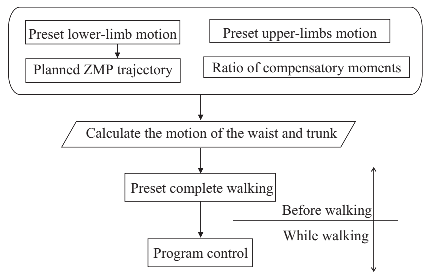

Figure 2: Control structure of WABIAN-RII.

This section describes a basic walking control approach for the WABIAN-RII to realize human-like motion. The control method consists of two main components as shown in Figure 2: a calculation of compensatory motion and program control. It is important for the biped robot to balance on the various environments. The combined motion of the waist and trunk compensates for not only the pitch axis and the roll axis but also the yaw axis moment around the preset ZMP before the biped robot starts to walk. In brief, the algorithm automatically computes the compensatory motion of the waist and trunk from the lower-limbs planned arbitrarily, the time trajectory of ZMP, and the planned motion of the upper-limbs, in consideration of the ratio of compensatory moments. This is composed of the following four main parts: 1) modeling of the biped robot, 2) derivation of ZMP equations, 3) computation of approximate motion of the waist and trunk, and 4) calculation of the strict motion of the waist and trunk by an iteration method.

The other component of the control method is a program control using a preset complete walking pattern transformed from the motion of the lower-limbs, the trunk, and the upper-limbs, while the biped robot is walking.

3.1 Modeling

We define five assumptions to model the biped robot as follows: a) the biped walking robot consists of a set of particles, b) the foothold of the robot is rigid and not moved by any force and moment, c) the contact region between the foot and the floor surface is a set of contact points, d) the coefficients of friction for rotation around the X, Y and Z-axes are nearly zero at the contact point between the foot and the floor surface, and e) The foot of the robot does not slide on the contact surface. The fifth assumption states that the friction coefficients between the foot and the contact surface are very large.

Suppose that the mass of the biped robot is distributed as shown in Figure 3. The moment balance around a contact point p on the floor can be written as

$$\sum_{i=1}^{n} m_i(\boldsymbol{r}_i - \boldsymbol{r}_p) \times (\ddot{\boldsymbol{r}}_i + \boldsymbol{G}) + \boldsymbol{T} - \sum_{j=1}^{n} (\boldsymbol{r}_j - \boldsymbol{r}_p) \times (\boldsymbol{F}_j + \boldsymbol{M}_j) = \boldsymbol{0}, \quad (1)$$

where m_i is the mass of the particle i. $\boldsymbol{r}_i$ denotes the position vector of the particle i with respect to the world coordinate frame $\mathcal{F}$. $\boldsymbol{r}_p$ be the potion vector of point p from the origin of $\mathcal{F}$. $\boldsymbol{G}$ is the gravitational acceleration vector, $\boldsymbol{T}$ is the moment vector acting on the contact point p. $\boldsymbol{F}_j$ and $\boldsymbol{M}_j$ denote the force and the moment vectors acting on the particle j relative to the frame $\mathcal{F}$. From the ZMP criteria, the resultant moment is zero on the contact point p.

The three-axis motion of the trunk is interferential each other and has the same virtual motion because the biped robot is connected by the rotational joints. Therefore, it is difficult to derive analytically a compensatory motion of the trunk from Equation (1). In order to get the approximate solution analytically, we assume that (1) the external force is not considered in the approximate model, (2) the moving frame $\bar{\mathcal{F}}$ does not rotate and (3) the waist and trunk does not move vertically. According to these assumption, we classify known and unknown variables of Equation (1) and compute the approximate motion of the trunk and waist using FFT(Fast Fourier Transformation).

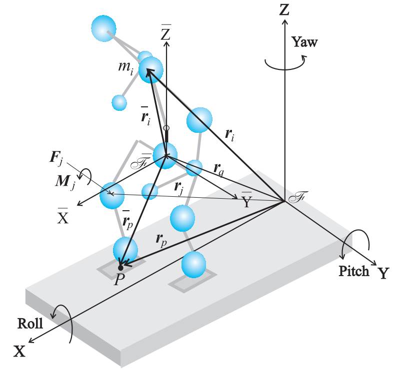

Figure 3: Coordinate frames of WABIAN-RII.

3.2 Recursive Calculation

An recursive method that iteratively computes the approximate solution of the ZMP equation is used to obtain the strict solutions of the trunk and waist motion. First, the approximate periodic solutions of the waist and trunk are calculated from the linearization of the model. Second, the approximate periodic solutions are substituted into the ZMP equation, and the errors of moments generated by the motion of the lower-limbs and upper-limbs are calculated according to the planned ZMP. These errors are accumulated to the linear equations. Finally, These computations are repeated until the errors fall below a certain tolerance level.

4. Human-like Walking

In this section, a human-follow walking and an emotion expression are described.

4.1 Follow-walking Motion

A follow-walking motion is realized by a human-follow walking method that selects and generates switchable unit patterns, based on the action model for human-robot interaction. The upper-limb's trajectory is decided by the force information applied on the robot's hand. Then, by judging the direction of the robot's tracking motion, the trajectory of the lower-limbs can be decided. For computing the upper-limb's trajectory, we use a virtual compliance control method. Figure 4 shows the coordinate system of the robot's arm. The equation of compliance motion of the robot'hand is written by

$$M\frac{d\bar{\boldsymbol{v}}}{dt} = \bar{\boldsymbol{F}} - \boldsymbol{K}\Delta\bar{\boldsymbol{x}} - \boldsymbol{C}\bar{\boldsymbol{v}}, \tag{2}$$

where $\boldsymbol{M} \in \Re^{6\times6}$ is the virtual mass matrix. $\boldsymbol{K} \in \Re^{6\times6}$ and $\boldsymbol{C} \in \Re^{6\times6}$ are the stiffness and damping matrices, respectively. $\bar{\boldsymbol{v}} \in \Re^6$ and $\bar{\boldsymbol{x}} \in \Re^6$ is the velocity and deviation vectors of the robot's hand, respectively.

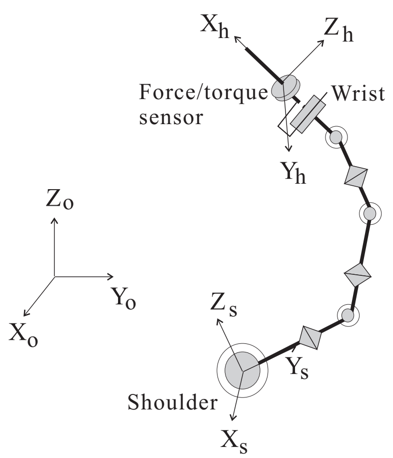

Figure 4: The upper-limb of WABIAN-RII.

In the case where our target is the full tracking ability of the hand like a method generally used in the direct teaching of an industrial manipulator, the stiffness components may be disregarded. Also, when the control loop time we apply is very short(5[ms]), we may think of the virtual mass as equal to zero. Therefore, the hand velocity can be obtained with respect to the hand coordinate frame $\{h\}$ as

$$^{h}\bar{\boldsymbol{v}}_h = \boldsymbol{C}^{-1}\bar{\boldsymbol{F}}. \tag{3}$$

We can find the hand velocity with respect to the shoulder frame $\{s\}$:

$$^{s}\bar{\boldsymbol{v}}_s = {}^{s}\boldsymbol{R}_h\, {}^{h}\bar{\boldsymbol{v}}_h, \tag{4}$$

where ${}^{s}\boldsymbol{R}_h$ is the rotation matrix of the frame $\{h\}$ relative to the frame $\{s\}$.

To calculate the joint angle velocity $\dot{\boldsymbol{\theta}} \in \Re^7$ from the hand velocity, the pseudo-inverse matrix $\boldsymbol{J}^+$ is used according to the redundancy of the arm of WABIAN-RII; that is,

$$\dot{\boldsymbol{\theta}} = \boldsymbol{J}^+\, {}^{s}\bar{\boldsymbol{v}}_s, \tag{5}$$

where

$$\boldsymbol{J}^+ = \boldsymbol{J}^T(\boldsymbol{J}\boldsymbol{J}^T)^{-1}.$$

where $\boldsymbol{J}$ is 6×7 Jacobian.

Figure 5 shows a control system for the follow motion of its upper-limb.

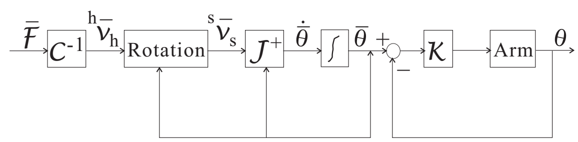

Figure 5: Control system for the upper-limbs.

The biped robot recognizes the guiding direction of human motion by the above arm control system, and then decides the next walking pattern while synchronizing it with the preset walking condition. In a case where no pattern is selected, we program to let the preset condition be continued by the biped robot.

In addition, we know from the transfer functions of ZMP equations that the above control method doesn't cope with initial value problem and doesn't satisfy the law causality, because of characteristics of the Lorenz function. From the simulation and experimental tests, we know that the trunk compensation motion begins to move earlier than the shift of ZMP on the floor. This means that the trunk compensation affects one or more steps before and after in a pattern time. To solve these problems, a method is described below.

(a) The motion patterns of the lower-limbs are given as unit patterns, which have one before and one after gait attributes of a step pattern (in consideration of the trunk's motion dynamics). By combining some simple and selective patterns, it is possible to realize a following motion by a biped robot similar to a human. The unit patterns that are combined from three gait patterns (step forward, backward, marking time) and are computed to have a continuous position, velocity and acceleration of its trajectory, are calculated offline.

(b) The trunk compensatory motion relative to the moment generated by the lower-limbs is computed offline, and it gives the biped robot sets of unit patterns in the same way as the lower-limb's patterns. Through experiments, we could clarify that in circumstance of movable margin of the trunk's angle, the ZMP shift caused by the upper-limbs' smooth motion could be ignored. This was done so that the change in attitude of the upper-limbs could be disregarded to make the control technique simpler.

Even during a high-speed motion, it is possible to make a unit pattern of the trunk motion by taking into account only one step before and after of a unit pattern as an attribute. The unit patterns were created using a software simulator, and include indexes for pattern searching and attribute of current, before and after steps. These unit patterns are preloaded as one step long angle data in the computer memory of the biped robot.

To confirm the validity of the fellow motion control, human-follow walking is experimented using the WABIAN-RII. As a result, human-follow walking is realized with the step velocity of 1.28[s/step] and the step length of 0.1[m/step].

4.2 Emotion Expression

If biped robots express emotions using their walking and body motion, we can smoothly communicate with the biped robots and greatly improve affinity. In this section, we describe how to parameterize emotion expression. In realizing a happy walking, the initial and final states of the biped robot are set as follows:

- the middle and final x-positions of the foot are set as 0.15[m] and 0.078[m], respectively.
- the initial and final accelerations of the foot are 0.05[m/s^2], respectively, and the y-position of the foot is -0.2[m], and the orientation of the roll axis of the foot is -20[deg];
- the initial angle of the yaw axis of the foot is set as 30[deg];
- the z-position of the waist in the middle of the swing phase is set as -0.1[m] for the waist to move up and down;
- the angle of the roll axis of the waist in the middle of the swing phase is -10[deg]. The initial and final angular velocities are -1.0[deg/s] and 1.0[deg/s], respectively;
- to shake largely the pitch axis, the ratio of the pitch and roll moments between the trunk and waist is 0.7. The angles of the pitch and roll axes of the head are -10.0[deg] and 10.0[deg], respectively;
- the ratio of the pitch angle of the shoulder to the yaw angle of the trunk is 2.5.

In consideration of these initial and final parameters, the position and orientation of the foot, waist and head $\boldsymbol{x}_{foot} \in \Re^6$, $\boldsymbol{x}_{waist} \in \Re^6$ and $\boldsymbol{x}_{head} \in \Re^3$ can be determined by a polynomial. In making a smooth motion, at least seven constraints are required. Three constraints come from the selection of the initial and final values:

$$\boldsymbol{x}(t_0) = \boldsymbol{x}_0,\ \boldsymbol{x}(t_f) = \boldsymbol{x}_f,\ \boldsymbol{x}(t_m) = \boldsymbol{x}_m, \qquad (6)$$

where t_0, t_m and t_f are the initial, intermediate and final times of a step, respectively.

The position and orientation $\boldsymbol{x}$ have an additional four constraints that are the zero initial and final velocity and acceleration:

$$\begin{aligned}\dot{\boldsymbol{x}}(t_0) = \mathbf{0},\ \dot{\boldsymbol{x}}(t_f) = \mathbf{0},\\ \ddot{\boldsymbol{x}}(t_0) = \mathbf{0},\ \ddot{\boldsymbol{x}}(t_f) = \mathbf{0}.\end{aligned} \qquad (7)$$

These seven constraints are satisfied by a polynomial of six degree. The sixth order polynomial is written as

$$\begin{aligned}\boldsymbol{x}(t) = \boldsymbol{a}_0 + \boldsymbol{a}_1 t + \boldsymbol{a}_2 t^2 + \boldsymbol{a}_3 t^3 + \boldsymbol{a}_4 t^4\\ + \boldsymbol{a}_5 t^5 + \boldsymbol{a}_6 t^6,\end{aligned} \qquad (8)$$

and the velocity and acceleration along the path are clearly

$$\begin{aligned}\dot{\boldsymbol{x}}(t) &= \boldsymbol{a}_1 + 2\boldsymbol{a}_2 t + 3\boldsymbol{a}_3 t^2 + 4\boldsymbol{a}_4 t^3 + 5\boldsymbol{a}_5 t^4 + 6\boldsymbol{a}_6 t^5,\\ \ddot{\boldsymbol{x}}(t) &= 2\boldsymbol{a}_2 + 6\boldsymbol{a}_3 t + 12\boldsymbol{a}_4 t^2 + 20\boldsymbol{a}_5 t^3 + 30\boldsymbol{a}_6 t^4.\end{aligned} \quad (9)$$

Combining Equation (8) and Equation (9) with seven constraints, we can specify a linear set of seven equations ($\boldsymbol{a}_0 \cdots \boldsymbol{a}_6$). The desired positions and orientations of the waist obtained from Equation (8) are changed by the compensatory motion control algorithm to compensate for the moments produced by the motion of the head, lower-limbs and upper-limbs during the walking. In addition, the compensatory trajectory of the trunk is obtained by the iteration method, depending on the ratio between the compensation moments of the trunk and the waist and the initial position and orientation of the trunk. Also, the arm trajectory is defined using forward kinematics, depending on the shoulder position and orientation.

We have conducted emotional walking experiments. In the experiments, three emotions such as happiness, sadness and anger are considered. The experimental schemes are as follows: (1) the preset walking patterns of the lower-limbs, waist and head are planned according to the motion parameters determined by emotional simulations: (2) the compensatory motion of the waist and trunk is calculated using the compensatory motion control algorithm to realize the stable emotional walking: (3) each emotional walking pattern is commanded to the WABIAN-RII using the program control.

In these experiments, the dynamic complete walking is realized with the step time of 1.28[s/step] and the step width of 0.15[m/step]. In addition, each emotional walking is evaluated by ten undergraduates as two steps(not agree or agree). Table 1 shows the evaluation of emotional walking. The agreement rates in the happy and sad walking are 90 percent and 80 percent, respectively. On the other hand, the agreement rate in the angry walking is 30 percent because the joint angles of the WABIAN-RII are limited.

Table 1: Evaluation of three emotional walking.

Walking style	Agreement [%]
Happy walking	90
Sad walking	80
Angry walking	30

5. Conclusion

There are many challenging aspects in building a biped humanoid robot that can interact and cooperate naturally with humans. To realize human-like walking such as the emotional walking and the follow walking, a pattern switching method and a parameterization of the walking motion are proposed. The follow walking and the emotional walking are confirmed by experiments.

Acknowledgment

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