Biped walking robots created at Waseda University: WL and WABIAN family

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This paper proposes the mechanism and control of the biped humanoid robots WABIAN-RIV and WL-16. WABIAN-RIV has 43 mechanical degrees of freedom (d.f.): 6 d.f. in each leg, 7 d.f. in each arm, 3 d.f. in each hand, 2 d.f. in each eye, 4 d.f. in the neck and 3 d.f. in the waist. Its height is about 1.89 m and its total weight is 127 kg. It has a vision system and a voice recognition system to mimic some of the capabilities of the human senses. WL-16 consists of a pelvis and two legs having six 1 d.f. active linear actuators. An aluminium chair is mounted on two sets of its telescopic poles. To reduce the large support forces during the support phase, a support torque reduction mechanism is developed, which is composed of two compression gas springs with different stiffness. For the stability of the robots, a compensatory motion control algorithm is developed. This control compensates for moments generated by the motion of the lower limbs, using the motion of the trunk and the waist that is obtained by the zero moment point concept and fast Fourier transform. WABIAN-RIV is able to walk forwards, backwards and sideways, dance, carry heavy goods and express emotion, etc. WL-16 can move forwards, backwards and sideways while carrying an adult weighing up to 60 kg.

Keywords: biped walking robot; stability; walking pattern; zero moment point compensatory motion; parallel mechanism

1. Introduction

The late Professor Ichiro Kato (1925–1994) who pioneered robots in Japan made students not to lose the hope of creating humanoid robots capable of coexisting with a human. In 1966, Professor Kato started studying not only a human-like robotic hand to be applicable to hand prostheses, but also a biped walking robot to analyse a human-walking mechanism. In 1967, an artificial biped walker, WL-1, was constructed on the basis of a human leg mechanism as shown in figure 1a, and the fundamental functions of biped locomotion were investigated. In 1969, WL-3 was developed, which had an electro-hydraulic servo-actuator as shown in figure 1b. It performed a little human-like movement in a swing phase and a stance phase using a master–slave control method. It also achieved a standing and sitting motion.

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One contribution of 15 to a Theme Issue ‘Walking machines’.
In 1969, an anthropomorphic pneumatically activated pedipulator, WAP-1, was developed as shown in figure 1c. Artificial muscles made of rubber were used for actuators. Planar biped locomotion was realized by teaching-playback control. In 1970, WAP-2 was constructed, which had powerful pouch-type artificial muscles instead of actuators as shown in figure 1d. It was controlled by automatic posture control based on pressure sensors implanted under the soles. In 1971, WAP-3 with PWM-driven actuators and a memory-based controller was constructed as shown in figure 2a, and was able to move its centre of gravity on the frontal plane. It performed three-dimensional automatic biped walking for the first time in the world.

In 1972, an 11 degrees of freedom (d.f.) biped robot (two 5 d.f. legs and a 1 d.f. trunk), WL-5, was developed, which had a laterally bendable body as shown in figure 2b. It was controlled by a minicomputer. In 1973, WABOT-1 was created, which was the world's first full-scale anthropomorphic robot (Kato et al. 1973). It was able to communicate with a human in Japanese and measure the distance and direction of objects using external receptors such as artificial ears and eyes. Hydraulically powered, it uses disproportionately large feet for stability. A shuffler more than a walker, WABOT-1 was able to walk statically. In 1980, we developed a 10 d.f. biped robot, WL-9DR, which was controlled by a 16 bit microcomputer (figure 2c). This robot achieved quasi-dynamic walking for the first time in the world. In 1983, WL-10R was constructed using rotary type
servo-actuators and carbon-fibre reinforced plastic as shown in figure 3a. It was able to walk forwards and backwards and turn on the plane. In 1984, WHL-11 was developed by Wasada and Hitachi, which walked more than 85 km at Tsukuba Science Expo ’85. In 1985, WL-10RD had torque sensors attached to the ankle and hip joint to achieve flexible control (figure 3b). Complete dynamic walking on a flat floor was achieved with a step time of 1.3 s per step using a program and sequence control (Takanishi et al. 1985, 1988).

In 1986–1990, a hydraulic biped robot, WL-12 family, which has a trunk and a 2 d.f. waist, was constructed to simulate more human motion. A balance control algorithm was developed to improve walking stably, which compensates for moments generated by the motion of the lower limbs. Using the control method, WL-12RIII performed complete dynamic walking on a stair with a height of 0.1 m with a step speed of 2.6 s per step and a step length of 0.3 m (figure 3c; Takanishi et al. 1990). On a trapezoid floor with a slope of 10°, it achieved complete dynamic walking with a step speed of 1.6 s per step and a step length of 0.3 m. Also, dynamic walking was realized under an unknown external force of 100 N applied to its back (Takanishi et al. 1991). WL-12RVI, developed in 1992, was able to maintain stable dynamic walking on unknown paths. A walk-learning method and an optimal path generator were created (Li et al. 1992). In 1995, WL-RVII performed dynamic walking on tatami (Japanese traditional mattress) with a step speed of 1.28 m s⁻¹ and a step length of 0.3 m. A foot mechanism using elastic pads had been proposed to absorb impact and contact forces (Yamaguchi et al. 1995).

As the second stage of robot studies began, WABIAN was created in 1996 with three design concepts: an adult-size robot, use of electric motors and the same step speed as a human. It consists of a total of 35 d.f.: two 3 d.f. legs, two 10 d.f. arms, a 2 d.f. neck, two 2 d.f. eyes and a torso with a 3 d.f. waist. It was able to dance with a human and carry goods. In 1997, WABIAN-R having 43 d.f. was developed for exploring robot–environment interaction (Setiawan et al. 1999a). In 1999, using WABIAN-RII, the emotional motion was presented, which was expressed by the parametrization of its body motion (Lim et al. 2000a). Human-following walking control was proposed, which has a pattern switching technique.

Figure 3. Photos of biped robots: (a) WL-10R, (b) WL-10RD and (c) WL-12RIII.
based on the action criterion of human–robot physical interaction (Lim et al. 2000b). An impedance control method for WABIAN-RIII was created to absorb the impact/contact forces generated between the landing foot and the ground, which can adjust impedance like the relaxed and hardened motion of muscles of a human (Lim et al. 2004a). An online locomotion pattern generation was developed for a biped humanoid robot having a trunk, which is based on visual and auditory sensors (Lim et al. 2004b).

Recently, many research institutes and companies have been interested in the robots industry and have developed many biped walking robots using a serial mechanism (Furuta et al. 2000; Hirose et al. 2001; Ishida et al. 2001; Kagami et al. 2001; Kanehiro et al. 2003). The conventional serial structure has many problems such as rigidity, power, position errors, etc. Thus, we have developed biped walking robots having a parallel mechanism, WL-15 (Sugahara et al. 2002) and WL-16 (Sugahara et al. 2004), since 2002. The parallel mechanism consists of six 1 d.f. active linear actuators. The robots were designed for multi-purpose use, for example, welfare and entertainment. An aluminium chair was mounted on the pelvis of WL-16. WL-16 performed dynamic biped walk carrying a human weighing up to 60 kg for the first time in the world.

To cooperate with humans, biped robots have to fulfil the function of stability and locomotion at the same time. However, the function of stability should take priority over the function of path control of the lower limbs to achieve dynamic stable walking. Therefore, this paper presents a compensatory motion control that cancels moments generated by the motion of the head, legs and arms using the motion of the trunk and the waist (Lim et al. 2002). At present, this control is used for a four-legged robot, Banryu (Tmsuk Co. Ltd). Our technologies will be connected with business more tightly very soon. Also, the mechanism of WABIAN-RIV and WL-16 is discussed in this paper.

2. Walking pattern generation

One walking cycle consists of five phases: stationary, transient, steady, transient and stationary phases. The transient phases in the walking cycle are regarded as a step after and before the stationary phase, respectively. The reason is that the dynamics of the upper body must be considered during the whole walking cycle for stability. In this study, we assume that the tip of the toe and the heel of the biped robot contact the ground at the same time.

A basic complete motion pattern is created offline by our pattern generator (Lim & Takanishi 2001). It generates a continuous walking pattern in real time as follows. First, walking parameters such as walking length, walking height and walking direction determined by visual and auditory information are inputted to the pattern generator. Second, the pattern generator makes a five-phase pattern of the lower limbs and sets a target zero moment point (ZMP) pattern in the stable polygon. Third, the compensatory motion of the trunk and the waist is calculated by using a compensatory motion control method based on the motion of the lower limbs and the ZMP. Finally, the middle step of the five-phase pattern including the compensatory motion pattern is selected as the next step, and is also used to make future steps.
Figure 4 shows the pattern generation of the lower limbs. The solid squares in figure 4 denote a selected pattern for the next step. We describe here how to generate the pattern of the lower limbs more in detail as follows.

(i) The five-phase pattern, which is composed of a steady phase, transient phases and stationary phases, is generated in real time as soon as the biped humanoid robot starts. In order to determine the smooth motion of the leg, the sixth-order polynomial is employed which considers angle, angular velocity, angular acceleration and the highest position of the foot. The sixth-order polynomial is written as

\[ x(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 + a_6 t^6, \] (2.1)

and the velocity and acceleration along the path are clearly

\[ \dot{x}(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4 + 6a_6 t^5, \] (2.2)

\[ \ddot{x}(t) = 2a_2 + 6a_3 t + 12a_4 t^2 + 20a_5 t^3 + 30a_6 t^4, \] (2.3)

where \( x \in \mathbb{R}^{12} \) is the position and orientation of the foot and waist. By using (2.1) and (2.3) and seven constraints, the seven coefficients \( (a_0 \ldots a_6) \) can be obtained. Substituting these coefficients in (2.1), the pattern of the foot is determined. Then, based on inverse kinematics, the knee and waist patterns are created. However, it can be changed depending on the compensatory motion of the trunk. The pattern generator selects from the first step to the third step at the beginning.

(ii) At the third step, a new five-phase pattern is determined including the second and the third step of the previous five-phase pattern and its fourth step is chosen as the next step as shown in figure 4. This pattern generation is repeated depending on the sensory information.


to realize biped walking, the functional role of parts of the biped humanoid robot should be divided. The lower limbs should be able to adapt to human living environments, while the upper body should be able to maintain walking stability. In this section, compensatory motion control is described, which cancels moments generated by the motion of the robot, which is based on the waist and trunk motion. For stability, this control method will be used not only for biped robots, but also for one-, four- and multi-legged robots and mobile robots.

(a) Coordinate frames

We consider a 43 d.f. biped model with rotational joints that consists of two 6 d.f. legs, two 7 d.f. arms, two 3 d.f. hands, a 4 d.f. neck, two 2 d.f. eyes and a torso with a 3 d.f. waist. To define mathematical quantities, a world coordinate frame $F$ is fixed on the floor where the biped robot can walk and a moving coordinate frame $\mathcal{F}$ is attached at the centre of the waist to consider the relative motion of each particle as shown in figure 5. To specify the dynamic behaviour of the biped model, five assumptions have been made as follows:

(i) the biped robot is modelled by a set of particles,
(ii) the foothold of the biped robot is rigid and not moved by any force and moment,
(iii) the contact region between the foot and the ground is a set of contact points,
(iv) the coefficients of friction for rotation around $X$, $Y$ and $Z$-axes are nearly zero at the contact point between the foot and the ground, and
(v) the feet of the robot do not slide.
Approximate waist and trunk motion

Under the modelling assumptions, the moment balance around a contact point \( p \) between the foot and the ground with respect to the world coordinate frame can be written as

\[
\sum_{i=1}^{n} m_i (\mathbf{r}_i - \mathbf{r}_p) \times (\mathbf{\dot{r}}_i + \mathbf{G}) + \mathbf{T} - \sum_{j=1}^{n} ((\mathbf{r}_j - \mathbf{r}_p) \times \mathbf{F}_j + \mathbf{M}_j) = 0, \tag{3.1}
\]

where \( \mathbf{r}_p \) is the position vector of the point \( p \) with respect to \( \mathbf{F} \); \( m_i \) is the mass of the particle \( i \); \( \mathbf{r}_i \) and \( \mathbf{\dot{r}}_i \) denote the position and acceleration vectors of the particle \( i \) with respect to \( \mathbf{F} \), respectively; \( \mathbf{G} \) is the gravitational acceleration vector; \( \mathbf{T} \) is the moment vector acting on the contact point \( p \); \( \mathbf{r}_j \) denotes the position vector of the particle \( j \) on which unexpected disturbances act, with respect to \( \mathbf{F} \); and \( \mathbf{F}_j \) and \( \mathbf{M}_j \) denote the force and the moment vectors acting on the particle \( j \) relative to the frame \( \mathbf{F} \), respectively.

Let ZMP be coincident with point \( p \). The moment \( \mathbf{T} \) is zero according to the ZMP concept. To get the relative motion of particles, (3.1) is rearranged relative to the moving frame \( \mathbf{\bar{F}} \) as follows:

\[
\sum_{i=1}^{n} m_i (\mathbf{\bar{r}}_i - \mathbf{\bar{r}}_{\text{ZMP}}) \times (\mathbf{\ddot{r}}_i + \mathbf{\dot{r}}_q + \mathbf{G} + \mathbf{\dot{\omega}} \times \mathbf{\dot{r}}_i + 2\mathbf{\omega} \times \mathbf{\dot{r}}_i + \mathbf{\ddot{\omega}} \times (\mathbf{\dot{\omega}} \times \mathbf{\dot{r}}_i))
- \sum_{j=1}^{n} ((\mathbf{\bar{r}}_j - \mathbf{\bar{r}}_{\text{ZMP}}) \times \mathbf{\bar{F}}_j + \mathbf{\bar{M}}_j) = 0, \tag{3.2}
\]

where \( \mathbf{\bar{r}}_{\text{ZMP}} \) is the position vector of ZMP with respect to \( \mathbf{\bar{F}} \); \( \mathbf{r}_q \) is the position vector of the origin of the frame \( \mathbf{\bar{F}} \) from the origin of the frame \( \mathbf{F} \); and \( \mathbf{\omega} \) and \( \mathbf{\ddot{\omega}} \) denote the angular velocity and acceleration vectors, respectively.

The three-axis motion of the trunk is interferential to each other and has the same virtual motion if the links of the biped robot are connected by rotational joints. Therefore, it is difficult to derive analytically the compensatory motion of the trunk and the waist from equation (3.2). To get the approximate solution analytically, we assume that

(i) the external forces are not considered in the approximate model,
(ii) the upper body is modelled as a four-mass model,
(iii) the moving frame does not rotate, and
(iv) the trunk and the waist do not move vertically.

The moment generated by the motion of the lower-limb particles, \( \mathbf{M} = [M_x, M_y, M_z]^T \), can be obtained as follows:

\[
\begin{align*}
& m_s (\mathbf{\ddot{r}}_s + \mathbf{\dot{r}}_q + \mathbf{G} + \mathbf{\dot{\omega}} \times \mathbf{\dot{r}}_s + 2\mathbf{\omega} \times \mathbf{\dot{r}}_s + \mathbf{\ddot{\omega}} \times (\mathbf{\dot{\omega}} \times \mathbf{\dot{r}}_s)) + m_t (\mathbf{\ddot{r}}_t - \mathbf{\bar{r}}_{\text{ZMP}}) \\
& \times (\mathbf{\ddot{r}}_t + \mathbf{\dot{r}}_q + \mathbf{G} + \mathbf{\dot{\omega}} \times \mathbf{\dot{r}}_t + 2\mathbf{\omega} \times \mathbf{\dot{r}}_t + \mathbf{\ddot{\omega}} \times (\mathbf{\dot{\omega}} \times \mathbf{\dot{r}}_t)) + m_w (\mathbf{\ddot{r}}_w - \mathbf{\bar{r}}_{\text{ZMP}}) \\
& \times (\mathbf{\ddot{r}}_w + \mathbf{\dot{r}}_q + \mathbf{G} + \mathbf{\dot{\omega}} \times \mathbf{\dot{r}}_w + 2\mathbf{\omega} \times \mathbf{\dot{r}}_w + \mathbf{\ddot{\omega}} \times (\mathbf{\dot{\omega}} \times \mathbf{\dot{r}}_w)) = -\mathbf{M}, \tag{3.3}
\end{align*}
\]

where \( m_s \) denotes the mass of both shoulders including the mass of the arms; \( m_t \) is the mass of the torso including the head, shoulders and arms; \( m_w \) is the mass of the waist; \( \mathbf{\bar{r}}_t \) and \( \mathbf{\bar{r}}_w \) are the position vectors of the neck and the waist with respect to \( \mathbf{\bar{F}} \), respectively; and \( \mathbf{\bar{r}}_s \) is the position vector of the shoulder with respect to the neck frame.

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In case the moments are not generated by the fictitious forces, the moment $M$ can be divided as three moment components such as pitch, roll and yaw moments. We assume that neither the waist nor the trunk particles move vertically, and the trunk arm rotates on the horizontal plane only. We put the terms relating to the motion of the upper-body particles on the left-hand side as unknown variables, and the terms relating to the moments generated by the lower-limb particles on the right-hand side as known parameters. The decoupled and linearized ZMP equations can be obtained as

$$\begin{aligned}
\dot{M}_{yt} + \dot{M}_{yw} &= \dot{M}_y(t) \\
\dot{M}_{xt} + \dot{M}_{xw} &= \dot{M}_x(t)
\end{aligned}$$

where

$$\begin{aligned}
\dot{M}_{yt} &= m_t(\ddot{z}_t - \ddot{z}_{zmp})\ddot{x}_t - m_t g_z \ddot{x}_t, \\
\dot{M}_{yw} &= m_w(\ddot{z}_w - \ddot{z}_{zmp})\ddot{x}_w - m_w g_z \ddot{x}_w, \\
\dot{M}_{xt} &= -m_t(\ddot{z}_t - \ddot{z}_{zmp})\ddot{y}_t + m_t g_z \ddot{y}_t, \\
\dot{M}_{xw} &= -m_w(\ddot{z}_w - \ddot{z}_{zmp})\ddot{y}_w + m_w g_z \ddot{y}_w, \\
\dot{M}_y(t) &= -M_y - (m_t(\ddot{z}_t - \ddot{z}_{zmp})\dddot{x}_q + m_t g_z \dddot{x}_q + m_w(\ddot{z}_w - \ddot{z}_{zmp})\dddot{x}_q + m_w g_z \dddot{x}_{zmp}), \\
\dot{M}_x(t) &= -M_x - (m_t(\ddot{z}_t - \ddot{z}_{zmp})\dddot{y}_q - m_t g_z \dddot{y}_q - m_w(\ddot{z}_w - \ddot{z}_{zmp})\dddot{y}_q - m_w g_z \dddot{y}_{zmp}), \\
\dot{M}_z(t) &= -M_z - (m_t(\dddot{x}_t - \dddot{x}_{zmp})(\dddot{y}_t + \dddot{y}_q) - m_t(\dddot{y}_t - \dddot{y}_{zmp})(\dddot{x}_t + \dddot{x}_q) \\
&+ m_w(\dddot{x}_w - \dddot{x}_{zmp})(\dddot{y}_w + \dddot{y}_q) - m_w(\dddot{y}_w - \dddot{y}_{zmp})(\dddot{x}_w + \dddot{x}_q)),
\end{aligned}$$

where $\theta_t$ is the vertical angle of the trunk; $l$ is the length between the neck and the shoulder; $\dot{M}_{xt}$ and $\dot{M}_{yt}$ denote the roll and the pitch trunk components of the moments, respectively; and $\dot{M}_{xw}$ and $\dot{M}_{yw}$ are the roll and the pitch waist components of the moments, respectively.

The compensatory motion of the trunk and the waist can be easily computed by Fourier transforms. $\dot{M}_{xt}$, $\dot{M}_{yt}$, $\dot{M}_{xw}$ and $\dot{M}_{yw}$ become the known functions because they are calculated by the motion of the lower limbs and the time trajectory of ZMP. In steady walking, they are periodic functions because each particle of the biped robot and ZMP move periodically with respect to the moving frame $F$. Comparing the Fourier transform coefficients of both sides of each equation, the approximate periodic solutions of the pitch and roll of the trunk and waist, $\dddot{x}_t$, $\dddot{y}_t$, $\dddot{x}_w$, $\dddot{y}_w$ and $\theta_t$, can be obtained.

This method is applicable to a complete walking that starts from a static standing state and returns to a static standing state again. By regarding the whole complete walking motion as one periodic walking motion and applying the method to it, the compensatory motion of the trunk and the waist for steady and transitional walking can be derived. Then, it is necessary to have a long period of standing time before starting motion and after stopping motion.

(c) Recursive calculation

A recursive method is used to obtain the strict solutions of the trunk and the waist motions. First, the approximate periodic solutions of the linearized equation (3.5) are calculated. Second, the approximate periodic solutions are
substituted into the moment equation (3.2) of the strict biped model, and the errors of moments generated by the trunk and waist motions are calculated according to the planned ZMP. These errors are accumulated in the right-hand side of equation (3.5). The approximate solutions are computed again. Finally, these computations are repeated until the errors fall below a certain tolerance level. As a result, the strict periodic solutions of the nonlinear equations are obtained by a convergent regularity. The limit value of an accumulated moment error on each axis, \( E_n \), is estimated as follows:

\[
E_n = \frac{2E_{n-1} + e_{n-1}}{2} \quad n = 3, 4, 5, \ldots, \quad E_1 = 0, \quad E_2 = e_1, \tag{3.6}
\]

where \( e_n \) is the \( n \)th moment error.

4. Biped humanoid robot, WABIAN-RIV

In this section, the mechanical and the electrical system of the full-scale anthropomorphic robot, WABIAN-RIV, is described (Lim et al. 2004b). This robot is able to dance with a human, carry goods and express emotions, and perform follow walking.

(a) Hardware of WABIAN-RIV

A 43 mechanical d.f. WABIAN-RIV with a human configuration was constructed in 2000 as shown in figure 6. The height of the WABIAN-RIV is about 1.89 m and its total weight is 127 kg. Table 1 gives its mass distribution.

Duralumin, GIGAS (YKK Corp.) and CFRP (carbon fibre reinforced plastic) are employed as the main structural materials used in WABIAN-RIV. The body and legs are driven by AC servo motors with reduction gears. The neck, hands and arms are actuated by DC servo motors with reduction gears, but the eyes are driven by DC servo motors without reduction gears. Two CCD cameras attached to the head observe the walking direction from human motion. A force/torque sensor attached to the wrist is used to detect interaction.

(b) Software of WABIAN-RIV

WABIAN-RIV is controlled by a PC/AT compatible computer PEAK-530 (Intel MMX Pentium 200 MHz CPU processor) run by MS-DOS 6.2/V (16 bit) as shown in figure 7. TNT DOS-EXTENDER SDK (v. 6.1) is employed to extend the OS to a 32 bit. It has three counter boards each with 24-bit 24 channels, three D/A converter boards each with 12-bit 16 channels and an 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 read to the computer through the counters. All the computations to control WABIAN-RIV are carried out by the central computer, which runs the control program 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.
To measure ZMP, a force/torque sensor is attached between the ankle and the foot. Electric power is the only external connection. The vision system of WABIAN-RIV is designed to mimic some of the capabilities of a human vision system. Two camera vision signals are used to sense three-dimensional information. IMB’s ViaVoice system is used as a voice recognition engine. The system recognizes a set of prior learnt words. The walking length is defined by compiling the text file of grammar rules. The time delay of the auditory system is about 3 s.

5. Parallel biped locomotor, WL-16

In this section, the mechanical and the electrical system of a multi-purpose biped locomotor WL-16 is described. WL-16 is the world’s first biped walking robot capable of carrying a human weighing up to 60 kg, and is applicable to medical, welfare and entertainment fields.

(a) Mechanical and electrical system of WL-16

WL-16 was developed in 2003, and has a 6 d.f. parallel mechanism for each leg as shown in figure 8. The parallel mechanism consists of six 1 d.f. active linear actuators, six 2 d.f. passive joints attached to the upper part of the leg and three 3 d.f. passive joints attached to the lower part of the leg. The 3 d.f.
A passive joint is composed of a ball joint in the centre and two yokes having two bearings attached to the axis of both ends of the ball joint. The movable angle of the 3 d.f. passive joint is from $-40^\circ$ to $+40^\circ$, while the movable angle of the 2 d.f. passive joint is from $-45^\circ$ to $+45^\circ$. A stroke of the linear actuator is 0.35 m. To deal with various environments, each linear motor is connected in parallel to each screw shaft, using a timing belt (figure 9). Thus, a large movable range is realized as shown in figure 10: 1.02 m to the direction of the $X$-axis, 1.36 m to the direction of the $Y$-axis and 0.34 m to the direction of the $Z$-axis.

A control computer is attached to the back of the pelvis, and a body angle detector and DC servo drivers are installed in the pelvis. Also, a chair on which a human can sit is attached to the pelvis. Polyacetal resin is used as the main structural material. Its height is about 1.2 m and its weight is 56 kg including batteries (Sugahara et al. 2004).

In order to reduce large support forces during the support phase, a support torque reduction mechanism was developed. This mechanism consists of two compression gas springs with different stiffness, and locks and unlocks them according to the support/swing phase shown in figure 11. During the support phase, the gas spring with a large reaction force is unlocked and activated, and the other is locked. However, during the swing phase, the gas spring with a small reaction force is unlocked and the other is locked. When the supporting state changes, the gas springs are switched by pushing down and releasing the switch pin of each gas spring using the solenoids.

WL-16 is controlled by a Pentium III-850 MHz CPU processor run by QNX. It has D/A converter boards with 12-bit 16 channels and three counter boards with 24-bit 4 channels. To detect the initial positions of the actuators, a photo-micro sensor is attached to each actuator. There is a three-axis position angle detector attached to the pelvis, and there are rotary encoders installed on the output shaft of each motor. Each foot has a six-axis force/torque sensor to calculate ZMP. A Ni-MH battery (43.2 V, 30.0 A, 7.3 A h) is employed for power supply, which is installed inside the pelvis. DC–DC converters change the power supply into $5V, 12V, 24V$. $5V$ is supplied to rotary encoders and photo-micro sensors, $5V, 12V$ and $24V$ are supplied to the master computer, and $24V$ is supplied to electromagnetic brakes.

Table 1. Mass parameters of WABIAN-RIV.

<table>
<thead>
<tr>
<th>parts</th>
<th>weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>foot</td>
<td>1.949 ($\times2$)</td>
</tr>
<tr>
<td>ankle</td>
<td>7.834 ($\times2$)</td>
</tr>
<tr>
<td>knee</td>
<td>5.307 ($\times2$)</td>
</tr>
<tr>
<td>head</td>
<td>2.419</td>
</tr>
<tr>
<td>neck</td>
<td>6.454</td>
</tr>
<tr>
<td>trunk</td>
<td>51.995</td>
</tr>
<tr>
<td>hand</td>
<td>0.5 ($\times2$)</td>
</tr>
<tr>
<td>wrist</td>
<td>0.508 ($\times2$)</td>
</tr>
<tr>
<td>elbow</td>
<td>0.869 ($\times2$)</td>
</tr>
<tr>
<td>shoulder</td>
<td>5.932 ($\times2$)</td>
</tr>
</tbody>
</table>

WL-16 is controlled by a Pentium III-850 MHz CPU processor run by QNX. It has D/A converter boards with 12-bit 16 channels and three counter boards with 24-bit 4 channels. To detect the initial positions of the actuators, a photo-micro sensor is attached to each actuator. There is a three-axis position angle detector attached to the pelvis, and there are rotary encoders installed on the output shaft of each motor. Each foot has a six-axis force/torque sensor to calculate ZMP. A Ni-MH battery (43.2 V, 30.0 A, 7.3 A h) is employed for power supply, which is installed inside the pelvis. DC–DC converters change the power supply into $5V, 12V, 24V$. $5V$ is supplied to rotary encoders and photo-micro sensors, $5V, 12V$ and $24V$ are supplied to the master computer, and $24V$ is supplied to electromagnetic brakes.
Figure 7. Control system of WABIAN-RIV.
Figure 8. Photo of WL-16.

Figure 9. Decomposition of a linear actuator.
The walking pattern based on the compensatory motion control is created in an external host computer. The host computer and the master computer are connected through LAN, and the master computer compiles and executes the control software sent from the host computer.

### (b) Experimental results

Through various experiments, the effectiveness of the mechanism and control of WL-16 is confirmed. Forward, backward, right and left walking with a step length of 0.3 m was realized. The maximum and the minimum step speed was 0.80 and 1.92 s per step, respectively. WL-16 turned 90° within two steps and walked on the ground with many pebbles. The robot can carry 80 kg of goods while walking dynamically. Using a compliance control, dynamic walking was achieved on uneven terrain with a few acrylic boards with a diameter of 150 mm and a thickness of 5 mm.

We showed in November 2003 that WL-16 can move forwards, backwards and sideways while an adult weighing 60 kg sits on the aluminium chair mounted on the pelvis. WL-16 is the world’s first walking robot capable of carrying a human, and will be used in medical, welfare and amusement fields.
6. Conclusion and discussion

Since 1966, we have studied biped walking motion with the aim to apply the biped robots to industrial and non-industrial areas. One thrust has been towards realizing complete dynamic walking on not only even or uneven terrain, but also hard or soft terrain. The other thrust has been towards exploring robot–environment interaction and human emotions.

In this paper, the control and the mechanism of the biped walking robots WABIAN-RIV and WL-16 were discussed. WABIAN-RIV consists of two 6 d.f. legs, two 7 d.f. arms, two 3 d.f. hands, a 4 d.f. neck, two 2 d.f. eyes and a torso with a 3 d.f. waist, while WL-16 is composed of a pelvis and two legs having six 1 d.f. active linear actuators, six 5 d.f. passive joints for each leg. Based on our biped robot technology, WL-16 was designed for practical use as a multi-purpose locomotor of robotic systems. WL-16 is essentially an aluminium chair mounted on two sets of telescopic poles.

A compensatory motion control algorithm was created to achieve stable dynamic walking. This control compensates for moments generated by the motion of the lower limbs. Using WABIAN family, many successful walking experiments have been conducted with visual and auditory systems, and the effectiveness of the control method and the online pattern generator has been confirmed. Also, using WL-16, human-carrying experiments were first achieved in the world. WL-16 can adjust its posture and walk smoothly even if a human it is carrying shifts in the chair.

At present, WL-16 can only step on an unknown obstacle with a maximum height of 5 mm, but we will make it capable of dealing with a normal flight of stairs in a few years. It will have a joy stick-like controller for the user. As a result, we hope this two-legged robot will enable wheel-chair users to climb up and down stairs and assist the movement of heavy goods over uneven terrain. Also, this robot will be applied to a walk assist system for the aged and the handicapped and a locomotion system for humanoid robots.

Our control algorithm and legged mechanism are applied to a four-legged robot, Banryu, developed by Tmsuk Co. Ltd and Sanyo Electric Co. Ltd. Owing to that, the robot can walk more stably, smoothly and fast. As a result, our technologies of the control algorithm and the legged mechanism will be connected with business more tightly very soon. However, for the legged robots to coexist with a human in human living environments, many problems such as human safety and human friendliness must be solved. We are currently studying the problems.

References


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