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Balance and Impedance Control for Biped Humanoid Robot Locomotion

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Abstract

This paper describes a locomotion control for biped humanoid robots based on a balance control and an impedance control. The balance control is employed during a whole walking cycle, which can compensate for the moments generated by the biped walking. In the control, the compensatory motion of the trunk and waist is calculated from the trajectories of the lower-limbs, arms, head and ZMP. The parameters of the impedance control are adjusted in real-time according to the gait phase. The large damping coefficient of the impedance is applied to the landing leg to absorb the impact/contact force during the contact phase, while the large stiffness is given to increase the momentum reduced by the viscosity of the landing leg during the first half single support phase. By dynamic walking experiments using a human-like robot WABIAN-RIII, the validity of the proposed control methods is verified.

1. Introduction

Humans and animals use their legs to locomote with great mobility, but we do not yet have a full understanding of how they do so. One sign of our ignorance is the lack of man-made robots that use legs to obtain high mobility. Specially, two legged robots that are suitable for locomotion in humans' living environments such as offices and homes have not been studied so many up to date.

The analysis, design, construction and control of biped robots on a level terrain have received in recent years a particular attention. Takanishi and coworkers [1, 2] developed the biped walking robot and proposed the trunk compensated control to walk on a plat ground. Kajita and Tani [3] developed the linear inverted pendulum model that is based on massless leg model, to control a biped walking on a level plane. Honda's humanoid robot called P2 showed the ability to walk forward, backward, right, left [4]. However, the above proposed methods are difficult to realize a fast and stable biped walking on even/uneven terrain.

Biped robots capable of cooperating with humans have to fulfill the function of the stability and locomotion at the same time when they walk. However, the function of the stability should take priority over the function of the path control of the lower-limbs to achieve the dynamic stable walking. Also, the elasticity of the biped robots should be changed depending on the gait phase to reduce impact/contact force. Several researchers have studied the impedance control [5, 6].

In this paper, an impedance control and a balance control are proposed for biped robots to walk stably on a human's living environment. The balance control based on the motion of the trunk and waist is applied to maintain a good balance and posture while the path of the lower-limbs is controlled according to the terrain. In order to absorb the impact/contact force generated between the contacting foot and the ground, the impedance control is introduced with the position control. The impedance parameters are changed in real-time according to the gait phase. Our goal is to understand a human's walking mechanism and to build a human-like biped robot that can help humans.

This paper is organized as follows. In section 2, we describe a balance control based on the motion of the trunk and waist. Section 3 describes an impedance control to deal with impact/contact force. Section 4 illustrates experimental results. Finally, Section 5 provides conclusions.

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2. Balance Control

A 43-DOF biped model with rotational joints is considered in this study, which consists of two 6-DOF legs, two 7-DOF arms, two 3-DOF hands, a 4-DOF neck, two 2-DOF eyes and a torso with a 3-DOF waist. In modeling the biped robot, five assumptions are defined as follows: a) the biped robot consists of a set of particles, b) the foothold of the biped 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 feet and the floor surface and e) the feet of the robot do not slide on the contact surface. To define mathematical quantities, a world coordinate frame $\mathcal{F}$ is fixed on the floor where the biped robot can walk and a moving coordinate frame $\bar{\mathcal{F}}$ is attached on the center of the waist to consider the relative motion of each part (see Figure 1).

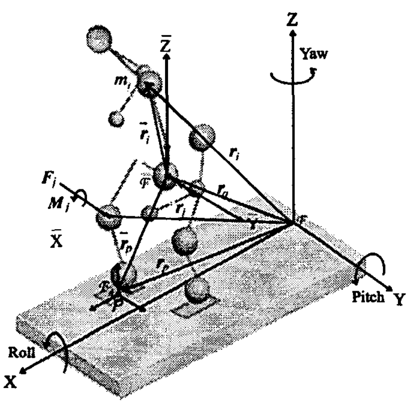


Figure 1: Coordinate frames.

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 $\boldsymbol{r}_p$ is the position vector of the point p from the origin of the $\mathcal{F}$. m_i is the mass of the particle i. $\ddot{\boldsymbol{r}}_i$ denotes the acceleration vector of the particle i with respect to the frame $\mathcal{F}$. $\boldsymbol{G}$ 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 $\mathcal{F}$.

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. It, therefore, is difficult to derive analytically the motion of the trunk and waist from Equation (1). For the approximate solutions of the trunk and waist, we assume that (a) the external forces are not considered in the approximate model, (b) the upper body is modeled as a four-mass model, (c) the moving frame does not rotate and (d) the trunk and waist does not move vertically. Each moment equation can be written by

$$\hat{M}_y = \hat{M}_{yt} + \hat{M}_{yw},\ \hat{M}_x = \hat{M}_{xt} + \hat{M}_{xw}, \\ \hat{M}_{zt} = m_t {R_t}^2 \ddot{\theta}_t,\ \hat{M}_{zw} = m_h {R_h}^2 \ddot{\theta}_w, \quad (2)$$

where

$$\begin{aligned} \hat{M}_{yt} &= -m_t(\bar{z}_t - \bar{z}_{zmp})\ddot{\bar{x}}_t + m_t g_z \bar{x}_t, \\ \hat{M}_{yw} &= -m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{\bar{x}}_w + m_w g_z \bar{x}_w, \\ \hat{M}_{xt} &= m_u(\bar{z}_t - \bar{z}_{zmp})\ddot{\bar{y}}_t - m_u g_z \bar{y}_t, \\ \hat{M}_{xw} &= m_w(\bar{z}_w - \bar{z}_{zmp})\ddot{\bar{y}}_w - m_w g_z \bar{y}_w. \end{aligned} \quad (3)$$

where $\bar{\boldsymbol{r}}_{zmp}$ is the position vector of ZMP with respect to the $\bar{\mathcal{F}}$. m_t and m_w are the mass of the trunk including the head and arms and the mass of the waist including the hips, respectively. $\bar{\boldsymbol{r}}_t = [\bar{x}_t\ \bar{y}_t\ \bar{z}_t]^T$ and $\bar{\boldsymbol{r}}_w = [\bar{x}_w\ \bar{y}_w\ \bar{z}_w]^T$ are the position vectors of the trunk and the waist, respectively. R_t and R_w are the radius of the trunk arm and waist arm, respectively.

In Equation (2) the moments $\hat{M}_x$, $\hat{M}_y$, $\hat{M}_{zt}$ and $\hat{M}_{zw}$ are known values, which are derived from the motion of the lower-limbs and a time trajectory of ZMP. $\hat{M}_{xt}$, $\hat{M}_{yt}$, $\hat{M}_{xw}$, $\hat{M}_{yw}$, $\hat{M}_{zt}$ and $\hat{M}_{zw}$ are periodic functions because each particle of the lower-limbs and the time trajectory of ZMP move periodically with respect to the moving frame $\bar{\mathcal{F}}$. Therefore, each equation can be represented as a Fourier series. Comparing the Fourier transform coefficients of both sides of each equation, the approximate periodic solutions of the pitch and roll trunk and waist can be obtained easily. By regarding a complete walking as one walking cycle and making static standing states before and after walking long enough, the approximate solutions of the compensatory trunk and waist for the complete walking can be derived. The strict solutions of the trunk and waist motion can be obtained by a recursive calculation.

3. Impedance Control

To reduce the impact/contact force/torque generated between the landing foot and the ground, an impedance control is presented in this section.

3.1 Problems

The above balance control based on the trunk and waist motion can maintain a good balance and posture, but is difficult to avoid the instability caused by the impact/contact force produced between the landing foot and the ground. Therefore, the reaction force and ZMP in a whole walking cycle are investigated through a walking experiment on the plane. Figure 2 describes the normal reaction force generated between the foot and the ground. The moment the swing leg is in contact with the ground, the reaction force increases largely. This makes the biped robot unstable. Figure 3. shows the reference ZMP and the actual ZMP with respect to the world coordinate frame. During the single support phase, the actual ZMP deviates from the reference ZMP due to the vibration caused by the impact force of the landing foot. Also, other reasons are that the physical parameter values of the mathematical model are different from those of the real biped robot and the robot bends due to the body elasticity. The results of the walking experiment indicate that the balance control is difficult to guarantee high stability. Therefore, a new control method is proposed, which can absorb the impact/contact force in the next section.

3.2 Position-based Impedance Control

A walking cycle of the biped humanoid robot consists of four major phases as shown in Figure 4: swing phase, contact phase, double support phase and single support phase. During the swing phase, one foot is not constrained from the ground while the other foot is on the ground. In the contact phase as soon as the swing foot reaches the ground, and the walking phase is changed to the double support phase. If only one foot is on the ground, the biped robot is in the single support phase. We assume that the tiptoe and the heel of the biped robot contact on the ground at the same time in this study.

In order to realize a stable biped walk, a learning method has been studied, which employs the compensative trunk motion calculated offline based on the contact force generated between the foot and the ground [7]. This method could slightly reduce instability caused by the disturbance, but would be difficult

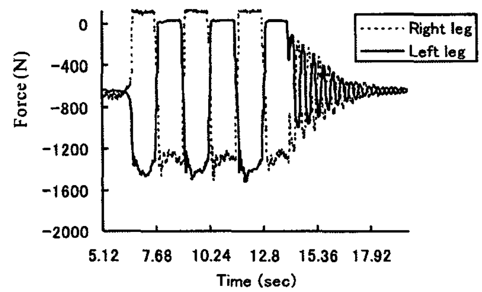
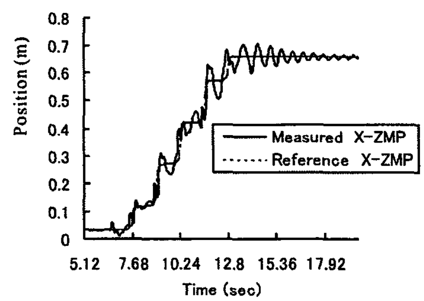
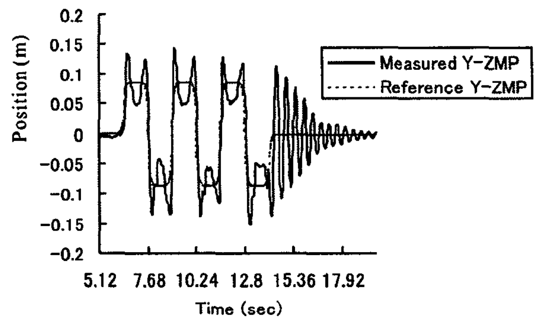


Figure 2: Normal contact force between the foot and the ground.



(a) Y-ZMP.



(b) X-ZMP.

Figure 3: Preset and actual ZMP trajectories.

to realize the variety of locomotion in a human living- and working-environments. When a human walks, he/she controls his/her leg muscles for shock absorption and posture. His/her muscles are relaxed to absorb the impact/contact force just before his/her landing foot makes a initial contact while his/her muscles are hardened to maintain the balance after landing. For higher guaranteed walking of the biped robot, we pay attention to the elasticity of its leg like a human's leg muscles. There are two control methods: a hybrid position/force control and an impedance control. The first method can be used only if a detailed description of the geometry of the environment is available. In most practical situations, a detailed model of the environment is not available. Thus, we select the second method that can deal with the contact force by using a mechanical impedance of adjustable parameters. To measure the impact/contact force, we assume that a force/torque sensor is mounted at each ankle.

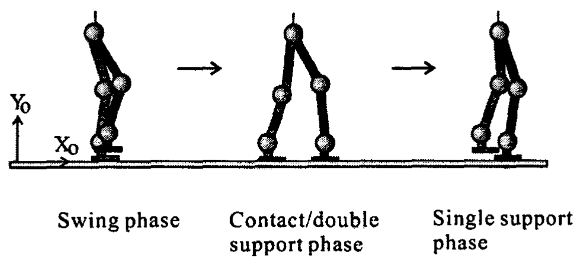


Figure 4: One walking cycle.

A foot coordinate frame $\mathcal{F}_{\mathcal{A}}$ is attached on the ZMP to eliminate the ZMP errors as shown in Figure 1. The impact/contact force between the landing foot and the ground, $\boldsymbol{F} \in \Re^6$, can be given by

$$\boldsymbol{M}_d\ddot{\boldsymbol{p}}_e + \boldsymbol{D}_d\dot{\boldsymbol{p}}_e + \boldsymbol{K}_d\boldsymbol{p}_e = \boldsymbol{F}, \qquad (4)$$
$$\boldsymbol{p}_e = \boldsymbol{p}_r - \boldsymbol{p}_d,$$

where $\boldsymbol{M}_d \in \Re^{6\times6}$ is the desired mass matrix. $\boldsymbol{D}_d \in \Re^{6\times6}$ and $\boldsymbol{K}_d \in \Re^{6\times6}$ are the damping and stiffness matrices, respectively. $\boldsymbol{p}_r \in \Re^6$ and $\boldsymbol{p}_d \in \Re^6$ denote actual position and desired position vectors, respectively. The angular velocity vector $\dot{\boldsymbol{p}}_e$ commanded to the landing leg joints can be obtained by

$$\dot{\boldsymbol{p}}_e = (\boldsymbol{M}_d^{-1}\int(\boldsymbol{F} - \boldsymbol{D}_d\dot{\boldsymbol{p}}_e - \boldsymbol{K}_d\boldsymbol{p}_e). \qquad (5)$$

$\dot{\boldsymbol{p}}_r$ can be measured by a proper encoder attached at each joint. The reaction force $\boldsymbol{F}$ is measured by the force/torque sensor. Figure 5 shows the block diagram of the position-based impedance control. In this control method, the impedance of the leg of the biped robot is modulated depending on the gait phase as follows: (1) in the swing phase, only the position control is employed, (2) in the contact/double phase, the impedance control with large viscosity is used to reduce the impact/contact force, (3) in the first half single support phase, the impedance control with large compliance is applied to maintain the natural balance and (4) in the last half single support phase, the revised pattern of the landing leg is returned to the preset walking pattern.

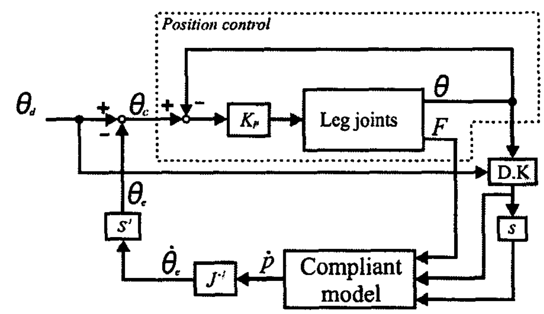


Figure 5: Impedance control system.

4. Walking Experiments

In this section, we show experimental evidence for the effectiveness of the impedance control.

4.1 System description

To explore the follow-walking motion, a forty-three mechanical degrees of freedom WABIAN-RIII with a human configuration has been constructed as shown in Figure 6. Its height and weight are about 1.88[m] and 130[kg], respectively. A force/torque sensor was equipped between each ankle and foot, which was used to realize more stable walking through the impedance control.

At the first stage of this study, the impedance control is applied to the ankle only. Table 1 shows the stiffness and damping coefficients used in walking experiments. All preset walking patterns are loaded to a main computer board of the WABIAN-III before walking, which is made by the balance control method.

During the walking, the WABIAN-RIII is controlled by the position-based impedance control. Then, the elasticity of the ankle is changed depending on the locomotion phase.

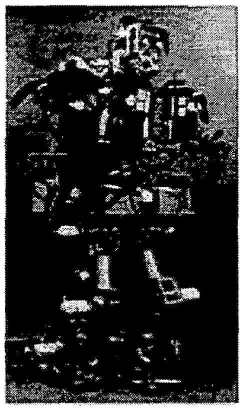


Figure 6: The Photo of WABIAN-RIII.

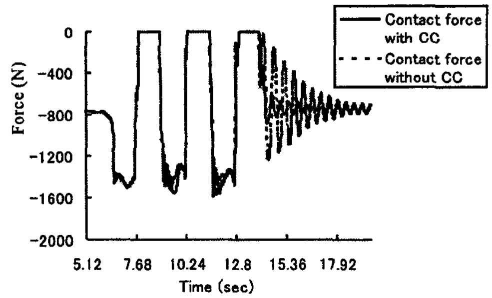
Table 1: The parameters of the ankle. C/DS denotes the contact/double support phase and FSS the first half single support phase.

Phase	Mass kg	Stiffness N/m	Damping Ns/m
C/DS	160	10	4000
SS	160	1000	500

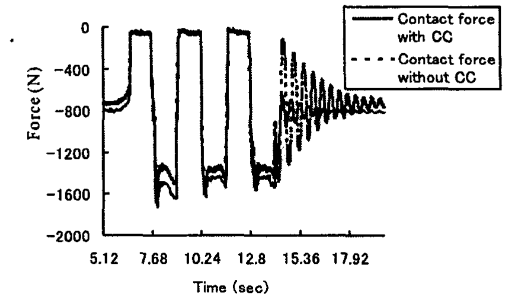
4.2 Experimental Results

The performance of the following control modes was evaluated in walking experiments: (1) the position-based compliance control and (2) the position control. The compliance control mode was applied to the ankle joint after 6.4[sec]. The results of contact forces of Z axis in the right leg contact are shown in Figure 7 (a) and those in the left leg contact are shown in Figure 7 (b). Figure 7 (a) and (b) illustrate that the contact forces are absorbed due to the compliance of the ankle. Especially, The contact forces are largely reduced in the last step. It means that the compliance control is effective on the slow locomotion.

Figure 8 illustrates the preset and actual pitch and roll ZMPs. The actual ZMP with respect to the world coordinate frame is calculated based on the reaction

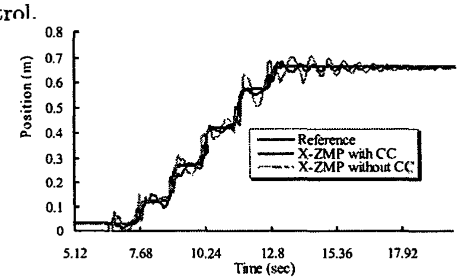


(a) Right leg.

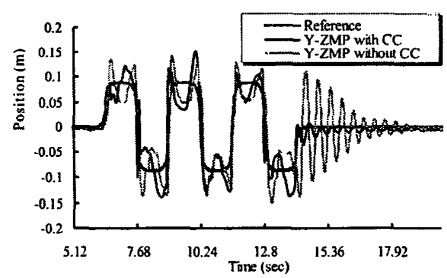


(b) Left foot.

Figure 7: Reaction force. CC denotes the compliance control.



(a) X-ZMP.



(b) Y-ZMP.

Figure 8: ZMP trajectories. CC denotes the compliance control.

force. The ZMP error in the impedance control is much smaller than that in the position control only. These results clarify that the position-based compliance control is effective on the stability.

5. Conclusions

An impedance control method for the biped robot was proposed to absorb the impact/contact force generated between the landing foot and the ground, which can adjust compliance like relaxed and hardened motion of a human muscles. Also, a balance control algorithm was presented to eliminate instability caused by the moment produced by the biped locomotion. To investigate the performance of the controllers, a human-like biped robot having a 43-DOF mechanical DOF has been constructed. The experimental results show that the controllers are effective for the sock absorption and the body and posture.

Acknowledgment

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