

# Balancing a Humanoid Robot Using Backdrive Concerned Torque Control and Direct Angular Momentum Feedback

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## Abstract

A novel balance control method for a humanoid robot is presented. It consists of a contact torque controller which is designed to have a good backdrivability and a feedback control of the total angular momentum and the center of gravity of a robot. A simulation result of a balance control using a 26 DOF humanoid robot model is shown.

## 1 Introduction

A humanoid robot has a center of mass at high position despite its small supporting area. Although it is mechanically unstable from its nature, the robot is also expected to do various maneuver just as a human does. For this reason an active balance control is a vital technology to realize a humanoid robot for practical use.

In this paper, we introduce a novel balancing control for a humanoid standing with one leg. In Section 2, we discuss a control of a contact torque which acts from the robot's sole to the ground surface. Particularly, we emphasize the importance of backdrivability of the contact torque controller and we show a two degrees of freedom feedback controller gives a good solution.

In Section 3, we introduce a new idea of a balance control using direct feedback of the total angular momentum and the position of the center of gravity of a robot. The performance of the controller is tested by using a simulation of a humanoid model of 26 DOF.

## 2 Backdrive concerned torque controller

Figure 1 illustrates a foot of a humanoid robot that is equipped with a 6-axis force sensor. The 6-axis force

sensor measures forces and torques acting from the robot to a ground and the information can be used for balancing and walking. In addition, the foot has a passive compliance to protect the force sensor and the robot itself from the landing-impact [1]. In Figure 1 the passive compliance is realized by an ordinal compliant material such as Neopren rubber.

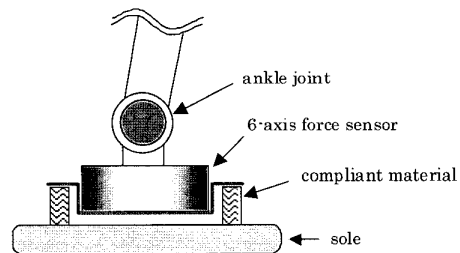


Figure 1: Foot structure with a 6-axis force sensor and passive compliance

The passive compliance also makes it possible to control the contact torque. In this paper we use the word *contact torque* as the moment that acts from the robot's sole to the ground surface. (NOTE: The contact torque is associated with the Zero Moment Point (ZMP) that is an important concept for the biped robot control [5, 6]. The ZMP is obtained when we divide the contact torque by the vertical element of the floor reaction force.)

Figure 2 shows how a robot controls a contact torque between the robot and the ground. By rotating the ankle joint the robot can generate the contact torque of desired magnitude. In the rest of this section we discuss a feedback controller to generate a specified contact torque using the force sensor.

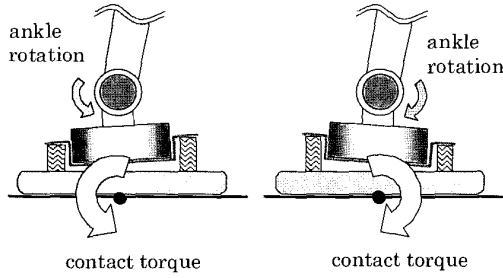


Figure 2: *Left: When a robot rotates the ankle CCW with respect to the leg, it generates CCW contact torque. Right: When a robot rotates the ankle CW with respect to the leg, it generates CW contact torque.*

## 2.1 Analysis of a conventional torque controller

To design a contact torque controller, we analyze a servomotor connected with an environment via a coil spring (Figure 3). In this model, we assume a servomotor with high-gain feedback control, which rotates the amount of  $q$  when a reference speed  $\omega^d$  is given.

$$q = P\omega^d \quad (1)$$

where  $P$  is a transfer function.

The passive compliance of a foot is modeled as a spring which yields torque  $\tau$  in proportion to the difference of angles between the motor and the environment.

$$\tau = k_e(q - q_e) \quad (2)$$

where  $k_e$  and  $q_e$  are the spring constant and the rotation of the environment respectively.

We treat the rotation of the environment as an independent parameter because we want to analyze how a motion of a ground affects the controlled torque. Moving ground is not an unusual situation since our torque controller is built under a local coordinate. For example, the ground is regarded as rotating with respect to the leg link when a robot is walking or sitting down.

As a torque controller, let us use following simple one.

$$\omega^d = C(\tau^d - \tau) \quad (3)$$

where  $C$  is a transfer function of the controller and  $\tau^d$  is the desired torque.

The block diagram of the total system is shown in Figure 4. Let us define a transfer function from a desired torque to an output torque ( $\tau^d \rightarrow \tau$ ) as  $G_1$ , and a transfer function from an environment rotation to

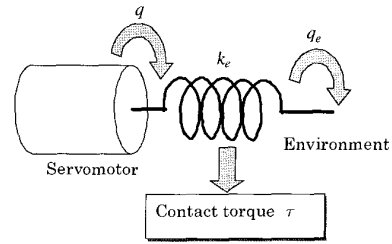


Figure 3: *Torque generation model*

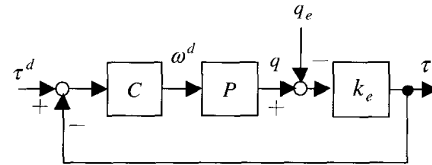


Figure 4: *A torque feedback controller*

an output torque ( $q_e \rightarrow \tau$ ) as  $G_2$ . They are calculated as follows.

$$G_1 = \frac{k_e PC}{1 + k_e PC} \quad (4)$$

$$G_2 = \frac{k_e}{1 + k_e PC} \quad (5)$$

Using  $G_1$  and  $G_2$ , the torque  $\tau$  is given as the following equation.

$$\tau = G_1 \tau^d - G_2 q_e \quad (6)$$

This equation shows that the contact torque is affected not only by the reference torque but also by the motion of the environment. The transfer function  $G_2$  presents the *backdrivability* of the torque control. In the case of a manipulator control, this term have not been seriously considered since the relative speed between a robot and an environment is small. However, for a humanoid robot, we need  $G_2$  as small as possible because of the large relative speed between a robot and an environment. As an ideal case, if a system have  $G_2 = 0$  at all frequencies, it has a maximum backdrivability and the system behaves as a direct drive motor or a pure torque generator. However, this is not possible when we build a torque control using a sensor feedback.

A typical frequency response of equation (4) and (5) is shown in Figure 5. At high frequency area ( $f \gg 10$

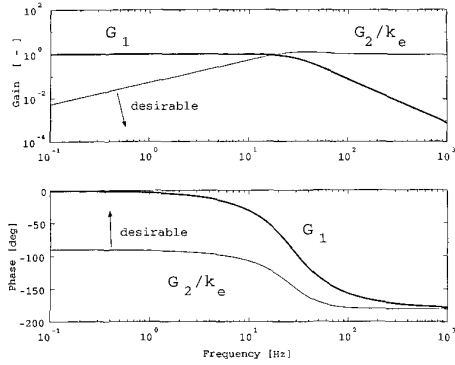


Figure 5: *Frequency response of a torque controller of Figure 4.  $G_2/k_e$  is plotted to match its physical dimension with  $G_1$ .  $P = 1/s(0.004s + 1)$ ,  $C = 0.3$*

Hz) of the plot, we have  $|G_1| \cong 0$ ,  $|G_2| \cong k_e$  which corresponds almost pure spring. This means that the environment moves quicker than the response speed of the servomotor.

We want to realize a maximum backdrivability ( $|G_2| \cong 0$ ) at low frequency area ( $f \ll 10$  Hz). However, the improvement of the backdrivability has a limitation. No matter what kind of controller  $C$  we use in Figure 4, the transfer function  $G_1$  and the backdrivability  $G_2$  always keep the following relationship.

$$G_1 + G_2/k_e = 1 \quad (7)$$

This equation forces us to make a trade off between  $G_1$  and  $G_2$ . We cannot merely improve the backdrivability  $G_2$  without affecting  $G_1$ , and eventually, that reduces the robustness of the closed loop. In the context of the robust control,  $G_1$  and  $G_2/k_e$  is called the complimentary sensitivity function and the sensitivity function respectively [7].

## 2.2 Two degrees of freedom torque controller

To improve the backdrivability of the torque control system, we examine a controller of different topology which has a direct feedback path from the output to the control input (Figure 6). With this controller, we have the following transfer function and the backdrivability.

$$G_1 = \frac{k_e P C_B}{1 + k_e P (C_A + C_B)} \quad (8)$$

$$G_2 = \frac{k_e}{1 + k_e P (C_A + C_B)} \quad (9)$$

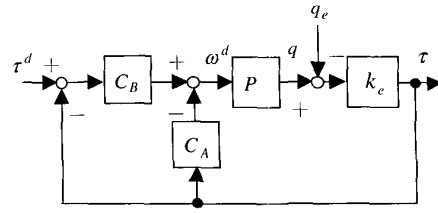


Figure 6: *Two DOF feedback control*

Unlike the first controller, now we have the following relationship.

$$G_1 + G_2/k_e = 1 - \frac{k_e P C_A}{1 + k_e P (C_A + C_B)} \quad (10)$$

This means there is a room to improve the backdrivability without affecting the transfer function of the reference torque. Since the controller gives a new degree of freedom to modify the transfer functions  $G_1$  and  $G_2$  independently, this is called a two degrees of freedom (2DOF) controller. Figure 7 shows the frequency response of the system under the 2DOF controller. Compared with Figure 5 we can see the backdrivability  $G_2$  is improved without side effects.

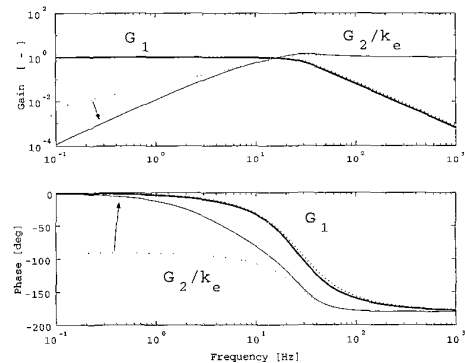


Figure 7: *Solid lines show the frequency response of 2DOF controller.  $P = 1/s(0.004s + 1)$ ,  $C_A = 0.083$ ,  $C_B = (0.25s + 8.33)/s$  Dotted lines show the response of the controller of Figure 4 for comparison.*

## 2.3 Simulation

We evaluate the performance of the controllers by using a simulation of a double inverted pendulum of Figure 8. It consists an upper link (0.4m) and a lower

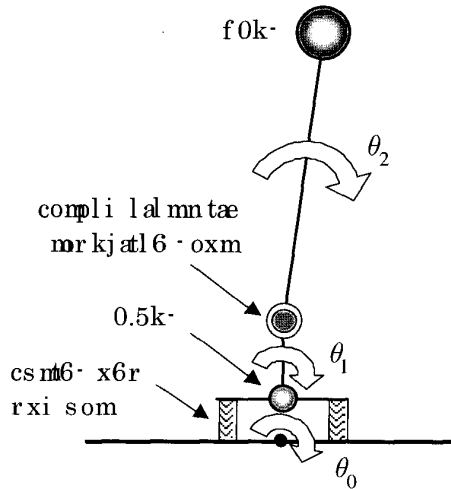


Figure 8: Double inverted pendulum with foot

link (0.1m) with a small foot (0.1m) that interact with the ground via springs and dampers. The relative angle between the upper link and the lower link can be controlled by a servomotor with a reduction gear.

In the first set of the simulation, a balancing on a moving ground is tested. To balance the pendulum, we apply a controller that will be explained in the next section. The balance controller calculates desired contact torque, then the torque controller attempts to realize it. Figure 9 shows a stick pictures of two pendulums under the 1DOF and the 2DOF torque controllers (By 1DOF controller, we refer the controller of Figure 4). The slope of the ground changes by 1Hz sinusoidal wave whose amplitude is  $\pm 15$  degrees. We can confirm that the 2DOF controller results better balancing performance.

The detailed behavior of the 1DOF controller in the same simulation is plotted in Figure 10. The controller does not realize the desired torque and as the result the foot can not track the ground motion and sometimes it even loose the contact with the ground.

On the other hand, in the result of the 2DOF controller (Figure 11), we can see it realizes the desired torque in good accuracy and the foot correctly follows the floor motion.

As the second set of simulation, we set zero as the reference for the contact torque controller. In this case, the pendulum is fall down keeping the contact torque zero. Figure 12 show the stick picture of the results. The Zero Moment Point (ZMP) is indicated to show the contact torque. Since the desired contact

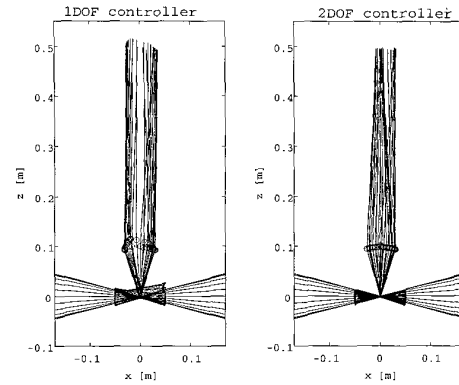


Figure 9: Balancing on a moving floor ( $\pm 15$ deg, 1Hz). Left:1DOF controller, Right:2DOF controller

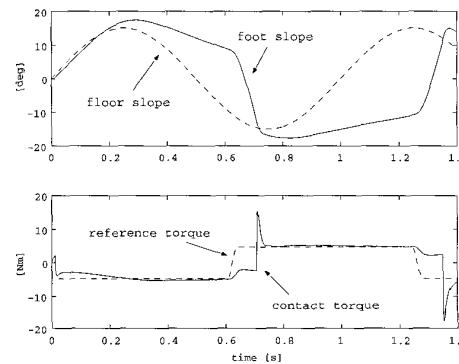


Figure 10: Balancing on a moving floor. The result of 1DOF controller.

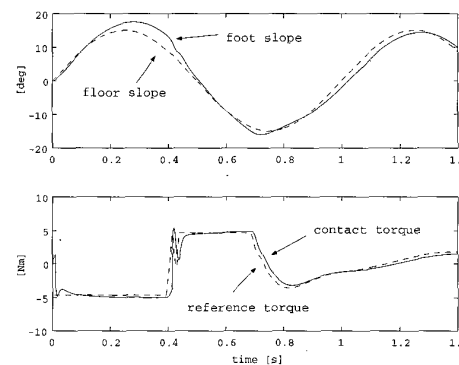


Figure 11: Balancing on a moving floor. The result of 2DOF controller.

torque is zero, it is expected that the ZMP remains in the center of the foot. However, the ZMP moves from the center under the 1DOF controller whereas the ZMP stays the center under the 2DOF controller. This result indicates the pendulum unwillingly generates a contact torque with the 1DOF controller. As we have already explained, the motion of the robot itself is regarded as the motion of the environment, and, therefore, we must give care to the backdrivability of the torque controller even on a solid ground.

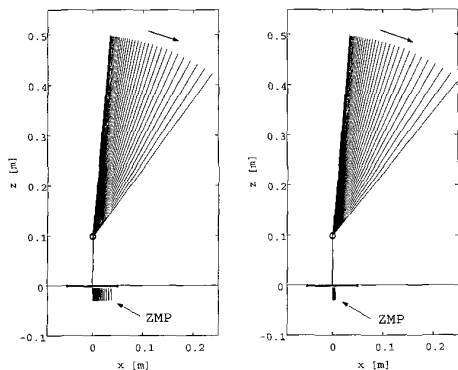


Figure 12: Simulation of free falling. The desired contact torque is specified as zero at all time. Left:1DOF controller, Right:2DOF controller

### 3 Dynamic Balance Control of a Humanoid Robot

#### 3.1 Direct angular momentum feedback

The basic idea of our balance control is a direct feedback of the total angular momentum  $\mathbf{L}$  and the position of the center of gravity  $\mathbf{r}_G$  as the state of the entire robot system (Figure 13). As discussed in the last section, we can control the contact torque  $\tau$  between the foot and the ground surface, therefore, we can regard it as inputs to the entire robot system. From the Euler's law of motion, we have

$$\frac{d}{dt}\mathbf{L} = M\mathbf{r}_G \times \mathbf{G} + \tau, \quad (11)$$

where  $M$  is the total mass of the robot,  $\mathbf{G}$  is the gravity acceleration vector and  $\tau \equiv [\tau_x, \tau_y, \tau_z]$  is the ground contact torque. This equation shows us how the total angular velocity changes under the given ground contact torque.

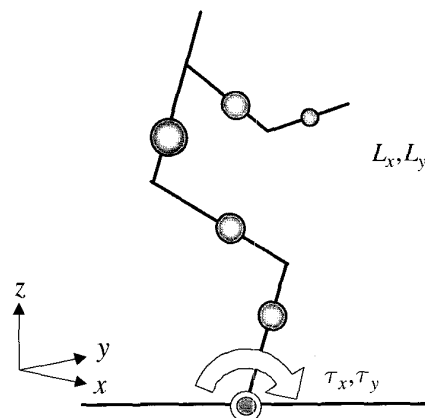


Figure 13: The basic idea of the balancing control. We use the contact torque  $\tau_x, \tau_y$  to directly manipulate the total angular momentum of the robot  $L_x, L_y$ .

The objective of the balance control is to realize  $L_x = L_y = 0$  and  $r_{Gx} = r_{Gy} = 0$ , then one of the simplest feedback law can be written by

$$\begin{aligned} \tau_x^d &= -k_{px}L_x - k_{vy}r_{Gy}, \\ \tau_y^d &= -k_{py}L_y - k_{vx}r_{Gx}, \end{aligned} \quad (12)$$

where  $k_{**}$ s are feedback gains.

In this feedback law, we do not control the  $z$  element of the angular momentum since our humanoid robot does not have a yaw axis in the foot mechanism, thus we can not control the yaw torque  $\tau_z$  in a way of Section 2.

To implement the feedback law of (12), we need to calculate the total angular momentum and the position of the center of gravity in real-time. It is possible by using the absolute posture and the angular velocity of the robot body measured by gyro sensors and the joint velocities measured by encoders. The total angular momentum  $\mathbf{L} \equiv [L_x, L_y, L_z]$  can be calculated by

$$\mathbf{L} = \sum_i (\mathbf{r}_i \times m_i \frac{d}{dt}\mathbf{r}_i + \mathbf{R}_i \mathbf{I}_i \omega_i), \quad (13)$$

where  $\mathbf{r}_i$ : position vector of the center of gravity of the  $i$ -th link,  $m_i$ : the mass of the  $i$ -th link,  $\mathbf{R}_i$ : orientation matrix of the  $i$ -th link frame, and  $\mathbf{I}_i, \omega_i$ : inertia tensor and angular velocity in the  $i$ -th link frame respectively.

The position of the center of gravity,  $\mathbf{r}_G \equiv [r_{Gx}, r_{Gy}, r_{Gz}]$  can be also calculated as

$$\mathbf{r}_G = \sum_i m_i \mathbf{r}_i / M. \quad (14)$$

In this control, only the ankle actuators (pitch and roll) of the support leg are used for the balancing, and we can arbitrary specify the motions of the other joints. This is a great advantage of the proposed control method. A similar feedback law was introduced by Sano and Furusho for the control of dynamic biped walk [3].

### 3.2 Implementation and simulation

We have implemented the feedback law given by Eqs.(12) , (13) and (14) on a dynamics simulator of a humanoid robot. We used a simulator which was developed as a part of MITI's Humanoid Robotics Project [2]. The simulated robot is the *testbed hardware*, a 26 DOF humanoid of 540 mm height and 8 kg weight that was developed in the same project.

In the first simulation, the robot is standing with two legs, and both of legs are controlled in the same manner. Only the balance control for pitching motion (around y-axis) was applied since the robot was stable around x-axis. Under the proposed balance control, the robot could successfully sit down, reach arms to the ground and stand up again. All joints except ankles were position-controlled to generate the desired motion. A snapshot of the motion is shown in Figure 14.



Figure 14: Sitting down to pick up an object from the ground

In the second simulation, a kicking motion was tested to demonstrate a three-dimensional balancing (Figure 15). The robot made full swing of the left leg

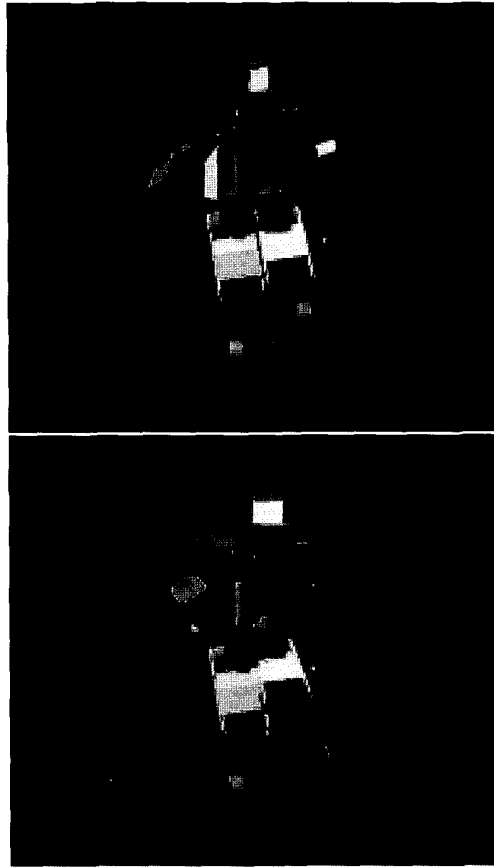


Figure 15: Kicking motion

in one second while balancing with the right leg. Under the proposed control, the robot was successfully kicked and balanced. The motion of the arms and the body was added just for natural outlook, but those were not necessary to keep the balance. All compensation was done by the ankle actuators of the supporting leg.

## 4 Summary and Conclusions

In this paper, we introduced a novel balancing control for a humanoid standing with one leg. First, we discussed a control of a contact torque which acts from the robot's sole to the ground surface. Particularly, we emphasised the importance of backdrivability of the contact torque controller and it was shown that a two degrees of freedom feedback controller gives a good result for this point of view.

Second, we introduced a new idea of a balance control using direct feedback of the total angular momentum and the position of the center of gravity. The performance of the controller was tested by using a simulation of a humanoid model of 26 DOF.

Currently, we are preparing an experiment using actual humanoid platform which was developed in the humanoid project. This will be discussed on our next report.

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