Body Stabilization of PDW toward Humanoid Walking

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ABSTRACT

Passive Dynamic Walking is one of the key issues toward humanoid walking with less energy consumption. There is few past studies on PDW of a robot having the similar body as a human, that is, having both legs, arms and a torso. This is because the 3-D motions of the robot with the upper body is complicated. In this paper, a controller is proposed to reduce the body rotation around the trunk axis by swinging the arms. Consequently, the walking can be regarded as the one in the sagittal plane, which make it possible to utilize the existing studies on 2-D PDW.

1 INTRODUCTION

Recently, there have been many humanoid robot projects, which have published their remarkable results. These approaches require very exacting work [1, 2]: they need strict strategies to plan trajectories very accurately, to control extremely precisely, and to adopt much powerful actuators. This is because the dynamical property of the robot is not effectively utilized. On the other hand, Passive Dynamic Walking (PDW) takes an extremely opposite approach to realize biped walking. A PDW robot can walk with simple strategies, that is, without any planning, any control nor any actuator, since the PDW robot fully utilizes its dynamic property. This approach may cast new light on the biped walking of a humanoid robot left behind in the traditional approaches and it is expected that humanoid walking can be attained with less control, therefore with less energy consumption by applying the PDW principle to humanoid robots.

PDW is originally proposed by McGeer [3]. He demonstrated that a PDW robot could walk in a stable gait cycle both in computer simulations and in real experiments. Since then, many researchers have studied this topic. Garcia et al. [4, 5] showed the stability and chaotic characters of PDW. Osuka et al. [6] demonstrated these characters in real robots. Recently, some researchers tried to make PDW robot walk not only on a shallow slope but also on a level floor [7, 8]. Collins [9] made a PDW robot that has two legs and the swinging arms attached to their opposing legs such that the swinging motions reduce the rocking motion and the rotation around the slope-normal axis. However, there is no PDW study on a robot that has an upper body, to the best of our knowledge.

In order to apply the idea of PDW to humanoid robots, it is necessary to take the effect of an upper body into account. Normally, the motions in 3-D are complicated. If the 3-D motions are restricted within the sagittal plane, the existing ideas on 2-D PDW can be used and it is easier to analyze the motions. In most of the previous studies on PDW, this issue is avoided by restricting the motions within 2-D utilizing more legs than two. However, in case of a PDW robot that has the similar body as a human, the other strategy is needed to restrict the motions within 2-D.

In this paper, we investigate on PDW of a robot that has an upper body consisting of both arms, legs, and a torso. This robot under no torque acting on the hip joints has no acceptable initial condition under which PDW is possible in our study so far. Therefore, a simple PD control is applied to just one hip joint between the stance leg and the torso, that is, the free leg is fully passive. The walking motions in 3-D is complicated by the body rotation in the horizontal plane. In order to suppress the rotation, a control scheme is proposed for the shoulder joint. The effectiveness of the proposed control scheme is demonstrated by 3-D simulations. As a result, we found that, by applying the proposed control scheme, the motions of the robot was regarded as the ones within the sagittal plane because of the reduction of the body rotation in the horizontal plane by the symmetrical arm swings. Therefore, it can be possible to utilize the existing studies on 2-D PDW and analyze the motions easily.

2 PDW ROBOT WITH UPPER BODY

A PDW robot with an upper body used here consists of five rigid links and four joints on which torque can act, shown in Fig.1: two leg links, one torso link, two arm links, two hip joints between the torso and each leg link, and two shoulder joints between the torso and each arm link. The parameters of the links are indicated in Fig.1 and Table1. The mass center of each rigid link is its center. θ_{leg}^{stance} is measured from slope-normal to the stance leg, θ_{leg}^{free} from the extended line of the stance leg to the free leg, θ_{arm}^{L} and θ_{arm}^{R} from the link of the torso to each arm, and θ_{w} from level ground-normal to the torso. The base coordinate system is defined as shown, and each of roll, pitch and yaw rotation is defined as a rotation around each of x, y, and z axis. The positive rotation is defined as counterclockwise around each axis.

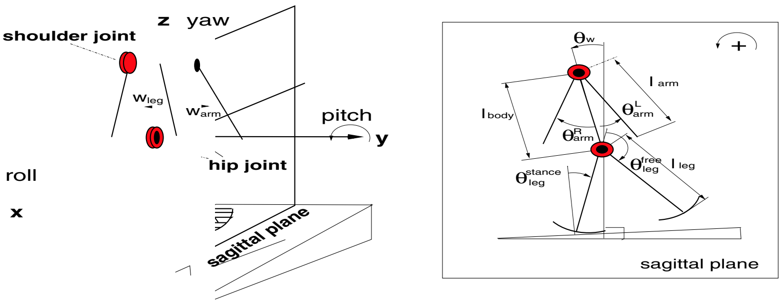


Figure 1: **PDW robot with the upper body and the parameters**

Table 1: **Parameters**

parameter	l_{leg}	m_{leg}	l_{body}	m_{body}	l_{arm}	m_{arm}	w_{leg}	w_{arm}
values	0.6 [m]	1.0 [kg]	0.5 [m]	1.0 [kg]	0.6 [m]	1.0 [kg]	0.05[m]	0.1 [m]

As shown in Fig.1, the robot has a curvature sole added to each of leg tip. Here, the width of the sole is 0.16[m] and the curvature radius is 0.3[m]. The role of the sole is suppression of the body rotation around the roll axis. Actually, in the 3-D simulations, the angular momentum around the roll axis induced by the asymmetrical leg swings is small enough for the width of the curvature sole to inhibit the roll rotation, but around the yaw axis not enough to suppress the yaw rotation since the angular momentum around the roll axis is considerably smaller than around the yaw axis (about 1/10).

In our simulations, the floor force is calculated with spring-dumper contact model and it is assumed that the collision of the free leg is ignored while the free leg passes through the stance leg.

3 PD CONTROL TO STAND TORSO UP

It is needed to stand the torso up during the walking. On condition that no torque acts to stand the torso up, the appropriate initial conditions under which PDW is possible have not been found in our study so far. Probably, such a walking mode is considerably unstable, and even if these pinpoint conditions should be found on computer simulation, in real world we could not reproduce these conditions. Then, we apply a simple PD control scheme given by,

$$\tau_w = -k_v\dot{\theta}_w + k(\theta_{wd} - \theta_w), \tag{1}$$

where both k_v and k are the control gain, θ_{wd} is the desired angle of θ_w, and τ_w is the torque acting on the one hip joint between the torso and the stance leg. No torque acts on the other hip joint between the torso and the free leg, that is, the free leg is a completely passive links.

4 CONTROL SCHEMES APPLIED TO SHOULDER JOINTS TO SUPPRESS BODY ROTATION AROUND TRUNK AXIS

During the walking of the PDW robot with the upper body, two kinds of the rotation around the roll and the yaw axis are induced. As described in section 2, the roll rotation can be reduced sufficiently by the curvature soles. Therefore, the suppression of the yaw rotation is indispensable in order to restrict the dynamics of the robot within the sagittal plane. In this section, we propose control schemes applied to each shoulder joint between the torso and each arm.

4.1 Control schemes based on countering angular momentum

Considering a performance of a sensor in the real world, it is almost impossible to measure angular acceleration exactly. And so, we do not utilize moment around the yaw axis for the control schemes, but to utilize angular momentum which can be calculated by measuring angular velocity and angles.

The angular momentum around the yaw axis, L, is given by,

$$L = L_{low} + L_{up}, \tag{2}$$

where L_{up} is the angular momentum induced by swinging the arms and L_{low} is the total angular momentum generated by swinging the legs and rotating the torso. Here, L_{up} is expanded as follows,

$$L_{up} = m_{arm} w_{arm} (r^L \dot{\theta}^L_{arm} - r^R \dot{\theta}^R_{arm}), \tag{3}$$

where r^L is the length along the z axis of the coordinate system from the left shoulder to the mass center of the left arm and r^R from the right shoulder to the mass center of the right arm. Substituting Eq.(3) for Eq.(2), Eq.(4) is obtained as follows,

$$L = L_{low} + m_{arm} w_{arm} (r^L \dot{\theta}^L_{arm} - r^R \dot{\theta}^R_{arm}), \tag{4}$$

where $\dot{\theta}^L_{arm}$ can be controlled via $\ddot{\theta}^L_{arm}$ by acting torque on the left shoulder joint and $\dot{\theta}^R_{arm}$ on the right shoulder joint. Therefore, in order to counter the angular momentum, a feedback control scheme applied to each shoulder joint is given by,

$$\tau^L_L = -KL, \tag{5}$$

$$\tau^R_L = KL, \tag{6}$$

where K is the control gain, and each τ^L_L and τ^R_L is the torque acting on each left and right shoulder joint.

When L is positive, the torque acting on the left shoulder joint is negative and on the right is positive. Then, the left angular acceleration is smaller and the right is bigger. And so, the left angular velocity, $\dot{\theta}^L_{arm}$, is smaller and the right, $\dot{\theta}^R_{arm}$, is bigger. Consequently, L is smaller. In the same way, when L is negative, L is bigger. Therefore, it is expected that the angular momentum around the trunk axis is countered by applying these control schemes described as Eq.(5) and Eq.(6).

4.2 Control schemes based on symmetrical arm swings

Applying the control schemes given by Eq.(5) and Eq.(6) to the PDW robot with the upper body, the walking is unstable since the swinging of both arms is not symmetry with respect to the origin of the coordinate system. Therefore, we apply other PD control schemes in order to swing the both arms symmetry.

We define a parameter, e, indicating the difference between the angle of the left arm and the right arm, given by,

$$e = \theta^L_{arm} + \theta^R_{arm}. \tag{7}$$

Then, the simple PD control schemes are given by,

$$\begin{aligned} \tau^L_{sym} &= G_v(\dot{e}_d - \dot{e}) + G(e_d - e), & (8) \\ \tau^R_{sym} &= G_v(\dot{e}_d - \dot{e}) + G(e_d - e), & (9) \end{aligned}$$

where e_d and $\dot{e}_d$ are the desired values of e and $\dot{e}$, both G and G_v are the control gain, and τ^L_{sym} and τ^R_{sym} are the torque acting on the left shoulder joint and the right respectively.

4.3 Control schemes applied to shoulder joints

We propose feedback control schemes applied to the shoulder joints in order to suppress the body rotation around the trunk axis, given by,

$$\begin{aligned} \tau^L &= \tau^L_L + \tau^L_{sym}, & (10) \\ \tau^R &= \tau^R_L + \tau^R_{sym}, & (11) \end{aligned}$$

where τ^L acting on the left shoulder joint is the sum of Eq.(5) and Eq.(8), and τ^R on the right shoulder is the sum of Eq.(6) and Eq.(9). It is expected that the PDW robot with the upper body under these proposed control schemes can walk in a stable gait cycle within the sagittal plane.

5 EFFICIENCY OF CONTROL SCHEMES FOR ARMS MOTION

On condition that the arms are fixed in the direction of level ground-normal, the PDW robot with the upper body under the control to stand the torso up, given Eq.(1), can walk at a stable gait cycle when the walking is started with leg angles and speeds within acceptable ranges. In this case, the yaw rotation, that is, the body rotation around the trunk axis, is induced by the asymmetrical leg swings, as shown in Fig.2 (dashed line), in which the elapsed time is described on the horizontal axis and the yaw rotation on the vertical axis.

On the other hand, on condition that the proposed control schemes are applied to the shoulder joints, the robot can also walk at a stable gait cycle with leg angles and speeds within acceptable ranges. Then, the yaw rotation is reduced by the symmetrical arm swings, which counter to the angular momentum induced by the leg swings, as shown in Fig.2 (solid line). The trajectories of the symmetrical arm swings are shown in Fig.3, in which the elapsed time is described on the horizontal axis and $\dot{\theta}^L_{arm}$ and $\dot{\theta}^R_{arm}$ on the vertical axis.

According to these simulation results, it is demonstrated that the proposed control schemes are effective in the suppression of the body rotation around the trunk axis.

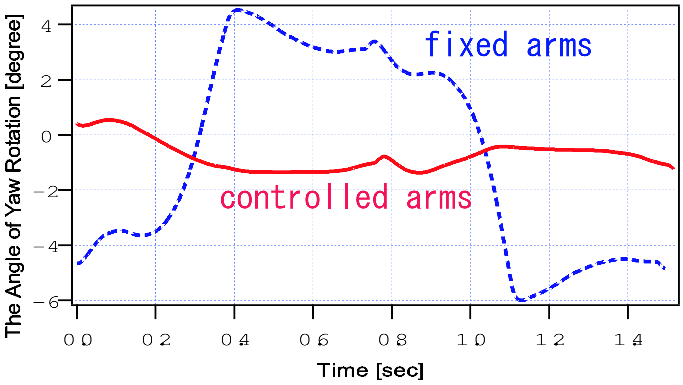


Figure 2: **The body rotation around the trunk axis from 6th to 7th step**

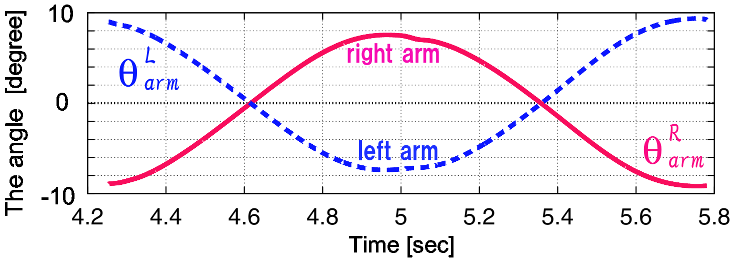


Figure 3: **The trajectories of the symmetrical arm swings from 6th to 7th step**

6 RELATED RESULTS AND DISCUSSIONS

6.1 Synchronized arm swings with leg swings

The cycle of arm swing is not given directly to the proposed control schemes (Eq.(10) and Eq.(11)). But, the cycle of the resultant arm symmetrical swings are synchronized with that of the leg swings. This is probably because the angular momentum, L, plays a role of an oscillator in the proposed control schemes. And so, it would be possible that, even if the gait cycle is unknown, the body rotation of the other humanoid robot is reduced by applying this control schemes.

6.2 Utilizing the dynamics property for arm swings

The output torque acting on the right shoulder is shown in Fig.4, in which the elapsed time is described on the horizontal axis and the torque on the vertical axis. The torque to swing the arm from fore to aft is rarely needed since the peculiar period of the arm matches with the required period by the control schemes to counter the angular momentum. On the other hand, the torque from aft to fore is needed more since the period does not match. And so, if the peculiar period can be changed to match with the required period by changing the inertia utilizing the elbow, the torque will be reduced.

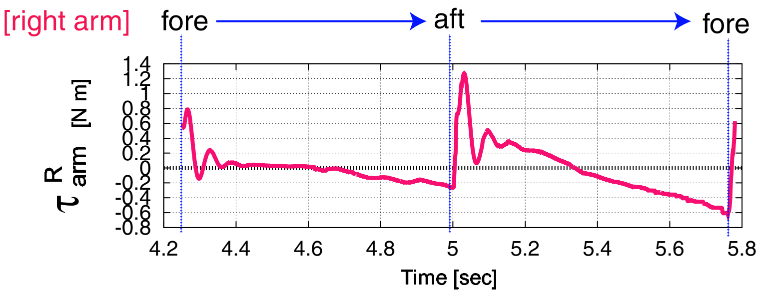
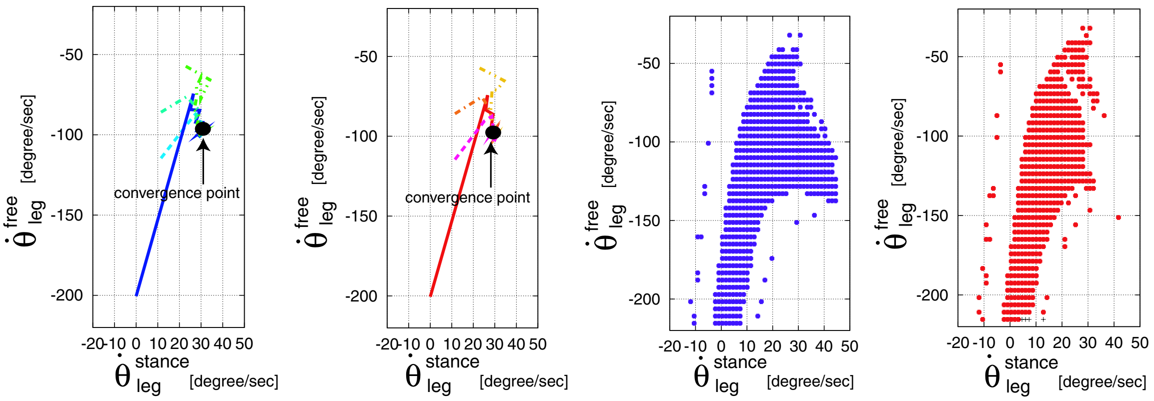


Figure 4: **Output torque acting on the right shoulder joint**

6.3 Stability of walking

Under which conditions that the arm is fixed or the arm is controlled by the proposed control schemes, the robot can walk at a stable gait cycle, as shown in Fig.5 (a) and (b), in which $\dot{\theta}^{stance}_{leg}$ is shown on the horizontal axis, $\dot{\theta}^{free}_{leg}$ on the vertical axis and the plotted points are measured at the moment of just crossing the legs each other. Moreover, the number of the acceptable initial conditions of the robot under the control schemes is a little fewer, as shown in Fig.5(c) and (d). Therefore, it may be said that the reduction of the body rotation does not always induce the stable walking. Conversely, it may be said that utilizing the body rotations increase the stability of the walking.



(a) **Transition (fixed)** (b) **Transition (controlled)** (c) **Init. area (fixed)** (d) **Init. area (controlled)**

Figure 5: **Stability of walking**

7 CONCLUSIONS AND FUTURE WORK

In this paper, we study on a PDW robot with an upper body consisting of both arms, legs and a torso. In order to reduce the body rotation in the horizontal plane, a control scheme is proposed for the shoulder joints . The efficiency is demonstrated by obtained 3-D simulation results. Consequently, the motions of the resultant walking are regarded as the ones within the sagittal plane by the reduction of the body rotation in the horizontal plane utilizing the arm swings. Therefore, the existing ideas on 2-D PDW can be used and it is easier to analyze the motions.

We are currently studying the reduction of the torque acting on the hip joint to stand the torso up utilizing some particular springs and the torque on the shoulder joints to inhibit the body rotation around the trunk axis utilizing elbows which make the dynamics of the arms changed. Moreover, to make sure the efficiency of the proposed control schemes, we are planning to build a real robot based on the obtained result.

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