Experimental Study of Biped Dynamic Walking in the Linear Inverted Pendulum Mode

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Abstract

An experimental study of a biped robot is presented. A new scheme, named the "Linear Inverted Pendulum Mode" is utilized for controlling biped walking on rugged terrain. We developed a 6 d.o.f. biped robot "Meltran II" which has light weight legs and moves in a two dimensional vertical plane.

To check the effects not well discussed in the theory, we carried out two experiments, the support phase experiment and the support exchange experiment. The support phase experiment was carried out to check the actual dynamics of biped walking when using the proposed control. It was shown that the dynamics of the robot can be regarded as linear even though the mass of the legs, which was neglected in the theory, exists.

The support exchange experiment was performed to check leg support exchange. We found that a smooth leg support exchange is achieved by making the foot contact with a certain vertical speed and holding two leg support for a certain short period. Based on these results, a whole biped control system was implemented. In our experiment the robot walked over a box of 3.5cm height at a speed of 20cm/s.

1 Introduction

Many studies of biped locomotion have been conducted worldwide [1]-[16]. One important approach has been to extract a dominant feature of its dynamic behavior. Because an original biped system has high-order and nonlinear dynamics, it is hard to understand unless we simplify it in some way.

A good analyzing technique helps us to understand the dynamics of biped locomotion and to establish an effective control law. Golliday and Hemami [2] used state feedback to decouple the high-order system of a biped into independent low-order subsystems. Miyazaki and Arimoto [11] used a singular perturbation technique and showed that biped locomotion can be divided into two modes: a fast mode and a slow mode. Furusho and Masubuchi [1] derived a reduced order model as a dominant subsystem which approximates the original high-order model very well by applying local feedback control to each joint of a biped robot. Raibert [13] used symmetry to analyze his hopping robots which are controlled by his 'three parts control'.

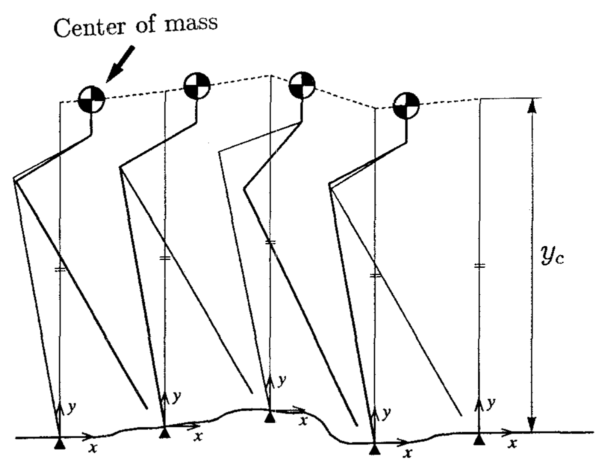

Figure 1: Walk on a rugged terrain

In a previous paper [5] we proposed a new scheme for the control of biped walking on rugged terrain. Figure 1 shows the basic concept of our walking control. We assume the robot knows the profile of the ground before it begins walking. First, the robot decides the foothold positions for each step (shown by the triangles). Then, it calculates a line (shown by the broken line) connecting the points at the same height above these foothold points. Hereafter, we call this line a 'constraint line' and refer to its height from the footholds as y_c. While walking, the support leg is assumed to be changed instantaneously. Therefore, the

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body is supported by exactly one leg at any given time. In each supporting phase the robot controls the center of mass (COM) to keep on the constraint line and controls its body posture to remain vertical. These 'constraint controls' are executed by the knee and the hip joint of the support leg. Under such control, if all mass is concentrated on the body (i.e. the legs are assumed massless), the horizontal motion of the COM with respect to the supporting point is represented as follows:

$$\ddot{x} = \frac{g}{y_c}x + \frac{1}{my_c}u_1 \qquad (1)$$

where g is gravity acceleration, m is the whole mass of the robot, and u_1 is the ankle torque of the support leg.

Equation (1) does not contain the term of the slopes of the constraint line. This means the dynamics of each support phase is always the same even when the robot walks up and down on uneven terrain. We call the dynamics of equation (1) the *Linear Inverted Pendulum Mode* and propose it for the design and the control of biped walking on rugged terrain [5].

In this paper, we describe how to implement the linear inverted pendulum mode on a real robot. There are two problems in applying our theory to a real biped robot. One problem is that the legs of a real robot have mass, but they were assumed to be zero in the theory. To learn what affect the leg mass has in the linear inverted pendulum mode, we carried out *the support phase experiment* detailed in section 3. In this experiment, the robot is controlled to stand on one leg and to keep its hip joint on the constraint line. The ankle joint of the support leg is then set free. Free motion is activated by pushing it by hand. By analyzing these trajectories, we could then estimate the horizontal dynamics of a real biped robot in the support phase.

The other problem in applying the theory lies in the support leg exchange. In our theory, we simply assumed that the body speed at the end of a particular support phase becomes the initial body speed of the next support phase across the support leg exchange. As described in section 4, we conducted a *support exchange experiment* to obtain adequate control for a smooth exchange. In this experiment, the robot is controlled to walk just a single step, that is, the robot exchanges leg support only once from one leg to the other leg. By analyzing the horizontal motion after the exchange, we could estimate how the speed of the body changes at the instant of the support leg exchange.

In section 5 we report on the experiment of biped walking on an uneven terrain using the control system based on the results of the experiments of sections 3 and 4.

2 Mechanism of the biped robot

Figure 2 shows our biped robot "Meltran II". Each leg is configured as a parallel link mechanism and is driven by two 11-Watt DC motors mounted on the body. These motors are equipped with rotary encoders.

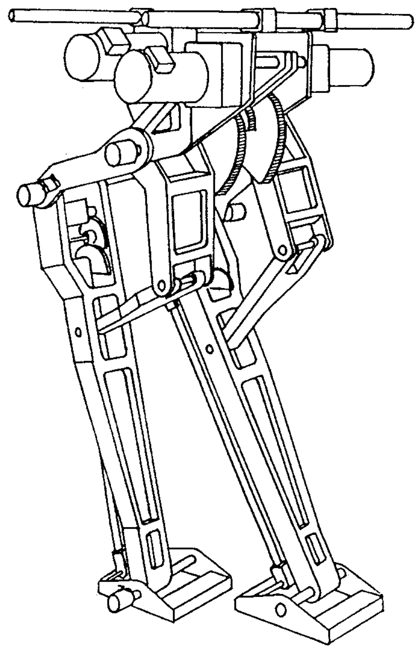


Figure 2: Biped Robot "Meltran II"

The ankle joint is driven by a 6.4-Watt DC motor mounted on each leg. The ankle, knee and hip joint of each leg have potentiometers to detect the angles between neighboring links. The walking motion is constrained in a sagittal plane by means of the laterally wide feet. Thus, all discussion in this paper is about two dimensional motion.

The parallel link design was adopted to reduce the weights of the legs and to emulate the massless leg model analyzed in a previous report [5]. However, the mass of the legs account for 47.4% of the total mass, so we can hardly regard them as massless.

3 Support phase experiment

3.1 Constraint control implementation

If the legs are massless, the center of mass (COM) of the whole robot would be the same as the COM of the body. In the case of a real biped, however, the legs are not massless. The COM of Meltran II exists near the hip joint but it moves about ±1cm according to swinging of the leg. To simplify the constraint control, the hip joint is controlled to move on the constraint line, rather than controlling the COM of the whole robot.

Figure 3 shows the coordinate system for the control of particular step. As shown in the figure, we assume that the foot touches the ground with its toe and heel, and the angle α between the normal line of foot and the y-axis already known [1].

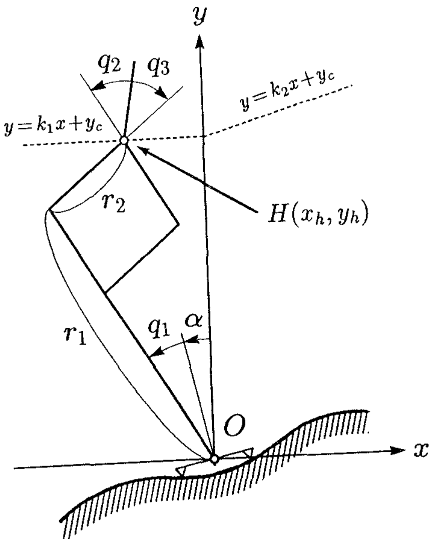


Figure 3: Constraint control

The constraint line (constraint condition) is represented in Cartesian coordinates whose origin is on the ankle.

$$\begin{cases} y_h = k_1 x_h + y_c & \text{if } x_h \le 0 \\ y_h = k_2 x_h + y_c & \text{if } x_h > 0 \end{cases} \tag{2}$$

where (x_h, y_h) is the position of the hip joint H, k_1 and k_2 are the slopes of the constraint line, and y_c is its intersection with the y axis. As explained in section 2, the slopes k_1 and k_2 are determined from the profile of the ground and changes step by step (k_2 of current step is the same as k_2 of the next step). On the other hand, y_c does not change throughout the walk. For all experiments in this paper $y_c = 34$ (cm).

The constraint control was realized using simple inverse kinematics. We applied local position feedback to the joint q_2 and q_3 of the support leg. As the reference for this feedback, q_{2ref} and q_{3ref} were calculated as follows.

$$q_{2ref} = q_1 + \alpha \tag{3}$$

$$q_{3ref} = -\gamma(q_1 + \alpha) - \beta + \pi/2 \tag{4}$$

[1]To simplify the experiment, we used ground for which the foothold place is always horizontal ($\alpha = 0$).

where

$$\gamma(q) = -\cos^{-1}\left(\frac{-r_1\sqrt{1+k^2}\cos(q+\beta) + y_c}{r_2\sqrt{1+k^2}}\right)$$

$$\beta = \tan^{-1} k$$

$$k = \begin{cases} k_1 & \text{if } x_h \le 0 \\ k_2 & \text{if } x_h > 0 \end{cases}$$

where q_1 is the angle of the ankle joint measured by the potentiometer of the supporting foot. The reference angles were calculated every 1ms.

3.2 Experiment

The support phase experiment is an experiment to learn the horizontal dynamics of a real robot under the constraint control. The robot was controlled to stand on one leg and the constraint control of eq.(3) and (4) were applied. To examine the horizontal dynamics, we freed the ankle joint of the support leg (i.e. ankle torque $u_1 = 0$), and pushed the robot by hand to start its body moving on the constraint line. During this experiment, the posture of the swing leg was fixed. Figure 4 shows the result of this experiment.

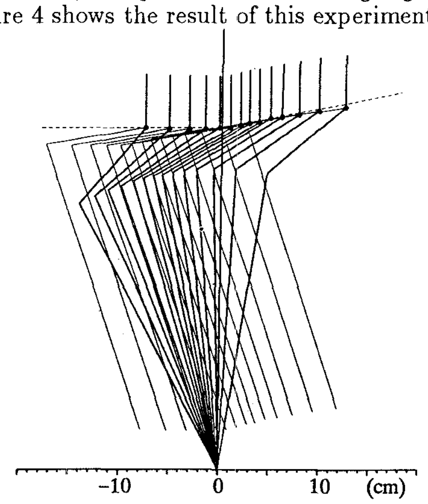


Figure 4: Support leg experiment
Constraint: $y_c = 34.0$(cm), $k_1 = 0, k_2 = 0.2$

The horizontal displacement of the hip joint is calculated from the angles of support leg, q_1, q_2 and q_3.

$$x_h = r_1 \sin q_1 + r_2 \sin(q_1 - q_2 + q_3) \tag{5}$$

where r_1 and r_2 are the length of the links.

First, we determined the 'balancing point', the point where the robot body moves neither forward nor backward, but stay in balance. We obtained $x_h \equiv x_{offset} \neq 0$ as the balancing point because the hip joint is not the real COM of the whole robot. Using this x_{offset}, we define x as the horizontal displacement of H to simplify the identification of the dynamics.

$$x = x_h - x_{offset} \tag{6}$$

The solid lines in figure 5 shows six different trajectories of $x(t)$. We obtained a different trajectory in every trial because of the different initial speed imparted by hand.

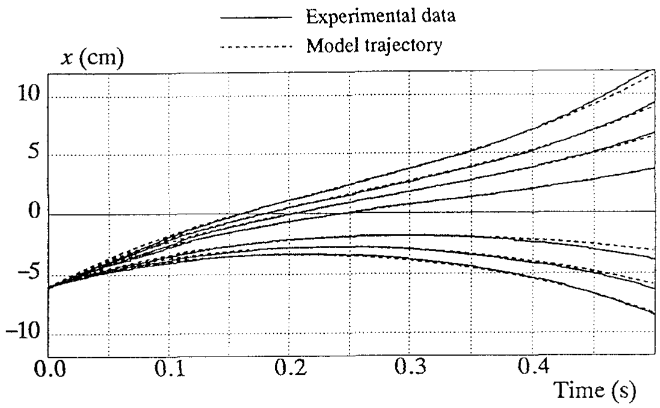


Figure 5: Horizontal motion of the body
Constraint: $y_c = 34.0(\mathrm{cm}), k_1 = 0, k_2 = 0.2$
Estimated: $y_{exp} = 31.7(\mathrm{cm}), d_{exp} = 1.9(\mathrm{s}^{-1})$

The experimental data can be explained by the following simple linear equation [6].

$$\ddot{x} = (g/y_{exp})x - d_{exp}\dot{x} \tag{7}$$

The broken lines in figure 5 indicate the trajectories of eq.(7) calculated by the curve fitting, and they correspond very well to the experimental data. From this curve fitting, we could also estimate the parameters y_{exp}=31.7(cm) and d_{exp}=1.9(s^{-1}).

In addition, we conducted another five sets of experiments using different slopes $k_1(=k_2) = -0.2, -0.1, 0.0, 0.1, 0.2$. In all experiments, we also obtained a good correspondence between the experimental data and the linear model eq.(7). Table 1 shows the estimated parameters from the experimental data. The important point to note is that y_{exp} and d_{exp} do not change remarkably with the slopes k_1 and k_2. From these results, we can conclude that the horizontal dynamics under the constraint control can be represented by the simple linear model of eq.(7).

3.3 Model following control

The dynamics of the support phase eq.(7) is a simple linear one, but it is unstable because a pole exists on the right half side of the complex plane. To guarantee predictable motion of the robot, we apply a 'model following control' using ankle torque u_1, which is an input force of the linear inverted pendulum mode as shown in eq.(1). u_1 is calculated as follows:

$k_1(=k_2)$	y_{exp} (cm)	d_{exp} (s^{-1})
−0.2	31.8	1.5
−0.1	31.5	2.4
0.0	32.4	2.0
0.1	32.3	1.7
0.2	32.9	1.6
mean value	32.2±0.5	1.9±0.3

Table 1: Estimated parameters of support phase ($y_c = 34.0(\mathrm{cm})$)

$$u_1 = k_P(x_{ref} - x) + k_D(\dot{x}_{ref} - \dot{x}) + k_I \sum (x_{ref} - x)\Delta t \tag{8}$$

where

u_1: ankle torque of supporting leg
Δt: sampling time(1ms)
k_P, k_D, k_I: feedback gains for model following control
$x_{ref}, \dot{x}_{ref}$: position and velocity of the reference trajectory.

To keep the sole of the support foot in contact with the ground, the absolute ankle torque $|u_1|$ must be limited

$$|u_1| \le u_{max} \tag{9}$$

where u_{max} is maximum ankle torque. When u_1 is saturated by eq.(9), calculation of the third term of eq.(8) is stopped to avoid the wind-up phenomenon of the integrate term.

u_{max} can be approximated from the total mass of the robot m and the distance between the ankle and toe (or the ankle and heel) d

$$u_{max} \simeq mgd \tag{10}$$

where g is the gravity acceleration. As the reference model for the model following control eq.(8), we used the following system:

$$\ddot{x}_{ref} = \frac{g}{y_m} x_{ref} \tag{11}$$

The parameter y_m is determined according to the experimental result of Table 1

$$y_m = \bar{y}_{exp} = 32.2 \ \ (\mathrm{cm})$$

By this model following control, the viscous effects estimated in the previous section are cancelled, and the horizontal motion of the support leg follows the solution of eq.(11).

4 Support exchange experiment

The support exchange experiment was performed to check and improve exchanges of leg support. Figure 6 shows the setup for this experiment. The robot walks on an iron plate covered with a rubber sheet of 2mm thickness to prevent a slip of the supporting foot as the soles of "Meltran II" are bare aluminum surfaces. A laser displacement sensor unit (Keyence LB-300) was used to measure the horizontal motion of the body.

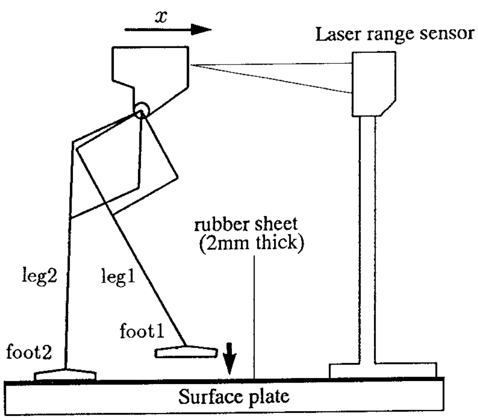
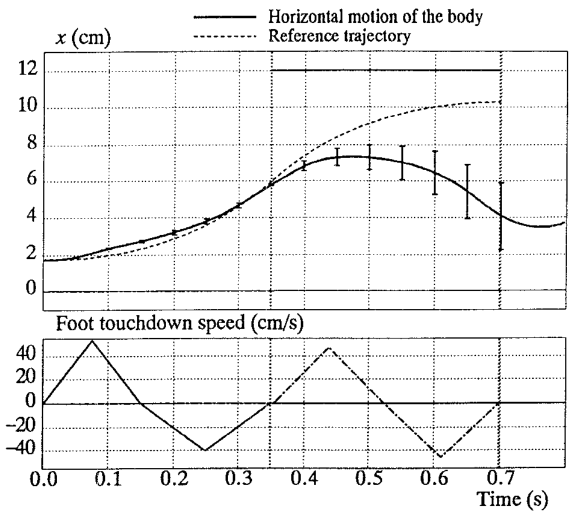


Figure 6: Support exchange experiment

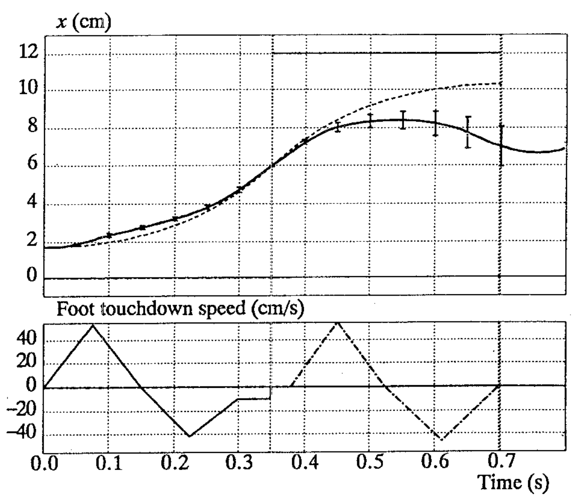
The control sequence of the support exchange experiment is as follows:

1. Standing with two legs.
2. **Start of walking**: Lift up foot1 (at 0.0s). Simultaneously, apply the constraint control to leg2 and apply the model following control to the ankle of foot2.
3. **Support of leg2**: The body moves horizontally following the reference model.
4. **Prepare for touchdown**: Set the foot1 down on the ground at 0.35s. Just prior to touchdown, stop the constraint control and model following control of leg2.
5. **Support exchange**: At 0.35s, apply the constraint control to leg1 and set the ankle torque of foot1 to zero. Lift up foot2 simultaneously.
6. **Support of leg1**: The body moves horizontally.
7. **Prepare for finish**: Set the foot2 down on the ground at 0.7s. Just prior to touchdown, stop the constraint control of leg1.
8. Return to two leg support.

By analyzing the horizontal motion that occurs during 6.**Support of leg1**, we can estimate how the speed of the hip joint changed at the instant of the support leg exchange. For smooth biped walking, the difference between the horizontal speed just before the exchange and just after it must be as small as possible.



(a) with basic touchdown pattern



(b) with improved touchdown pattern

Figure 7: Results of support exchange experiment

We carried out two sets of support exchange experiment using different touchdown and lift up patterns of swing leg. Each set of experiments was repeated ten times under the same conditions. The upper graphs of figure 7 (a) and (b) shows the horizontal motion of the body as the result of the support exchange experiment. The solid lines and error bars indicate mean trajectories and standard deviations of ten times trials. The broken lines indicate the reference trajectories of the ideal robot whose dynamics is eq.(11). We calculated this trajectory assuming that the speed does not change at the instance of the support leg exchange.

Comparing these two experiments, the body motion of figure 7(b) is more suitable for walking, because of its smaller loss of horizontal speed.

The lower graphs of figure 7 (a) and (b) shows the foot touchdown speed in each experiment. Solid lines and dash-dotted lines indicate the foot touchdown speed patterns of foot1 and foot2 respectively. In experiment (a), foot1 was controlled to touchdown with zero speed. In experiment (b), foot1 was controlled to hit the floor at a speed of -10cm/s. We can explain the better result of experiment (b) as follows. In experiment (a), foot1 was slowed down near the floor and occasionally touched the floor prior to the expected time (0.35s) due to position error and disturbances. But in experiment (b), foot1 had a specified speed and thus realized more punctual touchdown.

There was another difference between the swing leg motions in these experiments. In experiment (a), foot2 was lifted up from the floor as soon as foot1 touched down. But, in (b) foot2 was lifted 30ms after the touchdown of foot1, so there was a two leg support period of 30ms. This result shows that a two leg support state helps to smooth the exchange of support though it is very short (0.03s) compared with the step period (0.7s).

5 Walking experiment

The walking control system consists of the support leg control (described in section 3) and the swing leg control (partly described in section 4).

Figure 8 shows the robot walking over a box of 3.5cm height (strobe light 80times/min). The step length was 12cm and the step period was 0.6s [2]. The position and height of the box were measured and programmed before the experiment, and the robot started from a pre-defined position. The lines are the trajectories of the LEDs mounted on the hip joint and on the right ankle. We can see the trajectory of the hip joint which was controlled to be on the constraint line.

Figure 9 shows the data of which the robot walked over a step of 2cm height (the period of stepping up is indicated by an arrow). The upper graph shows the horizontal displacement of the feet with respect to the hip joint (thin line: right foot, thick line: left foot). The vertical lines at 0.1s,0.4s,1.0s,1.6s,2.2s,2.8s and 3.1s indicate the times of leg support exchange. The support leg was exchanged at these times.

While the foot is supporting the body (i.e. on the ground), we can regard the data as meaning the body motion with respect to the ankle. For example, in the period from 0.1s to 0.4s, the thick line indicates the horizontal motion of the hip joint H with respect to the left ankle. Then, the robot exchanged leg support from the left to right leg at 0.4s. From 0.4s to 1.0s, the thin line indicates the body motion with respect to the right ankle. For each support phase, the reference trajectory (x_{ref}) is indicated by a broken line.

[2] In this paper we use 'step length' for the distance between successive footholds, and 'step period' for the period between successive support leg exchange.

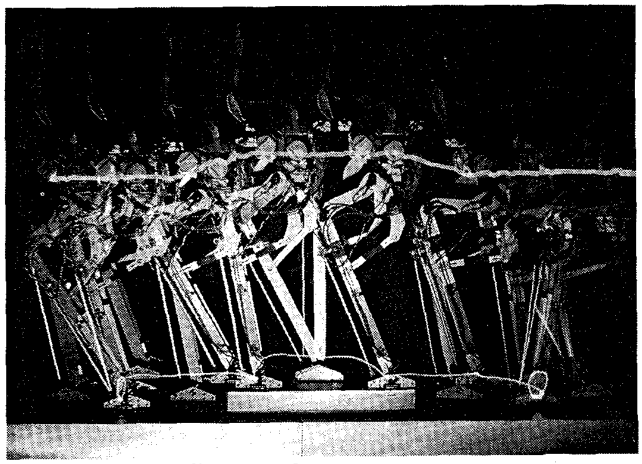


Figure 8: Walk over a box
(step length:12cm, step period:0.6s, box height:3.5cm)

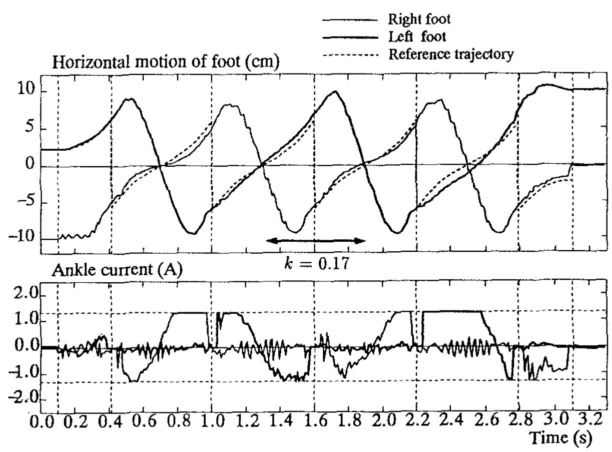


Figure 9: Experimental data

The lower graph of figure 9 indicates the ankle current (thin line: right ankle, thick line: left ankle). While a foot was in the support phase, its ankle torque was used for the model following control (eq.(8) in section 3.3) and the ankle joint consumed a large amount of current. For example the thin line from 0.4s to 1.0s, and the thick line from 1.0s to 1.6s show the ankle torque used for the support phase control.

While a foot was in swing phase, it was controlled to keep it parallel to the ground surface. The ankle joint consumed a small amount of current for this control.

As discussed in section 3.3 (eq.(9)), the absolute ankle current (torque) was limited (the horizontal dashed line). First, we calculated the maximum ankle current (torque) by eq.(10). If the maximum current was too large, the robot could not keep the sole in contact with the floor during its support, and if the maximum current was too small, the model following control (eq.(8)) did not work. In either of these cases, the walking was not stable. By carrying out several walking experiments, we determined that successful walking was realized with a maximum ankle current of 1.3A.

These walking experiments have been reported by way of video proceedings [9].

6 Conclusions

In this paper we developed a control system for a 6 d.o.f. biped robot "Meltran II" using a "Linear Inverted Pendulum Mode" theory. We carried out two experiments to check effects not well discussed in the theory. The support phase experiment showed that the support phase dynamics can be regarded as linear though the legs, which were assumed to be massless in the theory, have mass. The support exchange experiment was performed to check leg support exchange. We found that a smooth leg support exchange is achieved by making the foot contact with a specified vertical speed and by holding two leg support for a certain short period.

Based on these results, a whole biped control system was implemented. In our experiment, the robot successfully walked over a box of 3.5cm height at a speed of 20cm/s.

We hope to develop a more robust and more adaptive biped robot system based on both theoretical studies and experimentation.

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