Controlling Lateral Stepping of a Biped Robot by Swinging Torso Toward Energy Efficient Walking

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Abstract— **In this paper, we propose a controller for stable lateral stepping of a humanoid which utilizes the passive phase and changes the swinging phase of torso by the ground contact of the swing leg. Although the passive phase makes use of the gravitational power, the existence of the passive phase makes it difficult to control the period of the motion. We utilize the relationship between the amplitude of swinging torso and the motion period so that the desired period of lateral stepping is realized. Combined with a simple controller for walking in the sagittal plane, our proposed controller can enable 3-D walking with short step length.**

I. INTRODUCTION

Recently, the approaches that utilize dynamics of body to control of walking gather attentions to realize bipedal walking [10]. Passive dynamic walking (PDW) [6] is a walking mode on a shallow inclined slope without any control nor any energy input. PDW makes fully use of the benefits of intrinsic dynamics in a robot structure. However, the initial and environmental conditions to realize PDW are very severe. Following researchers after McGeer [6] have been trying to realize more stable and adaptive walking by adding a simple controller to PDW in the sagittal plane. Wisse and van Frankenhuyzen et al. [12] have realized stable bipedal walking in a real robot using pneumatic actuator. Pneumatic actuator is generally thought to be difficult to control precisely. Their controller only gives the timing to open and close air valves based on ground contact information. Ono et al. [8] shows a controller which applies torque to hip joint proportional to bending angle of knee joint in swing leg, can stabilize walking. Ogino [7] shows a simple ballistic controller can achieve the same energy efficient walking as human. These researches has confined their walking in sagittal plane because of its simplicity for analyzing, or their robots have 4 legs so as not to fall down laterally.

Recently, Collins et al. [1] has realized a 3-D passive dynamic walking in a robot with two legs and knees. However, the attempts to seek a simple controller for 3-D walking has not yet been fully succeeded. Miyakoshi et al. [5] applied central pattern generator (CPG) model, which is originally proposed for 2-D walking [9], to 3-D stepping motion in simulation environment. Van der Linde [3] has realized 3-D walking using pneumatic actuators in a robot which has translational joints instead of knees. Although these researches partially succeeded in 3-D walking, it remains unknown how to extend the existing controllers proposed for 2-D walking in a sagittal plane to 3-D walking. We suppose that controlling lateral stepping can help to extend 2-D walking in a sagittal plane to 3-D walking.

In this paper, we propose a controller for a lateral stepping which has the passive phase to gravity and the active phase to switch the torso posture to make the potential for opposite falling. The ground contact switches the phase of the swinging torso. Moreover, the amplitude of the swinging torso is correlated to the period of lateral stepping, which makes it possible to control the period of lateral stepping.

In the following sections, firstly our proposed controller for lateral stepping is introduced. Then, the parameter of the proposed controller is correlated with the period of lateral stepping and the experimental results to indicate controllability of the period of lateral stepping are shown. Finally, proposed controller are applied to 3-D walking, followed by a discussion.

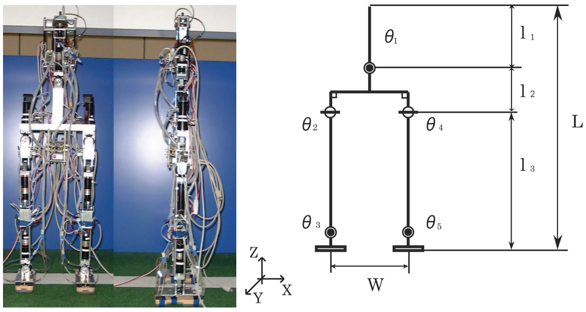
II. LATERAL STEPPING BY SWINGING TORSO

A. Robot model

The humanoid robot ONE used in this study is shown in Fig. 1. It is approximately 0.88 [m] in height and 6.55 [kg] in weight. Although it has 7 degrees of freedom, only 5 of them, a waist joint, two hip joints and two ankle joints in both legs, are used for research as shown in Fig. 1 (b). The weight and length of each part is shown in Table 1. The silicon sole is attached to each foot so that the impact force at the moment of ground contact is absorbed. 4 force sensors (force sensing register FSR) are planted between the silicon sole and a hard plate in each foot to detect ground contacts.

B. Control method

To realize stable lateral stepping, it is important to move the center of mass from the right leg to the left leg, and vice verse. For lateral stepping with short period, forcing oscillation is useful. If the upper body rotates in one



(a) The biped robot (b) Joint configuration

Fig. 1. The biped robot with a torso used for the experiments

direction, the lower part of the body rotates in another direction to conserve total angular momentum. However, it is difficult to realize long period lateral stepping motion in the same way because the gravitational force interferes with the force originated from momentum. It is important to make use of gravitational power for stabilizing the long period lateral stepping.

Fig. 2 shows the scheme of our proposed control method. In the first step (① in Fig. 2) in which the whole body is inclined to right, shifting of the torso posture to left makes the potential that causes the whole body inclining to left. In this gravitational potential, the whole body falls in the left direction until the opposite foot contacts with the ground (② in Fig. 2). The information of touching the ground triggers the posture change (③), which yields the potential causing the whole body falling to the right (④). After the right touches the ground, the same cycle begins as ①.

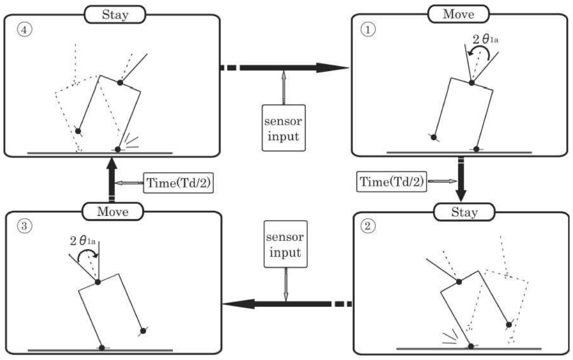


Fig. 2. Control algorithm for the lateral stepping of the biped robot

In this cycle, the reference trajectoryof the waist joint angle is given by

$$\theta_{1d}(t) = \begin{cases} \pm\theta_{1a}\cos\frac{\pi t}{T_d} & (0 \le t < \frac{T_d}{2}) \\ \mp\theta_{1a} & (\frac{T_d}{2} \le t \le \frac{T_d}{2} + T_s(\mathrm{or} T_s'), \end{cases} \tag{1}$$

where t is the time since the sensor input is occurred, $T_d/2$ is the time during which the posture of the torso changes (*Move* phase), T_s is the time during which the posture of the torso is fixed and the whole body is determined only by the gravitational force (*Stay* phase) as shown in Fig. 3. The reference trajectory mentioned above is given to the proportional integrative derivative (PID) controller.

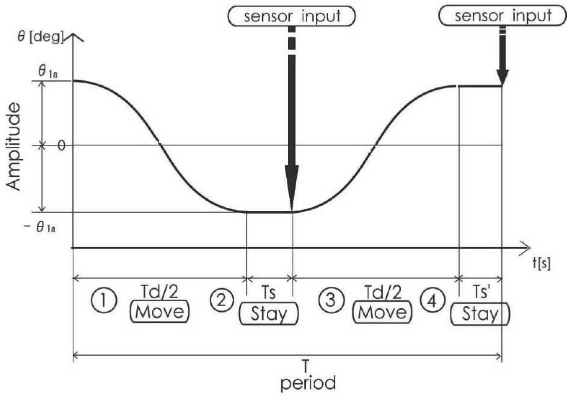


Fig. 3. The desired angle of the waist joint θ_1: the phase shifts by the touching information from the foot sensors

$$\begin{aligned} \tau_1 &= -K_P(\theta_1 - \theta_{1d}) - K_D(\dot{\theta}_1 - \dot{\theta}_{1d}) \\ &\quad -K_I \int_0^t (\theta_1 - \theta_{1d})dt \end{aligned} \tag{2}$$

The period of lateral stepping, T, is given by the summation of T_d, T_s, and T_s'. Note that in these parameters T_s(and T_s') cannot be determined by the designer.

C. Experimental result

Fig. 4 shows an experimental result. The ankle is fixed with the outside to be higher than the inside so that the tilted posture (①, ③) is stabilized to some extent. The fixed angle is 3 [deg]. When this ankle joint is fixed to be 0 [deg] (both feet are vertical to legs), weight cannot be shifted well and lateral stepping is not realized. Fig. 5 shows the time course data of the waist joint angle, foot sensors of both feet, and the tilt angle of the body from the vertical axis during lateral stepping. The *Move* phase of the torso indicated by hatching zone in the graph, is much shorter than the *Stay* phase in which the waist joint is fixed, so that the motion of the robot is fully determined by the gravity. This motion is quite different from the forced oscillation in which the motion of the controlled joint is synchronized with the entire body.

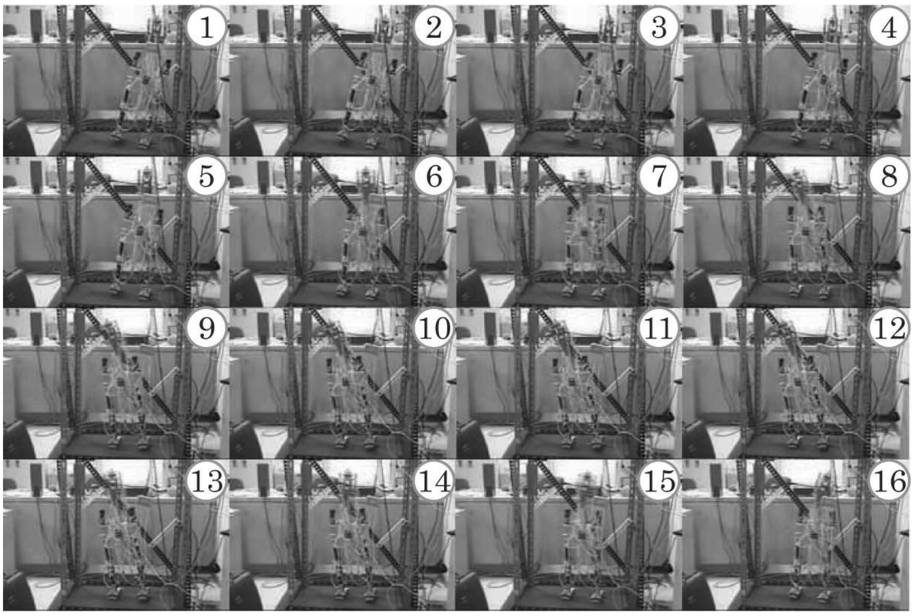


Fig. 4. Realized lateral stepping

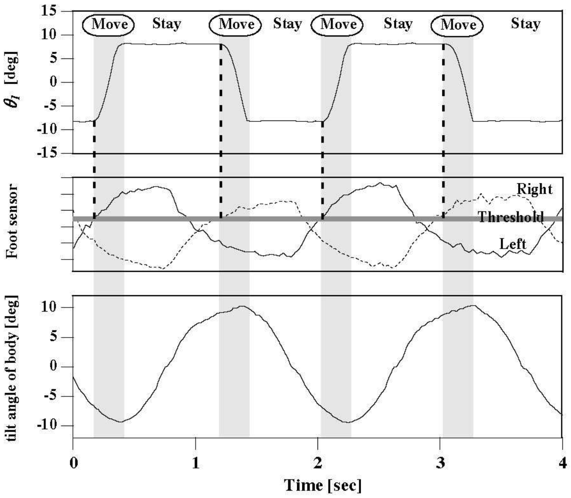


Fig. 5. The joint angle of the waist, foot sensors, and the tilt angle of the body

III. PERIOD CONTROL OF LATERAL STEPPING

A. Correlation between the amplitude of swinging torso and the period of lateral stepping

The proposed control for lateral stepping utilizes the passive phase to the gravity. This makes it difficult to control the period of lateral stepping directly. Although the parameter related to time cannot be used for controlling the period of lateral stepping, we found experimentally that the amplitude of the swinging torso, θ_{1a} affects the period of lateral stepping. Fig. 6 shows the correlation between the amplitude of the swinging torso and the period of lateral stepping. It shows the larger the amplitude of the swinging torso, the longer the period of the lateral stepping. The box indicates the variance of the period, and the bar shows the observed data from minimum to maximum value. The angle of the ankle joint is another important parameter concerning the period determination. It strongly affects the stable stepping region. We examines various values of ankle joint parameters, and found that 3.0 [deg] is the best value for realizing the largest stable region of lateral stepping (data not shown).

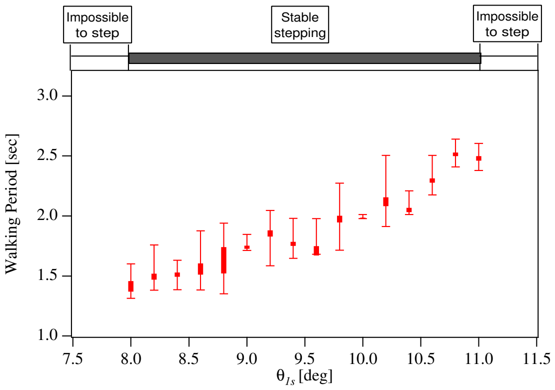


Fig. 6. Correlation between the amplitude of scillating torso and the period of lateral stepping

B. *Feedback control of lateral stepping period*

Using the characteristic mentioned above, we make a simple feedback controller which enables a robot to step laterally in the desired period. The relationship between the amplitude of the swinging torso, θ_{1a}, and the period of lateral stepping, T, can be modeled by the simple linearization,

$$\theta_{1a} = kT + a. \tag{3}$$

Let the desired period of lateral stepping T^* and the corresponding amplitude of the swinging torso, θ^*_{1a}, calculated by the above equation, then our proposed feedback controller can be given by the following equation,

$$\theta_{1a} = \theta^*_{1a} + k(T^* - T), \tag{4}$$

where k is the feedback gain which is the same value as the gradient value of equation 3, T is the observed period of lateral stepping.

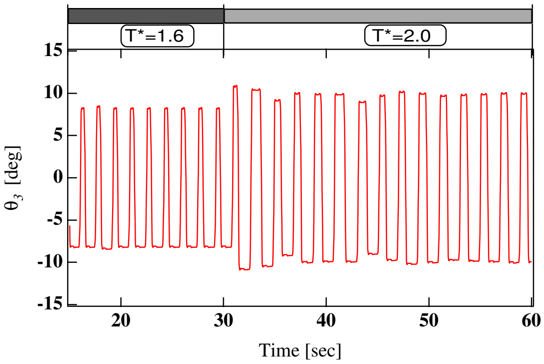
Fig. 7 shows the experimental result when the proposed feedback controller is applied to the real robot. When the desired value of stepping period, T^*, is changed from 1.6 to 2.0 [sec] at 11th [step], our feedback controller adjusts the amplitude of the swinging torso (Fig. 7 (a)), and successfully realizes the new desired period of the lateral stepping (Fig. 7 (b)).

IV. 3-D BIPEDAL WALKING USING TORSO

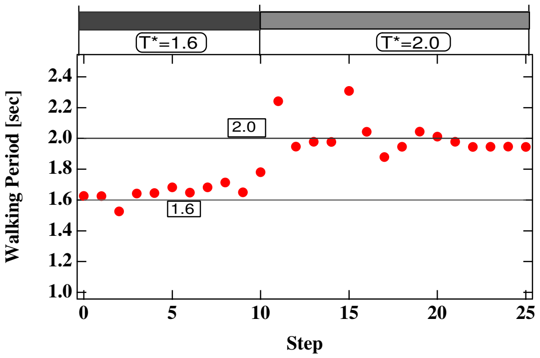
We apply the proposed feedback controller for lateral stepping to 3-D walking in a shallow slope. The controller for sagittal stepping is simple one as shown in Fig. 8. When the swing leg contacts with the ground, the swing leg is moved forward until the posture for the next contact is realized (① in Fig. 8). After that, the swing leg and the support leg are fixed (② in Fig. 8), until the swing leg contacts with the ground, and the same scheme is conducted successively.

Fig. 9 shows an experimental result of 3-D walking. Fig. 10 shows the time course of the waist joint, θ_1, hip joint, θ_2, and the walking period T.

The robot starts with forced oscillation from the stationary state. After 5 times steps of forced oscillation (the period is 0.5 [sec] and the amplitude is 8.0 [deg]), the proposed controller for lateral stepping is applied. The inclined angle of the slope is 4.0 [deg]. The amplitude of the hip joints, θ_{2a} and θ_{4a}, are set to 1.0 [deg], and so the maximum angle between the swing leg and the support leg in the sagittal plane is 2.0 [deg], which corresponds to 1.7 [cm] per step. The desired walking period is set to 1.8 [sec], and it is realized by the proposed controller as shown in Fig. 10. Our robot can walk when the amplitude of the hip joint, θ_{2a} (and θ_{4a}), is set to 2.0 [deg] (step length is 3.4 [cm]). However, when the amplitude is 3.0 [deg], our robot easily falls down and cannot keep walking more than 4 steps.



(a) The waist joint θ_1



(b) The period of lateral stepping T

Fig. 7. The angle of the waist joint θ_1 and the period of lateral stepping T when the reference period changes

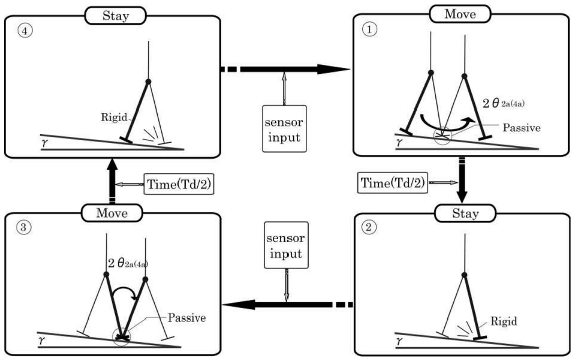


Fig. 8. Control algorithm for sagittal stepping

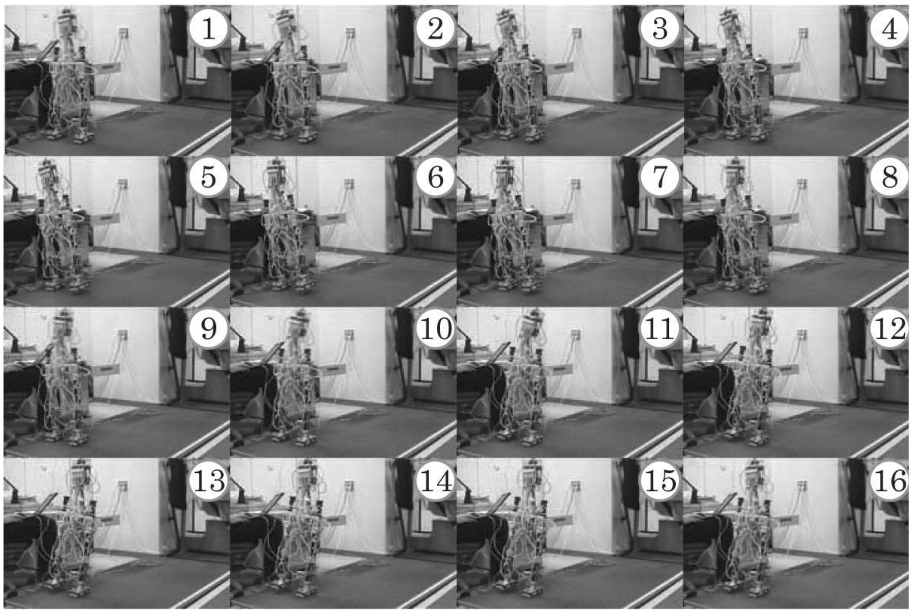
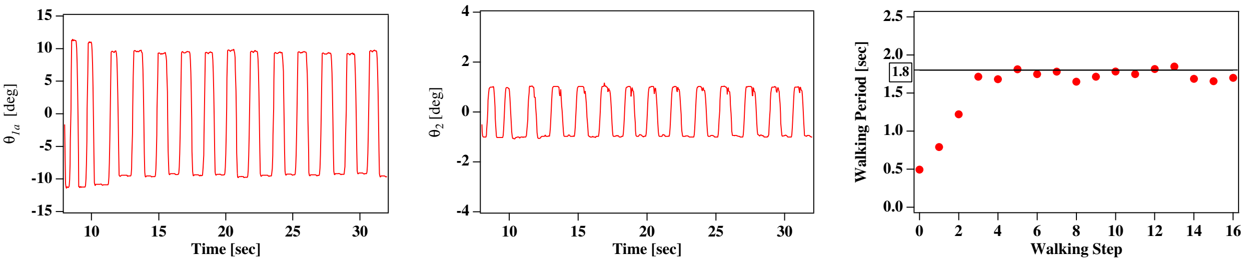


Fig. 9. The dynamic 3D biped walking



(a) The waist joint θ_{1a}

(b) The hip joint θ_2

(c) The period of the biped walking T

Fig. 10. The angle of the hip joint θ_{1a} and the hip joint θ_2, the period of the biped walking T when the angle of the hip joint θ_{2a} is 1.0 [deg]

V. DISCUSSION AND CONCLUSIONS

In this paper, we propose a controller for adjusting its amplitude of swinging torso to realize the desired period of lateral stepping. The proposed controller stabilizes lateral stepping by changing the phase of the swinging torso with the information of ground contact. Moreover, the feedback controller that makes use of the relationship between the amplitude of the swinging torso and the period of lateral stepping, can make lateral stepping converge to the desired period. Our proposed controller also realizes 3-D walking with short step length.

In human, the prediction of the passive movement in lateral stepping is thought to be important because injury lesion in cerebellum causes severe gait disturbances [4] [2]. In our model, the correlation between the period of lateral stepping and the amplitude of the swinging torso plays an important role for controlling the stepping period. The relationship is modeled by the linear equation as shown in eq. (3). Although the linear model may be too simple to describe this relationship, the feedback controller (eq. (4)) helps to complement the gap well between the real relationship and the modeled one in the area we tested. In the next stage, we are to replace a linear model with a neural network for modeling this relationship, so that the non-linear characteristics can be approximated well.

3-D walking with long step length cannot be realized in this paper. We think the cause of this is the unstable posture during the weight shift phase from one leg to another because of the inappropriate shape of foots. We are now making the improved version of the foot and trying to combine the proposed method and the existing method in the sagittal plane for stable 3-D walking.

Compared with human motion, the amplitude of the lateral swinging of the whole body looks rather large as shown in the lowest graph in Fig. 5. This is because our robot uses only one waist joint is used for weight shifting, while, in human, many joints (thurl joints, backs, foot joints) are coordinated well. Using appropriate joints to realize the less amplitude of lateral swinging is our next challenge.

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VI. REFERENCES

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