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Compass type biped walk utilizing kick motion of telescopic legs to control energy

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Abstract: This paper proposes a control method for bipedal walking using a compass-type telescopic-leg model. The main idea is to achieve energy control for locomotion through the kick motion of the rear support leg at the end of the double support phase. Computer simulations confirm that the compass-type walk can be achieved by controlling the energy to the desired value at the beginning of the double support phase.

Keywords: Biped control, compass type, telescopic leg, variable elasticity.

1. INTRODUCTION

Legged locomotion is advantageous to maneuver on uneven ground. Especially, biped walk is supposed to be suitable to move around in the human society constructed for the sake of humans that walk with two legs.

Comparing with other multi-legged locomotion, biped walk has high maneuverability in making the best use of the tumbling motion for its progress [1, 2]. However, the maintenance of the stability is crucial problem [3-5].

The nature of the tumble-based walking is well represented by the compass-type model. To keep the walking, the swing leg has to be placed on the ground before the upper body falls over to touch the ground. Although this support leg exchange ensures the stability in the sense of the avoidance of the tumble, it never produces the energy to progress forward.

To produce the force for the progress, we here pay attention to the kick motion of the rear leg at the end of the double support. Based on this view point, we propose a new control strategy for the compass type biped walk.

2. CONTROL STRATEGY

2.1. Control strategy

Biped walk is regarded as the repetition of tumble motion in the single support. Before the body falls over to the ground, the swing leg touches down the ground to support the body. Only at the moment of the double support, the static balance is being kept.

On the other hand, the walking accompanies the energy loss by such as the collision of the leg to the ground. To continue walking, the energy has to be gained in the same amount as being lost.

In this paper, we add the energy by kicking the ground at the instance when the walking phase transits from the double to the single support. Then, the kick force has to be adjusted strongly or weakly. Here, we will model the kick motion with the linear spring, and adjust the kick force by changing the stiffness of the spring.

† Satoshi Ito is the presenter of this paper.

2.2. Model and assumptions

Focusing on the kick effect, we introduce a compass-type biped model with massless telescopic legs, as drawn in Fig. 1(a). Assumptions are as follows:

- The motion is restricted within the sagittal plane.
- The ground is flat and horizontal.
- It consists of one point mass with two massless telescopic legs.
- The legs rotate around the mass without friction.
- The legs contact at the sole point with the point contact.
- The legs do not slip on the ground.
- The collision when the legs touch down the ground is perfectly inelastic.
- The leg's angles from the vertical, θ, as well as its length, r, are detectable.

The massless legs implies that the rotation around the point mass does not need any torque, and this rotation requires no time.

In this model, we can manipulate the extending force of two telescopic legs. In particular, we determine the kick force at the end of the double support phase. We suppose that the amount of the leg extension in the kick motion is always the same.

2.3. Control

2.3.1. Leg length control during single support

In Fig. 1, m is the mass of the body, F is the extending force of the leg in the single support as well as the front leg in the double support, and F_{kick} is the kick force by the rear leg in the double support and g is the gravitational acceleration.

In the single support phase, F_{kick}=0. If we keep the length of the supporting leg constant, its motion is described as the inverted pendulum, which makes the motion analysis easy. Thus, we define F as

$$F = -K_D\dot{r} + K_P(r_0 - r) - mr\dot{\theta}^2 + mg\cos\theta \quad (1)$$

to control the leg length to the constant value r_0.

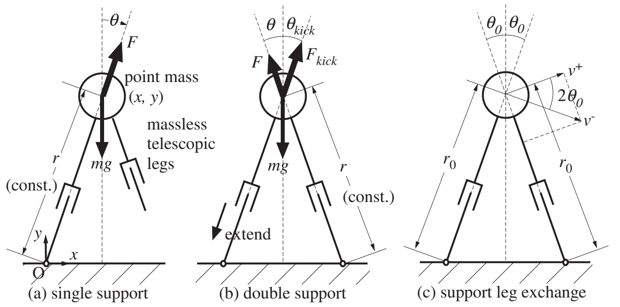


Fig. 1 A simplified model.

2.3.2. Posture control at support leg exchange

Before the inverted pendulum completely fall down to the ground, the support leg has to be exchanged. Here, we control the posture at this moment. The symmetrical posture at which the leg length is r_0 and the angle between two legs is $2\theta_0$, as shown in Fig. 1(c) is selected as the desired one. It can be achieved by controlling the length and angle of the legs appropriately during the inverted pendulum motion, which will be easy under the assumption here because massless leg can be set to arbitrary length and angle with instant time.

2.3.3. Kick force control

The rear leg in the double support produces the energy to continue the walk by its kick motion. We represent this kick motion by the linear spring. As we assumed that the leg extension is always constant Δr, the stiffness of the spring k is selected to control the force.

First, we define the desired energy level E_d,

$$E_d = \frac{1}{2} m r_0^2 \dot{\theta}_d^2 + m g r_0 \cos\theta_d \tag{2}$$

Note that E_d can be set by the desired state value $(\theta_d, \dot{\theta}_d)$ of the inverted pendulum.

As shown in Fig. 1(c), at the moment of support leg exchange, the inverted pendulum motion changes from the rotation by the rear support leg to the one by the front support leg. Let the velocity then v_- and v_+, respectively. Because we assume the perfectly inelastic collision, the velocity component parallel to the front (next) support leg in $v-$ is lost. In other words, only the velocity component normal to the front support leg in $v-$ remains. It indicates

$$v^+ = v^- \cos 2\theta \tag{3}$$

Considering the potential energy, the energy immediately before and after the leg collision, E^- and E^+ becomes

$$E^{\pm} = \frac{1}{2} m (v^{\pm})^2 + m g r_0 \cos\theta_0 \tag{4}$$

The lack energy to continue walking ΔE is given as

$$\Delta E = E_d - E^- (or = E^- - E^+) \tag{5}$$

This amount of energy is added from the ground kick motion by the rear support leg, the kick force of which is represented by the linear spring. As the energy stored to the spring has to be equal to ΔE, we get

$$\Delta E = \frac{1}{2} k \Delta r^2 \tag{6}$$

Thus,

$$k = 2\frac{\Delta E}{\Delta r^2} \tag{7}$$

To control the additional energy, we can manage the duration of the kick motion. Since the kick motion is represented as the mass-spring system, the time required for the stored elastic energy to be completely transferred is $T/4$, where T is the period of the harmonic oscillation of the mass-spring system. Namely, if the time from the kick start t satisfies

$$t < \frac{T}{4} = \frac{1}{2}\sqrt{\frac{m}{k}} \tag{8}$$

the extending force F is defined as

$$F_{kick} = k(r_0 + \Delta r - r) \tag{9}$$

Here, r is the rear leg length. Instead of (8), the condition that the leg extension is within Δr

$$r - r_0 < \Delta r \tag{10}$$

might be available as another method.

While the rear support leg is kicking the ground, the front support leg keep the leg length to achieve the inverted pendulum motion. Considering the effect of the kick force, we define the extending force of the front support leg as

$$\begin{aligned} F &= -K_D \dot{r} + K_P (r_0 - r) - m r \dot{\theta}^2 \\ &\quad + m g \cos\theta - F_{kick} \cos(\theta_{kick} - \theta) \end{aligned} \tag{11}$$

3. SIMULATION

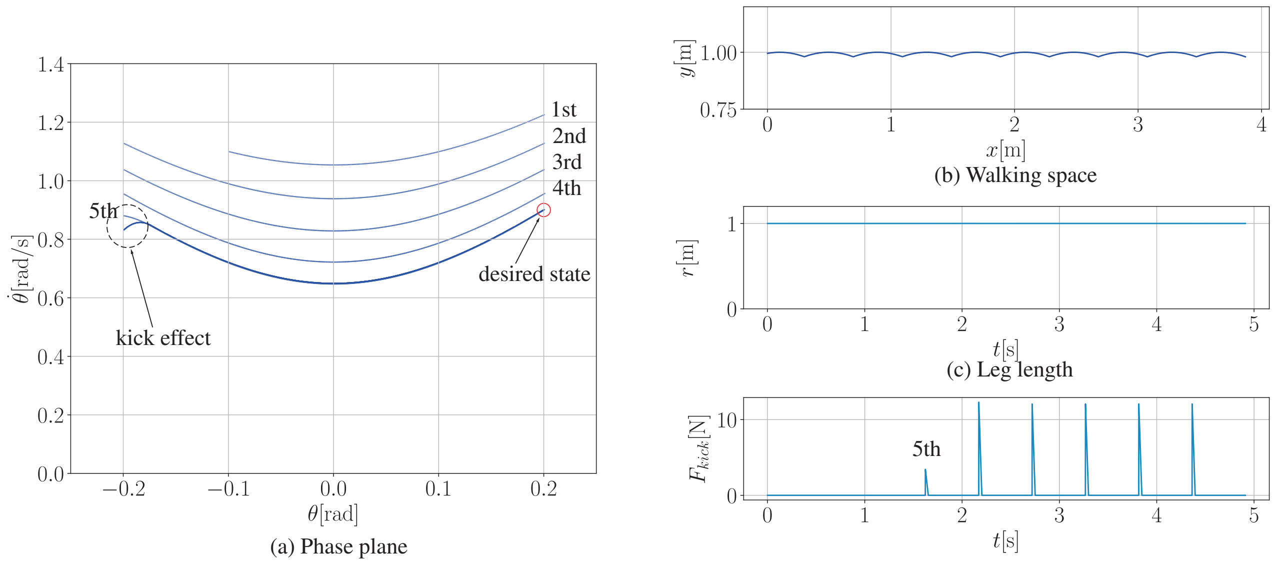
3.1. Purpose and conditions

The purpose of the simulation is to confirm whether the control law works effectively as we expect. We set $\theta_0 = 0.2$rad that determines the posture at the support leg exchange, and $(\theta_d, \dot{\theta}_d)$=(0.2rad, 0.9rad/s) that specify the desired walking by the stride length and the walking speed. The simulation starts at ($\theta(0)$, $\dot{\theta}(0)$) =(-0.1rad, 1.1rad/s).

The mechanical parameters are set as follows: m=1 kg, r_0=1m, Δr= 0.01m, K_D=4, K_P=4 and g=9.81 m/s^2. Eq. (10) is adopted to determine the finish of the kick motion. The fourth-order Runge Kutta method is adopted with the time step 0.1ms.

3.2. Results and remarks

The results of the simulation are illustrated in Fig. 2 containing ten step walk. Fig. 2(a) shows the phase plane orbit. Note here that the state jump from the right end of the orbit to the left end of the orbit of the next step because of the support leg exchange. In the fifth step, the state reach the desired one, the circle marker in the graph, given by to the posture of the support leg exchange. Afterwards, the walk continues at the same energy level as the desired state. Fig. 2(b) is the orbit of CoG in the walk space, in which the inverted pendulum motion appears. Fig. 2(c) represents the time course of the leg length in whole walk period. Because of the control law (11), the



(a) Phase plane
(b) Walking space
(c) Leg length
(d) Kick force

Fig. 2 Results of Simulation.

leg length is kept to r_0 (1m). Fig. 2(d) shows the kick force. The initial state has higher energy level than the desired state. The kick motion can add the energy but cannot reduce it. Thus, until the fourth step, the walk continues without kick to wait for the energy decreasing by the collision to the ground. At the fifth step, the energy level is controlled by the kick motion, and it repeats after that. As shown in the phase plane, the orbit after the fifth step is fluctuated at the onset by the effect of the kick motion.

4. CONCLUSION

In this paper, a control strategy of biped walk is proposed, where the energy for continuing the walk is supplied by the kick motion of the rear support leg at the end of the double support. The biped model is, however, simplified such as the massless legs, point-mass upper body and so on. As the future work, we should develop this control method to the multi-link model to achieve the walk in the real space.

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