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Adaptive Excitation Control for the Underactuated Biped Robot

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Abstract

A control method to make the chaotic gait converge to a stable cycle gait is proposed for the biped robot with knees. This control method is called adaptive excitation control. It is based on the principle of bionics and the principle of self-excited. The control law is a combination of sinusoidal input and sensory feedback control. The control torque is only inputted into the robot's hip. Therefore, the walking process is low energy consuming. Simulation results show that the control method proposed in this paper is effective. It can enlarge the basin of attraction of limit cycle and increase the gait stability.

*Keywords:*underactuated biped robot; adaptive excitation control; chaotic gait; limit cycle

1. Introduction

With the development of human living, the biped robot technology has been developed remarkably to help human. Most of the controllers are developed based on ZMP(zero moment point). While ZMP based methods have succeeded to make actual biped robots walking, many researchers are interested in higher energy efficient gait generation. Passive dynamic walking proposed by McGeer has been thought as one of the most energy efficient walking[1]. It can walk down slopes without using actuator torques[2]. It walks down the slight slopes using the effect of gravitational field. But the passive dynamic walking is sensitive to the initial state and the ground slope angle is narrow, most of researchers have been interested in studies of the applications of passive dynamic walking to make a high efficient walking[3-6]. Asano proposed a so-called virtual passive dynamic walking in which the virtual gravity was designed adequately by ankle and hip torque to restore kinetic energy dissipating on impact[7-8]. Asano etal. Applied a parametric excitation method to the biped robot with telescopical actuator in its legs[9-10]. Simulations shows that the biped robot can walk continuously with actuated knees only. Harata etal. also proposed parametric excitation based on inverse bending walking in which the knee was bent in inverse direction to human[11-12]. M.Spong studied the switching control applied to the passive gait, which can enlarge the basin of

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attraction of limit cycle[13-16]. Ono etal. proposed self-excitation control to make the planar biped robot walk stably for a wide range of parameter values[17]. S.H.Collins exploited the robot with only ankles actuators[18]. With the variation of the parametric, the biped robot will walk into the chaotic gait. The chaotic gait is sensitive to the initial state and is not periodic; therefore, the robot may fall down easily. How to drive the chaotic gait to a stable periodic gait is a hot topic. Zhenze Liu etal. has proposed the anti-phase synchronization control scheme to make the chaotic gait converge to a stable periodic gait[19-20]. In this paper, we design a control law based on the principle of self-excitation. And this control torques only work in the hip of robot, so this robot is belonged to the underactuated biped robot.

This paper is organized as follows: Section Ⅱ describes the model of the biped robot with knees. SectionⅢ presents the adaptive excitation control law, and apply this control law to the biped robot with knees. SectionⅣ does some simulation experiments to verify the effectiveness of the control law proposed in this paper. Section Ⅴ gives our conclusion.

2. Model of the biped robot with knees

In this section, model of the biped robot with knees is introduced. This robot does not have a torso and consists of two point feet and two legs[21]. Each leg has a thigh and a shank connected at a passive knee joint that has a knee stopper. The thigh and the shank of the swing leg are assumed to be kept straight by the knee stopper during a period from the knee collision to the end of the heel strike. Figure1 shows the diagram of the model of the biped robot with knees. Table1 lists the physical parameters and the values in simulation.

TABLE I. The physical parameters and the values in simulation

Symbols	Parameter	Value in Simulation
mH	The hip mass [kg]	8
m1	The shank mass [kg]	0.5
m2	The thigh mass [kg]	5
a1	Length between the heel and the shank COG of the swing leg [m]	0.375
b1	Length between the knee and the shank COG of the swing leg [m]	0.125
a2	Length between the knee and the thigh COG of the stance leg [m]	0.175
b2	Length between the hip and the thigh COG of the stance leg [m]	0.325
L	Leg length [m]	0.5
ϕ	The slope of ground [rad]	0.1194

The entire step cycle divided into four processes:

(1)The stance leg straightens out and the knee is locked, just like a single link. While the swing leg with unlock knee comes forward, just like two links connected by a frictionless joint. This stage is called unlocked swing stage.

The dynamical equation derived from the Lagrange kinetic theorem is

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + g(\theta) = \tau$$

where $\theta = [\theta_1, \theta_2, \theta_3]^T$, $\tau = [\tau_1, \tau_2, \tau_3]^T$ represent input torques. τ_1 is set between the hip and stance leg; τ_2 is set between the hip and swing leg; τ_3 is set at the knee of the swing leg. They are set to be identically zero in passive dynamic walking. $M(\theta)$ is the inertia matrix, $C(\theta,\dot{\theta})$ is the matrix of centripetal acceleration and coriolis terms, $g(\theta)$ is the gravity vector.

(2)When the swing leg straightens out, the knee of swing leg is locked. The knee strike occures. The impact takes place instantaneously. Since it is assumed that the knee collision occurs plastically, so the momentum and angular momentum are conserved before and after the knee collision. Angular velocities after the knee collision satisfies $\theta_1^+ = \theta_2^+$. So the knee collision can be described as an algebraic mapping as follows

$$\begin{bmatrix} \dot{q}_1^+ \\ \dot{q}_2^+ \end{bmatrix} = Q(q^-) \begin{bmatrix} \dot{q}_1^- \\ \dot{q}_2^- \\ \dot{q}_3^- \end{bmatrix}.$$

(3)After the knee strike, the knee of swing leg remains locked and the system switches to the double-link pendulum dynamics. Therefore, this stage is just like the swing stage of the compass gait model. This stage is called locked swing stage. The basic equation is

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + g(\theta) = \tau$$

where $\theta = [\theta_1, \theta_2]^T$, $\tau = \begin{bmatrix}\tau_1 & \tau_2\end{bmatrix}^T$ represents independently the input torque between the stance leg and hip, the swing leg and hip.

(4)The locked-knee swing leg hits the ground. The premises underlying this stage are that: the impact takes place instantaneously; the impact of the swing leg with the ground is assumed to be inelastic and without sliding; the tip of the support leg is assumed not to be slip, and the robot behaves as a ballistic double-pendulum. Then, the heel strike with ground can be described as

$$\begin{bmatrix} \dot{q}_1^+ \\ \dot{q}_2^+ \end{bmatrix} = Q(q^-) \begin{bmatrix} \dot{q}_1^- \\ \dot{q}_2^- \end{bmatrix}$$

The mapping $Q(q^-)$ can be found by applying the law of conservation of angular momentum.

After the end of the heel strike, the two-DoF link system becomes the three-DoF link system. The transition comes true through

$$\begin{bmatrix} \dot{q}_1^+ \\ \dot{q}_2^+ \\ \dot{q}_3^+ \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1^- \\ \dot{q}_2^- \end{bmatrix}.$$

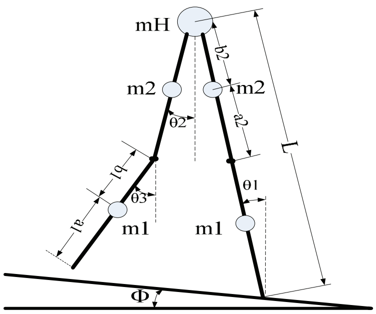


Figure 1. Model of the biped robot with knees

A stable periodic gait can be observed as a limit cycle through phase plot, just as fig.2.

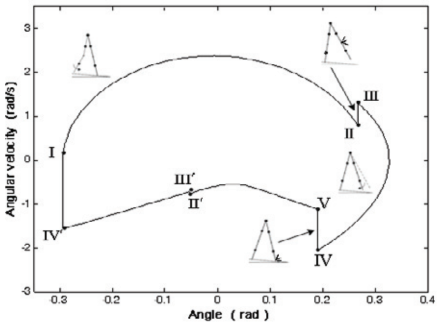


Figure 2. Limit cycle of passive walking

3. Adaptive excitation control

Based on the principle of bionics, the ankle of stance leg is passive and swing of the hip is the main energy resource [22].

Therefore, we design the control torque only inputted into the hip, when dynamic walking of the robot is in the swing stage. For the unlocked swing stage, we define the feedback torques in the ith step are

$$\tau = [k \cdot \theta_3, -k \cdot \theta_3, 0]^T,$$

which can excited a stable period gait, because the stiffness matrix is asymmetric. Gain coefficient k adaptively tune into

$$k = \begin{cases} l & \|p_i - p_{i-1}\| \geq \gamma \\ l \cdot (1 - \cos(\|p_i - p_{i-1}\| \cdot \pi / \gamma)) / 2 & \|p_i - p_{i-1}\| \leq \gamma \end{cases},$$

where $p_i \in R^{6\times1}$ is the initial state of the ith step, $p_{i-1} \in R^{6\times1}$ is the initial state of the (i-1)th step, γ is a positive constant, l is a positive constant. Gain coefficient k becomes small gradually with decreasing $\|p_i - p_{i-1}\|$. If k becomes to be zero, the biped robot does the passive dynamic walking.

For the locked swing stage, we use sinusoidal input to control the process of walking. The control torque is defined as follows:

$$\tau = [a \cdot \sin(t), -a \cdot \sin(t)]^T$$

where a is a positive constant. This torque is inputted into the hip of the biped robot.

4. Simulation results

To verify the effectiveness of adaptive excitation control method, we use the biped robot with knees presented in figure1 to do simulation experiments. The parameter values are listed in table1. The ground slope angle ϕ is 0.1194rad. Initial states are listed in table2. Figure3 shows that the biped robot will walk into chaotic gaits from this initial state, if there is no actuator. In order to make the chaotic gait converge to a periodic gait, we use the adaptive excitation control for the biped robot with knees. $\gamma = 2$, $l = 0.4$, $a = 2$. Figure4 lists the input torque variation with increasing time. Figure5 is the stick plot for the first four steps. Figure6 and figure7 are the joint angle variation with time changing and limit cycle of the swing thigh respectively. From the above figures, we can say that the control method proposed in this paper works well. It can drive the chaotic gaits to a stable periodic gait. Though the input torqueses are needed continuously, the input torqueses are small.

In order to justify the robustness of the control system, $[\Delta\theta_2, \Delta\dot{\theta}_2, \Delta\dot{\theta}_3] = [-0.2, 0.4, 0.2]$ and $[\Delta\theta_2, \Delta\dot{\theta}_2, \Delta\dot{\theta}_3] = [-0.6, 0.1, 0.2]$ are added into the initial state to be disturbances. Figure8 shows that the control system has weak sensitiveness to the initial state. Though the initial states are different, the dynamic walking converges to the same periodic gait. Moreover, the ground slope angle has a disturbance $\Delta\phi = -0.006$ rad in the process of walking. Figure9 is the phase plot with this slope disturbance. From the simulation results, adaptive excitation control increases the stability of the walking and enhances the robustness of the system.

TABLE II. Initial state in simulation

	θ_1	θ_2	θ_3
Initial angular/rad	0.2502	-0.489	-0.489
Initial angular velocity/(rad/s)	-1.197	1.2137	1.2137

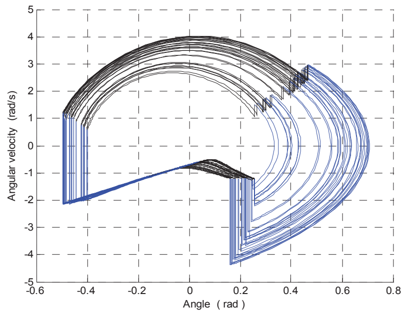
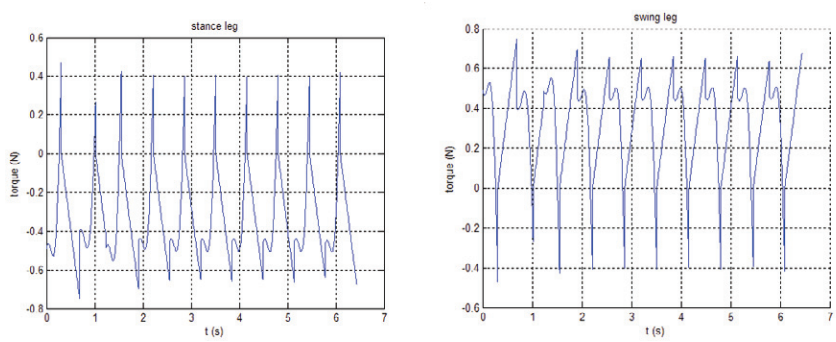


Figure 3. Chaotic gait without actuator



(a) (b)

Figure 4. Torques versus time

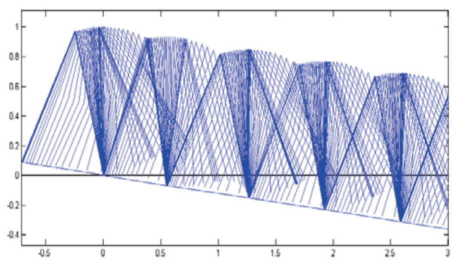


Figure 5. Walking stick of the first four steps

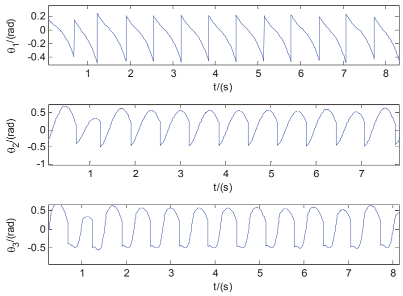


Figure 6. Joint angles versus time

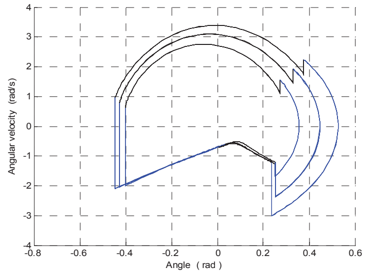


Figure 7. Periodic gait obtained with the controller

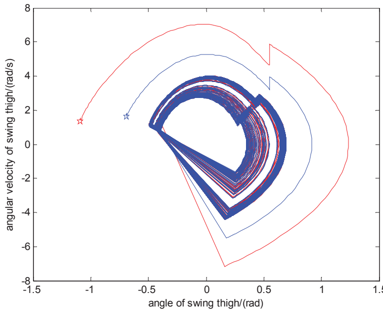


Figure 8. Limit cycle of the swing thigh with initial state disterbance

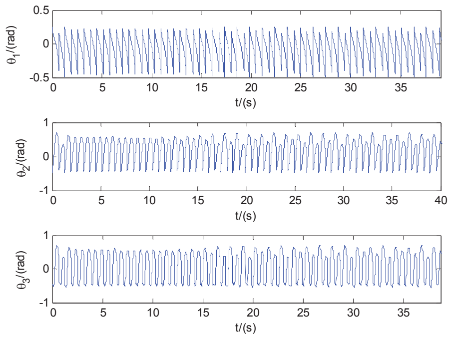


Figure 9. Joint angles versus time with slope disterbance

5. Conlusion

Adaptive excitation control method for the biped robot with knees is proposed in this paper. It is based on the principles of self-excitation and bionics. This control law can drive the chaotic gait into a stable periodic gait. Then the robot can walk continuously and stably, just as human being. Simulations show that the method is effective. With this control law, the robot will have an energy efficient dynamic walking.

The next research is to study the stability of the control system with mathematics tool.

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