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Trot Gait Design and CPG Method for a Quadruped Robot

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Abstract

Developing efficient walking gaits for quadruped robots has intrigued investigators for years. Trot gait, as a fast locomotion gait, has been widely used in robot control. This paper follows the idea of the six determinants of gait and designs a trot gait for a parallel-leg quadruped robot, Baby Elephant. The walking period and step length are set as constants to maintain a relatively fast speed while changing different foot trajectories to test walking quality. Experiments show that kicking leg back improves body stability. Then, a steady and smooth trot gait is designed. Furthermore, inspired by Central Pattern Generators (CPG), a series CPG model is proposed to achieve robust and dynamic trot gait. It is generally believed that CPG is capable of producing rhythmic movements, such as swimming, walking, and flying, even when isolated from brain and sensory inputs. The proposed CPG model, inspired by the series concept, can automatically learn the previous well-designed trot gait and reproduce it, and has the ability to change its walking frequency online as well. Experiments are done in real world to verify this method.

Keywords: quadruped robot, trot gait, series CPG model, foot trajectory

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1 Introduction

Quadruped robots can step over obstacles and walk through irregular ground. They are stable and powerful than biped, which make them well suited for outdoor tasks. Their walking design is a complex and challenging task, which needs to cooperate many joints to produce necessary skillful movements and also to resist perturbations from environment[1]. The design actually includes two aspects, cooperating all the legs and designing the movement for each single leg.

Living organisms show amazing abilities to interact adaptively with the environments. It is generally believed that neural networks in the spinal cord, referred to as “Central Pattern Generators (CPG)”, are capable of producing rhythmic movements, such as swimming, walking, and flying, even when isolated from brain and sensory inputs[2]. Acting as a locomotion control mechanism, CPG possesses many advantages: (1) It can produce periodic signals even without sensory inputs or higher level commands. However, sensory inputs and higher orders can modulate the output of CPG. (2) It is a distributed control method. Normally, one CPG unit controls one joint. A CPG network can coordinate all joints to complete a movement. Therefore, by modulating the parameters of a CPG network, we can get different phase relationships and therefore, different gaits. (3) It can adapt to the environment. The aim is to obtain robust locomotion patterns that exhibit stable limit cycles to resist perturbations. The robustness is obtained by providing sensor feedbacks to CPG to compensate for irregularities and obstacles on the ground.

CPG related methods have been studied and used to control many types of robots and different modes of locomotion. For example, Ayers and Witting developed a robot lobster to walk in shallow sea shore[3]; Pinto *et al*. designed a gait for a hexapod robot[4]; Ijspeert *et al*. manufactured a lamprey-like robot which can transfer its locomotion between swim and walk[5]; Kimura *et al*. built a quadruped robot “Tekken” which could walk on irregular terrains[6]; Saif designed a controller for a biped robot[7]; Wang *et al*. proposed a neural controller for a robot cheetah[8]. However, all of these applications did not specify how they obtained the desired walking pat-

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tern or gait.

With reference to the concept introduced by Raibert *et al.*[9,10], grouped legs can be represented by one virtual leg to simplify the walking design. So the trot gait design for quadrupeds usually can be equivalent to the one for bipeds. Speaking of bipeds, we will think of human. There are two prevailing theories of human walking. The six determinants of gait are kinematic features of gait proposed to minimize the energetic cost of locomotion by reducing the vertical displacement of the body Center of Mass (COM)[11]. The inverted pendulum gait proposes that the stance leg acts like a pendulum, prescribing a more circular arc for the COM rather than a horizontal path. These two theories have been well referred in robot walking design. The six determinants of gait are more about the plan of kinematics. For example, in the walking design of Sony's AIBO dog, researchers established the kinematics model, designed the movement of COM and foot trajectory, and used policy gradient algorithm, genetic algorithm and reinforcement learning to learn a set of kinematic parameters[12–14]. On the other hand, the inverted pendulum gait is more like the passive dynamic gait, which was originally developed by McGeer[15]. These same principles were applied to powered walking on level ground[16], as demonstrated by several recent walking machines[17–18].

Even one has acquired a good gait, how to connect the gait with CPG? Most present CPG models[19–21] only produce sine or quasi- sine signals. But the signal one needs is specified. If a CPG model cannot produce the specified gait one designed, the gait design work becomes meaningless. In this context, we designed a trot gait for our parallel-leg quadruped robot, Baby Elephant. The gait design is based on kinematic method and different walking patterns were tried to keep body steady. Then, a series CPG model was proposed to learn and reproduce this gait. Controlled by the CPG model, Baby Elephant can change its walking frequency online. Experiments were done in real world to verify this method.

2 Baby Elephant quadruped robot

Baby Elephant is a quadruped robot (see Fig. 1) designed by Prof. Gao's group from Shanghai Jiao Tong University. It has a 10 kW DC motor and a 10 kW battery onboard to drive the hydraulic system, and can walk 1 hour with 50 kg payload after fully charged. It is controlled by a PC104 computer and CAN bus. Besides, gyro and hydraulic cylinder pressure sensors are onboard. Other parameters can be found in Table 1. It can manned walk, pass through small rock field and go up and down a 10-degree slope. The distinguishing features of this robot lie in: (1) Parallel-leg mechanism (see Fig. 2). With this type of leg, the maximum power of single hydraulic cylinder decreases compare to serial-leg mechanism. (2) No drivers and electronic equipments on lower legs. The legs are purely mechanical. So this robot can walk through shallow water or under special circumstance. (3) Battery onboard. Most present quadruped robots can only walk with a power cable[22,23], while Baby Elephant aims to long time outdoor walk. This adds to its applications in real world.

3 Kinematics

Three cylinders are installed on one leg (see Fig. 2), in which two control the stretch and one controls the swing. The lengths of the three cylinders are Cy_{up}, Cy_{dn} and Cy_{sw}. The positions of the foot tip are $\boldsymbol{P_b}(x_p,y_p,z_p)$.

Fig. 1 Baby elephant quadruped robot.

Table 1 Parameters of baby elephant

Parameters	Value
Size	120 cm × 50 cm × 100 cm
Weight	130 kg
Active DOFs on each leg	3
Passive DOFs on each leg	2
Maximum speed	1 m·s^{-1}
Maximum payload	100 kg

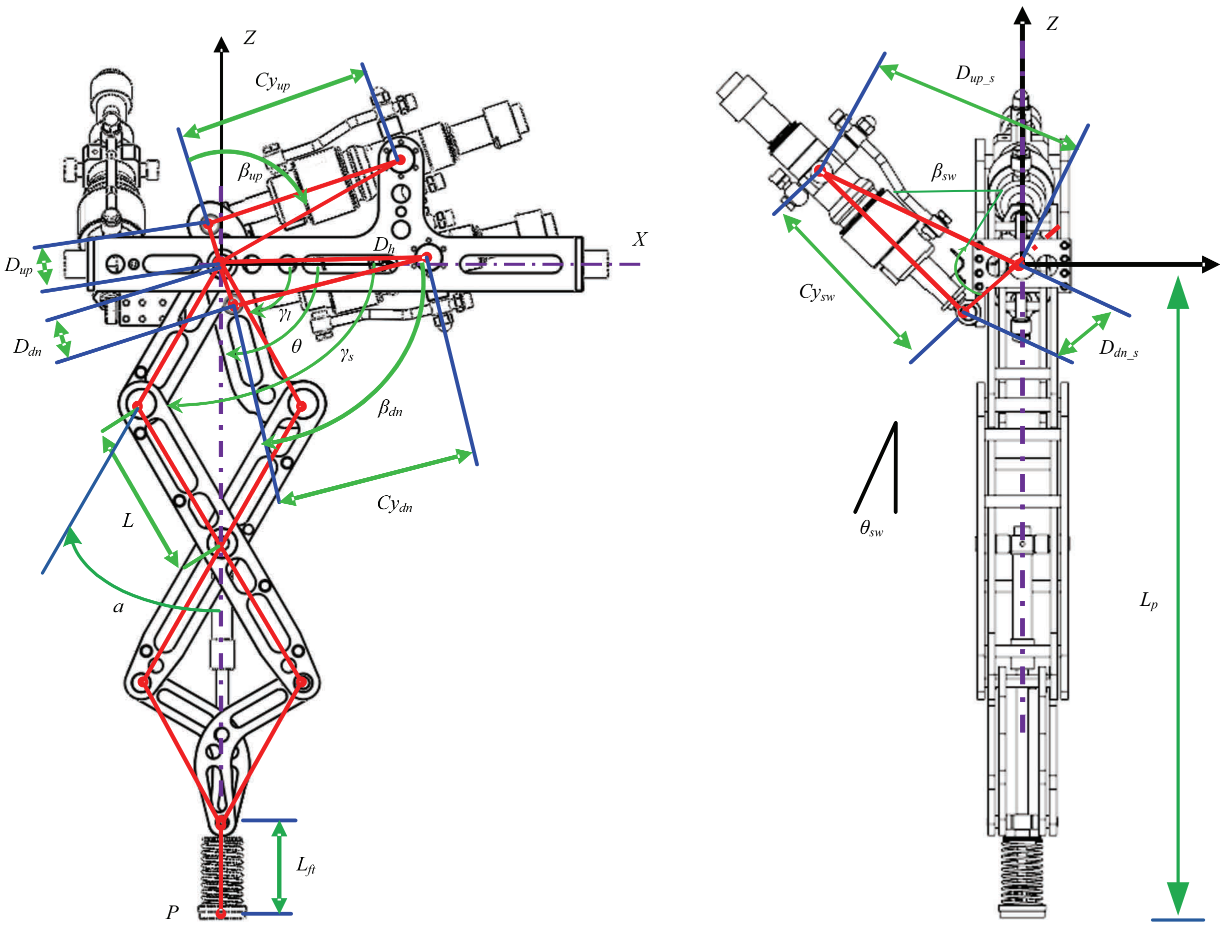

Fig. 2 Definition of the parameters.

For the kinematics,

$$\beta_{up} = \arccos\left(\frac{D_{up}^2 + D_h^2 - Cy_{up}^2}{2D_{up}D_h}\right),$$
$$\beta_{dn} = \arccos\left(\frac{D_{dn}^2 + D_h^2 - Cy_{dn}^2}{2D_{dn}D_h}\right), \tag{1}$$
$$\beta_{sw} = \arccos\left(\frac{D_{dn\_s}^2 + D_{up\_s}^2 - Cy_{sw}^2}{2D_{dn\_s}D_{up\_s}}\right).$$

Then we got γ_l, γ_s, and θ_{sw} from

$$\theta = \frac{\gamma_l + \gamma_s}{2},$$
$$\alpha = \gamma_l - \theta = \frac{\gamma_l - \gamma_s}{2}, \tag{2}$$
$$L_p = 4L\cos(\alpha) + L_{ft}.$$

With Eq. (2), the foot tip position without swing, $\boldsymbol{P}(L_p\cos\theta, 0, L_p\sin\theta)$, were calculated. Further, with

$$\boldsymbol{R}_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sw} & \sin\theta_{sw} \\ 0 & -\sin\theta_{sw} & \cos\theta_{sw} \end{bmatrix}, \tag{3}$$

we got the final foot tip position

$$\boldsymbol{P}_b(x_p, y_p, z_p) = \boldsymbol{R}_x^{-1}(\theta_{sw})\boldsymbol{P}(x, 0, z).$$

Vice versa, the inverse kinematics can be calculated if $\boldsymbol{P_b}(x_p, y_p, z_p)$ is known.

4 Trot gait design

Quadruped animals have different gaits to fit for different terrains and speeds. Trot is a common gait in robot walking control, in which the diagonal legs lift simultaneously while the other two supporting the body as shown in Fig. 3.

In a kinematics based gait design, we have to consider the body posture, walking frequency, step length, duty ratio, foot trajectory, and so on[24]. But in the first place, we should decide the movement of body COM. One feature of the six determinants of gait is to keep COM horizontal. The inverted pendulum gait is more efficient in power saving. While, for our robot, once it is powered on, the pressure and the rate of flow of hydraulic system are set as constants. Even the robot stands still, it consumes energy as much as it walks. So power saving is beyond our consideration here.

To ensure a steady walk, in our design the robot body moves forward horizontally with a constant speed as shown in Fig. 4. The origin of coordinate system is at the left front shoulder. Forward is x axis, sideward is y axis and upward is z axis. The step length is 100 mm, step height 50 mm, body height 720 mm, duty ratio 0.7, and period 1 s. Two foot trajectories are designed. The Mode 1 is, in supporting phase, the foot stride forward 1/4 step length while push backward 3/4 step length, which keeps the body before the supporting point most of the time and ensures a trend to go forward. The Mode 2 is just normal, which has equal step length before and after the supporting point as shown in Fig. 4. There are 2 passive DOFs on each foot. The foot springs will be compressed and the body height decreases about 5 mm when the number of supporting legs switching from 4 to 2. Therefore, the supporting legs should stretch a bit to compensate the body decrease. Fig. 5 is the final foot trajectory in x-z frame in Mode 1, and Fig. 6 is in Mode 2. There is no side movement in this gait.

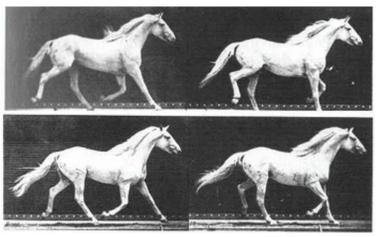

Fig. 3 The phase relationship in a trot gait.

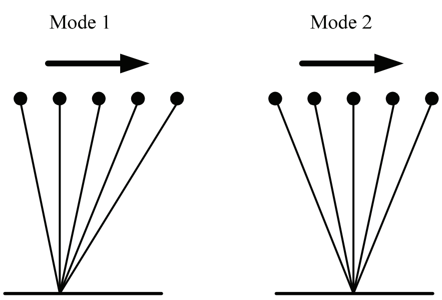

Fig. 4 Body movement under the trot gait.

Experiments were done to test which mode is better in real world. The roll angle was recorded to show the stability of the body. The results are shown in Fig. 7 and Fig. 8. In Mode 1, the average roll angle is below 1.5 degrees. While, in Mode 2, the value is about 2 degrees. So Mode 1 is credited better.

With the inverse kinematics, we can calculate the movement of each cylinder in Mode 1. Take the left front leg for example, the upper and lower cylinder lengths are shown in Fig. 9 as the red dashed lines. Here we call them reference signals.

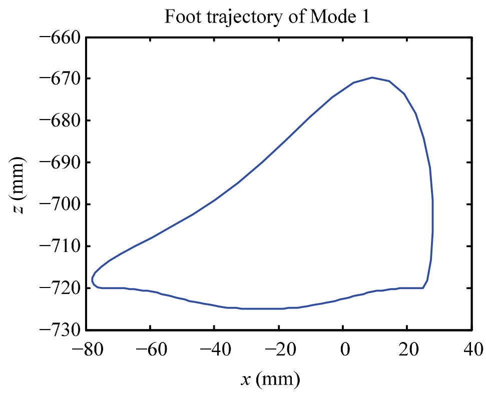

Fig. 5 Left front foot trajectory in Mode 1.

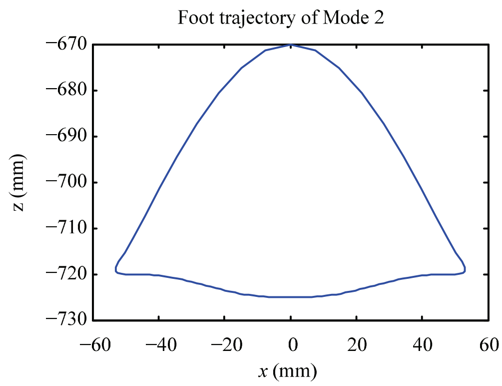

Fig. 6 Left front foot trajectory in Mode 2.

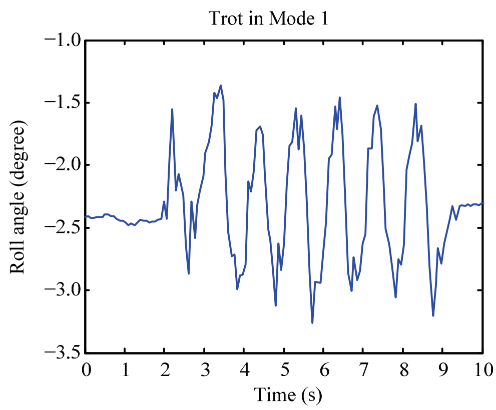

Fig. 7 Roll angle when trotting in Mode 1.

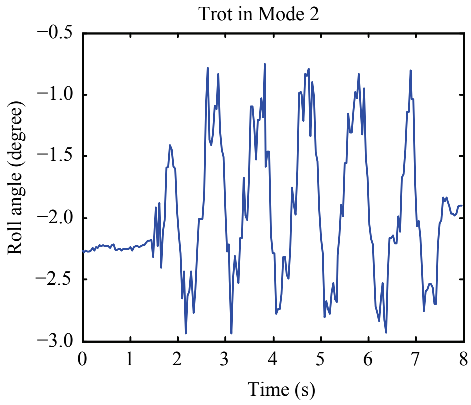

Fig. 8 Roll angle when trotting in Mode 2.

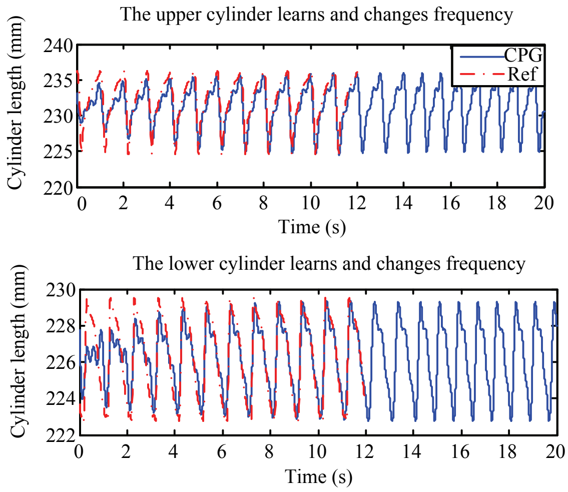

Fig. 9 CPG learns and changes frequency online. The red dashed lines are reference signals which exist in the first 12 seconds. The blue solid lines are CPG outputs. They gradually learned the reference signals and sustained even after the reference signals disappeared. At the time 14.0 s, CPG changing its period from 1 s to 0.8 s caused no chaos in the system.

5 Series CPG model design

Normally, CPG output is used directly or only after minor modification to control a joint. While, most CPG models (*e.g.* the Matsuoka, the Kuramoto, and the Van der Pol models) can only produce sine or quasi-sine signals, which may work well to control serpentine movements like snakes[25], but not optimal to control walking patterns. As shown in Fig. 9, the ideal reference signals are far from sine or quasi-sine shape. So the above CPG models cannot work properly here. Based on the original idea of Righetti *et al.*[26], the series CPG model was proposed. According to Fourier series, any periodic function $f(t)$ can be written in the form of Eq. (4), in which, A_0 is a DC component and n is a limited integer. The first n dominant harmonics plus a DC component can be used to approach $f(t)$. For a given $f(t)$, A_0 and ω can be easily got. ω is the fundamental harmonic's angular velocity. The rest is to decide A_i and $i\omega t+\varphi_i$. The proposed CPG model can learn A_i and $i\omega t+\varphi_i$ automatically, so theoretically, this model can approach any periodic signals.

$$f(t) \approx A_0 + \sum_{i=1}^{n} A_i \cos(i\omega t + \varphi_i). \tag{4}$$

The basic model can be written in Eq. (5).

$$\begin{aligned} \dot{r}_i &= (\alpha_i - r_i^2) r_i + \varepsilon F \cos(\phi_i), \\ \dot{\phi}_i &= i\omega - \frac{\varepsilon}{r_i} F \sin(\phi_i), \\ \dot{\alpha}_i &= \eta r_i F \cos(\phi_i), \end{aligned} \tag{5}$$

where

$$F = f(t) - (A_0 + \sum_{i=1}^{n} r_i \cos\phi_i),$$

is the error between the reference signal and the CPG output, ε is a feedback gain, η is a learning rate. r, ϕ and α are three state variables. $r_i\cos\phi_i$ in Eq. (5) indicates A_i-$\cos(i\omega t+\varphi_i)$ in Eq. (4). With the learning goes on, F gradually approaches 0. When F is small enough, it is switched to 0. Then, r_i becomes a constant and ϕ_i increases with the velocity of $i\omega$. The CPG output, $A_0 + \sum_{i=1}^{n} r_i \cos\phi_i$, will approach $f(t)$.

However, there is no phase relationship between every $r_i\cos\phi_i$ right now. So the phase of CPG output cannot be adjusted online. To do this, we define $\theta_i=\phi_i-i\phi_1$ and it is the phase difference between the *ith* and the 1*st* sub-components in Eq. (5). After learning, θ_i is recorded and Eq. (6) is designed to replace Eq. (5). In normal situation, $\lambda\sin(-i\phi_1-\theta_i+\phi_i)$ will be 0. Once it is needed to adjust the phase of CPG output, one can only adjust ϕ_1, then all the rest ϕ_i in Eq. (6) will follow up to keep the previous phase difference θ_i. The CPG model still outputs the learned periodic signal but with a new phase.

$$\begin{aligned} \dot{r}_i &= (\alpha_i - r_i^2) r_i, \\ \dot{\phi}_i &= i\omega - \lambda \sin(-i\phi_1 - \theta_i + \phi_i), \end{aligned} \tag{6}$$

Till now, we have built a CPG model which can produce any periodic signals and adjust its phase online.

Since each CPG model can only control one joint, for the quadruped walking issue, we have 12 joints. So, 12 such CPG models are needed. The phase relationship among every CPG model should be defined, too. With the experience in Eq. (6), we can define the phase relationship through ϕ_1 from every CPG. If the phase relationship among every CPG model is adjusted, each ϕ_1 from every CPG should be adjusted. Then it goes back to Eq. (6). The whole system will work properly[27].

6 Experiments

The trot gait designed in section **4** can be learned and recorded with the proposed CPG model. We define the connection configuration between every cylinder or joint as shown in Fig. 10. In this figure, the circled 1, 2, 3 and 4 are the upper cylinders on each leg. The circled 5, 6, 7 and 8 are the lower cylinders. The arrows mean one CPG unit can affect the other one. The first 3 harmonics (n = 3 in Eq. (4)) are used to learn the reference signals. The learning process is shown in Fig. 9. The reference signals existed in the first 12 seconds. Afterwards, the reference signals disappeared. The blue solid lines are CPG outputs. The CPG outputs gradually caught up to the references. Even after the reference signals disappeared, the CPG outputs still existed. That means the reference signals had been recorded by CPG. So, the CPG model can produce similar cylinder movement trajectories and can be used to control the robot.

Fig. 11 is the experiment result on Baby Elephant. We recorded its walking process and took screenshots out. The left front leg went into the swing phase first. It lifted up, moved forward, touched down and switched to supporting phase. Then, the right front leg did in the same mode. The body was steady and there was no much difference compared to the normal trot gait except the body roll angle increased a little bit (see the first 9 seconds in Fig. 12).

To show the adaptive property of CPG, we changed its walk frequency online. The walking period was changed from 1 s to 0.9 s in Fig. 12 at the time 9 s and the walking period was changed from 1 s to 0.8 s in Fig. 13 at the time 9 s. The results show that the transfer process was smooth and with higher frequency, the body stability was improved. The average roll angle when walking in period of 0.8 s was about 1 degree, which was better than the result in Fig. 7.

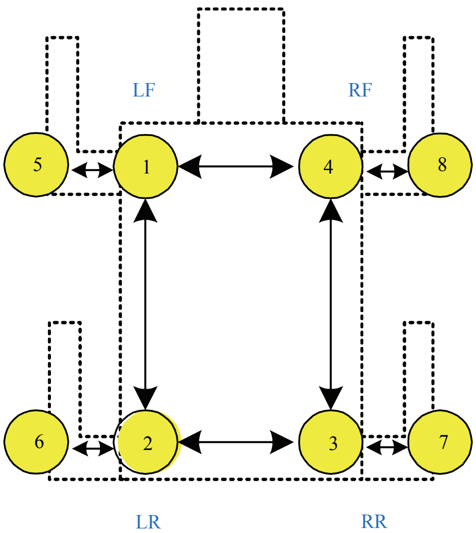

Fig. 10 Connection configuration between every cylinder.

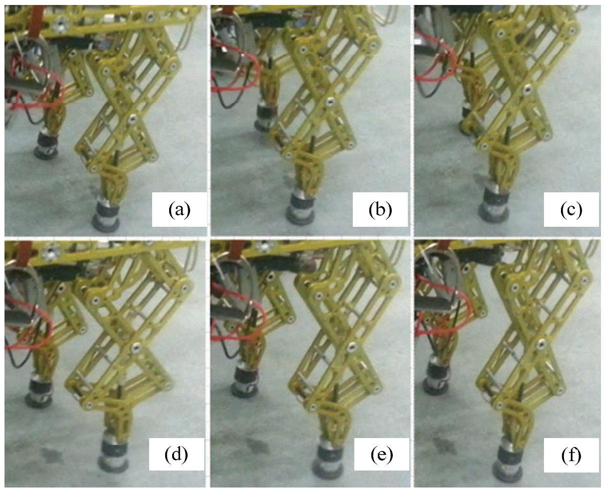

Fig. 11 Trot gait with CPG method. (a) the right front foot is about to lift; (b) the right front foot is in the air; (c) the right front foot touches down; (d) the left front foot is in the air; (e) the left front foot touches down; (f) all the feet are on ground.

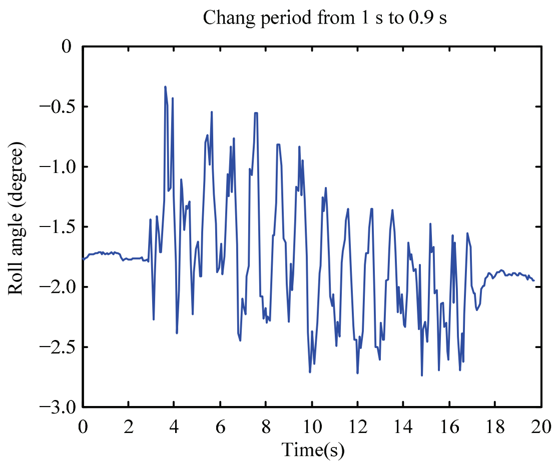

Fig. 12 CPG changed period from 1 s to 0.9 s.

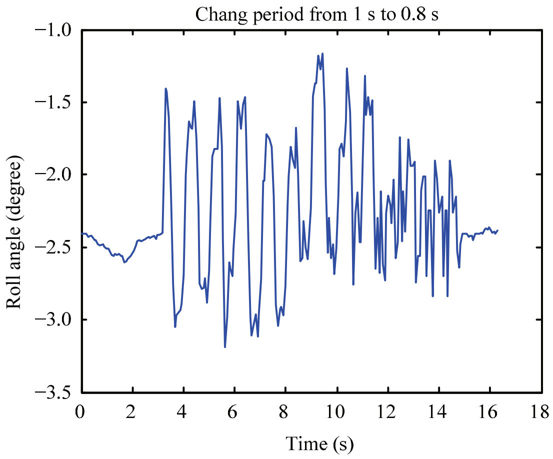

Fig. 13 CPG changed period from 1 s to 0.8 s.

7 Conclusion

This paper designed a trot gait for a quadruped robot, Baby Elephant. Based on the idea of the six determinants of gait, the body COM was scheduled to move horizontally with constant speed. Other gait parameters were set, while two different foot trajectories were tested. The experiments show that keeping the COM before the supporting point ensures the body a trend to go forward, therefore stabilizes the body. Then, a fine trot gait was acquired. Since CPG has advantages in rhythmic walking control, a series CPG model was proposed to produce this gait. With the first 3 harmonics, the CPG learned the gait and reproduced the gait even after the reference signals had disappeared. With the CPG method, the robot still walked well. Furthermore, we changed its walking period online. The transfer processes were smooth both for period 0.9 s and period 0.8 s. Also, we can see that decreasing the walking period helps to improve the walking quality. The average roll angle decreased, so the robot walked more steady.

In this paper, we changed the period manually just to test whether the CPG method could work well. In the future, we will introduce sensor information to change CPG parameters automated according to terrain information. The robot will have a better adaptive ability then.

Acknowledgments

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