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CPG Driven Locomotion Control of Quadruped Robot

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***Abstract*—According to biological evidences, central pattern generators(CPGs) are neural networks responsible for the generation of rhythmic movements for animals, such as breathing, heartbeat, and locomotion, even when isolated from the brain and sensory inputs. Inspired by this mechanism, researchers have proposed the CPG driven control method as a new way to generate rhythmic control policies for the locomotion of legged robots. In this work, we design a CPG control construction for controlling the locomotion of a quadruped robot, which is capable of realizing the different gaits and gait transitions. Firstly, a body CPG network is constructed by mutually coupled phase oscillators, which can produce multiple phase-locked oscillation patterns that correspond to the four basic quadruped gaits. The gait transitions can be realized by altering the internal oscillator parameters. Then, we design a robotic platform based on Webots and AIBO, and realize dynamic locomotion with the designed CPG network for AIBO. The Simulation and experimental results demonstrate the proposed CPG network is effective to generate gait patterns for quadruped robots.**

***Keywords*—CPG, quadruped robot, gait pattern, gait transition, AIBO, Webots**

I. INTRODUCTION

The locomotion control of legged-robot is a great challenge that has not yet been completely solved. The most popular motion design method is the trajectory-based method[1]. The basic idea of this method is to find motion trajectories for every foot and then calculate the movements for the other joints. These trajectories are usually designed by trial-and-error or from some optimization algorithms[2-4]. There have disadvantages for this method: Firstly, we have to possess a perfect knowledge of the robot's dynamics; Secondly, it is not suit for unknown environment. Presently, inspired by animals' rhythmic motion mechanism in nature, researchers have proposed the CPG driven control method as a new way to generate adaptive control policies for the locomotion of robots.

In biology, neurobiologists revealed the evidence that animals have specialized neural circuits, referred to as "central pattern generators" (CPGs), which can produce rhythmic movements even when isolated from the brain and sensory inputs[5-8]. CPG networks present several interesting properties including distributed control, the ability to deal with redundancies, fast control loops, and allowing modulation of locomotion by simple input signals[9]. Inspired by biological CPGs properties, researchers found a new way to building control blocks for rhythmic movements control in articulated robots. With this method, we do not need to build kinetics models of the system and can get better adaptive ability to the environment.

In robotics, CPGs are often modeled as coupled dynamical systems, which can generate complex output waveforms. At present, CPGs are often simulated by neural oscillator model (e.g. Hodgkin-Huxley(H-H) model, Fitzhugh-Nagumo model, integrate-and-fire neuron models), and nonlinear oscillators (e.g. Hopf oscillator, Rayleigh oscillator and Van der Pol oscillator). The dynamic characteristic analysis of CPG network is usually difficult because of its nonlinear and chaotic property. So far, very few methods are useful to modulate the parameters for generating a periodic signal with a specific shape. This is a certain limitation in the development of CPG driven engineering systems.

CPGs have been already employed by researchers in the generation of gaits for robots. Such as, inspired by insect locomotion, CPGs have been used to control hexapod and octopod robots[10][11]; CPG networks inspired by lamprey have been used for controlling lamprey-like robots[12][13]. Quadruped locomotion control has been extensively explored, like for example by Kimura on quadruped robots Patrush and Tekken[14][15], Ijspeert on salamander robot[16], and Ilg W.[17], Billard[18], Tsuchiya[19][20] in quadruped robots too. CPG driven methods are also increasingly used for the control of biped locomotion, often inspired by Taga's work on neuromechanical simulations[21].

Our work follows the research line taken by Ijspeert et al. with their results in the generation of gaits for the lamprey, but

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we try to slightly improve in several points: First, we introduce a general body CPG architecture, with which we can get several gait patterns and realize gait transitions easily; Second, we use a more complex robot AIBO, whose every leg has three degrees of freedom that must coordinate, and a meaningful control CPG network is constructed; Third, we apply CPG control network to the real AIBO robot. The organization of this paper is as follows: In Section II, by using simple phase oscillator adapted from *Kuramoto* model[22], we construct a body CPG network, and by changing internal parameters, the gait transitions can be realized easily; In Section III, based on the previous work we have done on AIBO, we realize the dynamic locomotion with CPGs control network for AIBO. By applying Webots software and real AIBO, we validate the CPG driven method. Finally, concluding remarks and future work are given by section IV.

II. CONSTRUCTION OF THE CPG NETWORK FOR QUADRUPED ROBOTS

In this section, we will construct a CPG network by means of coupled oscillators to generate the joint trajectories for the quadruped robots. The CPG model should satisfy several properties, such as:

- Has limit cycle behavior. So the oscillatory patterns are robust against transient perturbations; And, the limit cycle can be smoothly modulated by some parameters which offer the possibility to smoothly modulate the gait patterns;
- The coupled oscillators of CPG must be synchronized and phase locked.

A. CPG model

Phase oscillator is probably the simplest type of oscillator, where the radius is completely neglected, only the phase is retained. In this paper, we apply an extension phase oscillator, called ACPO (amplitude controlled phase oscillator), adapted from[22][23], which oscillatory radius is controlled by a differential equation with a fixed point attractor as follows

$$\dot{\theta}_i = w_i + \sum_{j=1}^{N} \lambda_{ij} \sin(\theta_j - \theta_i - \Delta\phi_{ij}) \qquad (1)$$

$$\ddot{r}_i = \mu_i^2 (R_i - r_i) - \frac{3}{2}\mu_i \dot{r}_i \qquad (2)$$

$$x_i = r_i [1 + \sin(\theta_i)] \qquad (3)$$

Equation(1) is a modified *Kuramoto* model of a population of N coupled phase oscillators. θ_i is the phase of the ith oscillator. w_i is frequency parameter. Each oscillator in (1) tries to run independently at its own frequency, while the coupling term λ_{ij} tends to synchronize it to all the others[22]. $\Delta\phi_{ij}$ denotes the desired phase shift between oscillator *i* and *j*. Equation (2) ensures that the amplitude r_i will asymptotically and monotonically converge to R_i this allows us to smoothly modulate the amplitude of oscillations, and μ_i is a positive constant. Equation (3) is the transform of instantaneous internal phase to external angle signal.

Such a CPG model has limit cycle behavior and the output forms can be adjusted by explicit parameters. For example, the amplitude and frequency can be modulated easily as shown Fig. 1.

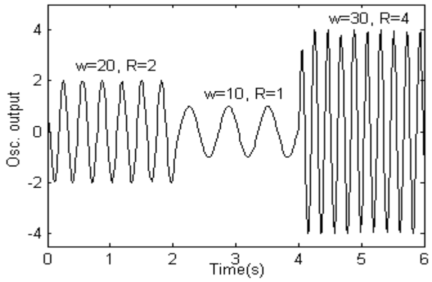


Fig. 1 Change in frequency and amplitude of the oscillator

B. CPG Network Architecture

For animals, the patterns produced by the CPGs variously change to meet the surrounding environment, such as horses, they select different gait patterns in accordance with the desired locomotive speed. As in Fig. 2, there are four basic quadrupedal gaits: the walk, trot, pace and bound.

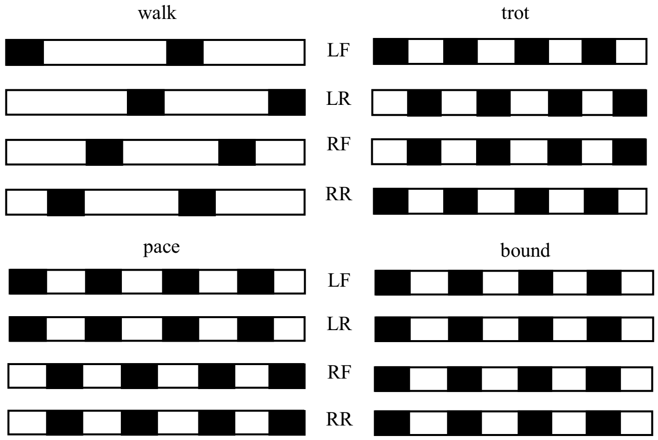


Fig. 2 The phase of typical gaits (black: standing phase, white: swing phase)

In the present study, we construct a quadrupedal body locomotor CPG as a network of four coupled phase oscillators. Each oscillator controlled one joint movements of a single limb. By connecting the oscillator of each limb, oscillators are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between the oscillators of the limbs results a gait. And by changing the phase difference between the oscillators, we can get the four basic gaits.

In our study, we are only interested in interlimb coordination, i.e., the relative phases between the limbs (CPG oscillators) of the quadruped. So we set amplitude parameters $R_i = 2$ and frequency parameters $w_i = 10$ for all oscillators. Coupling coefficients λ_{ij} set to 4 for all the oscillators, and the phase differences between neighbor oscillators are set to positive for the descending connections and negative for the ascending connections. Fig. 3 is an example for walking pattern, gait according the order 1-3-2-4. Four oscillators are coupled together according to a connection matrix $\Omega_{con.walk}$. The connection matrixes between the oscillators denote the phase difference. By designing the connection matrix, we can get the other three basic gaits easily as show in Fig. 4.

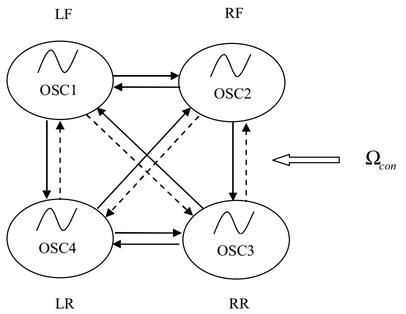
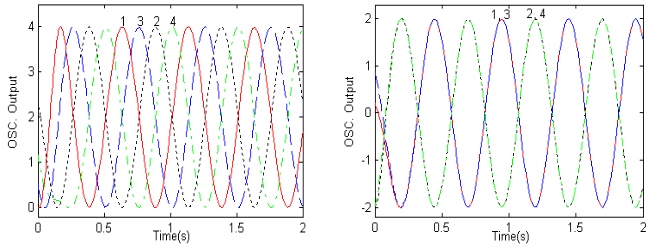


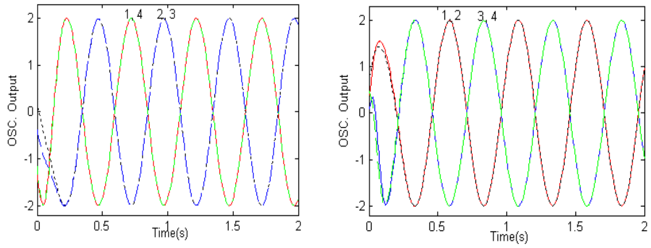
Fig. 3 Walking network and connection relation between the body OSC.



$$\Omega_{con.walk}=\begin{bmatrix} 0 & \pi & \pi/2 & 3\pi/2 \\ -\pi & 0 & -\pi/2 & \pi/2 \\ -\pi/2 & \pi/2 & 0 & \pi \\ -\pi/2 & -\pi/2 & -\pi & 0 \end{bmatrix}$$

$$\Omega_{con.trot}=\begin{bmatrix} 0 & \pi & 0 & \pi \\ \pi & 0 & \pi & 0 \\ 0 & \pi & 0 & \pi \\ \pi & 0 & \pi & 0 \end{bmatrix}$$

(a) waking pattern (b) trotting pattern



$$\Omega_{con.pace}=\begin{bmatrix} 0 & \pi & \pi & 0 \\ \pi & 0 & 0 & \pi \\ \pi & 0 & 0 & \pi \\ 0 & \pi & \pi & 0 \end{bmatrix}$$

$$\Omega_{con.bound}=\begin{bmatrix} 0 & 0 & \pi & \pi \\ 0 & 0 & \pi & \pi \\ \pi & \pi & 0 & 0 \\ \pi & \pi & 0 & 0 \end{bmatrix}$$

(c) pacing pattern (d) bounding pattern

Fig. 4 Four basic gait patterns and the connection matrixes

In order to illuminate the robustness against perturbation property, we present the case when the state variable for the left front leg gets fixed for 0.1s and then released again during walk. The two vertical lines show the time when the leg is fixed and released again. As can observed in Fig. 5, after release the fixed term, the leg can catch up with the other legs to fulfill the requirement of the gait pattern quickly. This is a significant advantage of CPG driven methods for controlling locomotion over other methods (e.g. trajectory-based method).

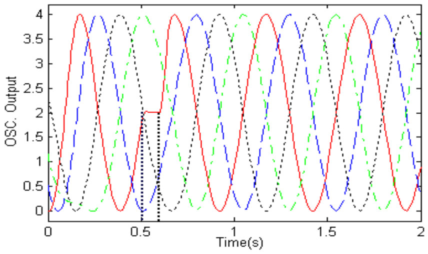


Fig. 5 Walking pattern with perturbation

C. *Gait Transitions*

Quadruped walking animals can easily change their gait patterns to suite the environment, but shifting locomotion patterns is a difficult task for legged-robot. Two methods are usually used to realize the gait transitions for CPG driven method: one is changing the driving signal to CPG; another is changing coupling configuration[15]. In this section, we attempt to realize the gait transitions by switching the coupling structure, i.e. by changing the connection matrix $\Omega_{con.}$ to realize the smooth gait transition. Fig. 6 shows examples of gait transitions: walk-trot-pace and trot-walk-bound.

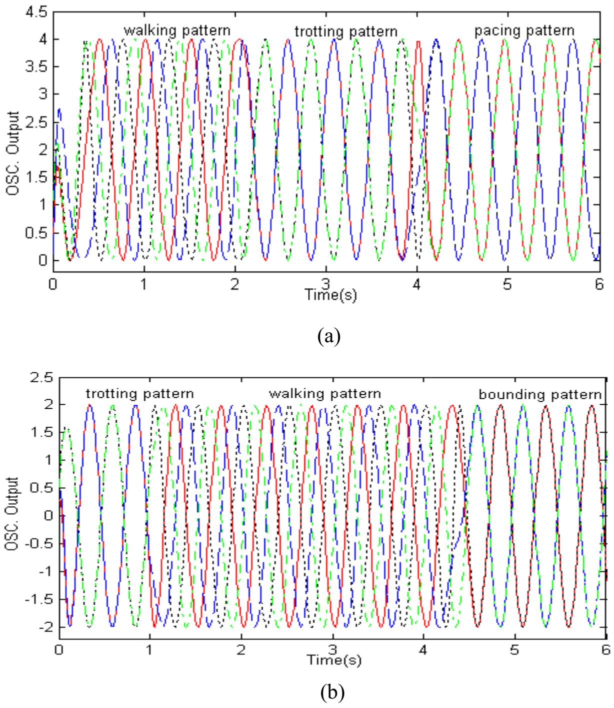


Fig. 6 Examples of gait transitions: (a) walk-trot-pace, (b) trot-walk-bound

III. ROBOTIC PLATFORM—— AIBO ROBOT

A. *Previous Work with AIBO*

The four legged robot AIBO has 20 degrees of freedom and the coordination of all them to obtain a locomotion pattern is very difficult. Our team has been used AIBO to play soccer in the RoboCup for many years.

Previously, we realized locomotion control of AIBO based on conventional trajectory-based methods. We built the kinetic model of robot and then designed trajectories for every leg. The loci experienced from rectangle, parabola, ellipse, modified ellipse to 3-D polygon. In this section, we take parabola locus with Lagrange interpolation, as Fig. 7 shows, for trajectory plan as example. Fig. 8 shows the angular value plots for joint rules which are calculated with inverse kinematics: The first one is for the shoulder joint which controls the moving forward; the second one is for the other shoulder joint which controls the moving side; the third one is for the knee joint.

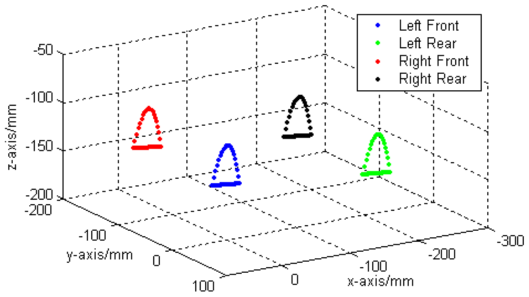


Fig. 7 Locus of walking gait. Each locus of every leg are generated by applying Lagrange interpolation

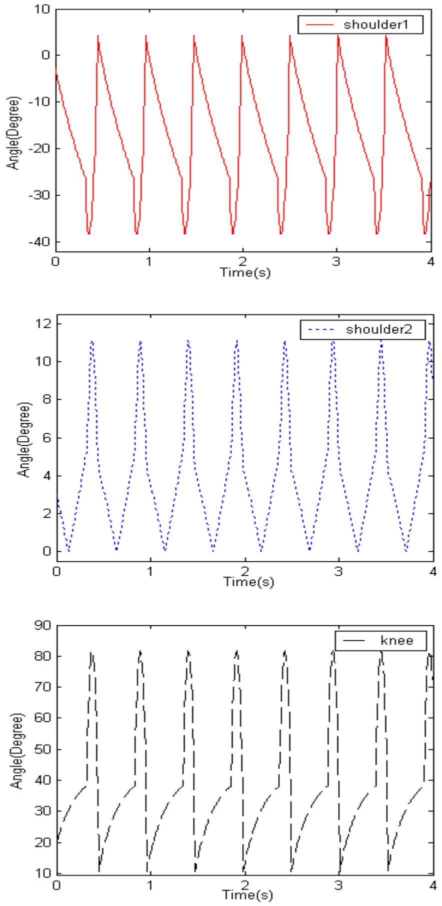


Fig. 8 The control rules to the three joint angles on the left front leg

B. CPG Control Network for AIBO

In the present work, we evolve a CPG controller for the AIBO to produce the same locomotion trajectories that we have developed for AIBO with trajectory-based method above, which is much more meaningful than previous work to walk in real world. For the locomotion, we only focus on the 12 degrees of freedom on four legs.

Fig. 9 shows the structure of whole CPG network. Body oscillators 1, 2, 3 and 4 indicate the four shoulder joints controlling to move forward. In the left front leg, oscillator 5 and 6 indicate the shoulder joint controlling to move side and knee joint, respectively. We let two adjacent oscillators are coupled in both directions, and the oscillators are chained along the legs.

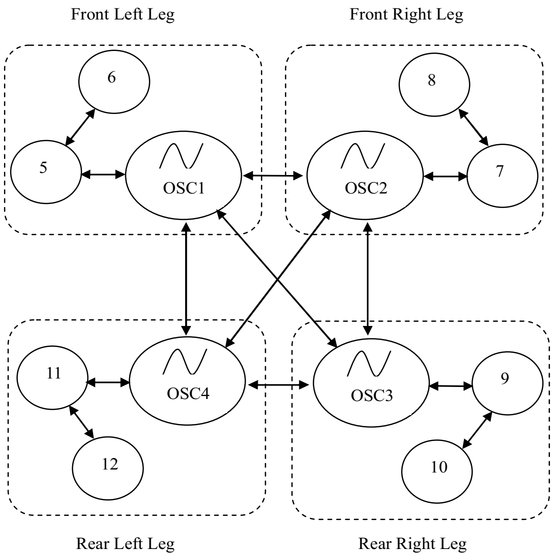


Fig. 9 Structure of CPG for AIBO

Before using the outputs of CPG network to control the locomotion of AIBO, we have to do some transformation, including frequency transformation, phase relationship adjustment and amplitude transformation. In this section, we take the walking pattern for example.

1) Frequency transformation

To get to know the expected frequency, we do FFT to the three joints on the left front leg, which are got in the above section as Fig. 10.

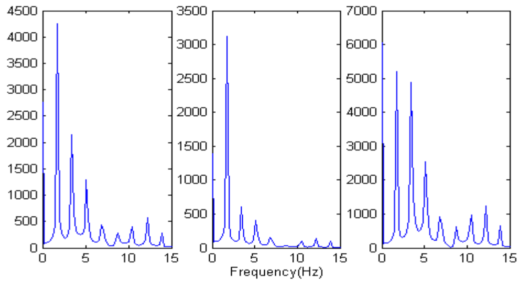


Fig. 10 FFT results of the three joints of LF leg

From the results, we can select the first term of the Fourier series for the first two joints. By adjusting parameter w_i in (1), we can get the frequency we want. For the knee joint, we want to select the first two terms and that will be closer to the real knee movement, but that will complicated the CPG network. So in this work, we only consider the first term of the Fourier series for all the joints. As for the AIBO, we set $w_i = 12.6$ for all the oscillators.

2) *Phase transformation*

From Fig. 11, we can find that positive direction of the joint angles for the rear legs is backwards, which is opposite to the front legs. For our CPG model, it's easy to change the output waveform in-phase or anti-phase status.

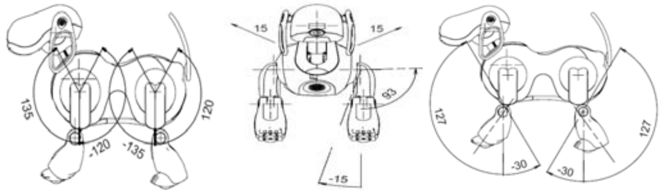


Fig. 11 The definition of the joint angles on legs

3) *Amplitude transformation*

From previous experiment, take left front leg as example, we know that the angles of AIBO in the shoulder joint which controls the moving forward change (on average) in the range $(-40.3987^\circ, 16.1272^\circ)$ and in the shoulder joint which controls to move side in the range$(-1.8532^\circ, 26.0041^\circ)$ and in the knee joint in the range $(23.9449^\circ, 90.9948^\circ)$. To obtain the output control signals in above ranges the following scaling can been done

$$\begin{aligned} X_1 &= -12.1358 + 28.2629 \times x_1 \\ X_2 &= 12.0754 + 13.9287 \times x_2 \\ X_3 &= 57.4698 + 33.5249 \times x_3 \end{aligned} \tag{4}$$

With all the above transformation work, we get the final results as Fig. 12.

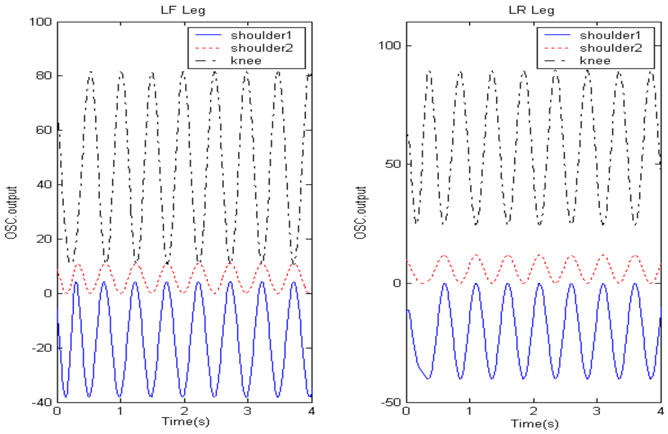


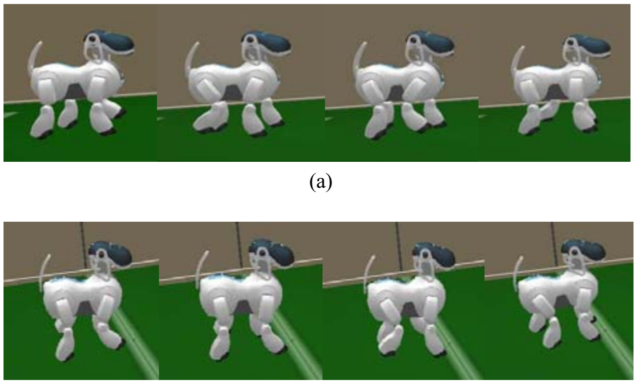
Fig. 12 The output of the CPG network (LF and LR legs)

As we have mentioned above, by change parameters in (1) and (2), we can change the frequency and the amplitude online easily. Thanks to this property, so we can adjust the frequency and amplitude of the outputs online to let the robot adapt the environment. And because of the limit cycle behavior, transient perturbations to the network can be ignored.

C. *Experimental Results*

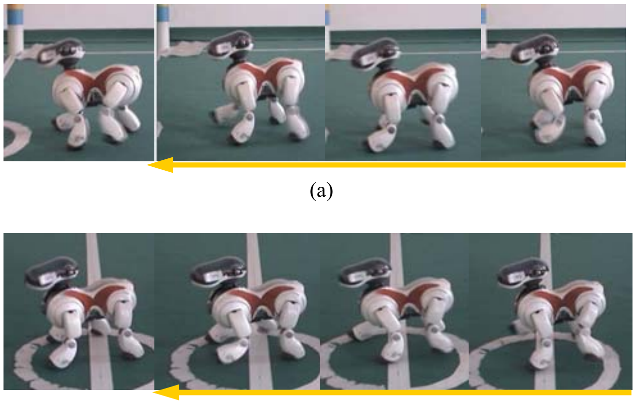
1) *Typical locomotion gaits*

In our experiment, we focus on two basic gait patterns: walking and trotting. Fig. 13 shows the snapshots of simulated AIBO' walking and trotting gaits sequences. And Fig. 14 is the real experiment on the real AIBO. From the results we can find that the real robot can walk and trot in the same manner as the simulated robot with some minor difference.


(a)

(b)

Fig. 13 Simulated AIBO (a) walking sequence (b) trotting sequence


(a)

(b)

Fig. 14 Real AIBO (a) walking sequence (b) trotting sequence

2) *Control of speed during walking*

As we have mentioned above, by change w_i in (1), we can change the frequency online easily. So if this parameter could be affected by some feedbacks, robot can adapt to environment. In our experiment, we enlarge parameter w_i to get faster dynamic walking speed, but too large w_i makes dynamic walking unstable.

3) *Gait transition during walking*

By changing the connection matrix $\Omega_{con.}$, we can realize the basic gait transitions easily. From our experiments, we find that the gait transitions can complete within one or two gait cycles. In this paper, we have not considered the affect of the variation of the gravity center, so the experiments results are not as perfect as we want.

What we have done in this paper is only a part of our whole work. Compared to trajectory-based method, CPG driven approach is more meaningful for AIBO to realize adaptive and dynamic locomotion in the real world. If adding the learning process, the transformation work will be much easier than we have described in the paper because most of the parameters can be acquired by the learning process.

IV. CONCLUSION AND FUTURE WORK

The present paper shows how a CPG network can be used to generate gaits for a complex quadruped robot with 12 degree of freedom. The CPG constructed by the coupling oscillators with locked phase difference and synchronization. The output gait forms can be adjusted on line by the internal parameters. We realized the basic smooth transitions of the four gaits, and compared to the other transition methods, it's very easy and effective.

In this paper, our CPG network does not integrate the sensor's feedback, in the future work, we will construct a CPG network with a reflex system which may be helpful in front of unpredicted circumstances. Many things will be done in future: (1) How to evolve the structure of CPG network to improve the control efficiency; (2) By combining conventional methods to compensate the disadvantages of the CPG driven method; (3) Control the real robot accurately to adapt undetermined environment.

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