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Coordination between Oscillators: An Important Feature for Robust Bipedal Walking

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Abstract— **Biological inspired control approaches based on central pattern generator (CPG) have been used to generate human-like rhythmic locomotion for bipedal robots. CPG consists of several oscillators with coupled mutual inhibition. In the application of CPG to bipedal walking, one of the important problem is how to coordinate oscillators so as to achieve stable walking, since without proper coordination the rhythmic trajectory generated by CPG may fail to control the walking.**

To solve this problem, this paper presents a method of coordination between two oscillators using phase information. In the method, approximated phase values of the oscillators are derived and used as the feedback to coordinate two oscillators. Furthermore, coordination between multiple oscillators with different frequencies and phases has also been explored. This method is verified with a 2D robust walking controlled by four oscillators. Several walking scenarios are tested: adding external force, change walking frequency and step length during walking. Robust walking is achieved in our simulation.

I. INTRODUCTION

Bipedal walking of humanoid robot is a complex and challenging task. Various approaches have been extensively proposed to realize this task. Such studies range from model-based, ZMP-based to learning and biologically inspired [1]. Human beings walk gracefully and with good efficiency. Neurophysiological studies have revealed that the basic rhythm of movement is controlled by a neural rhythm generator present in locomotion system [2]. These neural rhythm generators are referred to as central pattern generators (CPGs) [3]. With the rapid growth of interest in biological inspired research, CPG has been adopted widely for robot rhythmic control.

CPG always consists of a structure which combines multiple coupled oscillators to generate walking gait. An oscillator is the basic component of a CPG structure. Various models of oscillator have been proposed [4] [5] [6] [7]. Among them, neural oscillator is most commonly used due to its good properties, such as entrainment and adaptation properties. Beside oscillator model design, CPG structure needs to be well designed for the control of motion [8] [9] [10]. By properly design the structure for the oscillators, a bipedal robot can achieve smooth walking in both simulation and real implementations [11] [12] [13].

The primary goal of this work is to design a coordination control structure for oscillators. One of the key issues is the manipulation of phase relationship between oscillators. The phase relationship of oscillators in CPG determines the sequence of sub-motion generated by the oscillators and therefore the behavior of the robot. This relationship will shift because of the external sensory feedback. Klavins et al. proposed a general analysis of coordination between oscillators by phase regulation [14]. Other interesting works include the synchronization of Kuramoto oscillator [15] and coordination of a group of mobile robot by CPG [16].

In this paper, we present a novel method to coordinate neural oscillators. Since the manipulation of phase relationship between oscillators could achieve coordination, phase difference between oscillators is used as a feedback to control the phase relationship between oscillators. The method is initially developed for coordination between two neural oscillators. An interesting aspect of our approach is that an arbitrary phase relationship could be adjusted and maintained between oscillators with same or different frequencies. The method could also be applied to coordinate multiple oscillators.

This paper is organized as follows: In Section II, basic properties of neural oscillators and the coordination problem are discussed. Section III introduces our proposed method which is implemented in Section IV on a 2D bipedal walking in different scenarios. Conclusion and future work are given in Section V.

II. NEURAL OSCILLATOR DESCRIPTION

A. Neural Oscillator Model

Neural oscillator model was inspired by the behavior of a biological neuron. It can output rhythmic signal without external input and has limit cycle property. A neural oscillator model proposed by Matsuoka is as follows [4]:

$$\tau_1 \dot{u}_1 = c - u_1 - \beta v_1 - a[u_2]^+ - \sum h_j [g_j]^+ \quad (1)$$

$$\tau_2 \dot{v}_1 = [u_1]^+ - v_1 \quad (2)$$

$$\tau_1 \dot{u}_2 = c - u_2 - \beta v_2 - a[u_1]^+ + \sum h_j [g_j]^- \quad (3)$$

$$\tau_2 \dot{v}_2 = [u_2]^+ - v_2 \quad (4)$$

$$[u_1]^+ = \max(0, u_1) \qquad [u_1]^- = \min(0, u_1) \quad (5)$$

$$Y = [u_1]^+ - [u_2]^+ \quad (6)$$

where $u_{1(2)}$ is the state of the neuron; $v_{1(2)}$ is the degree of neural adaptation; c is the constant stimuli; τ_1 and τ_2 are time constants; β is the parameter that indicates the effect of adaptation; a represents the strength of inhibition connection between neurons; g_j is the external input which usually serve as the feedback pathway for the oscillator; h_j is a factor to adjust the input; Y is the oscillator output.

B. Properties

Based on Poincaré-Bendixson theorem, the neural oscillator model described by (1)-(6) has a unique limit cycle behavior if [17]

$$a - 1 - \frac{\tau_1}{\tau_2} > 0 \quad (7)$$

$$a - 1 - \beta < 0 \quad (8)$$

Limit cycle will be maintained even if there is external perturbation through input.

In our simulation analysis, we found that neural oscillator has low-pass filter property. Hence, high frequency noise will not affect the output of the neural oscillator.

When there is no external input, the frequency and amplitude of the oscillator are dependent only on the oscillator parameters. For the neural oscillator described by (1)-(6), the frequency is determined by [18]

$$F = \frac{1}{2\pi\tau_1}\sqrt{b(1+(\frac{\beta}{a}-1)(1+b))} \quad (9)$$

where $b = \frac{\tau_1}{\tau_2}$, which is usually set as a constant. The approximate amplitude is given by [17].

$$Amp = \frac{2c}{1+\beta+a} \quad (10)$$

Equations (7)-(10) show the relationship between the parameters and the oscillator output. Same relationship has been numerically obtained by previous research [10]. In this paper, these equations will be used to obtain the values of the oscillator parameters.

C. Problem

When implementing CPG on robot control, oscillators are coupled to give the control signal. The problem is how to make them work synchronously even when there is external sensory feedback. For example, using the oscillators to control the top end of a 2-link planar robot to move horizontally (Fig.1). The top end of the 2-link robot will move forward and backward in X direction while keeping constant height in Y direction. To achieve the motion, reference joint angles could be obtained from inverse kinematics. These angle trajectories of two joints have a similar form as a sinusoidal wave. Two neural oscillators are used to generate desired angle trajectory. The forward kinematics could be described by:

$$x = L1\cos(os1) + L2\cos(os1+os2) \quad (11)$$

$$y = L1\sin(os1) + L2\sin(os1+os2) \quad (12)$$

Fig.1 also shows the oscillators' arrangement. Two oscillators have inhibitory connections as in [9]. Because we merely want to demonstrate the coordination problem, we omit the part on how we design the oscillators' parameters for this task. It is similar to the way we obtain the parameters and implement oscillators on bipedal walking in the later part of this paper.

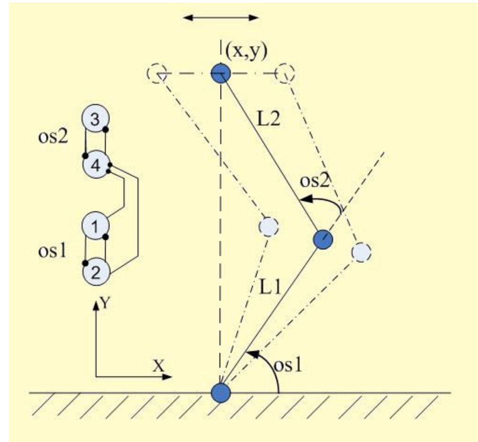

Fig. 1. Two-link planar robot model and oscillators arrangement

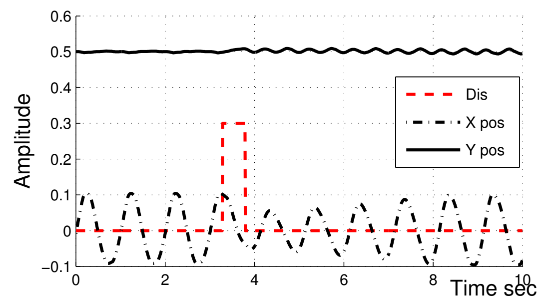

Fig. 2. Trajectory of 2-link planar robot when external input exists

When there is an external input to the oscillator, (eg. from sensory feedback) the trajectories generated by the oscillator may fail to drive the 2-link robot to follow the desired motion. As shown in Fig. 2, the external input affects the output trajectories of the oscillators. This is the result of the oscillator adjustment with the external input. However, when the external input is removed, the oscillators still fail to return back to the desired trajectory and the Y direction becomes oscillation. This is because the phase relationship between two oscillators changes after receiving the external input. As shown in Fig.3, the time difference between the peak values of Os1 and Os2 is 0.3 seconds before the external input was introduced, while the difference changes to 0.21 seconds after the external input. This is because different oscillator may response differently to the external input. Although single oscillator has limit cycle property, the trajectory generated by several oscillators may not has this property. Hence it is required to design an adjustment structure capable of coordinating the oscillators to follow the desired motion under the influence of the external input.

III. METHODOLOGY

A. Proposed Method

Williamson found that when an oscillatory input is applied to an oscillator, the oscillator can entrain the input and lock onto the input frequency [10]. However, we are interested in not only controlling the frequency but also manipulating

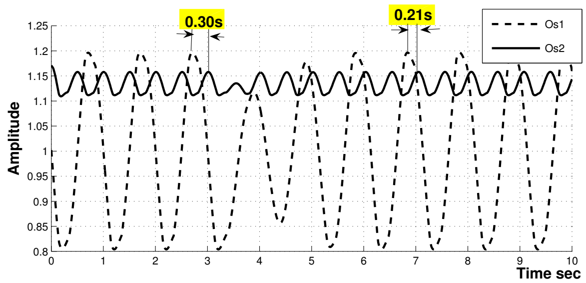

Fig. 3. The phase relationship between the two oscillators before and after the external input

the oscillator phase. As for the neural oscillator, there is no parameter which directly indicates the phase value. Many methods could reflect oscillator output with phase value. In this paper, we get the approximate phase angle of oscillator by using inverse *sin* function. Actually, when $|a-1-b|$ is small, oscillator output is close to a sinusoidal wave. The approximate phase value is used as a feedback to adjust the oscillator phase.

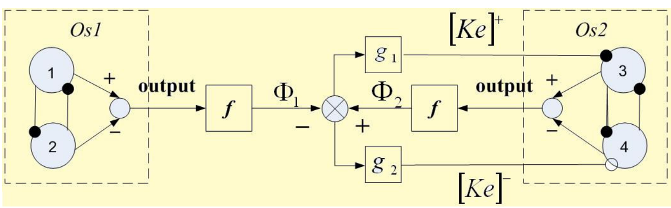

Fig. 4. The structure to adjust the phase difference between oscillators

Fig. 4 shows the proposed structure to coordinate two oscillators. Os1 and Os2 are two oscillators which have the same frequencies but different initial phases. Function f is used to calculate the approximate phase value of the oscillator output:

$$f(x) = \begin{cases} -\frac{\pi}{2} & x < -AMP \\ \arcsin(\frac{x}{AMP}) & -AMP <= x <= AMP \\ \frac{\pi}{2} & x < AMP \end{cases} \quad (13)$$

where x is the output of oscillator; AMP is the amplitude of the oscillator. The phase difference between Os1 and Os2 is $e = \Phi_2 - \Phi_1$, where Φ_1 and Φ_2 are phase values of Os1 and Os2 respectively. Functions g_1 and g_2 select e to adjust Os2. The rule is that if e is negative, it will inhibit neuron 4 of Os2 through g_j; if e is positive, it will inhibit neuron 3:

$$g_1 = K\min(e,0), \qquad g_2 = K\max(e,0) \quad (14)$$

where K is the scaling factor to modify the speed of adjustment. In this method, Os1 offers the reference phase information to Os2. The phase error will be feedback to Os2 so that it will try to adjust its phase angle to be the same as that of Os2. An example of such a coordination is shown in Fig. 5.

Fig. 5 also shows that the coordination may affect the amplitude of the oscillator. Although it is not desirable, it may be useful for walking. For example, when the robot's body is moving ahead while the swing leg motion is late and behind, a larger and faster swing step may help to balance the walking cycle. Such an effect will be further explored in the future research.

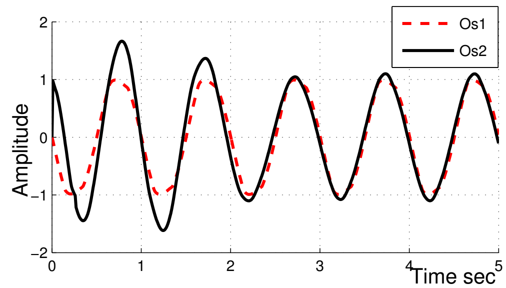

Fig. 5. Phase adjustment example between oscillators with same frequency and different initial phase

Phase adjustment example shows that the phase angle of an oscillator could be adjusted to be the same as reference oscillator when they share the same frequency. However, in most cases of CPG implementation, we need to coordinate oscillators with different frequency and maintain certain phase relationship. These differences should be maintained with the aid of external input.

The oscillator could be synchronized and converged to the reference oscillator with phase value feedback. To coordinate oscillator, the key issue is to generate reference phase value from the reference oscillator. To maintain certain phase difference between two oscillators which have the same frequency, the new reference phase value is $\Phi_1 + \Phi_d$, where Φ_d is the desired phase different between Os1 and Os2. The new error input becomes $e = \Phi_2 - \Phi_1 - \Phi_d$. Phase difference Φ_d could be maintained.

To coordinate oscillators with different frequency, the new reference phase value is $mod(\frac{F_2}{F_1}\Phi_1, 2\pi)$. Function mod helps the reference phase value change as fast as target oscillator phase value. Generated by the reference oscillator, the reference phase exactly follows the output of the reference oscillator. Hence, by using these reference phase value to coordinate other oscillators, all the oscillators are coordinated by the reference oscillator.

Fig.6 shows the model for coordinating oscillators which are different in frequencies and phase. Φ_{ri} is the reference phase to the oscillator i. Equation of f_i is used to get the reference phase for target oscillator from main oscillator. The equation of f_i is

$$\Phi_{ri} = f_i(\Phi_1) = mod(\frac{F_i}{F_1}\Phi_1, 2\pi) + \Phi_{di} \quad (15)$$

where F_i is the frequency of the ith oscillator; Φ_{di} is the desired phase different between Os1 and Osi.

B. Numerical Simulation

Here we give an example of coordination between two different frequency oscillators. The frequency of one oscillator is twice of the other. The output trajectory is the sum

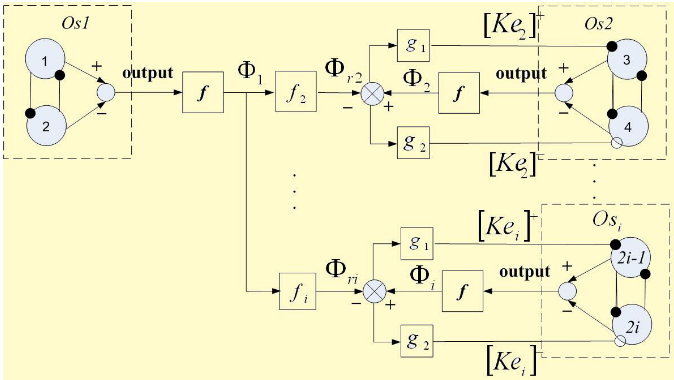

Fig. 6. The model to adjust the phase between oscillators with different frequencies and phases

output of the two oscillators. Fig. 7 shows the performance of the two oscillators. When there is disturbances from external inputs, the oscillators can adjust the phase and recover to the original target output. However, when there is no phase adjustment between two oscillators, the output is different from the initial trajectory under the effect of the external input.

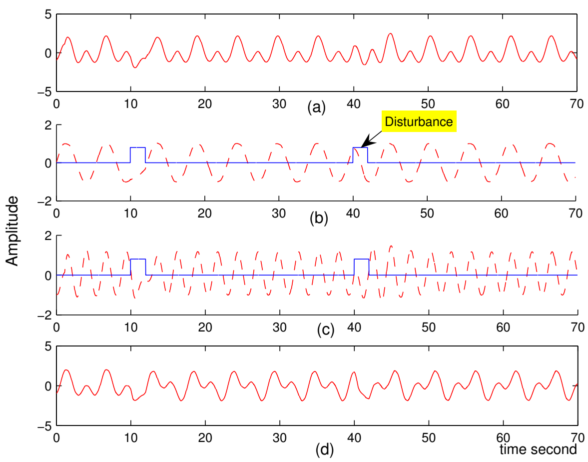

Fig. 7. Phase adjustment between two oscillators with different frequency. (a) The output of os1+os2;(b)The output of os1 with disturbance; (c) The output of os2 with disturbance; (d) The output of os1+os2 when there is no phase adjustment

In the previous 2-link planar robot example, when the two oscillators are connected by phase adjustment, there will be no oscillation in Y direction as shown in Fig. 8. The phase relationship will recover under external input as shown in Fig. 9.

IV. DYNAMIC SIMULATION

To further verify our proposed method, we test it on a 2D biped for walking. Firstly, we will present our control architecture and control strategy. Then, several walking scenarios on level ground are adopted. External force is given to test the robustness of the walking behavior.

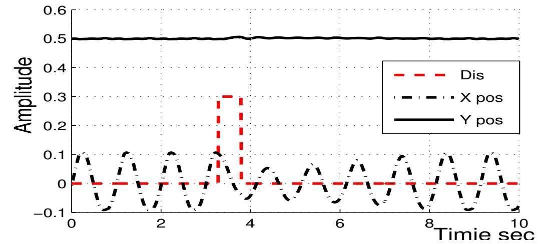

Fig. 8. Trajectory of 2-link planar robot with phase adjustment

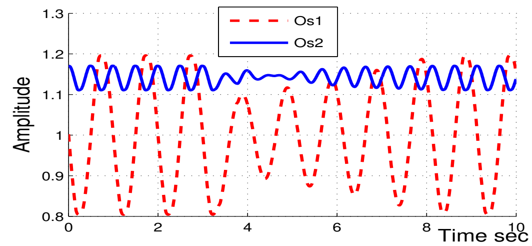

Fig. 9. The phase relationship between two oscillators' output with adjustment

A. Control Architecture

In this 2D simulation, the simulation model is built based on a real 3D robot NUSBIP-II ($http://guppy.mpe.nus.edu.sg/legged\_group/$). It has an ankle, a knee and a hip pitch joints in each leg. Our simulation is carried out in Yobotics environment. Yobotics is a Java package for simulating multibody dynamic system ($http://www.yobotics.com/$). Fig.10 shows the simulation model. The dimension and mass distribution are listed in Table I.

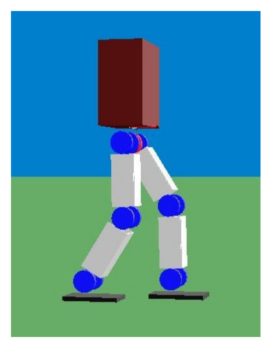

Fig. 10. 2D simulation model in Yobotics environment.

In this approach, we propose a CPG arrangement with

TABLE I

THE SPECIFICATION OF SIMULATION MODEL

link	mass(kg)	Ixx(kgm^2)	Iyy	Izz	length(m)
Body	25.26	0.6954	0.0842	0.5189	0.30
Thigh	4.25	0.0240	0.0196	0.0096	0.256
Shank	5.10	0.0269	0.0227	0.0100	0.256
Foot	2.52	0.0042	0.0037	0.0035	0.10

respect to the position of the leg in the Cartesian coordinate space (see Fig.11). The oscillators are arranged to control X direction of stance leg's hip(Hip_x) and X and Z direction of swing foot($Foot_x$,$Foot_z$). The reference joint angles are calculated by inverse kinematics. We employed position based control in joint space. Compared to joint space implementation, this arrangement significantly reduces the total number of oscillators' parameters and provides an intuitive way to find the effective feedback pathways.

As shown in Fig.11, we assign the reference frame at the ankle joint of the stance leg. Based on the reference frame, during walking Hip_x trajectory always moves from negative to positive value. The trajectory of Hip_x is shown in Fig.12(dot line). The trajectory are not continuous when the support leg switches. To obtain a continuous trajectory, we inverse Hip_x at every time when a particular support leg touches the ground. The resulting trajectory is shown in Fig.12.

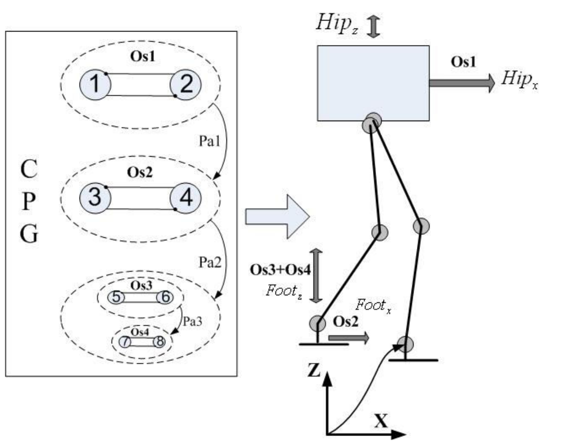

Fig. 11. Oscillator arrangement of the biped

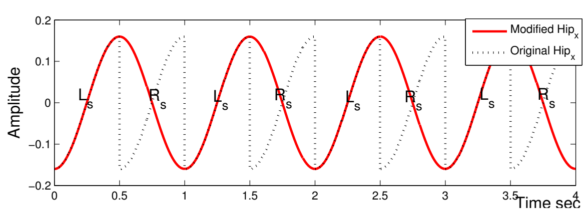

Fig. 12. Reference Hip_x trajectory.

For example, assuming that the robot stands with left support, the reference Hip_x trajectory corresponds to the 1st half period of the neural oscillator's trajectory. When the robot stands with right support, the reference Hip_x trajectory is corresponding to the 2nd half period but negated. We adopt the same strategy for the swing foot horizontal position $Foot_x$ which is also in reference to the stance angle joint. We assume that the robot walks with constant hip height, that is Hip_z is a constant. The foot vertical position $Foot_z$ is designed to be close to a parabola which could be the sum of two sinusoidal wave form. Therefore, we use two oscillators to generate $Foot_z$ trajectory. Fig.13 shows the reference trajectories of stance hip and swing foot. Os1 gives the Hip_x trajectory; Os2 gives the $Foot_x$ trajectory; $Foot_z$ is generated by the sum of Os3 and Os4. Phase adjustments are given between these oscillators. Os1 gives the reference phase to other oscillators. Foot X position (Os2) adjusts the Foot Z position (sum of Os3 and Os4) such that the swing leg will not touch down until it is fully extended.

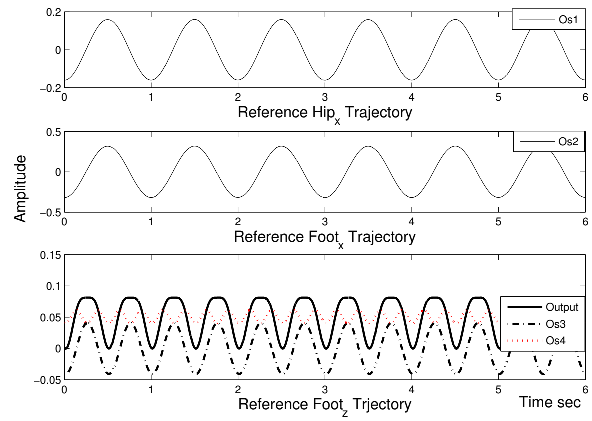

Fig. 13. Reference trajectory of stance hip and swing foot.

A strategy that we use herein to improve the stability is called swing leg retraction. In human walking, the swing leg moves forward to maximal extension and then it moves backward just prior to ground contact. This backward motion is called swing leg retraction (Fig. 14) [19]. Wisse et al. proved that the action will increase the walking stability [19]. In our approach, adding swing leg retraction is simple. Since we have phase adjustment between oscillators, we could shift the phase of Os2, which generates $Foot_x$ trajectory, a little forward to make the swing leg reach the maximal forward extension before touching down. Therefore, the swing leg can move back just prior to touching down.

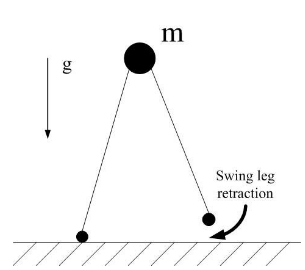

Fig. 14. Swing leg retraction in simple inverse pendulum model

B. Sensory Feedbacks

Sensory feedbacks are used to adjust the oscillator's output. They are given through g_j. Two kinds of sensory feedbacks are used: pitch and orbital energy [20] as shown in Fig.15. The body pitch is mainly used to adjust the output of Os1. Controlling the hip horizontal position of support leg could help to adjust the body pitch value. Orbital energy value is used to adjust the output of Os1 and Os2. The horizontal velocities of the body and the swing foot affect the orbital energy. Feedbacks are used to control the body position and step lengths to stabilize the walking. There is no connection between feedbacks Os3 and Os4. However, Os3 and Os4 could be adjusted by Os2 by phase adjustment which allow the swing foot height to be adjusted according to the swing foot horizontal position.

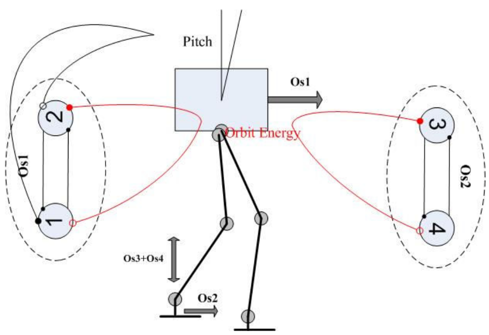

Fig. 15. Feedback pathway for robot motion

C. Simulation Result

In the previous section, we indicate that, with proper parameters, oscillator could output approximate sinusoidal wave form. The trajectories we design for the walking are approximate sinusoidal wave forms. In the simulation, the oscillators' parameters are derived by the following rules:

1) To simplify the frequency calculation, we let $\beta = a$. The frequency formula becomes $F = \frac{1}{2\pi\tau_1}\sqrt{b}$;
2) Let $\frac{2c}{1+\beta+a} = A$, where A is the desired amplitude;
3) The value of b is chosen to make $|a-1-b|$ small;

By this procedure, we can roughly obtain all the values of the oscillator parameters which satisfy our requirement. In the simulation, the walking step length is 0.6m and walking period is 1 second. The walking speed is approximately 0.6 m/s. Fig.16 shows the snapshots of normal level ground walking for the bipedal.

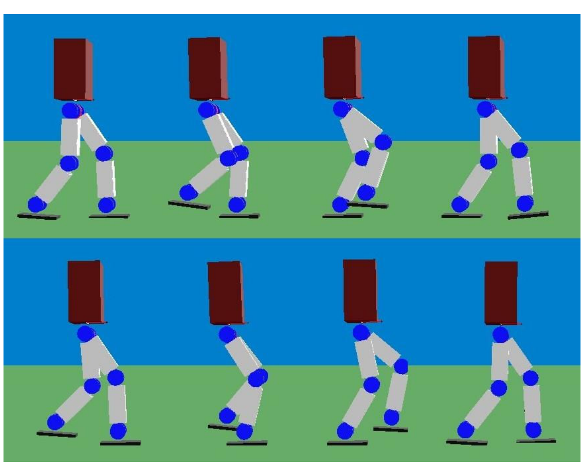

Fig. 16. Snapshots of straight forward walking in simulation

In the simulation, the oscillators are coupled with designed phase relationship. Feedback pathway needs to be well designed to enable oscillators to respond correctly to the environment changes. Here, the feedback parameters are selected by genetic algorithm(GA). A 50N external force is applied randomly on the robot hip for 0.5s. The robot shows a robust walking even with the perturbation. As seen in Fig.17, the robot tries to increase the step length and step height to adjust the motion and reduce the effect of the perturbation. This is because the pitch and orbital energy feedbacks affect the oscillators' output. The oscillators' output and feedback are shown in Fig.18.

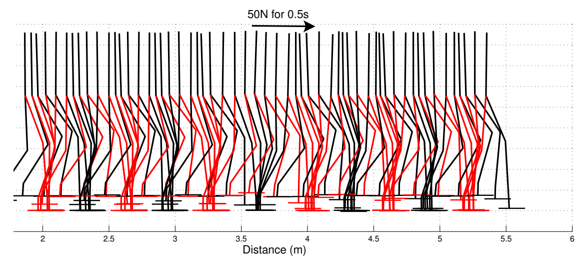

Fig. 17. Stick diagram of walking with external force

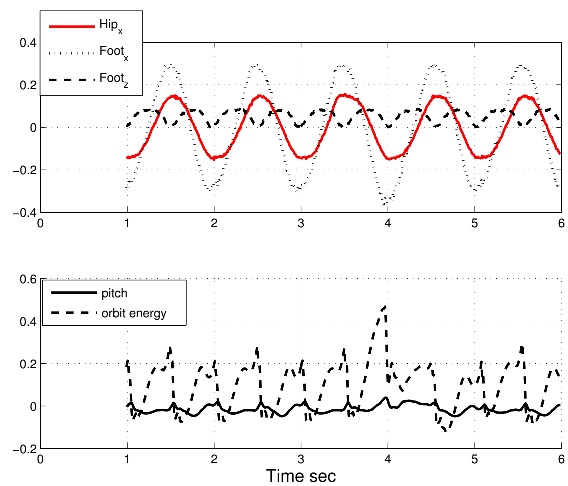

Fig. 18. Os1,Os2 and Os3 coordination and their feedback in the straight walking with external force

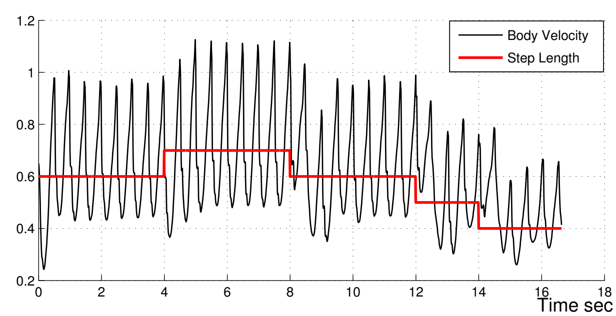

Fig. 19. Change of walking step length during walking

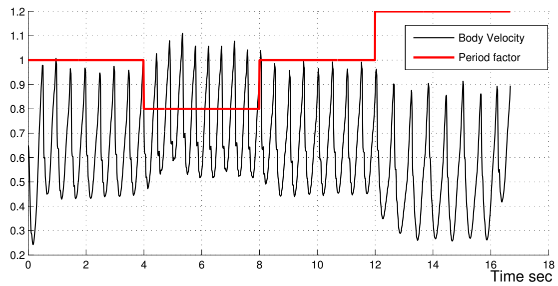

Fig. 20. Change of walking frequency during walking

Different walking frequencies and step lengths are tested in the simulation. The step length is changed on-line by step length scaling factor. The walking frequency is changed on-line by changing the time constant τ_1, while keeping a constant ratio between τ_1 and τ_2 of the oscillator. As shown in Fig.19, the step length changes from 0.6m to 0.7m and then reduces to 0.4m. The speed varies from 0.7m/s to 0.4m/s. Fig.20 shows the frequency change during walking. The step length is constant, namely 0.6m. The frequency is 1Hz in the first 4 seconds; it increase to 1.25Hz in the second 4 seconds and reduced to 0.83Hz later. The result shows that the oscillators can adjust their output when walking step length and frequency are changed on-line.

V. CONCLUSION

This paper presents a method for coordinating oscillators in CPG to achieve robust walking behavior. Numerical simulations demonstrate that the method could adjust the phase of oscillators. We have also tested it on a 2D biped and achieved stable walking. Appropriate sensory feedbacks are selected to help the oscillators respond correctly to the environmental changes. With the proper coordination between oscillators, the robot achieves a robust walking behavior.

In this paper, the coordination structure works well when reference wave-form is given. Using the sinusoidal wave-form is a simple and effective way to get the phase value. However, it restricts the performance of the oscillator in that the output of the oscillator should be close to the sinusoidal wave-form. Future work could focus on exploration of the method to coordinate oscillators without using the sinusoidal wave-form. If this restriction can be eliminated, the coordination structure will be capable of generating more complex periodic wave-forms.

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