Coordination in CPG and its Application on Bipedal Walking

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***Abstract*—Research of bipedal walking has been motivated by its great flexible in rough terrain walking, as well as its benefits to prosthesis development. This paper aims to achieve coordination of central pattern generator (CPG) and asymptotically stable walking behavior. CPG is always referred as several oscillators with coupled mutual inhibition. In this paper, the oscillator model proposed by Matsuoka was used. We use output difference between two oscillators as the feedback to adjust the output of the target oscillator. Further exploration achieves to coordinate multiple oscillators with different frequencies. To verify the method, we demonstrate a 3D robust walking controlled by a simple CPG structure with several oscillators.**

***Index Terms*—CPG, Neural Oscillator, Coordination, Bipedal Walking.**

I. Introduction

CPG research is greatly motivated by the rapid growth of interest in biological inspired research. Biped walking of humanoid robot is a complex and challenging task. However, human beings walk gracefully and with good efficiency. CPG research will help to understand the basic strategy of how human or animal perform walking or running. Walking seems basic and simple for human and animals, while it is daunting for legged robots. Well understanding of the research problem could lead to an advance in humanoid robotics research and breakthrough in prothesis development. With an effective CPG structure, robots could achieve more natural, efficient and robust locomotion.

CPG always refers to a structure which combines multiple coupled oscillators to generate walking gait. Oscillator is a basic component of CPG structure. Various models of oscillator have been proposed to explain the mechanism of the automatic oscillatory activities [1] [2] [3]. Among these models, neural oscillator is most commonly used which has many good properties such as bio-inspired, entrainment and adaptation properties. Besides oscillator model design, CPG structure needs to well designed to control the motion [4] [5] [6]. By properly designing the structure of the oscillators, a biped robot can achieve smooth walking in both simulations and real implementations [7] [8].

In these works, designing a coordination control structure is the primary goal. To do this, manipulation of phase relationship between oscillators is very important, since it determines the sequence of each sub-motion controlled by oscillator and therefore the behavior of the robot. These relationship will shift because of the external sensory feedback. Klavins et al. proposed a general analysis of coordination between oscillators by phase regulation [9]. Other interesting work includes the synchronization of Kuramoto oscillator [10] and coordination of a group of mobile robots by CPG [11].

In this paper, we focus on the coordination between oscillators to achieve the smooth walking. The oscillator model we use is neural oscillator model proposed by Matsuoka. We present a novel method to coordinate oscillator with feedback. An interesting aspect of our approach is that an arbitrary phase relationship could be adjusted and maintained between oscillators with the same or different frequency. It could be also applied to the case of multiple oscillators. The present study closely connects the oscillators in CPG which synchronize by the main oscillator.

This paper is organized as follows. In section II, we introduce the neural oscillator model and its entrainment properties. The proposed method is presented in the section III. We further explore the method to the case of different frequency and multiple oscillators. Numerical results are given. In Section IV, we verify the method by implementing it on a 3D bipedal robot to achieve walking behavior. In Section V, we present discussion of our results and future work.

II. Neural Oscillator Description

A. Neural Oscillator Model

Neural oscillator is the most commonly used oscillator model in CPG research.It was inspired from the behavior of biological neuron. It can output rhythmic signal without external input and has limit cycle property. The mathematical model is described by the following equations [1].

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

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

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

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

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

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

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Here $u_{1(2)}$ 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 the 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 could be the feedback pathway to oscillator; h_j is a factor to adjust the input; Y is the oscillator output.

The oscillator model consists of two simulated neurons arranged in mutual inhibition; each neuron has an inner adaptation variable v_i, as shown in Fig.1. The tonic excitation **c** determines the amplitude of the oscillator, with amplitude proportional to **c**. The two time constant τ_1 and τ_2 determine the frequency of the oscillator and the parameter β affects the shape of oscillator output.

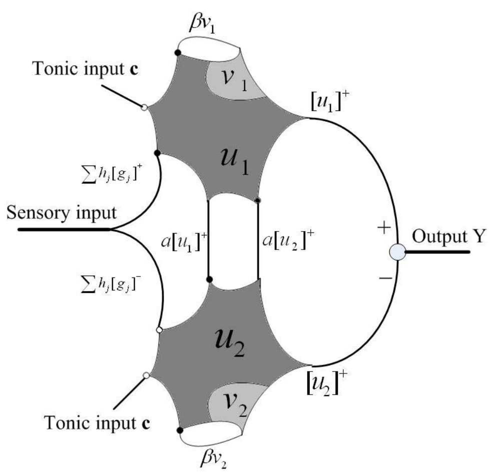

Fig. 1. Schematic of Matsuoka neural oscillator model; white cycle means excitation and black cycle means inhibition

B. Entrainment Property

Oscillator has the entrainment property. Williamson found that when an oscillatory input is applied, the oscillator can entrain the input, lock onto the input frequency [6]. When the external input signal is large and constant, the oscillator output could be suppressed by the signal. Fig.2(top) shows an example that the oscillator output locks to a sinusoidal input, and Fig.2(bottom) illustrates an example that the oscillator output is suppressed by a large constant external input.

Entrainment locks the oscillator output with the external input, which hopes to design the natural response of oscillator. Research work includes operate a 'Silink' toy to coordinate the motion of two arms by the entrainment property. Although the frequency could be locked to the external input, their phase relationship is unclear.

Here, we use the error between oscillator output and sensory input as the new external input to the neural oscillator. Fig. 3 shows the structure where K is the scaling parameter. We surprisedly found that the oscillator could be converged to the external input. Fig.4 shows the example; the oscillator output tries to follow the external input. For demonstration, here parameter 'K' only has value when time is between 2 to 6 seconds; 'K' equals 0 in the other time.

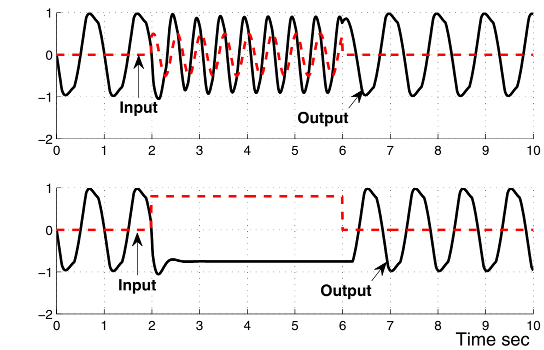

Fig. 2. Properties of neural oscillator; top: entrainment property, bottom: suppression of oscillator by a large constant input

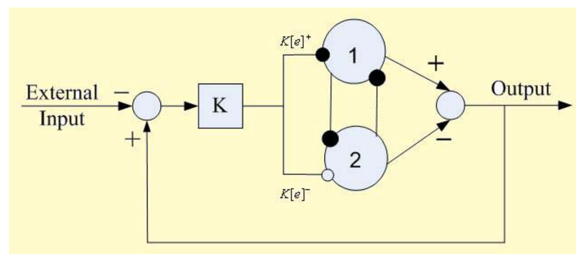

Fig. 3. New structure where the error between oscillator output and sensory input is considered as an external input

Many other different types of sensory inputs are given to verify the congregation of oscillator. In Fig.5, three different types of sensory inputs are given: triangular wave, square wave and small constant value. The oscillator can track these different types of sensory inputs. Here the constant could not be 0, because 0 is one of the stable point of oscillator. If the oscillator states value go to 0, it will never oscillator again. Therefore, we set a small value which is 0.01.

III. Methodology

A. Proposed Method

Oscillator has the entrainment property. This property could be used to coordinate oscillators in CPG. As we have discussed in the previous subsection, when the external input of the oscillator becomes the error between the oscillator output and

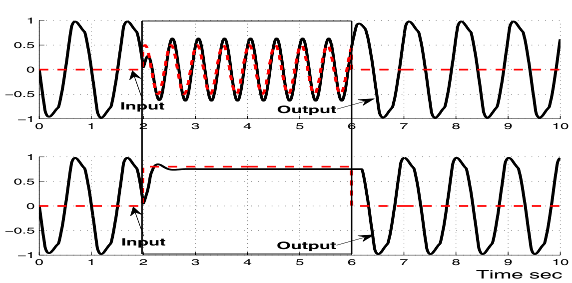

Fig. 4. Examples of oscillator converging to sensory inputs with new structure where K only has value between 2-6 seconds

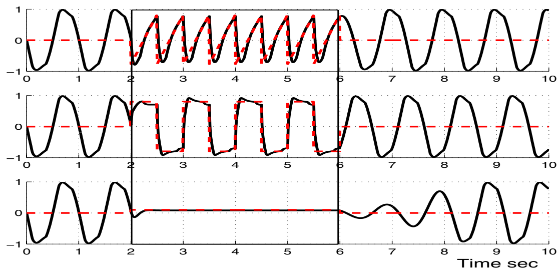

Fig. 5. Example of oscillator congregation with different types of sensory input where K only has value between 2-6 seconds

the sensory input, the oscillator could be converged to the sensory input. This brings about the potential solution for the coordination between oscillators. If the reference oscillator output is one of the sensory input of the target oscillator, the target oscillator could be synchronized by the reference oscillator.

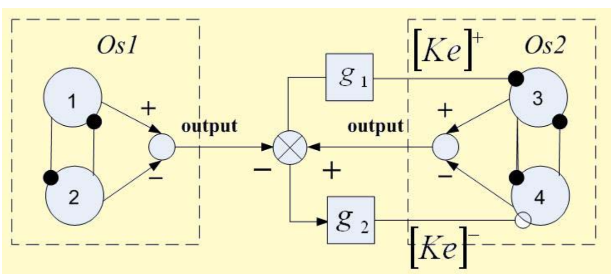

Fig. 6. The model to coordinate two neural oscillators with same frequency

Fig.6 shows the proposed method to adjust the output between two oscillators. Here g_1 and g_2 are selection function.

$$g_1 = K\max(e, 0), \qquad g_2 = K\min(e, 0) \tag{7}$$

where e is the error between Os2 and Os1; K is the scaling factor to modify the speed of adjustment. In this structure, Os1 offers the reference output to Os2. The output error will feedback to Os2 and Os2 will try to match the match of Os1. Fig. 7 shows an example of oscillator adjustment. In Fig.7, Os1 and Os2 have the same frequency but different initial phases. Os1 is able to synchronize Os2 and make Os2 converge to Os1. Fig. 7 also shows that sometimes amplitude may be affected in the coordination. Although it is not the desired one, it may play a positive effect on the 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. The influence of this effect will be further explored in the future research.

B. Applied in Coordination

Based on previous method, the target oscillator output will converge to reference oscillator output. However, in the most case of CPG, we do not want oscillators have exactly same output. We want the oscillators with different initial phase and frequency to synchronize together. These different could be

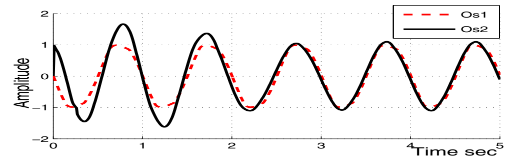

Fig. 7. Coordination example between oscillators with same frequency and different initial phase

maintained after the effect of external input. A simple way to solve the problem is to give a reference trajectory for each oscillator and these reference trajectories are generated by one main oscillator.

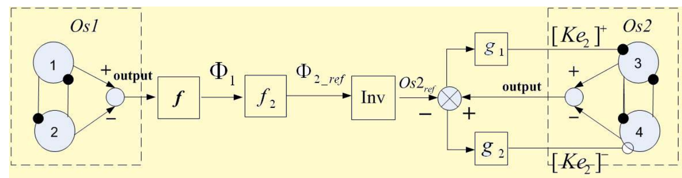

Fig. 8. The model to coordinate oscillators with different frequencies and phases

The proposed method is to get the phase value of main oscillator and then convert it to the reference phase value of target oscillator whose frequency and initial value is different from main oscillator. The reference phase is changed to reference input to target oscillator by Inv function which has a unique mapping form phase to output value. Fig.8 shows the proposed method structure. Os1 and Os2 are two oscillators which have different frequencies and different initial phases. Function f is used to calculate the approximate phase value of the oscillator output. For each cycle of oscillator output, we divide its phase from 0 to 2π.

$$\Phi_1 = f(g(x)) \tag{8}$$

$$g(x) = \begin{cases} -\frac{\pi}{2} & x < -A_{mp} \\ \arcsin(\frac{x}{A_{mp}}) & -A_{mp} <= x <= A_{mp} \\ \frac{\pi}{2} & x < A_{mp} \end{cases} \tag{9}$$

$$f(y) = \begin{cases} mod(y, 2\pi) & s = 1 \\ \pi - y & s = -1 \end{cases} \tag{10}$$

where Φ_1 is the approximate phase value; x is the output of oscillator; A_{mp} is the amplitude of the oscillator. The output range of arcsin is $[-\frac{\pi}{2}, \frac{\pi}{2}]$. To convert the phase range to $[0, 2\pi]$, we define a parameter s. The parameter s indicates the direction change of the oscillator: $s = 1$ indicates an increase of the oscillator value while $s = -1$ indicates a decreases of oscillator value. The function f_2 is used to get the reference phase of Os2.

$$\Phi_{2\_ref} = f_2(\Phi_1) = mod(\frac{F_2}{F_1}\Phi_1, 2\pi) + \Phi_{d2} \tag{11}$$

where F_2 is the frequency of the 2th oscillator; Φ_{d2} is the desired phase different between Os1 and Os2. For example, two oscillators Os1 and Os2 need to maintain phase difference Φ_d. The reference phase Φ_r will be equal to $\Phi_1 + \Phi_d$. Since Os2 will converge to Φ_r because of the coordination, the phase difference is maintained. When two oscillator frequencies are different, function $mod(\frac{F_2}{F_1}\Phi_1, 2\pi)$ will help to make the reference phase change as fast as the phase of target oscillator. Since each phase has only one oscillator output, we build a unique mapping from phase value to oscillator output. 'Inv' function gives the oscillator output according to reference phase. In this case, the reference input is the same type of oscillator output as the target oscillator.

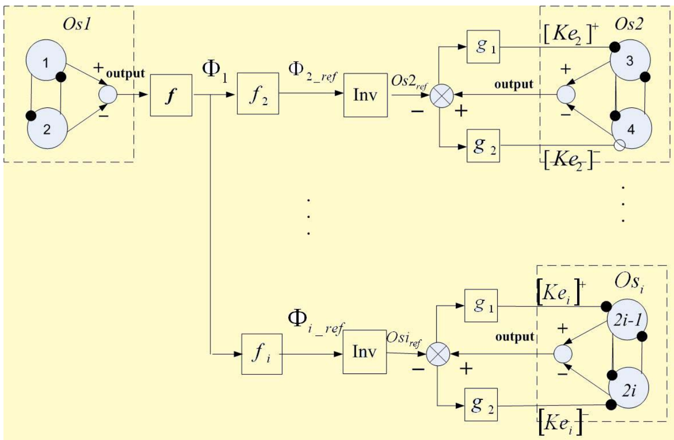

Fig. 9. The model to coordinate between multiple oscillator

The proposed method could also be applied to the coordinate between multiple oscillations. Fig.9 shows the model which could be used to adjust multiple oscillators.

Here we give an example of coordination between two oscillators which have different frequencies and initial phase values. The frequency of one neuron is twice of the other. The target output trajectory is the sum of the outputs of the two oscillators. When there is an external input through g_j which is always the sensory input, the shape of trajectory changes as shown in Fig. 10. The reason is that the phase relationship between two oscillators is changed, as indicated by the red cycle. This is because two oscillators response differently to the external input. When CPG is applied to control certain motion task, change to sensory input is necessary. It helps balance walking according to environment changes. However, the desired trajectory need to be recovered after the affection of external input. When there is no coordination between oscillators, this can not be achieved.

When the coordination is connected between oscillators, the desired oscillator output could be recovered. Fig. 11 shows the performance of the two oscillators with coordination. When there is external inputs, the oscillators are able to adjust the phase and recover to original target output.

IV. Dynamic Simulation

To further verify our proposed method, we have tested it on a 3D biped for walking. Firstly, we will present our control

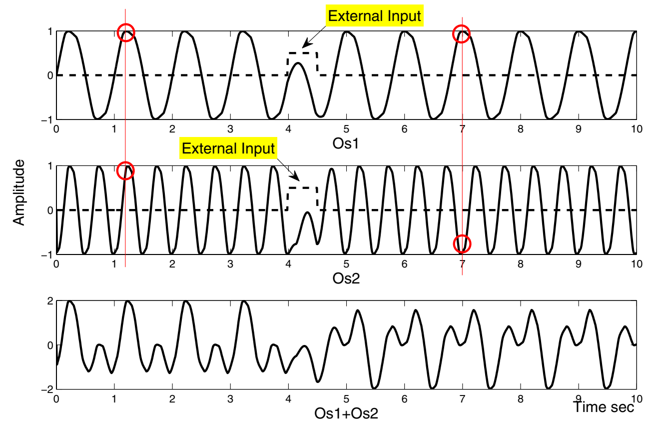

Fig. 10. No coordination between oscillators when external input was added

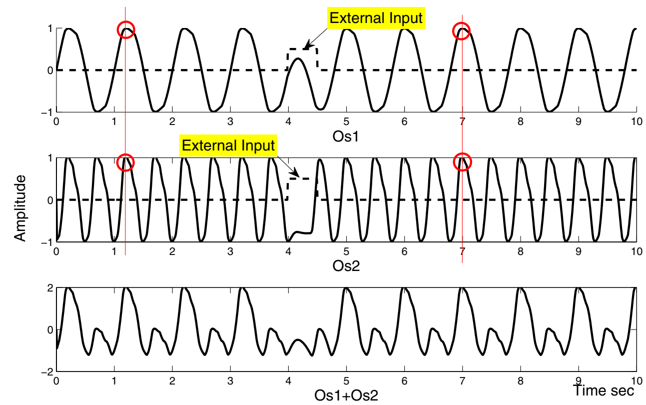

Fig. 11. Coordination between oscillators when external input was added

architecture and control strategy. Then, the dynamic walking simulation on level ground is implemented.

A. Control Architecture

In this 3D simulation, the simulation model is built based on a real 3D robot NUSBIP-II ($http://guppy.mpe.nus.edu.sg/legged\_group/$). Each leg has six degrees of freedom: three on hip, one on knee and two on ankle. Our simulation is carried out in Yobotics environment. Yobotics is a Java package for simulating multibody dynamic system ($http://www.yobotics.com/$). Fig.12 shows the simulation model. The dimension and mass are shown in Table I.

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

In this approach, we propose a CPG arrangement with respect to the position of the leg in the Cartesian coordinate space (see in Fig.12). The oscillators are arranged to control X and Y direction of stance leg's hip(Hip_x and Hip_y) and X and Z direction of swing foot($Foot_x$,$Foot_z$). Since the target is straight level ground walking, the desired motion of hip Z direction and foot Y direction are set to be constant. The reference joint angles are then calculated by inverse kinematic. 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 a simple way to find effective feedback pathways.

As shown in Fig.12, we assign the reference frame on the ankle joint of the stance leg. Based on the reference frame, during walking Hip_x trajectory always moves forward. The trajectory of Hip_x is shown in Fig.13(dot line). The trajectory are not continuous when the support leg switches. To obtain continuous trajectory, we inverse Hip_x every time when a particular support leg touches the ground. The resulting trajectory is shown in Fig.13.

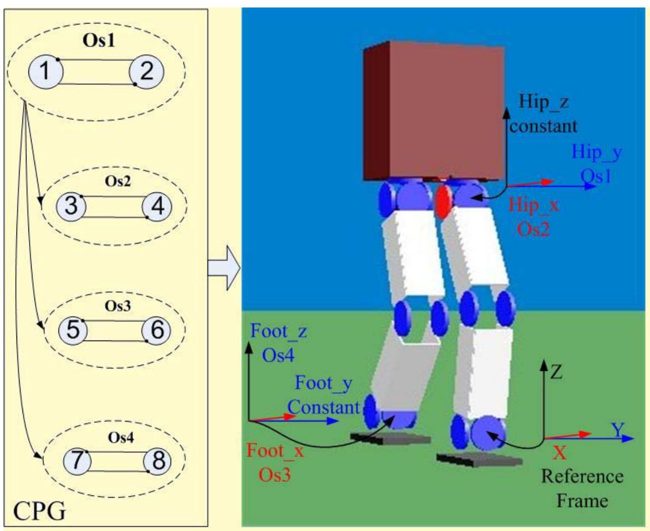

Fig. 12. Oscillator arrangement of the biped robot

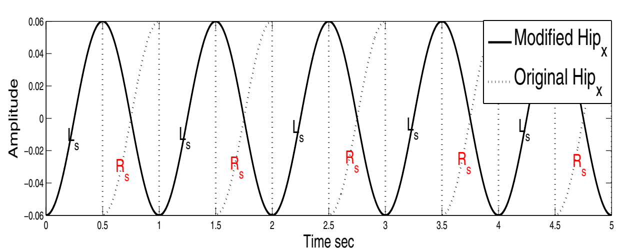

Fig. 13. Reference Hip_x trajectory.

For the stance hip, a neural oscillator generates a periodic trajectory. Assuming that the robot stands with left support, the reference trajectory for the left supporting hip is corresponding to the 1st half period of the neural oscillator's trajectory and the reference trajectory for the right supporting hip is corresponding to the 2nd half period but negatived. We adopt the same strategy for the swing foot horizontal position $Foot_x$ reference to the stance foot. The hip Y direction trajectory is designed to be close as sinusoidal wave [12]. We assume that the walking height is constant which means Hip_z is a constant.

The foot vertical trajectory $Foot_z$ is generated by an oscillator. To achieve a double support phase, we set a threshold for oscillator output. The value val determines the double support period.

$$Foot_z = \begin{cases} Os4 - val & Os4 \geq val \\ 0 & Os4 < val \end{cases} \quad (12)$$

Fig.14 shows the reference trajectory of stance hip and swing foot. Os1 and Os2 give the Hip_x and Hip_y trajectories; Os3 gives the $Foot_x$ trajectory; $Foot_y$ is generated by Os4. Coordination adjustment is connected between these oscillators. Os1 gives the reference information to other oscillators(Fig.12).

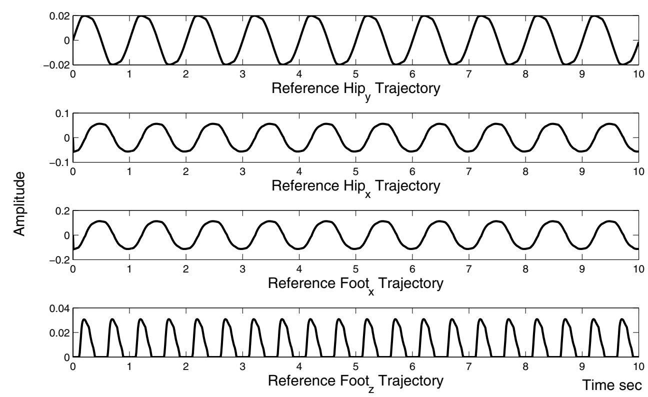

Fig. 14. Reference trajectory of stance hip and swing foot.

B. Sensory Feedbacks

Two simple sensory feedbacks are used to adjust the oscillator's output: body pitch and roll(Fig.15). They are given through g_j. The roll angle is used to adjust Hip Y direction motion while the pitch angle is connected to all the oscillators to balance the walking. The scaling factors of these feedback are optimized by GA method.

C. Simulation Result

In the simulation, the oscillators' parameters are derived using the following rules [13]:

1) To simplify the frequency calculation, we let $\beta = a$. The frequency formula becomes $F = \frac{1}{2\pi\tau_1}\sqrt{b}$ where $b = \frac{\tau_1}{\tau_2}$;
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 0.24m and walking period is 1 second. The walking speed is approximate 0.24 m/s. When there is no sensory feedback and robot is controlled by

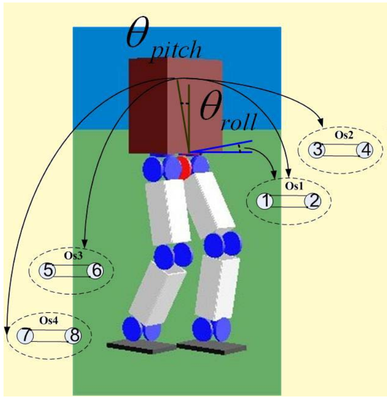

Fig. 15. Feedback pathway for robot motion

the planed CPG trajectory, the CPG fails to balance the walking and the robot falls(Fig.16). However, when proper feedback add on the CPG, the trajectory will be modified according to the environment and robot achieves a robust walking behavior. In Fig.18, we plot the trajectories generated without and with feedback. It is obvious on these graphs that the pitch and roll feedback modified the trajectories to balance the walking. Fig.17 shows the snapshots of normal level ground walking for the biped.

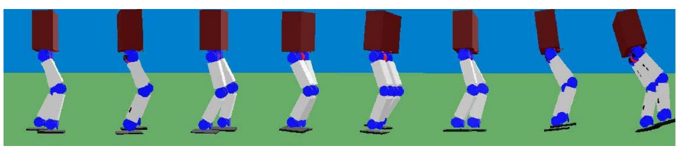

Fig. 16. Robot falls in the level ground walking when when no feedback adds on the CPG

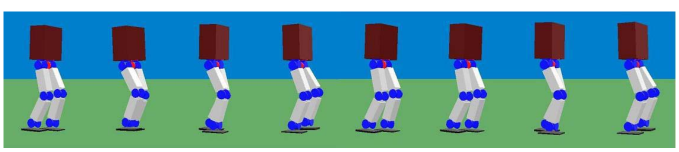

Fig. 17. Robust level ground walking when proper feedback adds on the CPG

V. Conclusion

This paper presents a method to coordinate oscillators in CPG to achieve robust walking behavior. Numerical simulations demonstrate that the method could adjust the phase of oscillators. We have also tested the approach on a 3D biped to achieve stable walking. An appropriate sensory feedback is selected to help the oscillators response correctly to the environment changes. With the coordination between oscillators, the robot shows a robust walking behavior. In this paper, proper sensory feedback helps balance the walking behavior. More efficient feedback pathway will be studied. Different way to coupling oscillator will be explored in the future research.

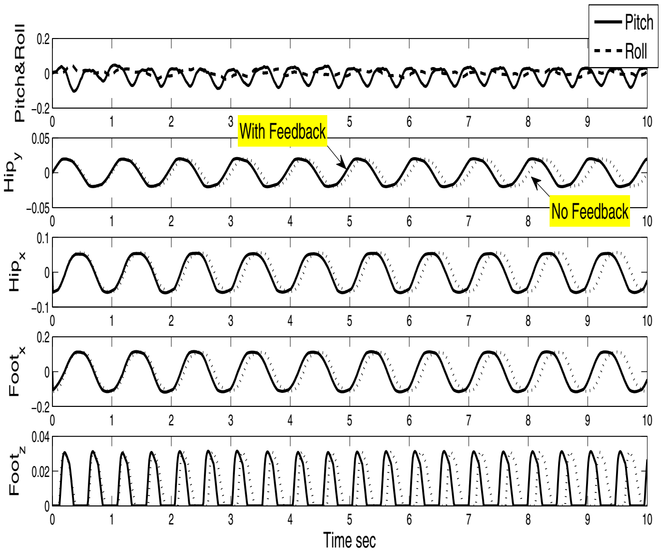

Fig. 18. Effect of feedback on the generation of trajectory

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