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Adaptation in Bipedal Locomotion Using Phase Oscillator Networks

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Abstract − Stable and robust dynamic locomotion has been gaining increasing attention to enhance the applicability of biped humanoids to dynamically changing environments. In this work, we propose an efficient neural oscillator network that controls the phase of the gait by incorporating sensory signals detecting the changes in terrain slope. This enables biped humanoids to reliably control periodic features of legged locomotion adapting to changing environments. Specifically, locomotion trajectories of individual limbs are designed as predetermined functions of the reference phase of the gait sent from the phase generator. These trajectories are autonomously modified to keep the posture of the humanoids balanced by exploiting phase adaptation through sensory feedback. In order to verify the validity of the proposed scheme, we perform experiments with a real robot under various conditions of terrain.

Keywords − CPG, Neural oscillator, Bipedal locomotion, Phase generator, Humanoid

1. Introduction

Most vertebrates keep the periodic rhythms of locomotion adapting to changing environments. It is known that these rhythms are generated by central pattern generators (CPGs) in their spinal cord. CPGs can be mathematically modeled by an artificial neural oscillator, [1], [2] and applied to biologically inspired locomotion control systems [3], [4]. Our work will be devoted to developing new applications of the neural oscillator network to enable humanoid robots to generate dynamic biped walking adapting to various environments and conditions. Even though neural oscillators possess such desirable property as "entrainment" to the environment, it is generally quite difficult to design their interconnected relation and feedback pathways, which also entails an intensive, time-consuming effort of manually tuning the system parameters in order to achieve the desired behavior [5], [6]. Therefore, to decrease uncertainty and degree of nonlinearity in the response characteristics of the neural oscillators as well as to increase the predictability of adaptation in humanoid locomotion, we will employ predetermined nominal trajectories of the locomotion that are subject to change according to the reference phase of the gait. The reference phase can be determined by detecting the heel strike phase with the foot pressure sensor. It is expected that the proposed approach will yield a robust yet efficient motion generation algorithm for biped humanoid locomotion.

2. Locomotion Control Algorithm

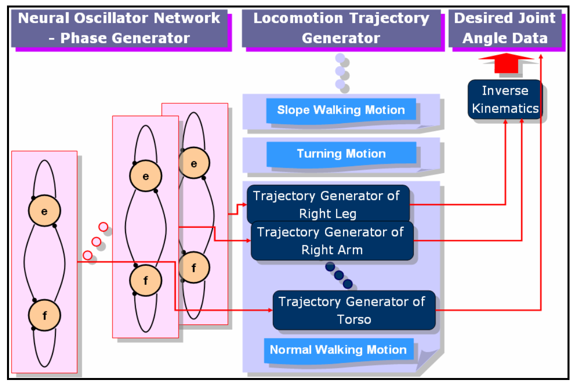

Fig. 1 locomotion control with phase oscillator

Fig. 1 describes the proposed locomotion control algorithm in this work that is organized into the phase generator and the locomotion trajectory generator. The phase generator comprises the main phase generator with sensory feedback and the phase generator of individual limbs that include two arms, two legs, and one torso. The locomotion trajectories for generating various motions of individual limbs are designed as functions of the phase to be sent from the phase generator. Hence, if the reference phase is adjusted reflecting the feedback sensory signals from the foot, the locomotion trajectory generator autonomously modifies the normal trajectory. The joint angle trajectories of individual limbs can then be obtained by solving the respective inverse kinematics problems for the determined locomotion trajectories. Note that biped humanoid locomotion requires that the resulting motions should satisfy the dynamic stability criterion. Therefore, incorporating the sensory signals detecting the changes in terrain slope, how to make a stable trajectory is the main key to the proposed approach. In the following section, we describe the underlying principle to keep the robot stable while adapting to changing environments.

3. Phase Oscillator Network

3.1 A Neural Oscillator Network

In this paper, we design a neural oscillator network to embody the above-mentioned phase generator. The oscillator consists of two simulated neurons arranged in mutual inhibition as shown in Fig. 2 [1], [2]. This model is represented by a set of nonlinear coupled differential equations given by

$$
\begin{aligned}
T_r \dot{x}_{ei} + x_{ei} &= -w_{fi} y_{fi} - \sum_{j=1}^{n} w_{ij} y_j - b v_{ei} - \sum k_i [g_i]^+ + s_i \\
T_a \dot{v}_{ei} + v_{ei} &= y_{ei} \\
y_{ei} &= [x_{ei}]^+ = \max(x_{ei},\ 0) \\
T_r \dot{x}_{fi} + x_{fi} &= -w_{ei} y_{ei} - \sum_{j=1}^{n} w_{ij} y_j - b v_{fi} - \sum k_i [g_i]^- + s_i \\
T_a \dot{v}_{fi} + v_{fi} &= y_{fi} \\
y_{fi} &= [x_{fi}]^+ = \max(x_{fi},\ 0),\ (i = 1,\ 2,\ \cdots,\ n)
\end{aligned}
\qquad (1)
$$

where $x_{e(f)i}$ is the inner state of the i-th neuron which represents the firing rate; $v_{e(f)i}$ represents the degree of the adaptation, modulated by the adaptation constant b, or self-inhibition effect of the i-th neuron; the output of each neuron $y_{e(f)i}$ is taken to be the positive part of the firing rate and the output of the whole oscillator is denoted as $Y_{(out)i}$; $w_{ij}y_i$ represents the total input from the neurons inside a neural network; w_{ij} is a weight of inhibitory synaptic connection from the j-th neuron to the i-th neuron, and w_{ei}, w_{fi} are also a weight from extensor neuron to flexor neuron, respectively; the input is arranged to excite one neuron and inhibit the other by applying the positive part to one neuron and the negative part to the other; the inputs are scaled by the gains k_i; T_r and T_a are time constants of the inner state and the adaptation effect of the i-th neuron respectively; s_i is an external input with a constant rate.

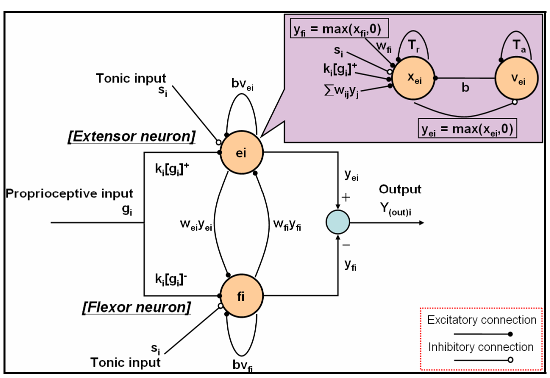

Fig. 2 Schematic diagram of the half-center CPG model

The schematic of the above-mentioned neural oscillator is shown in Fig. 2. Two neural oscillators can be coupled to each other by establishing four connections weighted w_e, w_f, w_{ef}, and w_{fe}, respectively as shown in Fig. 3. According to the connecting method, the outputs of neural oscillators have phase differences of $\pm\pi$ or 0. The cross connection between two oscillators will have the opposite effect such that the outputs of neural oscillators have phase differences of $\pm\pi$ or 0. Generally, if w_e and w_f exist, w_{ef} and w_{fe} can be omitted due to mutual inhibition of the output's phase of each neuron. If not, the inputs/outputs of neurons will be complicated and the final phase relies on initial conditions of each oscillator. This oscillator network could have a variety of periodic motions that plays an important role to control the state of phase of individual limbs.

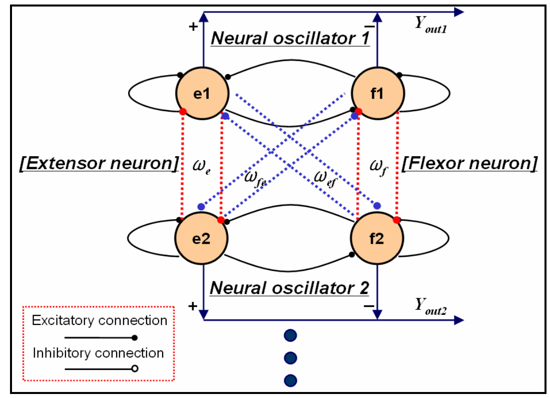

Fig. 3 Schematic diagram of neural oscillator network

3.2 Phase Generator Based on Neural Oscillator

A simple phase generator based on coupled neural oscillators is illustrated in Fig. 4. The blue rectangles represent the phase generator of each limb. There are inhibitorily connected links between the respective individual neural oscillators of the opposite limbs. These inhibitory connections are denoted by the blue line and blue circles at the end of connections. That is, the phases for bipedal locomotion are designed such that the legs and arms swing in the opposite phase, and the legs and their contralateral arms swing in the same phase. Also, the gait cycle is controlled by the main phase generator. The arrows with the black line and blue dotted line indicate the flow direction of the output of phase interacted between the neural oscillators, and the red dotted lines show the sensory signals sent from the environment. The reference phase will instantly be adjusted by the sensory signals that detect the changes in the periodicity of heel strikes. In Fig. 4, each output, Y, implies the phase signal determined by the phase generating oscillator. The sum of Y_{M1} and Y_{M2} generates a reference phase incorporating S_1 and S_2, and is summed with $Y_{L,L}$, $Y_{L,A}$, $Y_{R,L}$ and $Y_{R,A}$ determined from the individual limb phase generators. Thus, the phase oscillator network will enable biped humanoids to adapt their locomotion to the changes in terrain.

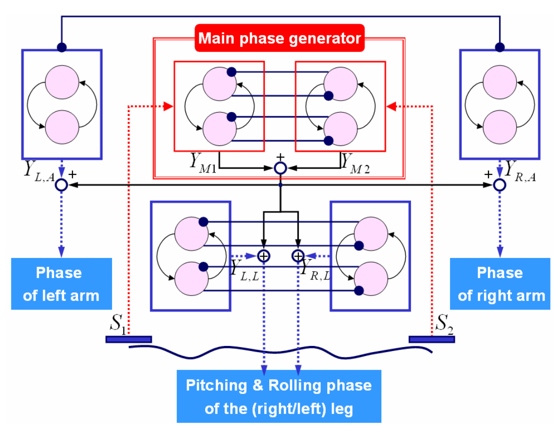

Fig. 4 Design of phase generator network

4. Locomotion Trajectory Generation

Fig. 5 illustrates the kinematic schematic of the humanoid robot employed in this work. In the figure, AJoint denotes arm joints and LJoint does leg joints. AJoint3 and Ljoint1 are engaged in the yawing motion of an arm and a leg. AJoint2 and LJoints2, 6 are engaged in the rolling motion. Ajoints 1, 4, 5 and Ljoints 3, 4, 5 are engaged in the pitching motion. HJoint and TJoint denote the head joint and the torso joint. The locomotion trajectory generator generates the Cartesian trajectories of respective limbs. Specifically, the swing foot trajectory can be a cycloid and the hip trajectory vaults like an inverted pendulum over the supporting foot. The designed swing foot trajectory is shown in Fig. 6. The upper and lower figures show the trajectories of the right and left foot, respectively. The first step of the right foot is designed to have the half interval.

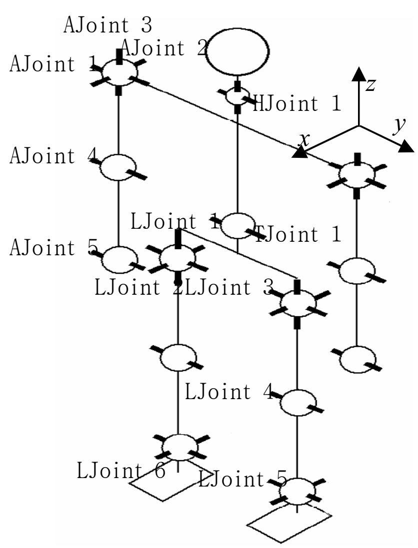

Fig. 5 Kinematic schematic of humanoid robot

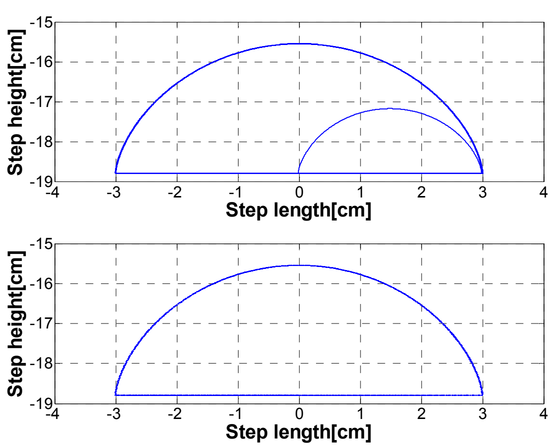

Fig. 6 Predetermined foot trajectory

Using the nominal foot trajectories in Fig. 6, we investigate how the trajectories are adapted to unknown environments. In Fig. 7, it is observed that the trajectories are modified appropriately conforming to the slope. The foot pressure sensor detects the changing period of foot strike with the ground and sends this information to the main phase generator. Fig. 8 shows the results of phase changes in individual limbs. The upper, middle, and lower lines are the phases of the left leg (or the right arm), the main phase, and the right leg (or the left arm), respectively. The phases abruptly jumped by about 6° at the instant when the sensory signals, S_1 and S_2, are fed from the foot pressure sensor (see Fig. 4). Thus, locomotion trajectories associated with the pitching motion are switched automatically while the posture is kept balanced.

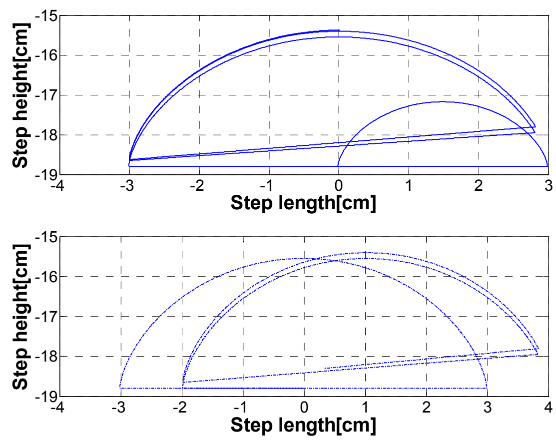

Fig. 7 Changes in foot trajectories in a 6° uphill walking

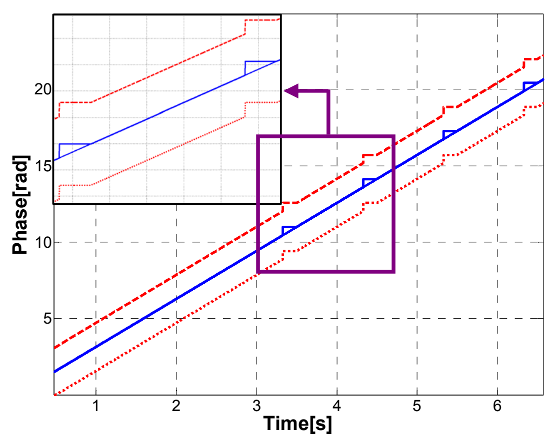

Fig. 8 Phase signal from the phase generator

5. Experimental Test

We performed experiments to verify the proposed locomotion control algorithm using a Fujitsu's HOAP model. Figs. 9 and 10 show that the robot walks straight forward on the flat ground with different stride lengths. Specifically, a joint-level PD controller is employed with the phase and trajectory generators in the host computer.

The robot communicates with the host computer through a universal serial bus every 1ms.

In the experiments, various locomotion gaits were tested such as walking backward, turning left and right while walking forward (See Figs. 11, 12 and 13). In particular, the turning motions were easily realized by applying a sinusoidal input to Ljoint1. This input should be synchronized in phase with the rolling motion. Fig. 14 shows that the robot climbed a 6° uphill slope by adapting its nominal phase appropriately. In future experiments, we will continue to test walking through a variable slope in a terrain.

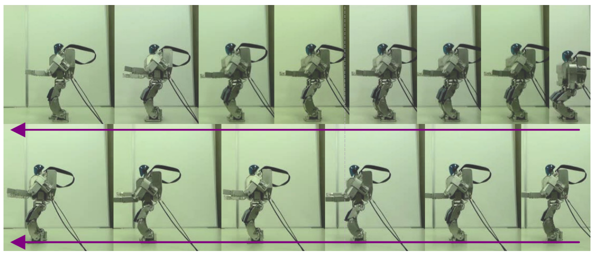

Fig. 9 Flat terrain forward walking with a 6cm stride

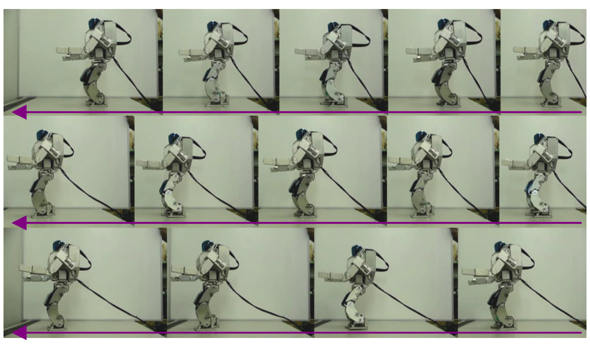

Fig. 10 Flat terrain forward walking with a 10cm stride

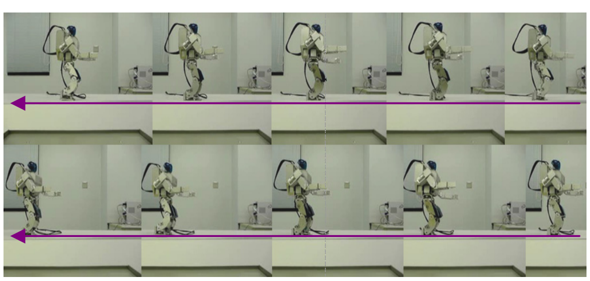

Fig. 11 Flat terrain backward walking

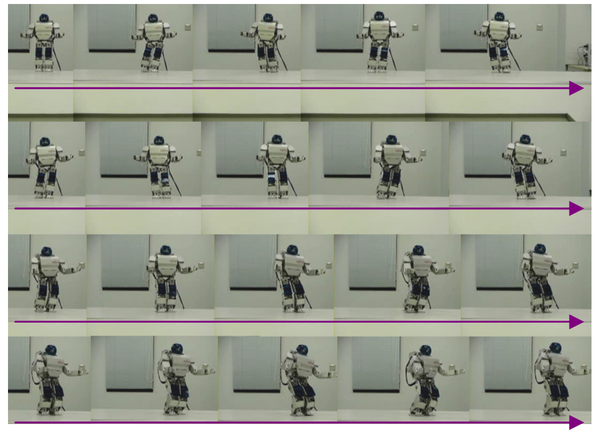

Fig. 12 Turning counterclockwise while walking forward

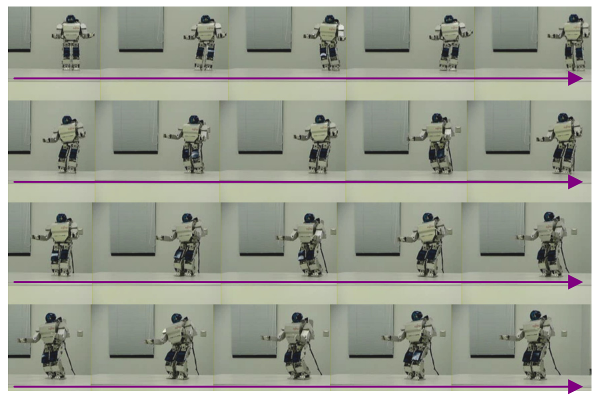

Fig. 13 Turning clockwise while walking forward

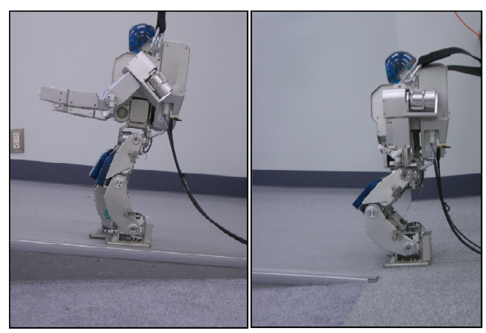

Fig. 15 HOAP uphill walking

6. Conclusion

In order to keep the robot balanced during locomotion using rhythmic movements, we propose a neural oscillator network that consists of the phase generator and the locomotion trajectory generator. Specifically, the rhythmic movements are controlled by the time-varying phase of the phase generator that closely interacts with the individual limb oscillators by incorporating sensory signals. Synchronizing the motions of the individual limbs, the configuration of the body can be modified appropriately to sustain stability as the terrain changes. We demonstrate various gait patterns of biped locomotion with a real robot. In our future study, we will show that humanoid robots with phase adaptation capability will naturally adapt to widely varying environments or task conditions.

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