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Automatic Selection Method of Some Locomotion Signals in a CPG Network

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Abstract—We have proposed a central pattern generator (CPG) network model with independent controllability, in terms of the amplitude and period of each output signal, and phase difference between CPGs. In our previous research, the CPG network was applied to a quadruped locomotion signal generator and generated typical quadruped locomotion signals. In this research, we propose an automatic selection method of several locomotion signals from possible signals. These selected signals satisfied some constraints defined by a designer and included not only the typical quadruped locomotion signals but also strange ones.

1. Introduction

Locomotion signals for walking, running and swimming are generated and controlled by central pattern generators (CPGs)[1]. Some CPG network models have been investigated and applied to autonomous quadruped robots [2]. These CPG networks consist of local CPGs which act as nonlinear oscillators and have a mutually connection among CPGs. It is not so easy to control the output signal of each CPG because of the CPG network structures.

In order to generate locomotion signals, the CPG must satisfy two necessary and sufficient conditions: the CPG must have (1) a limit cycle, which is represented by higher order nonlinear differential equations, and (2) high controllability for the amplitude and period of the signal in the stable state, i.e. in the limit cycle. Moreover, in the CPG network, phase differences between the CPGs must be controlled. The van der Pol (VDP) equation [3] is the simplest model with a limit cycle, and has the feature of high controllability for the amplitude and period. Thus, the VDP equation is suited well to locomotion signal generator model [4].

We have proposed a CPG network based on the VDP equation [5]. The CPG network is composed of a rhythm generator (RG) and some CPGs. The amplitude and period of the CPGs are independently controlled because the CPG model inherits the controllability of the VDP equation. The phase differences between the CPGs are decided by connections between the RG and each CPG independently of the amplitude and the period of each CPG. Moreover, the configuration of the CPG network can be logically and uniquely decided based on a gait transition. It is considered that the proposed model is suited well for locomotion signal generator because the model has the feature of independent controllability. In our previous study, we confirmed that the CPG network can generate the locomotion signals for the typical quadruped gaits such as walk, trot, gallop and bound modes [5].

In this paper, we propose an automatic generation method of several locomotion signals including these typical quadruped locomotion signals. The locomotion signals meet some specifications defined by a designer in advance. In the conventional CPG network, the connection weights need to be decided by trial and error for generating the desired locomotion signals. On the other hand, in our CPG network, several configurations of the CPG network can be automatically decided if only the designer defines these specifications beforehand.

2. Central pattern generator network

In this section, we explain the CPG network proposed in [5]. The network is comprised of some CPGs and one RG, and is designed based on the VDP equation. The VDP equation has a limit cycle and inherits a feature of independent controllability in terms of the amplitude and period of the limit cycle.

2.1. CPG model

The ith CPG model(CPG$_i$) is written as follows,

$$\frac{d^2x_i}{dt^2} - 2\epsilon\left(A^2 - x_i^2\right)\frac{dx_i}{dt} + B_i^2 x_i = 0, \tag{1}$$

where the parameter ϵ is a small constant and is called a nonlinearity coefficient. The value of x_i is the output signal of CPG$_i$ (i= 1, 2,$\cdots$, n). A and B_i determine the value of the amplitude and period of x_i in the stable state, respectively [4] [5] [6]. Especially, the period is inversely proportional to the parameter B_i, and the amplitude reaches $2A$ in the stable state. n denotes the required number of CPGs in the CPG network.

In order to control the phase difference between CPGs, the phase of each CPG must be temporally shifted. The parameter B_i represented in the following equation is utilized to control the phase.

$$B_i = B + b_i, \tag{2}$$

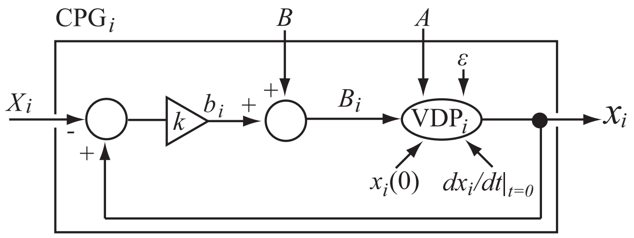

Figure 1: Block diagram of the CPG$_i$.

$$b_i = k(x_i - X_i), \tag{3}$$

where B and k denote the natural frequency of the CPGs and gain factor, respectively. The value of b_i determins the amount of phase shift of CPG$_i$. After the value of the phase difference $(x_i - X_i)$ becoumes 0, the value of b_i approaches 0. The value of k can control the time until the stable state.

The block diagram of the CPG$_i$ is shown in Figure 1. The period of the output signal x_i is controlled by the b_i so that the phase difference between the control and target signals becomes 0.

2.2. Rhythm Generator

The Rhythm Generator (RG) is designed as the target signal generator and also designed based on the VDP equation.

$$\frac{d^2x_R}{dt^2} - 2\epsilon\left(A^2 - x_R^2\right)\frac{dx_R}{dt} + B^2x_R = 0. \tag{4}$$

The values of x_R and $\frac{dx_R}{dt}$ are used as the target signals. The target signal X_i is represented as equation (5). The values of c_{i1} and c_{i2} take −1, 0, or 1 and are decided by the gait transitions which we intend to control. Either c_{i1} or c_{i2} always takes 0.

$$X_i = c_{i1}x_R + c_{i2}\tau\frac{dx_R}{dt}, \tag{5}$$

where τ arranges the dimensions of x_R and $\frac{dx_R}{dt}$, and adjusts the amplitude of $\frac{dx_R}{dt}$ to always make the amplitudes of x_R and $\frac{dx_R}{dt}$ constant even if the parameter A and B are changed. τ can be defined as follows,

$$\tau = \frac{\max(x_R)}{\max(\frac{dx_R}{dt})} = \frac{2A}{\max(\frac{dx_R}{dt})}, \tag{6}$$

where $max(\cdot)$ is max function. Since the amplitude of x_R is controlled by the parameter A, the value of $\max(x_R)$ can be rewritten as $2A$. On the other hand, the value of $\max(\frac{dx_R}{dt})$ is measured from simulation results, because the value cannot be estimated beforehand. Figure 2 shows the block diagram of the RG. The values of the parameter A and B of the RG are equal to the ones of the CPG in Figure 1. Desired target signals of the CPGs are selected by a target signal selector in Figure 2. The function of the selector is expressed as equation (5). For instance, $-x_R$ is selected for the target signal X_i, the combination of c_{i1} and c_{i2} is decided as c_{i1}=−1 and c_{i2}=0.

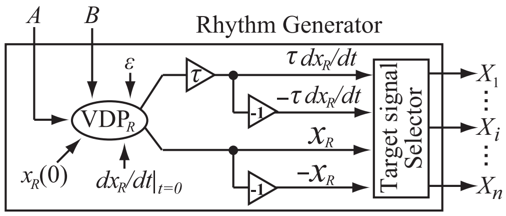

Figure 2: Block diagram of the Rhythm Generator.

2.3. CPG network

The proposed CPG network can be composed of one RG and n CPGs based on a gait transition. Figure 3 shows the gait transition and the configuration of the CPG network in walk mode. LF, LH, RF and RH stand for left fore-leg, left hind-leg, right fore-leg and right hind-leg, respectively. The arrows represent directions of phase transition. We define that the output signals of CPG$_1$, CPG$_2$, CPG$_3$ and CPG$_4$ are sent to the legs of LF, RF, LH and RH, respectively. The connections of the CPG network can be logically and uniquely decided based on the gait transition. The procedure for designing the CPG network in the walk mode is represented as follows:

1. One RG and n CPGs are prepared. In this paper, the number of CPG is four, because we aim to compose the quadruped locomotion signal generators (n=4).

2. The parameter A and B are input to the RG and CPGs. Because of this structure, each CPG can obtain the independent controllability in terms of the amplitude and period of the output signal x_i.

3. The output signal of each CPG is allocated as the control signal to each leg.

4. The target signal X_i of CPG$_i$ is decided based on the gait transitions. In this paper, we focus on the walk mode.

5. x_R is selected as the target signal X_1. This process is common one in other gait modes. The output signal of CPG$_1$ works as the reference signal for calculating the phase differences between CPG$_1$ and the other CPGs. (c_{11}=1, c_{12}=0)

6. The output signal x_2 controls the RF. Since the phase difference between LF and RF is π, $-x_R$ is selected for the target signal of X_2. (c_{21}=−1, c_{22}=0)

7. $\tau\frac{dx_R}{dt}$ is selected for the target signal of X_3, because the phase difference between LF and LH is $\frac{3\pi}{2}$. (c_{31}=0, c_{32}=1)

8. $-\tau\frac{dx_R}{dt}$ is selected for the target signal of X_4, because the phase difference between LF and RH is $\frac{\pi}{2}$. (c_{41}=0, c_{42}=−1)

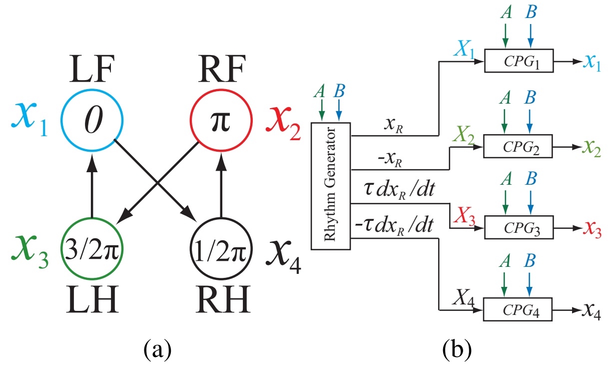

Figure 3: Walk mode. (a)Gait transition, (b)Configuration of the CPG network

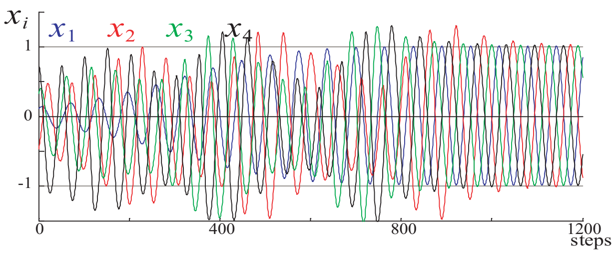

Figure 4: Output signals of CPGs in walk mode.

The configuration of the CPG network in the walk mode is presented as Figure 3(b). Figure 4 shows a simulation result in the mode. It is confirmed that the phase differences between the CPGs were controlled as the gait transition of Figure 3 (a). In this mode, c_{i1} and c_{i2} were decided as follows. c_{11}=1, c_{12}=0, c_{21}=−1, c_{22}=0, c_{31}=0, c_{32}=1, c_{41}=0, c_{42}=−1. In the same way, the CPG network can be logically and uniquely decided in trot, bound and gallop modes [5]. Table 1 shows the combinations of c_{i1} and c_{i2} in the typical quadruped locomotion signals.

3. Transition matrix

From the configuration of the CPG network, a transition matrix is obtained. In the walk mode, the transition matrix is represented as follows,

$$\begin{aligned}&[c_{11}, c_{12}, c_{21}, c_{22}, c_{31}, c_{32}, c_{41}, c_{42}] \\ &= [1, 0, -1, 0, 0, 1, 0, -1]\,. \end{aligned} \tag{7}$$

Table 1: Combinations of c_{i1} and c_{i2} in the typical quadruped locomotion signals.

mode	$[c_{11}, c_{12}]$	$[c_{21}, c_{22}]$	$[c_{31}, c_{32}]$	$[c_{41}, c_{42}]$
walk	$[1, 0]$	$[-1, 0]$	$[0, 1]$	$[0, -1]$
trot	$[1, 0]$	$[-1, 0]$	$[-1, 0]$	$[1, 0]$
bound	$[1, 0]$	$[1, 0]$	$[-1, 0]$	$[-1, 0]$
gallop	$[1, 0]$	$[0, -1]$	$[0, 1]$	$[-1, 0]$

Table 2: Designed constraints.

constraint 2	$\sum c_{i1} = 0$ and $\sum c_{i2} = 0$
constraint 3	$c_{21} + c_{22} = 1$ or $c_{21} + c_{22} = -1$ $c_{31} + c_{32} = 1$ or $c_{31} + c_{32} = -1$ $c_{41} + c_{42} = 1$ or $c_{41} + c_{42} = -1$
constraint 4	$X_2 \neq X_4$ and $c_{31} \neq 1$

Table 3: Combination of c_{i1} and c_{i2}.

mode	$[c_{11}, c_{12}]$	$[c_{21}, c_{22}]$	$[c_{31}, c_{32}]$	$[c_{41}, c_{42}]$
mode 1	$[1, 0]$	$[-1, 0]$	$[0, -1]$	$[0, 1]$
mode 2	$[1, 0]$	$[0, -1]$	$[-1, 0]$	$[0, 1]$
mode 3	$[1, 0]$	$[0, 1]$	$[-1, 0]$	$[0, -1]$
mode 4	$[1, 0]$	$[0, 1]$	$[0, -1]$	$[-1, 0]$

In this paper, a method for automatically generating the matrix under some constraints is proposed. These constraints are defined by design concept beforehand based on structural and mechanical properties and are explained in the next section.

4. Design of constraints

In this section, how to define the constraints are discussed for designing the quadruped locomotion signal generators. Three constraints are defined based on the combinations of c_{i1} and c_{i2} in the Table 1. In addition, based on the mechanism of legs of quadruped animals, the fourth constraint is defined. These constraints are represented as follows,

1. c_{11} and c_{12} always take 1 and 0, respectively.
2. Both of the summation of c_{i1} and c_{i2} with respect to i is 0.
3. $c_{i1} + c_{i2}$ are 1 or −1, because either x_R or $\tau\frac{dx_R}{dt}$ is surely selected as the target signal X_i.
4. The control signals of LF-FH and RF-RH are not in-phase in natural gaits.

Table 2 shows equations expressing the above constraints. These constraints make it easy to choose several transition matrices automatically from the possible transition matrices, the number of which is 3^8.

5. Simulation results

In order to verify the effectiveness of the proposed method, the transition matrices and output signals of CPGs were investigated with the 4th order Runge-Kutta method.

From the simulation results, it is confirmed that the number of the transition matrcies satisfying these constraints was 8 including the typical quadruped locomotion signals. From these 8 modes, one suitable mode should be selected

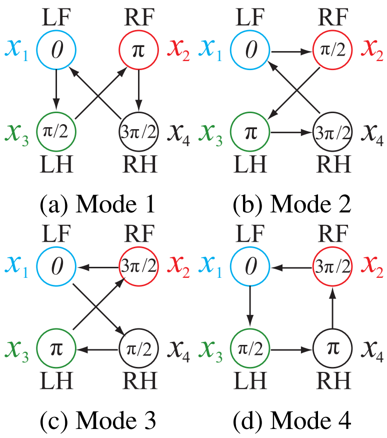

Figure 5: Acquisition of gaits satisfying constraints other than the typical quadruped locomotion signals.

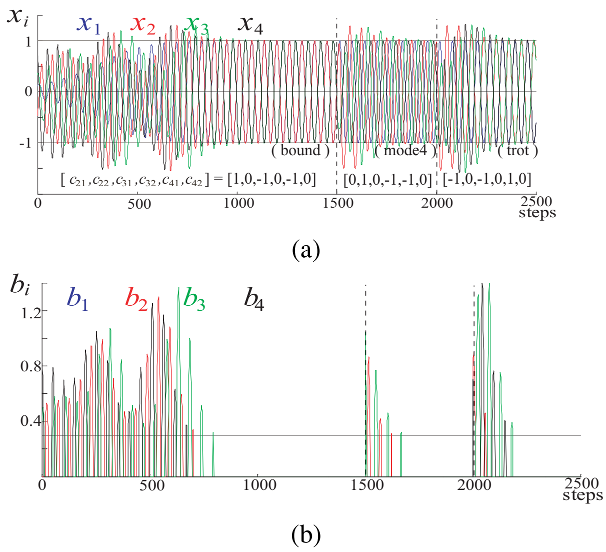

Figure 6: Simulation results of acquisition of Gaits. Figure (a)Output signals of CPGs x_i, (b)Output signals of each b_i.

based on some evaluation criteria, e.g. energy consumption. In this paper, the mode was randomly selected from 8 modes because the aim of this paper is to confirm that the transition matrices were precisely generated under these 4 constraints. Table 3 represents the combinations of c_{i1} and c_{i2} other than that of the typical quadruped locomotion signals. Figure 5 shows gait transitions of the modes in Table 3. These modes may generate strange gaits because these gaits do not exist in the natural world.

Figure 6 shows simulation results of the CPG network. At 0, 1500 and 2000 steps, the transition matrix was randomly selected under these 8 modes. The values of c_{i1} and c_{i2} take either -1, 0 or 1. In this simulation, ϵ=0.2, k=1, initial values of x_R=0.1, x_1=0.1, x_2=$-$0.5, x_3=0.3, x_4=0.7, $\frac{dx_R}{dt}$=0.1, $\frac{dx_1}{dt}$=0.1, $\frac{dx_2}{dt}$=0.3, $\frac{dx_3}{dt}$=0.3 and $\frac{dx_4}{dt}$=0.2. The parameter A and B were 0.5 and 1. In this simulation, bound mode, mode 4 and trot mode were randomly selected at 0, 1500 and 2000 steps. From Figure 6 (b), it is found that b_i approached 0, after the value of the phase difference between the output signal x_i and the target signal X_i became 0. In this simulation, the value of b_i omitted 0.3 or less, because X_i was not always corresponding to the value of x_i even after b_i is controlled. A horizontal line in Figure 6 (b) represents a value of b_i=0.3. From these simulation results, it is confirmed that, in the stable state, the value of the amplitude and period of each CPG held a constant value even if the gaits are changed. Moreover, these generated gait modes satisfied these 4 constraints.

6. Discussions

In this paper, we proposed a method of automatically selecting gaits in the proposed CPG network. Several gaits were generated and switched under the constraints which were set beforehand by a designer. The signals include not only the typical quadruped locomotion signals but also strange ones. Of course, these strange signals can make quadruped robots to walk, because three legs always stand on the ground during locomotion. We are allowed to make hypothesis that these strange signals disappeared in the process of animal evolution by some reasons. We would emphasize that the proposed CPG network can contribute to an advance in research for the locomotion signal generators.

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