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PAPER

Central Pattern Generator Network with Independent Controllability

Tatsuji Tokiwa and Takeshi Yamakawa

Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology.
2-4 Hibikino, Wakamatsu-ku, Kitakyushu, Fukuoka 808-0196, Japan
E-mail: tokiwa-tatsuji@edu.brain.kyutech.ac.jp

Abstract **In this paper, we propose a central pattern generator (CPG) network with independent controllability for a quadrupedal locomotion signal generator. The proposed model comprises several CPGs and one rhythm generator (RG). Each CPG and the RG are described by the van der Pol (VDP) equation. The VDP equation has a limit cycle and a feature of independent controllability in terms of the amplitude and period of the limit cycle. The amplitude and period of an output signal from each CPG and the RG are independently controlled by external signals, because the CPGs and RG are designed such that the feature of the VDP equation is maintained. In order to control the phase shift between CPGs, the period of the output signal from each CPG is temporarily controlled through connections that are only conjunctions between the RG and each CPG. The proposed CPG network is applied to a quadrupedal locomotion signal generator, and generates typical quadrupedal locomotion signals, which are the walk, trot, bound and gallop modes.**

Keywords: central pattern generator, van der Pol equation, quadrupedal locomotion signal generator, quadrupedal gaits

1. Introduction

Locomotion signals such as walking, running, swimming and flying are generated and controlled by the central nervous system so called the central pattern generator (CPG) [1]. Locomotion signals of terrestrial animals can be classified into some periodic patterns that are gaits. In recent years, many CPG network models [2]-[4] have been reported.The CPG network models comprise some oscillators that are described by higher-order differential equations. In this paper, the oscillators are called CPGs. In conventional network models, CPGs are coupled to each other through connection weights because these structures of the CPG network are designed from the viewpoint of physiology.

One of the applications that we are aiming at is a walking robot. Each leg of the robot is controlled by an output signal from each CPG. Output signals of the CPGs are controlled by adjusting some connection weights through trial and error and by changing configurations in the CPG network. Generally, walking speed can be controlled by changing the amplitudes of a signal. Additionally, if it is necessary to change to a faster speed, periods of the signals must be controlled. However, it is not so easy to control and analyze the output signals of the CPG network in terms of the amplitude and period of each CPG, and the phase difference between CPGs. This is because these CPG networks consist of some CPGs that are described by higher-order differential equations and have mutual connections between CPGs.

To solve these problems, in this paper, we propose a CPG network with independent controllability in terms of amplitude, period and phase difference [5], [6]. In order to design a locomotion signal generator, 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) a 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, the phase differences between the CPGs must be controlled. The proposed CPG network comprises a rhythm generator (RG) and some CPGs. Each CPG and the RG are described by the Van der Pol (VDP) equation. The VDP equation suits the CPG model well, because the VDP equation is the simplest model that has a limit cycle and features independent controllability with respect to the amplitude and period of the limit cycle [7]. The amplitude and period of the output signal from each CPG are controlled almost independently by external signals. The phase difference between CPGs is controlled by changing connections that are connected between the RG and each CPG independently of the amplitude and period of each CPG. Moreover, the configuration of the CPG network can be logically and uniquely determined on the basis of a gait transition. In this study, we apply the CPG network in the quadrupedal locomotion signal generator and confirm that

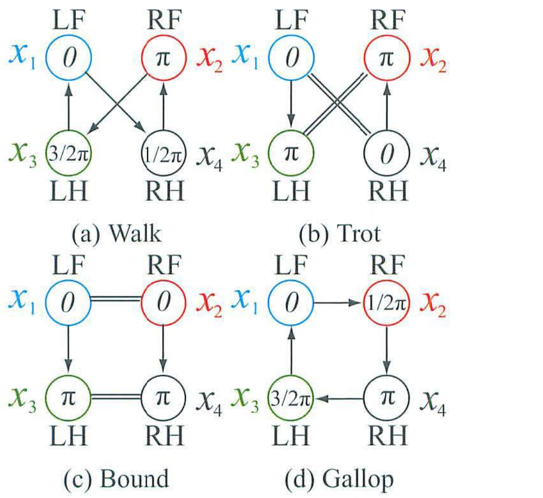


Fig. 1 Phase relations for four common quadrupedal gaits

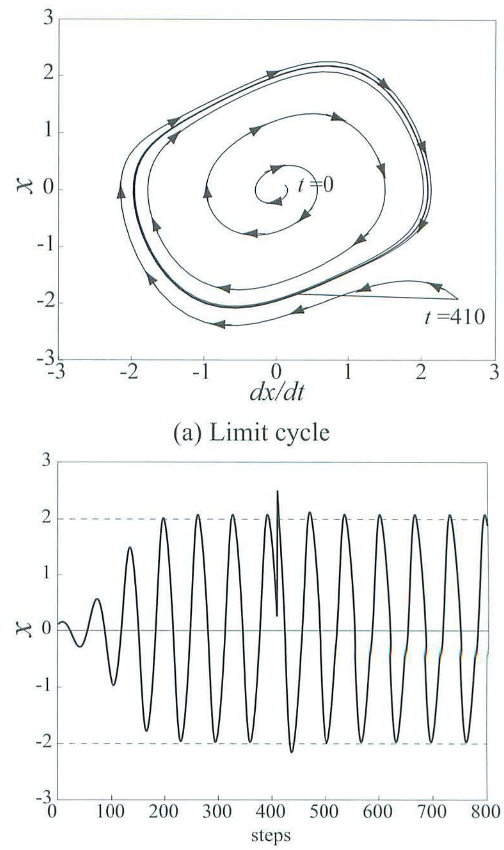
the network can generate typical quadrupedal locomotion signals, which are the walk, trot, bound and gallop modes.

2. Background and Methods

2.1 Quadrupedal gaits

Locomotion signals of quadrupedal animals are separated in some periodic patterns so called gaits. These gaits are generated and controlled depending on their speed of locomotion and the condition of terrain [8]. In this paper, we focus on four of the most common quadrupedal gaits - the walk, trot, bound and gallop modes. These four gaits are shown schematically in Fig. 1. LF, LH, RF and RH stand for the left foreleg, left hindleg, right foreleg and right hindleg, respectively. The arrow and equal sign indicate the direction of the phase difference and in phase, respectively. In the walk mode, which is a slow gait, the limbs move in the order of LF, RH, RF and LH with a quarter period. The phase relations of the walk mode are shown in Fig. 1(a). In the trot mode, which is a medium-speed gait, diagonal limbs, e.g., LF and RH, move together and in phase, and pairs of diagonal limbs move half a period out of phase with one another. Fig. 1(b) shows the phase relations of the trot mode. The bound mode is a fast gait. In this mode, the front and hind limbs, respectively, move together and in phase, as Fig. 1(c) shows. The gallop mode, which is also a fast gait, resembles a bound, except for the limbs of the front and hind pairs being slightly out of phase with each other. Fig. 1(d) shows the phase relations of the gallop mode. Other quadrupedal gaits, such as the canter, exist, however, they are less common than these four gaits and are therefore not considered in this paper.

In the present study, the CPG network model was considered to be in a particular gait mode when the relative phases of the respective oscillator output signals were within 10% of a gait cycle of those expected for the ideal gait. The above criterion was considered reasonable, given the variability of natural animal gaits [9], [10].



(a) Limit cycle

(b) Output signal x

Fig. 2 Simulation results of the VDP equation

2.2 Van der Pol equation

The VDP equation was proposed by Van der Pol in 1926 [11]. The VDP equation describes the theory of vacuum-tube oscillators, and is one of the simplest model that has a limit cycle. The VDP equation is derived from the enhanced and damped oscillations. To express a limit of the amplitude, the term of a nonlinearity coefficient is assumed. The VDP equation is given by eq. (1).

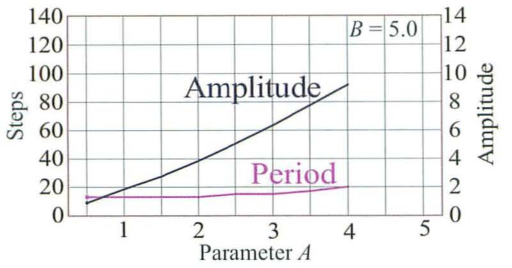
$$\frac{d^2x}{dt^2} - \epsilon\left(1 - x^2\right)\frac{dx}{dt} + x = 0 \qquad (1)$$

Here, ϵ describes the nonlinearity coefficient and affects the shape of its waveform. When the parameter ϵ is small ($0<\epsilon\ll 1$), the solution of the VDP equation is a sustained sinusoidal oscillation.

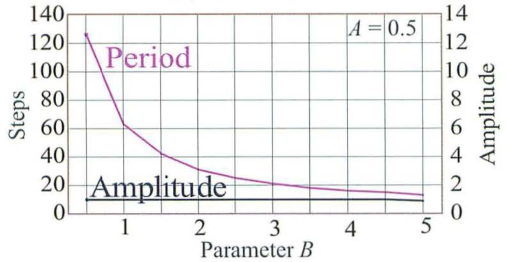
Two sets of control parameters are inputted in the VDP equation: the amplitude parameter A and the frequency parameter B [12], [13].

$$\frac{d^2x}{dt^2} - 2\epsilon\left(A^2 - x^2\right)\frac{dx}{dt} + B^2x = 0 \qquad (2)$$

Kryloff and Bogoliuboff have devised a method for the approximate solution of eq. (2) [14]. Hereafter, eq. (2) is



(a) Parameter A



(b) Parameter B

Fig. 3 Amplitude and period of limit cycle with two parameter arrangements

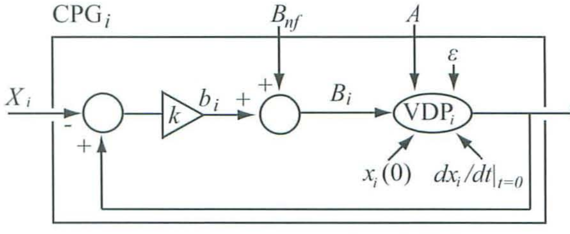


Fig. 4 Block diagram of CPG model

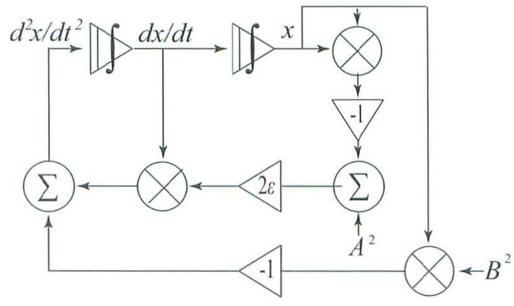


Fig. 5 Block diagram of VDP equation

called the VDP equation. The mathematical method is based on the fact that this equation becomes a harmonic oscillation if ϵ=0 in the VDP equation.

$$\frac{d^2x}{dt^2} + B^2x = 0 \tag{3}$$

Eq. (4) is derived from eq. (3).

$$x = a\sin(Bt + \phi) \tag{4}$$

Here, a and ϕ are arbitrary constants. Eq. (4) shows that the period can be controlled by adjusting the parameter B. By Kryloff and Bogoliuboff approximation, furthermore, the following equations are obtained.

$$\frac{da}{dt} = a\epsilon(A^2 - \frac{a^2}{4}) \tag{5}$$

$$\frac{d\phi}{dt} = 0 \tag{6}$$

From eq. (5), it can be seen that the amplitude reaches a steady state, *i.e.*, $\frac{da}{dt}$=0, then a=2A. In an actual simulation, however, the amplitude does not accurately become 2A because a mathematically approximation method is used. Eq. (6) shows that the period does not depend on time. From eqs. (4) and (5), it is proved that the period and amplitude of the limit cycle can be independently controlled by adjusting the parameters B and A, respectively. Fig. 2 shows the simulation results of the VDP equation, where, A, B, ϵ, the initial value of x and the initial value of $\frac{dx}{dt}$ were 1, 1, 0.2, 0.1 and 0.1, respectively. The stimulation of x=2.5 was added in the 410 step. Fig. 3 shows the simulation results of the VDP equation under some conditions of the parameters A and B. In this simulation, ϵ, and the initial values of x and $\frac{dx}{dt}$ were 0.2, 0.5 and 0.1, respectively. In the simulation, the amplitude and period were measured. In the case of A=0, the VDP equation operated as the damped oscillation. Oscillatory solutions are always obtained from the VDP equation in the range of $A<B$. Fig. 3 shows that the amplitude and period of the limit cycle could be independently controlled by adjusting the parameters A and B.

From these results, it is confirmed that the VDP equation has a limit cycle and an independent controllability. It is considered that the features must suit the CPG model well [7].

3. CPG Network Model

In this section, we explain the CPG network with independent controllability in terms of the amplitude and period of the limit cycle, and the phase difference between CPGs. The CPG network comprises some CPGs and one rhythm generator (RG), and can be designed on the basis of the VDP equation.

3.1 CPG model

The proposed CPG model holds the feature of the VDP equation. The ith CPG model(CPG$_i$) is written as eq. (7).

$$\frac{d^2x_i}{dt^2} - 2\epsilon\left(A^2 - x_i^2\right)\frac{dx_i}{dt} + B_i^2x_i = 0 \tag{7}$$

Here, the parameter ϵ is a small constant and is called a nonlinearity coefficient. x_i is the output signal of CPG$_i$ (i= 1, 2,$\cdots$, n). A and B_i determine the amplitude and period of x_i in the stable state, respectively. The amplitude and period are independently controlled by the parameters A

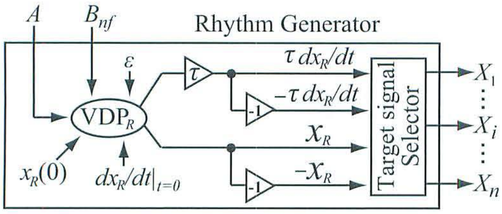


Fig. 6 Block diagram of rhythm generator

Table 1 Combinations of c_{i1} and c_{i2}

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	$[1, 0]$	$[0, -1]$	$[0, 1]$	$[-1, 0]$

and B_i, respectively [7], [14]. In particular, 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 design the CPG network, the phase difference between CPGs must be controlled. To control the phase difference, in this study, the phase of each CPG is temporally shifted. The parameter B_i represented in the following equation is utilized to control the phase.

$$B_i = B_{nf} + b_i \tag{8}$$

Here, B_{nf} denotes the natural frequency of each CPG. The phase shift of each CPG is controlled by the parameter b_i. When we define the target signal X_i that has a desired signal of the ith CPG x_i, the parameter b_i is operated as shown in eq. (9).

$$b_i = k(x_i - X_i) \tag{9}$$

Here, k denotes the gain factor and can control the time until the stable state is reached. b_i is proportional to the phase difference between the target signal X_i and the output signal x_i. After the phase difference $(x_i - X_i)$ becomes 0, b_i approaches 0. The parameter k always takes 1 in this paper. The reason for this will be discussed in section 4.

The block diagram of CPG$_i$ is shown in Fig. 4. X_i, k, b_i and ϵ denote the target signal, the gain factor, the value proportional to the phase difference $(x_i - X_i)$, and the nonlinearity coefficient, respectively. The period of the output signal x_i is controlled by adjusting b_i so that the phase difference between the control and target signals becomes 0. When the target signal is obtained in advance, the phase of the output signal x_i can be temporally shifted in the CPG model.

3.2 Rhythm generator

In order to define the desired target signals for quadrupedal gaits, in this section, the rhythm generator

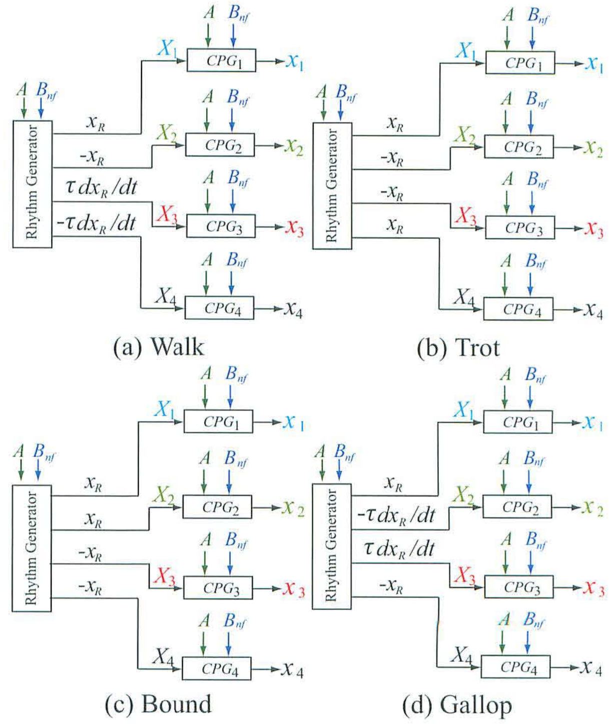


Fig. 7 Configurations of CPG network

(RG) is proposed. We define that the waves of LF, RF, LH, and RH are calculated and controlled by CPG$_1$, CPG$_2$, CPG$_3$, and CPG$_4$. From Fig. 1, it is found that the types of controlled phase differences are expressed on the basis of LF and are four, which are 0, π, $\frac{\pi}{2}$ and $\frac{3\pi}{2}$. These signals can be generated using the VDP equation because x and $\frac{dx}{dt}$ are always calculated. Fig. 5 shows a block diagram of the VDP equation. The calculation results of x and $\frac{dx}{dt}$ are used as the target signals. For instance, when x and $-\frac{dx}{dt}$ are used as the target signals of X_1 and X_2, respectively, the phase difference between the output signals x_1 and x_2 becomes $\frac{\pi}{2}$. In the same way, these four types of phase difference can be controlled using $\pm x$ and $\pm\frac{dx}{dt}$ as the target signals.

Therefore, the RG can be designed based on the VDP equation using the subscript R.

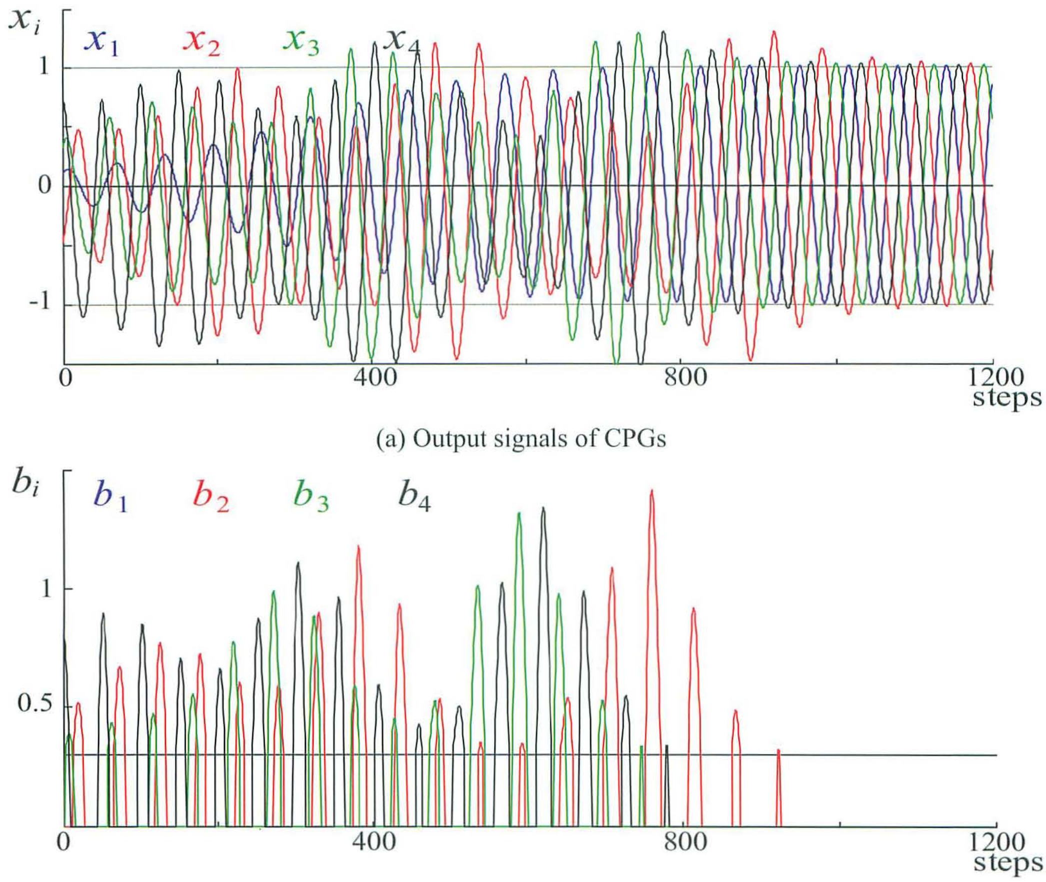
$$\frac{d^2 x_R}{dt^2} - 2\epsilon\left(A^2 - x_R^2\right)\frac{dx_R}{dt} + B_{nf}^2 x_R = 0 \tag{10}$$

The target signal X_i is described in eq. (11). c_{i1} and c_{i2} take -1, 0, or 1 and are decided on the basis of the gait transitions, which we intend to control. c_{i1} or c_{i2} always takes 0.

$$X_i = c_{i1} x_R + c_{i2}\tau\frac{dx_R}{dt} \tag{11}$$

Here, τ determines 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 parameters A and B_{nf} change. τ can be defined as in eq. (12).

$$\tau = \frac{\max(x_R)}{\max(\frac{dx_R}{dt})} = \frac{2A}{\max(\frac{dx_R}{dt})} \tag{12}$$



(a) Output signals of CPGs

(b) Transition of b_i

Fig. 8 Simulation result in walk mode

Here, the max function $max(\cdot)$ denotes the amplitude of each signal of x_R and $\frac{dx_R}{dt}$. Since the amplitude of x_R is controlled by adjusting the parameter A, $\max(x_R)$ can be rewritten as $2A$. On the other hand, $\max(\frac{dx_R}{dt})$ is measured from the simulation results, because it cannot be estimated beforehand. Fig. 6 shows a block diagram of the RG. The parameters A and B_{nf} of the RG are equal to those of the CPG in Fig. 4. The desired target signal of the CPG is selected by a target signal selector. The function of the selector is expressed by c_{i1} and c_{i2} as eq. (11). For instance, $-x_R$ is assigned as the target signal X_i, and a combination of c_{i1} and c_{i2} is decided as $c_{i1}=-1$ and $c_{i2}=0$.

The output signal x_i controls the stepping movements of the ith single limb. In this research, interlimb coordinations, such as the phase relations between limbs, are discussed. Interlimb coordinations result from the coupling between the CPGs and the RG. The architectural differences between the CPGs and the RG are in terms of whether or not the target signal X_i is input and the number of signals that are pulled out from the ith CPG and RG. In other words, one signal is output as the output signal x_i from the ith CPG and n signals are output as target signals of CPGs from the RG.

3.3 CPG network

The proposed CPG network can be composed of one RG and n CPGs on the basis of gait transition. The connections of the CPG network can be logically and uniquely determined based on gait transition. The procedure for designing the CPG network in the walk mode is represented as follows:

1. The RG and n CPGs are prepared. In this paper, the number of CPG is four, because we aim to fabricate quadrupedal locomotion signal generators (n=4).
2. The parameters A and B_{nf} are input in the RG and CPGs. Because of this configuration, each CPG can feature 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 determined on the basis of a gait transition. In this paper, we focus on the walk mode.

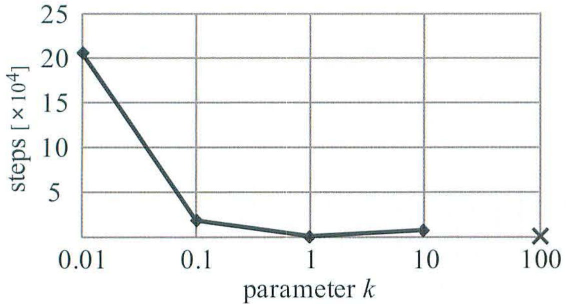


Fig. 9 Relationship between the parameter k and number of steps until reaching the stable state

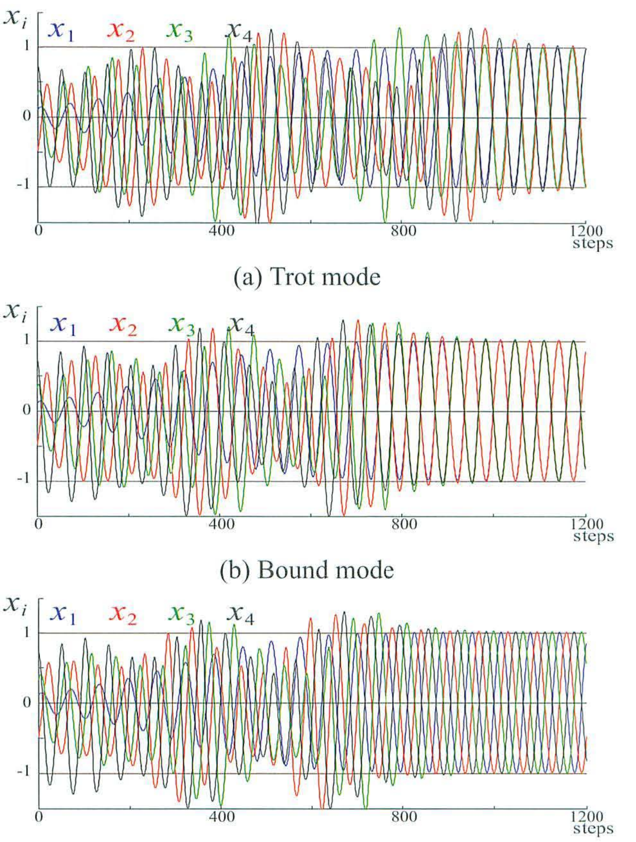
5. x_R is selected as the target signal X_1. This process is common in other gait modes. The output signal of CPG_1 works as the reference signal for calculating the phase differences between CPG_1 and the other CPGs. (c_{11}=1, c_{12}=0)
6. The output signal x_2 controls the RF. Since the phase difference between LF and RF is π, $-x_R$ is selected as the target signal of X_2. (c_{21}=−1, c_{22}=0)
7. $\tau\frac{dx_R}{dt}$ is selected as 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 as the target signal of X_4, because the phase difference between LF and RH is $\frac{\pi}{2}$. (c_{41}=0, c_{42}=−1)

The configuration of the CPG network in the walk mode is presented in Fig. 7(a). In the walk mode, c_{11}=1, c_{12}=0, c_{21}=−1, c_{22}=0, c_{31}=0, c_{32}=1, c_{41}=0, and c_{42}=−1. In the same way, the CPG network can be logically and uniquely decided in the trot, bound, and gallop modes, as shown in Figs. 7(b)-(d). Table 1 shows the combinations of c_{i1} and c_{i2} in typical quadrupedal locomotion signals.

If the other gaits such as six- or eight-leg locomotion signals can be defined by the four types of phase difference, the proposed CPG network can also be applied in these multilegged locomotion signal generators by a similar procedure. For instance, it is well known that one of the typical gaits of a walking stick, which is a six-legged insect, is an alternating tripod gait. A locomotion signal for the gait can also be designed using the proposed CPG network because locomotion signals can be denoted by two types of phase difference, which are 0 and π.

4. Simulations and Discussion

In order to verify the effectiveness of the proposed method, the output signal of each CPG was investigated with the 4th-order Runge-Kutta method. In this paper, we aim to obtain typical quadrupedal gaits, which are the walk, trot, bound, and gallop modes. The parameters A and B_{nf} are provided by external signals.



(a) Trot mode

(b) Bound mode

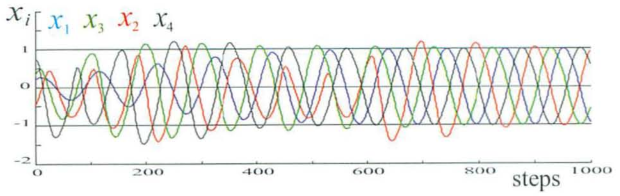
(c) Gallop mode

Fig. 10 Output signal of CPGs in (a) trot, (b) bound, and (c) gallop modes

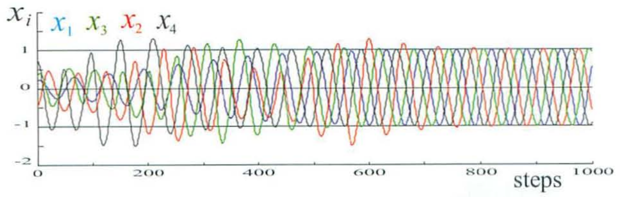
Figs. 8(a) and 8(b) show the simulation results of the walk mode. In these simulations, ϵ, k, and the initial values of x_R, x_1, x_2, x_3, and x_4, and $\frac{dx_R}{dt}$, $\frac{dx_1}{dt}$, $\frac{dx_2}{dt}$, $\frac{dx_3}{dt}$, and $\frac{dx_4}{dt}$ were 0.2, 1, 0.1, 0.1, −0.5, 0.3, 0.7, 0.1, 0.1, 0.3, 0.3, and 0.2, respectively. A and B_{nf} are 0.5 and 1, respectively. The output values of CPGs and b_n were measured up to 1200 steps. In Fig. 8(a), it is confirmed that the amplitude of the limit cycle becomes almost $2A$ and the phase differences between CPGs are controlled, as shown in Fig. 1. In Fig. 8(b), it is found that b_i becomes 0 after the phase of each x_i was controlled by adjusting the target signal X_i. In this simulation, the operation that the value of b_i omits 0.3 or less was added, because X_i is not necessarily equal to x_i. In Fig. 8(b), the horizontal line indicates that b_i=0.3.

Fig. 9 shows the relationship between the parameter k and the number of steps to reach the stable state. The simulation conditions were the same as those of the walk mode excluding k. The steps were measured at k=0.01, 0.1, 1, 10, and 100. Oscillatory solutions were not obtained in the case of k=100. In the simulation results, it is observed that the steps are shortest at k=1. Therefore, for simplicity, k was always set to 1 in the following experiments.

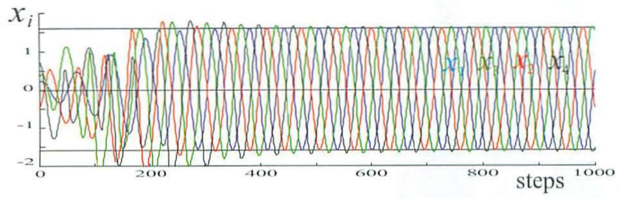
Fig. 10 shows the simulation results of three gait modes: the trot, bound, and gallop modes. The simulation



(a) $A = 0.5$ and $B_{nf} = 0.6$, T=105 (steps)

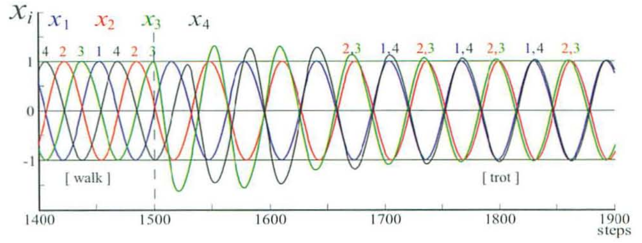


(b) $A = 0.5$ and $B_{nf} = 1$, T=62 (steps)

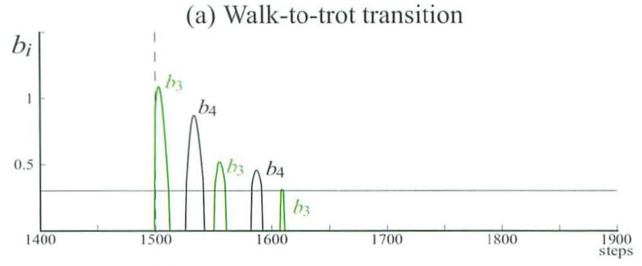


(c) $A = 0.8$ and $B_{nf} = 1$, T=63 (steps)

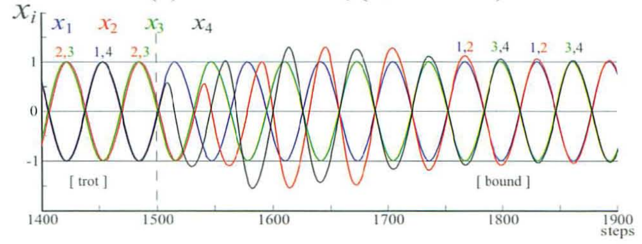
Fig. 11 Output signals of CPGs with various parameter arrangements in walk mode



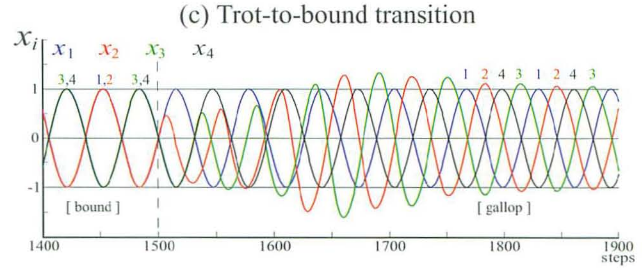
(a) Walk-to-trot transition



(b) Transition of b_i (walk-to-trot)



(c) Trot-to-bound transition



(d) Bound-to-gallop transition

Fig. 12 Gait transitions

conditions were the same as those in the walk mode. From the simulation results, it is found that the phase differences between the CPGs were controlled as the gait transition in Fig. 1 and that the amplitude of the limit cycle became almost $2A$. From Figs. 8 and 10, it is confirmed that the proposed CPG network generates and controls typical quadrupedal locomotion signals.

In Fig. 11, the output values of each CPG were measured under several values of A and B_{nf}. In this simulation, ϵ, dt, k, and the initial values of x_R, x_1, x_2, x_3, and x_4, and $\frac{dx_R}{dt}$, $\frac{dx_1}{dt}$, $\frac{dx_2}{dt}$, $\frac{dx_3}{dt}$, and $\frac{dx_4}{dt}$ were 0.2, 0.1, 1, 0.1, 0.1, −0.5, 0.3, 0.7, 0.1, 0.1, 0.3, 0.3, and 0.2, respectively. From Fig. 11, it is confirmed that the period was inversely proportional to the parameter B_{nf} and that the amplitude reached a steady state, $2A$ (solid lines), with the phase difference being held at $\frac{\pi}{2}$, which is the walk mode. Moreover, both amplitude and period are independently controlled. T describes the period of each output signal.

By changing the combinations of c_{i1} and c_{i2}, some gait transitions could be obtained with the proposed CPG network. Fig. 12 shows part of the simulation results: the walk-to-trot, trot-to-bound, and bound-to-gallop transitions. The combinations were changed after 1500 steps on the basis of Table 1. In this simulations, the ϵ, k, and the initial values of x_R, x_1, x_2, x_3, and x_4, and $\frac{dx_R}{dt}$, $\frac{dx_1}{dt}$, $\frac{dx_2}{dt}$, $\frac{dx_3}{dt}$, and $\frac{dx_4}{dt}$ were 0.2, 1, 0.1, 0.1, −0.5, 0.3, 0.7, 0.1, 0.1, 0.3, 0.3, and 0.2, respectively. A and B_{nf} were 0.5 and 1, respectively. It is confirmed that the phase differences between the CPGs were controlled as the gait transition in Fig. 1, and it took about 200 steps for the gait transition.

Fig. 12(b) shows the transition of b_i in the walk-to-trot transition. In the transition, only b_3 and b_4 were changed, because the target signals X_3 and X_4 must be changed to obtain the walk-to-trot transition. In Fig. 12(b), the horizontal line indicates that b_i=0.3. b_i omitted 0.3 or less, because X_i did not always correspond to x_i. Four numbers from 1 to 4 in the figures denote the number of the output signals x_i. The simulation results show that each gait transition can be successfully obtained.

5. Conclusions

In this paper, we proposed a CPG network with independent controllability for a quadrupedal locomotion signal generator. The proposed model comprises several CPGs and one rhythm generator (RG). Each CPG and the RG are described by the van der Pol equation. The amplitude and period of the output signal from each CPG and the RG were independently controlled by external signals. Moreover, in order to control the phase shift between CPGs, the period of each output signal is temporarily controlled through connections that are only conjunctions between RG and each CPG. The proposed CPG network was applied in the quadrupedal locomotion signal generator. From some simulation results, it was confirmed that the desired output signals could be obtained, and that the proposed model holds the feature of independent controllability in terms of the amplitude and period of each output signal, and the phase difference between CPGs even after some gait transitions. If some gaits for multilegged locomotion signals can be defined by the four types of phase difference, the proposed CPG network can also be applied in multilegged locomotion signal generators.

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Tatsuji Tokiwa received his B. Eng. and M. Eng. degrees from Kyushu Institute of Technology, Japan in 2004 and 2006, respectively, where he is currently working toward his Ph.D. degree. His research interests include signal prosessing, central pattern generator and robotics.

Takeshi Yamakawa received his B. Eng. degree in electronics engineering in 1969 from Kyushu Institute of Technology, Tobata, and his M. Eng. degree in electronics engineering in 1971 from Tohoku University, both in Japan. He received his Ph.D. degree for his studies of electrochemical devices in 1974 from Tohoku University, Japan. He was a former Associate Professor at Kumamoto University. He joined the faculty of Computer Science and Systems Engineering, Kyushu Institute of Technology (KIT), Iizuka, Japan as a Professor in April, 1989. He established a national foundation, the Fuzzy Logic Systems Institute (FLSI), in Japan in 1990. He is currently the vice chairman of FLSI and also a Professor of the Faculty of Life Science and Systems Engineering of KIT, Wakamatsu, Kitakyushu, Japan. His main research interest is in hardware implementation of fuzzy systems, fuzzy neural networks, chaotic systems and self-organizing systems as well as micro-devices for biochemical analysis. He holds 11 patents in the U.S.A., 4 patents in Europe, 1 patent in Australia and 1 patent in Taiwan; he has also applied for more than 90 patents in Japan. He received fifteen awards such as the International MOISIL Prize and the Gold Medal in 1994. Dr. Yamakawa is a Fellow of the International Fuzzy Systems Association (IFSA) and Japan Society of Fuzzy Theory and Intelligent Informatics (SOFT), and a senior member of IEEE. He is a member of the editorial board and a regional editor of 10 international professional journals. He contributed to more than 80 international conferences as an organizer or a member of the organizing/programming committee. He has served and is currently serving as the chairman of various academic societies and institutes.

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