Journal of Signal Processing, Vol. 13, No. 4, pp. 315-318, July 2009

SELECTED PAPER

Central Pattern Generator Network with Adaptability to Changing Situations

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Abstract

A central pattern generator (CPG) network with adaptability to changing situations is proposed in this paper. The proposed network can generate some locomotion signals even after some legs are broken. In order to verify the effectiveness of the proposed method, a hexapod robot is designed and the proposed CPG network is implemented on the robot. Through some simulations, we confirm that the designed robot can walk on a flat ground and continue walking even if the number of active legs is changed.

1. Introduction

It is well known that locomotion signals, such as for walking, running, swimming and flying, are generated and controlled by the central nervous system, the central pattern generator (CPG) [1]. These locomotion signals can be classified into some periodic patterns that correspond to gaits. A CPG network with independent controllability has been proposed [2]. This network has been applied to a quadruped locomotion signal generator which generates typical quadruped locomotion signals, which are the walk, trot, bound and gallop mode. We confirmed that the CPG network can independently control the amplitude and period of output signals from each CPG and phase differences between CPGs.

However, the CPG network could not adapt to an environmental change such as a change in the number of active legs. It is well known that stick insects sometimes remove their legs by themself for escaping from their enemies. And then new legs regenerate through repeating their molting. Under these conditions, they can generate an optimum locomotion signal depending on the situations. In order to imitate this insect behavior, in this paper, we partly modify the CPG network. We consider that the proposed method is suitable for hexapod robots even after a number of legs are broken. The proposed model will contribute to design a robot which has a feature of fault tolerance.

2. CPG Network Model

The CPG network [2] that has high controllability comprises several CPGs and one rhythm generator(RG). The CPG can be represented by Eq. (1) and was derived from the Van der Pol (VDP) equation [3]. The VDP equation has a limit cycle and independent controllability for both the amplitude and the period of the limit cycle. The feature of high controllability must suit the CPG model well. Therefore, we adapted the VDP equation as the CPG model.

2.1 CPG model

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

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

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). The value of the amplitude and period of x_i in the stable state can be controlled by parameters A and B_i, respectively [2]. 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 control the phase difference between CPGs, the phase of each CPG must be temporally shifted. The parameter B_i represented in the following Eq. (2) is utilized to control the phase.

$$B_i = B_{nf} + b_i \qquad (2)$$

$$b_i = k(x_i - X_i) \qquad (3)$$

Here, X_i, B_{nf} and k denote a target signal, natural frequency of the CPGs and gain factor, respectively. The target signal is an oscillation which has a desired phase difference of CPG$_i$ and is assigned by designers beforehand. The assigned method is discussed in chapter 2.2. The value of b_i determines the amount of phase shift of CPG$_i$. After the value of the phase difference between the output signal x_i and target signal X_i becomes 0, the value of b_i approaches 0. The value of k can control the time taken to attain the stable state.

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

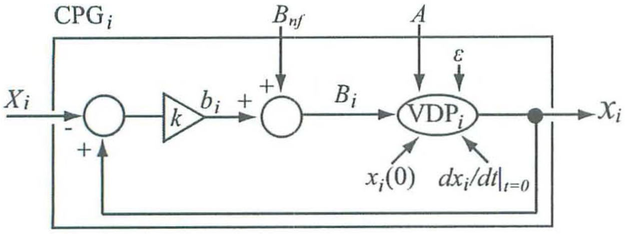


Figure 1: Block diagram of CPG$_i$

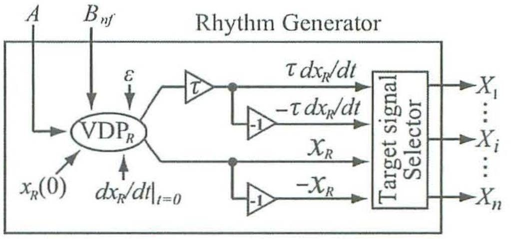


Figure 2: Block diagram of rhythm generator

Moreover, in order to add a feature of the adaptability to changing situations, another phase control method is proposed. The method can control the phase differences of x_i to be $\frac{2\pi}{n_a}$. n_a represents the total number of legs which are nonbroken legs. It is well known that the output signals that have a phase difference of $\frac{2\pi}{n_a}$ can be used as locomotion signals, because, in a case of four or more legged robots, three or more legs always stand on the ground during locomotions. Because the sum of all output signals with phase differences of $\frac{2\pi}{n}$ is always 0, the parameter b_i is controlled such that the sum becomes 0. The operation can be described as follows.

$$b_i = \pm\frac{\Sigma_{i=1}^{n} x_i}{n_a} \tag{4}$$

Here, n_a represents the total number of legs which are considered as nonbroken legs. In this case, the output signals x_i of the broken legs are assigned as 0. If one or more legs are broken, parameter b_i is calculated on the basis of not Eq. (3) but Eq. (4).

2.2 Rhythm generator

The rhythm generator (RG) is designed as the target signal generator X_i and on the basis of the VDP equation.

$$\frac{d^2x_R}{dt^2} - 2\epsilon\left(A^2 - x_R^2\right)\frac{dx_R}{dt} + B_{nf}^2 x_R = 0 \tag{5}$$

Either $\pm x_R$ or $\pm\frac{dx_R}{dt}$ is used as the target signals X_i of each output signals x_i. The method of deciding X_i is represented as Eq. (6). 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. For instance, when $-x_R$ is selected for the target signal X_i, the combination of c_{i1} and c_{i2} is set to be $c_{i1}=-1$ and $c_{i2}=0$.

$$X_i = c_{i1}x_R + c_{i2}\tau\frac{dx_R}{dt} \tag{6}$$

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 parameters A and B_{nf} are changed. τ can be defined as Eq. (7).

$$\tau = \frac{\max(x_R)}{\max(\frac{dx_R}{dt})} = \frac{2A}{\max(\frac{dx_R}{dt})} \tag{7}$$

Here, $max(\cdot)$ is the max function. Since the amplitude of x_R is controlled by 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 taken from simulation results, because the value cannot be estimated beforehand. Figure 2 shows the block diagram of the RG. The values of parameters A and B_{nf} of the RG are equal to those of the CPG in Figure 1. The desired target signals of the CPGs are selected by the target signal selector in Figure 2. The function of the selector is expressed as Eq. (6).

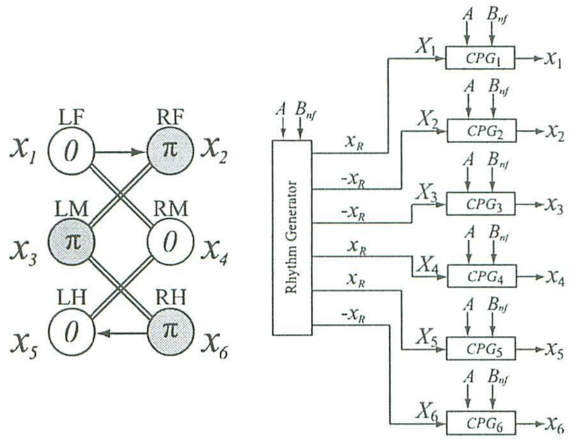
3. Development of Hexapod Robot

In order to apply the CPG network, the hexapod robot termed Yamac-H is designed. In this chapter, the specification of the robot and the configuration of the CPG network for generating a tripod gait are introduced.

3.1 CPG network design for Yamac-H

Figure 3(a) shows the gait transition termed the tripod gait which is a typical gait of hexapod animals. LF, LM, LH, RF, RM, and RH stand for left foreleg, left middle leg, left hind leg, right foreleg, right middle leg and right hind leg, respectively. The arrows in Figure 3(a) represent the directions of phase transitions. We define that the output signals of CPG$_1$, CPG$_2$, CPG$_3$, CPG$_4$, CPG$_5$, and CPG$_6$ are sent to the LF, RF, LM, RM, LH and RH, respectively. The configuration of the CPG network can be logically and uniquely decided on the basis of the gait transition. The procedure for designing the CPG network in the tripod gait is represented as follows.

1. One RG and 6 CPGs are prepared. The number of CPGs corresponds to the number of legs.
2. Parameters A and B_{nf} are input to the RG and CPGs. Because of this structure, each CPG can obtain independent controllability in terms of the amplitude and period of the output signal x_i.



(a) Gait transition (b) Network configuration

Figure 3: Gait transition and network structure of tripod gait

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 on the basis of the gait transitions. In this study, the target signal X_i is designed on the basis of the gait transition (Figure 3(a)).
5. x_R is selected as the target signal X_1. The output signal of CPG$_1$ acts 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. $-x_R$ is selected for the target signal of X_3, because the phase difference between LF and LM is π. (c_{31}=−1, c_{32}=0)
8. x_R is also selected for the target signal of X_4, because the phase difference between LF and RM is 0. (c_{41}=1, c_{42}=0)
9. x_R is selected for the target signal of X_5, because the phase difference between LF and LH is 0. (c_{51}=1, c_{52}=0)
10. The output signal x_6 controls the RH. Since the phase difference between LF and RH is π, $-x_R$ is selected for the target signal of X_6. (c_{61}=−1, c_{62}=0)

The configuration of the network is represented in Figure 3(b). Figure 4 shows a simulation result of the CPG network. In this simulation, ϵ, dt and k were 0.2, 0.1 and 1. Parameters A and B_{nf} were 0.5 and 1, respectively. Initial values of x_i and $\frac{dx_i}{dt}$ were decided randomly. And the following values were selected. x_R=0.4, x_1=0.1, x_2=−0.3, x_3=0.4, x_4=−0.1, x_5=−0.4, x_6=0.7, $\frac{dx_R}{dt}$=0.5, $\frac{dx_1}{dt}$=0.2, $\frac{dx_2}{dt}$=0.3, $\frac{dx_3}{dt}$=−0.3, $\frac{dx_4}{dt}$=−0.2, $\frac{dx_5}{dt}$=0.3 and $\frac{dx_6}{dt}$=−0.1. The simulation result represents that the phase differences of output signals are accurately controlled to be 0 or π in a stable state as shown by Figure 3(a).

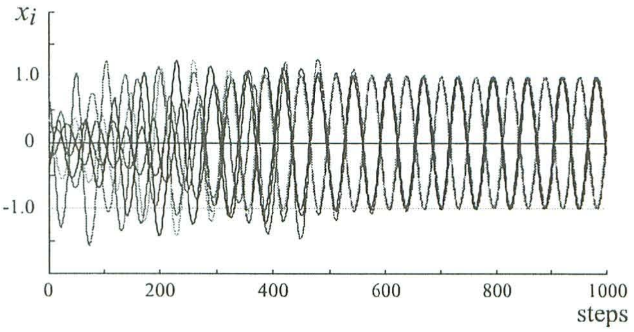


Figure 4: Simulation results of tripod gait

3.2 Hexapod robot Yamac-H

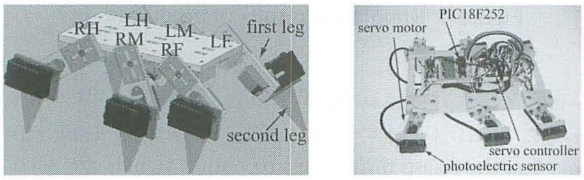
In order to implement the proposed CPG network, the hexapod robot called Yamac-H has been designed. Figure 5 shows the designed 3D robot and the actual robot. The blueprint was designed with software named Autodesk Inventor. Each part of the robot was made of acrylonitrile-butadiene-styrene (ABS) resin shaped into the desired size with an NC cutting machine. The robot has 6 legs with two links in each leg. The components of Yamac-H is shown by Table 1. The tip of each leg has a photoelectric sensor that can detect the timing when the tip of the leg collides with the ground. The sensors are utilized as a tool for detecting a change in the number of legs. The proposed CPG network is calculated with a Peripheral Interface Controller (PIC) with the product number PIC18F252. The first legs are controlled by the output signals x_i from CPGs. Each second leg is moved in accordance with the movement of the first leg. The peripheral circuit of the PIC is represented in Figure 6. The power supplies of 9[V], 7.2[V] and 12[V] are assigned for controlling the motor controller, servo motors and sensors, respectively. A power supply for controlling the PIC can be obtained from the servo controller as an output voltage.

4. Simulation Results

In order to verify the effectiveness of the proposed method, operations of the CPG network were investigated by a 4th-order Runge-Kutta method. In this simulation, ϵ, dt and k were 0.2, 0.1 and 1, respectively. As has been mentioned, for the hexapedal locomotion generator, c_{11}, c_{21}, c_{31}, c_{41}, c_{51}, c_{61}, c_{12}, c_{22}, c_{32}, c_{42}, c_{52}, and c_{62} were decided as 1, -1, -1,

Table 1: List of Yamac-H components

Name	Model name	no.
Servo motor	Futaba S3110	12
Servo controller	AGB65-RSC	1
PIC	PIC18F252	1
Battery	Kyosho Ni-MH Racing Battery	1
Cell	Alkaline Battery (9V)	1
Sensor	Keyence PZ-V11	6



(a) Robot 3D design (b) Robot appearance

Figure 5: Designed hexapod robot

1, 1, -1, 0, 0, 0, 0, 0 and 0, respectively. Parameters A and B_{nf} were 0.5 and 1. Initial values of x_i and $\frac{dx_i}{dt}$ were randomly decided. In this simulation, the following values were assigned: x_R=0.1, x_1=0.1, x_2=−0.5, x_3=0.3, x_4=0.7, x_5=0.1, x_6=0.3, $\frac{dx_R}{dt}$=0.1, $\frac{dx_1}{dt}$=0.1, $\frac{dx_2}{dt}$=0.3, $\frac{dx_3}{dt}$=0.3, $\frac{dx_4}{dt}$=0.4, $\frac{dx_5}{dt}$=0.2 and $\frac{dx_6}{dt}$=0.2.

Figure 7 shows a simulation result of the tripod gait including the change of situation. We can confirm that, up to 1500 steps, phase differences were controlled with either 0 or π. In addition, from 1500 steps to 3000 steps, 5-leg locomotion signals, that are phase differences with $\frac{2\pi}{5}$ were accurately generated. Finally, after 3000 steps, phase differences between CPGs were controlled again to either 0 or π for the hexapedal locomotion signal, that is, the tripod gait.

The above results include the proposed method has a feature that it can generate a locomotion signal even if the number of legs is changed. We consider that the feature is highly suitable as a locomotion signal generator for the implementation of autonomous hexapod robots

Moreover, the output signals x_i as shown by Figure 4 and Figure 7 were implemented to Yamac-H, and, through those experiments, we confirmed that the hexapod robot can continue walking on a flat ground even if the number of legs is changed.

5. Conclusions

We proposed a central pattern generator network with adaptability to changing situations. The network was implemented on a hexapod robot termed Yamac-H. Through experiments, it was confirmed that the hexapod robot can continue walking even when a number of active legs are changed. We emphasize that the proposed network will contribute to the improvement of fault tolerance in robotics.

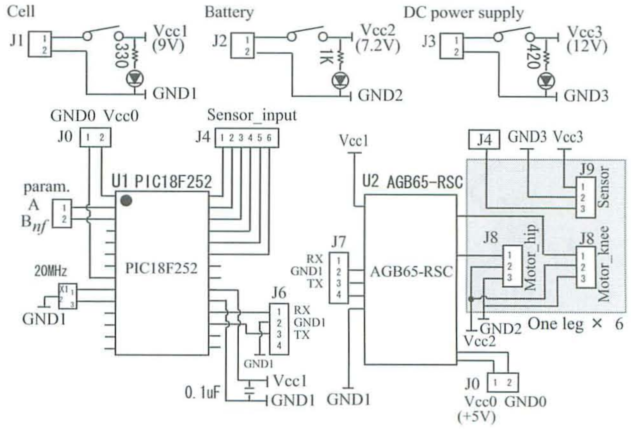


Figure 6: Circuit design

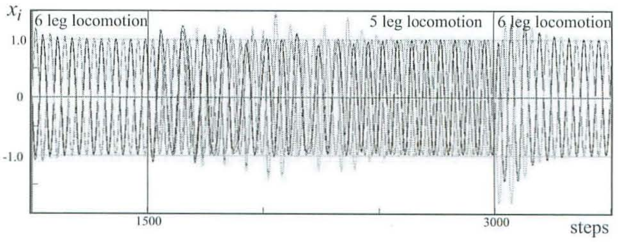


Figure 7: Output signals of tripod gait including the change of situation

Acknowledgment

This work was supported by a Grant-in-Aid for Specially Promoted Research (Project No.20001008) granted by the MEXT of Japan.

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