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3D Locomotion of a Snake-like Robot Controlled by Cyclic Inhibitory CPG Model

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***Abstract*— With 3D (3-dimensional) movement's ability and rhythmic locomotion mode, a nature snake makes itself survive in rugged terrains. The rhythmic activities of most creatures are generated by the CPG (Central Pattern Generator). Based on this fact, the sustained-type neuron has been adopted to construct a cyclic inhibitory CPG model for a snake-like robot whose joints are perpendicularly connected in series. Having compared with the sustained-type neuron and the mutual inhibitory CPG, the cyclic inhibitory CPG was proven to generate capably rhythmic output with the least number of differential equations. In this paper, we introduce the neuron network organized by the cyclic inhibitory CPGs connected in line with unilateral excitation to control the 3D locomotion of a snake-like robot, and present the necessary condition for the CPG neuron network to sustain a rhythmic output. By implementing this control architecture to a simulator with consideration of mechanical dynamics of a real snake-like robot "Perambulator", preliminary parameter setting of the CPG neuron network for its 3D locomotion is obtained. Moreover, it is shown that "Perambulator" can successfully exhibit 3D locomotion by using the output of the proposed CPG network. The obtained results have also provided a bran new approach to understand the unknown neuron network of nature snakes.**

Index Terms - Snake-like robot, 3-dimensional locomotion, cyclic inhibition, central pattern generator (CPG), stability analysis

I. Introduction

With 3D movement's ability and rhythmic locomotion mode, a nature snake makes itself survive in rugged terrains [1]. For example, sinus-lifting is observed during the regularly creeping locomotion at high speed. The snake raises part of the body that is at the peak of the body curve, which in dynamic terms is seen to be the result of an adaptive redistribution of the body weight. Side-winding locomotion is the gliding method that the snakes lift part of their body while gliding and propelling themselves like a tumbling spiral coil. It can improve the locomotion efficiency on the sands where sliding friction resistance is small. All these are the familiar modes of 3D locomotion observed in snakes. The snake-like robot research to imitate the structure and locomotion of the nature snake has been paid more attention and much work has been done by the researchers all over the world. ACM-R3, a snake-like robot developed by Hirose's group can realize many kinds of 3D locomotion through the shape imitation in 3-dimensional spaces [2]. GMD-SNAKE2, a robot for inspection tasks in terrains where are difficult to access by humans, is applicable not only to snake-like movement but also to the wheeled robot which is able to control the curvature of its path [3]. The serpentine robot developed by Ma's group is composed of the novel designed joints with coupled-driven mechanism which providing more powerful torque under the same condition, and therefore allowing it to perform some kinds of locomotion effectively in 3-dimensional space [4].

The common movements of the nature snake [5] are some kinds of rhythmic movements. Most rhythmic patterns in the locomotive motion of animals (such as locomotion of quadruped animals, flying of birds, and swimming of fish) are generated in CPG (Central pattern generator), and basically any sensory signal is unnecessary to produce them [6]. In recent years, a couple of models have been proposed to demonstrate the neural rhythm of CPG. The CPG model widely adapted to control the locomotion of animal like robot [7] is the mutual inhibitory CPG proposed by Matsuoka [8], and was adopted by Ma's group to control the 2D locomotion of the snake-like robot [9]. However it is hard to control the 3D locomotion of the snake-like robot. Since the neurons in the mutual inhibitory CPG must have adaptation to sustain a rhythmic output, the number of the calculation in the control system is a serious problem.

In this paper a new type cyclic inhibitory CPG model was proposed to control the locomotion of the snake-like robot whose joints are perpendicularly connected in series. The mechanism of the rhythm generation in this cyclic inhibitory CPG is completely different from which in the mutual inhibitory CPG. The cyclic inhibitory CPG does not necessitate adaptation but only strong cyclic inhibition for the rhythm generation. The combined joint is controlled by the output of the combination of each two different neurons in this CPG model, which make the number of the differential equations in the neural control system reduced at least 50%. As a result the computation in the system decreased greatly.

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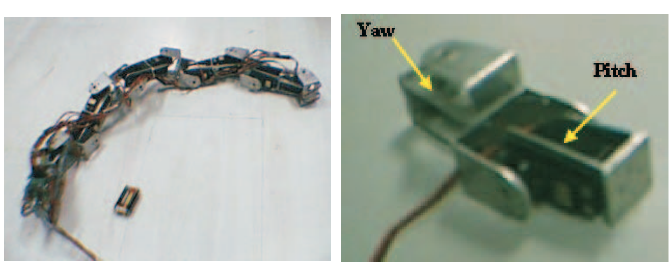
The reminder of this paper is organized as follows: In section II, we specify the structure of the snake-like robot named "perambulator". The proposed cyclic inhibitory CPG is defined in section III. In section IV, the control architecture constructed by the cyclic inhibitory CPGs is adopted to control the 3D locomotion of the snake-like robot. Moreover, the dynamic simulations carried out to verify the proposed architecture for the robot to realize 3D motion are addressed in section V. In section VI, an experimental result is presented to show the validity of the proposed method. Finally, the conclusion of this paper is discussed in section VII.

II. STRUCTURE OF "PERAMBULATOR"

"Perambulator" is the snake-like robot developed in Robotics Laboratory, Shenyang Institute of Automation, Chinese Academy of Sciences. It is constructed by a head unit and several joints with rotating axis connected perpendicularly, as shown in Fig.1a. Its parameters are shown in Table I. The rotational data of each joint is sent from the head unit through a COM of the computer. Then it is converted into a PWM signal of the joint's motor. The combined joint is specified as a pair of joints perpendicularly connected in the direction of rotational axis, as shown in Fig.1b. The 3D locomotion of the snake-like robot is realized through the rotation of the combined joints.

TABLE I
PARAMETERS OF "PERAMBULATOR"

Shape of a unit	Rectangular solid
Dimension of a unit [m]	0.07×0.055×0.055
Workspace of a unit [deg]	± 90
Mass of a unit [kg]	0.2
Mass of a head [kg]	0.4
Gross mass [kg]	2.0
Maximum Velocity [deg/s]	273
Gross length [m]	0.7
Number of unit	8 (Pitch 4,Yaw 4)
Power [w]	0.84
Torque [Nm]	1.2



(a) Whole robot (b) Combined joint

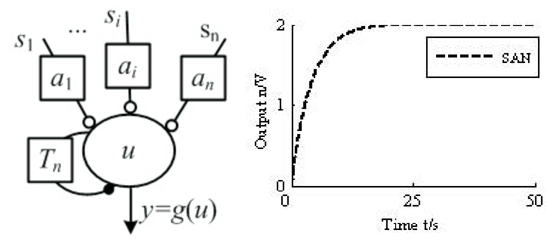
Fig. 1. "Perambulator"

III. CONSTRUCTION OF THE CYCLIC INHIBITORY CPG MODEL

In order to control the combined joint, a new kind of cyclic inhibitory CPG model is proposed in this section. The particular mechanism for it to generate an oscillating output is proven to be the result of the strong cyclic inhibitory connection among the neurons. In this paper, CPG is specified as the minimum functional unit in the motor system, and the isolated neuron does not necessitate adaptation.

A. Sustained-type Neuron Model

Although many types of neuron models have been proposed so far [10], the analog neuron is adopted widely because of its mathematical simplicity. Since this model considers the impulse frequency of a neuron as a continuous variable with time, it is suitable for modeling the neuron in which the impulse frequency changes very slowly in comparison with the impulse interval as in the case of the rhythmic locomotion of the snake. The structure of the SAN (sustained-type of the



(a) Structure (b) Step response

Fig. 2. SAN model

analog neuron) is shown in Fig.2a, and the dynamics of SAN is described as follows:

$$T_n\dot{u} + u = \sum_{i=1}^{n} a_i s_i \qquad (1)$$

$$y = g(u), g(u) = max(0, u) \qquad (2)$$

where u is the membrance potential of the SAN, T_n is the time constant, s_i is the input stimulus ($s_i \geq 0$), a_i is the weight of a synaptic conjunction ($a_i > 0$ for an excitatory synapse and $a_i < 0$ for an inhibitory synapse), and y is the output, respectively. When a step input is given to the SAN, the output increases monotonically with respect to time and approaches to a stationary state, u=s_0=$\sum_{i=1}^{n} a_i s_i$, as shown in Fig.2b. Although adaptation used to be taken as a common behavior of a neuron, in this paper, it is defined as a functional character occurred when the neurons are connected to form a CPG. In the motor system, the neuron which can receive and send stimulus is the least structural unit, and CPG which can generate an oscillating output is the minimal function unit [6].

B. Mutual Inhibitory CPG Model

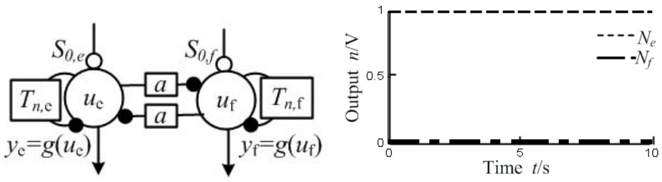
According to the mutual inhibitory theory, we adopt the above SANs to form a CPG, as shown in Fig.3a. This mutual inhibitory CPG is composed of n_e (extensor neuron) and n_f (flexor neuron). The dynamics of the mutual inhibitory CPG is described by the following equations:

$$T_{n,e}\dot{u_e} + u_e = s_{0,e} - ag(u_f) \qquad (3)$$

$$T_{n,f}\dot{u_f} + u_f = s_{0,f} - ag(u_e) \qquad (4)$$

$$y_{\{e,f\}} = g(u_{\{e,f\}}), g(u_{\{e,f\}}) = max(0, u_{\{e,f\}}) \qquad (5)$$

$$c\_out = y_e - y_f \qquad (6)$$



(a) Structure (b) Output of the neurons

Fig. 3. Mutual inhibitory CPG model

where a is the weight of the mutual inhibitory connection; $s_{0,e}$ and $s_{0,f}$ are constant, positive input, each of which is the summation of all inputs to n_e or n_f by the weight of synaptic conjunction, excepting the output of the opposite neuron inner the CPG; u_e and u_f are the corresponding membrance potentials of n_e and n_f; $T_{n,e}$ and $T_{n,f}$ are the corresponding time constants of n_e and n_f; y_e and y_f are the corresponding output of n_e and n_f; and c_out is the output of the CPG.

Throughout the paper we will only deal with the case where the inputs to neurons are positive, since it is obvious that any solution of (3) or (4) converges to a single stationary state if $s_{0,e}$ or $s_{0,f}$ is not positive, as shown in Table II.

TABLE II
STATIONARY SOLUTIONS

Conditions	**Stationary states(u_1, u_2)**	**Stability**
$s_{0,e} < 0, s_{0,f} > 0$	$(s_{0,e} - as_{0,f}, s_{0,f})$	Stable
$s_{0,e} > 0, s_{0,f} < 0$	$(s_{0,e}, s_{0,f} - as_{0,e})$	Stable
$s_{0,e} < 0, s_{0,f} < 0$	$(s_{0,e}, s_{0,f})$	Stable

From a simple calculation, we find out that (3) or (4) has one or three stationary solutions according to the values of a, $s_{0,e}$ and $s_{0,f}$ (Details in reference [11]).

Consequently there is at least one stable stationary solution in each case. Besides, we can prove with Bendixon's theorem that (3) and (4) have no limit cycle, which holds for any continuous function $g(u)$. Thus, they do not yield any oscillatory behavior. The outputs of n_e and n_f in the mutual inhibitory CPG are lines, as shown in Fig.3b. Therefore, the mutual inhibitory CPG without adaptation is not an appropriate model to explain an oscillatory behavior such as the rhythmic locomotion of the snake.

C. Cyclic Inhibitory CPG Model

According to the cyclic inhibitory theory, we adopt the SANs mentioned in section III.A to form a CPG, as shown in Fig.4. This cyclic inhibitory CPG is composed of n_y (yaw neuron), n_p (pitch neuron), and n_m (modulator neuron). The dynamics of the cyclic inhibitory CPG is described by the following equations:

$$T_{n,1}\dot{u_1} + u_1 = s_{0,1} - ag(u_2) \tag{7}$$

$$T_{n,2}\dot{u_2} + u_2 = s_{0,2} - ag(u_3) \tag{8}$$

$$T_{n,3}\dot{u_3} + u_3 = s_{0,3} - ag(u_1) \tag{9}$$

$$y_i = g(u_i), g(u_i) = max(0, u_i) \quad i = 1, 2, 3 \tag{10}$$

$$y\_out = y_1 - y_3 \tag{11}$$

$$p\_out = y_2 - y_3 \tag{12}$$

where a is the weight of the cyclic inhibitory connection; $s_{0,1}, s_{0,2}$ and $s_{0,3}$ are constant, positive input, each of which is the summation of all inputs to n_y, n_p and n_m by the weight of synaptic conjunction, excepting the output of the neurons in the CPG; u_1, u_2 and u_3 are the corresponding membrance potential of n_y, n_p and n_m; $T_{n,1}$, $T_{n,2}$ and $T_{n,3}$ are the corresponding time constant of n_y, n_p and n_m; y_1, y_2 and y_3 are the corresponding output of n_y, n_p and n_m; y_out and p_out are the corresponding output of the CPG to control the yaw rotation and pitch rotation.

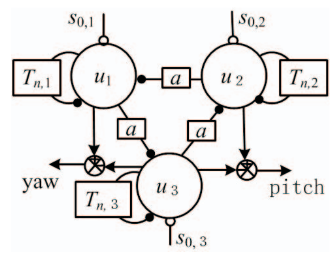


Fig. 4. Cyclic inhibitory CPG model

The most interesting point from the viewpoint of the control of the snake-like robot locomotion is the case where (7), (8) and (9) have no stable stationary solution. The condition for this is given by the following theorems:

Theorem 1. Under the condition $T_{n,1}$=$T_{n,2}$=$T_{n,3}$=τ and $s_{0,1}$=$s_{0,2}$=$s_{0,3}$=0, Equations (7), (8) and (9) have no stable stationary solution, if and only if

$$a \geq 2 \quad or \quad a \leq -1. \tag{13}$$

Proof. Because (7), (8) and (9) are strictly linear in the neighborhood of the stationary states, we can discuss the stability of the stationary states by investigating the characteristic equation of the linear differential equations. The characteristic equation of (7), (8) and (9) with respect to the case of three neurons excited is

$$(\tau\lambda + 1 + a)(\tau^2\lambda^2 + (2 - a)\tau\lambda + (a^2 - a + 1)) = 0 \tag{14}$$

Where λ is the eigenvalue. The condition that the stationary solution is unstable is shown in (13). Conversely if the condition (13) is satisfied, there exists only one stationary states and it is unstable; That is, (7), (8) and (9) have no stable stationary state under the condition (13). Q.E.D

As for the global behavior of (7), (8) and (9) we can prove that any solution does not diverge to infinity with respect to time.

Theorem 2. Any solutions of (7), (8) and (9) are bounded for $t > 0$ under the condition $a \geq 0$.

Proof. Solving the equations in (7), (8) and (9) with respect to u_i, we obtain

$$\begin{aligned} u_i(t) &= \tfrac{1}{\tau}u_i(0)e^{-\frac{t}{\tau}} + \tfrac{1}{\tau}s_{0,i}(1 - e^{-\frac{t}{\tau}}) \\ &-\tfrac{a}{\tau}e^{-\frac{t}{\tau}}\int_0^t g(u_j(x))e^{\frac{x}{\tau}}dx, \quad (i, j = 1, 2; 2, 3; 3, 1) \end{aligned} \tag{15}$$

Since $g(u_j(x))(j=1,2,3)$ is non-negative

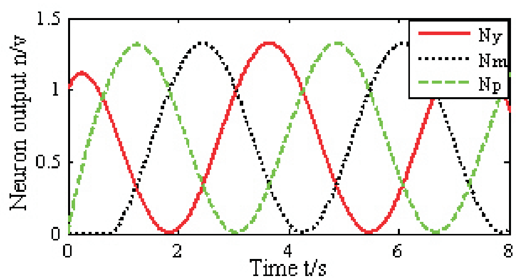
$$u_i(t) \le \frac{1}{\tau}(|u_i(0)| + |s_{0,i}|), \quad i=1,2,3 \qquad (16)$$

Thus we obtain $g(u_j(x))(j=1,2,3)$ is bounded. The range is $[0, max(u_j(t))](t>0)$. (More specifically is $[0, |u_j(0)| + |s_{0,j}|](j=1,2,3)$). Applying this to (15), we obtain

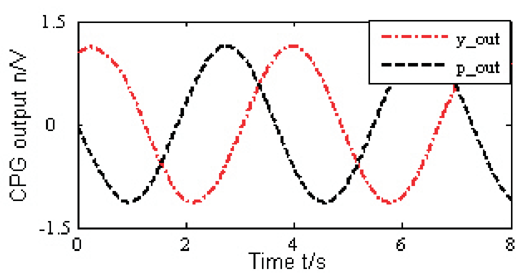
$$\begin{aligned} u_i(t) \ge -\tfrac{1}{\tau}(|u_i(0)| + |s_{0,i}|) - (|u_j(0)| + |s_{0,j}|), \\ (i,j = 1,2;2,3;3,1) \end{aligned} \qquad (17)$$

From (16) and (17) we can conclude that any solution of (7), (8) and (9) is bounded for $a > 0$. Q.E.D

From Theorem 1 and 2 we can know, any solution of (7), (8) and (9) must be in an oscillatory behavior under the condition $a \ge 2$. Fig.5a shows the oscillating solutions of (7), (8) and (9) computed by computer simulation (Runge-Kutta method). We can see that the dominance of the three neurons changes periodically. The oscillating outputs of the cyclic inhibitory CPG are shown in Fig.5b.



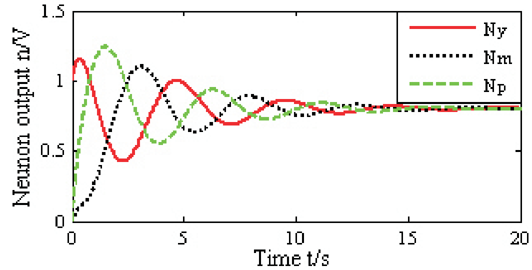
(a) Output of the neurons



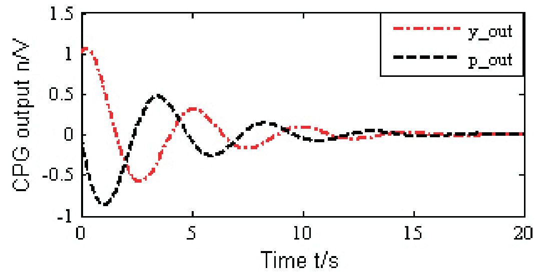
(b) Output of the cyclic inhibitory CPG

Fig. 5. Step response ($T_{n,1}$= $T_{n,2}$= $T_{n,3}$=1, $s_{0,1}$=$s_{0,2}$=$s_{0,3}$=1, a=2)

We also carried out some simulations (Runge-Kutta method) to show that the output of the CPG did not output any oscillating rhythm under the condition $0 \le a < 2$, as shown in Fig.6. The mechanism of the rhythm generation in this cyclic inhibitory CPG is completely different from which in the mutual inhibitory CPG whose neurons must have adaptation, as mentioned in [12]. Here, if n_y is firing, n_p's activity will be suppressed. So n_m will become firing, n_y will be suppressed, and so on. Thus the alternation of the firing neuron is caused by the negative feedback loop of this network. This network, therefore, does not necessitate adaptation but only strong cyclic inhibition for the rhythm generation.



(a) Output of the neurons



(b) Output of the cyclic inhibitory CPG

Fig. 6. Step response ($T_{n,1}$= $T_{n,2}$= $T_{n,3}$=1, $s_{0,1}$=$s_{0,2}$=$s_{0,3}$=1, a=1.5)

IV. CPG CONTROL ARCHITECTURE FOR 3D LOCOMOTION OF THE SNAKE-LIKE ROBOT

The cyclic inhibitory CPGs mentioned in section III.C are connected in series by the single excitatory synapse from head to tail. The CPG network is adopted to construct a controller of the snake-like robot, as shown in Fig.7.

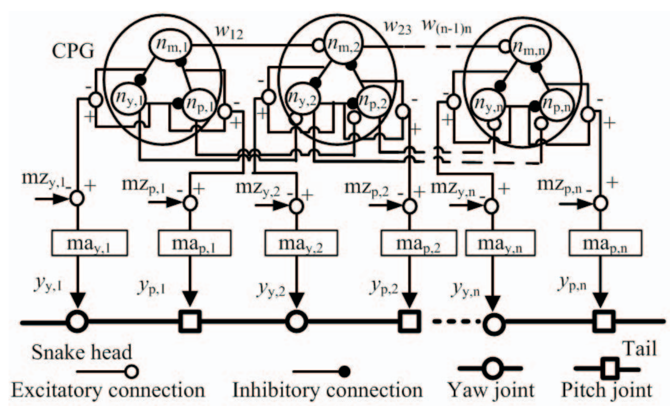


Fig. 7. CPG control architecture of the snake-like robot

The dynamics of the CPG control architecture is described by the following equations:

$$\begin{aligned} T_{\{y,p,m\},i}\dot{u}_{\{y,p,m\},i} = -u_{\{y,p,m\},i} + w_{\{y,p,m\},i}y_{\{m,y,p\},i} \\ + s_{0,\{y,p,m\},i} + \textstyle\sum_{j=1}^{n} w_{ij}y_{\{y,p,m\},j} \end{aligned} \qquad (18)$$

$$c\_out_{\{y,p\},i} = ma_{\{y,p\},i}((ma_{\{y,p\},i} - y_{m,i}) - mz_{\{y,p\},i}) \qquad (19)$$

$$ma_{\{y,p\},i} = \alpha_{max}\frac{\max(y_{\{y,p\},i})}{\max(y_{\{y,p\},j})}, \quad j = 1, ..., n \tag{20}$$

$$mz_{\{y,p\},i} = \frac{\sum_{j=r}^{r+q-1}(y_{\{y,p\},i,j} - y_{m,i,j})}{q} \tag{21}$$

where $u_{\{y,p,m\},i}$ describes respectively membrance potentials of n_y,n_p,n_m of $i-th$ CPG, $T_{\{y,p,m\},i}$ shows respectively time constants of membrance potential of n_y, n_p or n_m of $i-th$ CPG, $w_{\{y,p,m\},i}$ gives respectively connection weight among n_y, n_p or n_m of $i-th$ CPG, w_{ij} is connection weight between $i-th$ and $j-th$ CPG, $s_{0,\{y,p,m\},i}$ are constant, positive input, each of which is the summation of all inputs to n_y,n_p,n_m by the weight of synaptic conjunction, excepting the output of the neuron in the $i-th$ cyclic inhibitory CPG mode, $y_{\{y,p,m\},i}$ are outputs of n_y,n_p,n_m of $i-th$ CPG, $c\_out_{\{y,p\},i}$ are CPG control signal of yaw or pitch joint of $i-th$ combined joint, $ma_{\{y,p\},i}$ are amplitude coefficient of the CPG control signal of yaw or pitch joint of $i-th$ combined joint, $mz_{\{y,p\},i}$ are phase coefficient of the CPG control signal of yaw or pitch joint of $i-th$ combined joint, n is the quantity of CPG in the neuron network, i,j are coefficients, α_{max} is the rotational range of the joint, r is the start point of sampling in the stable region, and q is the sampling range in the stable region.

In order to specify the stability of the neuron system to sustain a rhythm output, we set $T_{\{y,p,m\},i}$=τ; $s_{0,\{y,p,m\},i}$=0; $w_{\{y,p,m\},i}$=α; w_{ij}=w $(j = i+1, i = 1...n)$;

M=$\begin{vmatrix} \lambda+\frac{1}{\tau} & 0 & \frac{\alpha}{\tau} \\ \frac{\alpha}{\tau} & \lambda+\frac{1}{\tau} & 0 \\ 0 & \frac{\alpha}{\tau} & \lambda+\frac{1}{\tau} \end{vmatrix}$;N=$\begin{vmatrix} -\frac{w}{\tau} & 0 & 0 \\ 0 & -\frac{w}{\tau} & 0 \\ 0 & 0 & -\frac{w}{\tau} \end{vmatrix}$;

O=$\begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix}$.

The determinant of the neuron network is specified as follows:

T=$\begin{vmatrix} M & O & O & O & O & \\ N & M & O & O & O & \\ O & N & M & O & O & \\ O & O & N & M & O & \\ O & O & O & N & M & \\ & & & & & \cdots \end{vmatrix}$.

According to the algorithm of triangle determinant we can conclude that if the oscillating conditions for all separated CPGs are satisfied, then the neuron network organized by the cyclic inhibitory CPGs connected in series with unilateral excitation will also oscillate. Thus the necessitate condition for the neuron network to sustain a rhythmic output is $w_{\{y,p,m\},i} \geq 2$, where $w_{\{y,p,m\},i}$ are connection weights among n_y, n_p and n_m of $i-th$ CPG, $i = 1...n$.

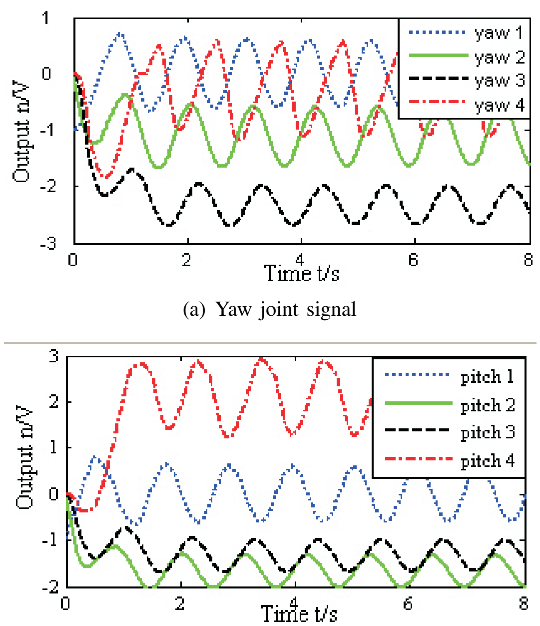
V. COMPUTER SIMULATION

According to the parameters of "Perambulator", we adopted ADAMS software to construct a 3D dynamic model of the snake-like robot. The contact between the robot and the environment is defined as a coulomb friction. The coefficient of the static friction is 0.3, and the coefficient of the dynamic friction is 0.1. The output of the CPG neuron network was adopted as the input of the 3D dynamic model of the snake-like robot. The parameters of the CPG neuron network are listed in Table III.

TABLE III
PARAMETERS OF THE CPG NEURON NETWORK

Positive input $s_{0,\{y,p,m\},i}/V(i = 1, ..., 4)$	1
Time constant $T_{\{y,p,m\},i}/s(i = 1, ..., 4)$	0.3
Connection weight among neurons $w_{\{y,p,m\},i}(i = 1, ..., 4)$	2
Connection weight among CPGs $w_{ij}(j = i+1; i = 1, ..., 4)$	2
Rotation angle range $\alpha_{max}/(rad)$	$\pi/3$
Start point of sampling r/s	10
Sampling range q/s	30

When we set $ma_{\{y,p\},i}$=1 and $mz_{\{y,p\},i}$=0 $(i = 1, ..., 4)$, the CPG neuron network's outputs are shown in Fig.8. Although the rhythmic outputs are acquired, they are not suitable for the practical control.

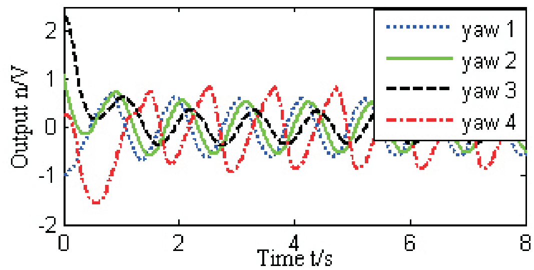


(a) Yaw joint signal

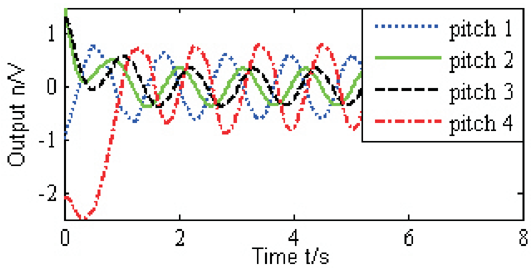
(b) Pitch joint signal

Fig. 8. Joint signal outputted by the CPG neuron network

We adopt (20) and (21) to specify $ma_{\{y,p\},i}$ and $mz_{\{y,p\},i}$ $(i = 1, ..., 4)$, and the corresponding control signals of the joints are shown in Fig.9. The stable rhythmic outputs are achieved after 5s. The above control signals are put into the 3D dynamic model of the snake-like robot to realize the dynamic simulation. The runtime is 50s, and the sampling time is 0.2s. The simulation result is shown in Fig.10. The 3D dynamic model of the snake-like robot successfully realized sidewinding locomotion. The robot head moved 0.84m in the left direction, and the corresponding average velocity in this direction is 0.017m/s. It moved forward 0.21m, and the corresponding average velocity in this direction is 0.004m/s. The maximum amplitude value of the robot body shape in the horizontal plane is 0.12m, and is 0.08m in the vertical plane.



(a) Yaw joint signal



(b) Pitch joint signal

Fig. 9. Optimized joint signal

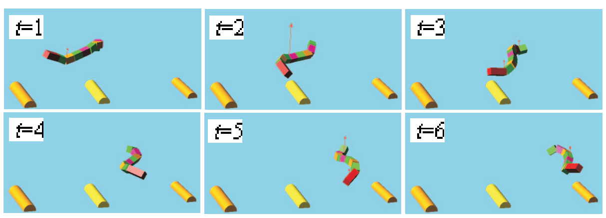


Fig. 10. Locomotion of the 3D dynamic model

VI. EXPERIMENTAL RESULTS

Some experiments were carried out on "Perambulator" to testify the validity of the proposed CPG control architecture. The CPG parameters shown in table III are adopted to specify the CPG control system of "Perambulator", and the robot moves on the smooth floor. The runtime is 50s, and the sampling time is 0.2s.

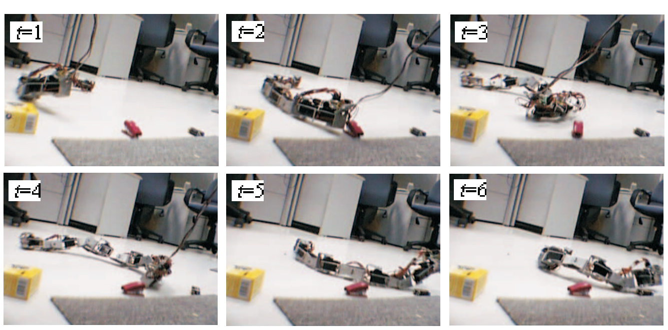


Fig. 11. Locomotion of "Perambulator"

The result is shown in Fig.11. The robot head moved 0.4m in the left direction, and the corresponding average velocity in this direction is 0.008m/s. The head also moved forward 0.1m, and the corresponding average velocity in this direction is 0.002m/s. The maximum amplitude of the robot body shape in the horizontal plane is 0.13m, and is 0.09m in the vertical plane. The experimental results show that "Perambulator" successfully realized 3D locomotion. Although the real snake-like robot mechanism and the environment cannot be identical with which in the simulator, it is the case that both experimental results and simulation results show the same trend.

VII. CONCLUSIONS

According to the theory of cyclic inhibition, the SANs were adopted to construct the CPG model for the locomotion control of the combined joint. It was also proven to sustain a rhythmic output with the least number of differential equations. Through connecting the CPG in series with single direction excitation synapse, we successfully constructed the neuron network for the 3D locomotion control of the snake-like robot whose joints are perpendicularly connected in series. The necessitate conditions for the proposed control architecture sustained a rhythm output have also been presented in this paper. The valid parameters for the 3D locomotion control were obtained through the simulation of the dynamic model with the method of trial and error. Finally "Perambulate" successfully realized 3D locomotion under the control of the CPG control architecture. Both the simulation and the experiment results showed the validity of the proposed CPG control architecture for the locomotion control of the 3D snake-like robot. The results also provided a bran-new approach to the study of the unknown neural network of nature snakes.

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