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Adaptive creeping locomotion of a CPG-controlled snake-like robot to environment change

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Abstract In this paper, we present a biomimetic approach which is based on Central Pattern Generator (CPG) to solve the difficulty in control of a snake-like robot with a large number of degrees of freedom. A new network with a feedback connection is proposed, which can generate uniform outputs without any additional adjustment. The relations between the CPG parameters and the characteristics of output are also investigated. A simulation platform is also established for the analysis of the CPG-based locomotion control of a snake-like robot. To figure out adaptive creeping locomotion of the robot to the environment with changed friction or the given slope, the relations of CPG parameters and locomotion efficiency by the proposed curvature adaptive principle have been discussed.

Keywords Snake-like robot · CPG network · Feedback connection · Motion control · Adaptive locomotion

1 Introduction

As we know, a natural snake can move well in many kinds of environments. The advantage of a snake-like robot imitating the locomotion of real snake is that it can move well in unstructured environments, like narrow pipe, rough or soft ground, and even water. However, it is difficult to control a snake-like robot effectively due to the fact that the robot has high degrees of freedom. Some of the eel-like or snake-like robots present elegant mechanical designs or life-like movement, like McIsaac and Ostrowski (2000), Ma (2001), and Mori and Hirose (2002). These snake-like robots were controlled to imitate the observed body shape of natural snakes. However, most of them have a complicated model with numerous calculations or little environmental adaptability. Furthermore, it is also inconvenient to change gait patterns.

Recently, researchers turn their attention upon the bio-inspired control method for the robot locomotion. Animals can spontaneously carry out running, flying and respiration without any careful planning. Most of these rhythmic motions of animals are controlled by a rhythm generating mechanism, which is called the Central Pattern Generator (CPG) (Mattia et al. 2004; Ijspeert 2008). This CPG can generate the self-induced oscillation even without a high command signal from the brain or central nervous system. Due to the advantage of the CPG in rhythmic motion control, many researchers have taken the CPG schemes into the control of robots. By implementing the CPG oscillators into the mechanism of a robot arm, more adaptive movement was performed (Williamson 1998). Dynamic walk was achieved through using a neural system model on a quadruped robot (Fukuoka et al. 2003). Based on biomimetic central pattern generators and on information from distributed distance sensors, neuromuscular motion control for an undulatory robot models was presented (Sfakiotakis and Tsakiris 2008). By implementing the CPG as a system of coupled nonlinear oscillators in the modular robotic system, Sproewitz ad-

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dressed the problem of learning to locomote in modular robotic systems which composed of multiple modules that can be configured into different robotic structures (Sproewitz et al. 2008).

The rhythmic creeping motion of a natural snake is also generated by a CPG mechanism. Many researches have studied the snake-like robot locomotion controlled by CPG, like Conradt and Varshavskaya (2003), Inoue et al. (2004), Matsuo et al. (2007), and Ijspeert and Crespi (2007). However, how the CPG parameters affect snake-like robot locomotion and how the adaptive motion is generated to the change of environment by CPG-based control is little discussed. Inoue et al. (2007) have undertaken some work on the CPG-based control of a snake-like robot to adapt to changing ground friction, but they have not given a clear criteria of optimal locomotion into consideration.

In order to achieve a better signal without any additional calculation, a network with a feedback connection, which can perform uniform output amplitude and phase difference, is proposed for the control of snake-like robot in this paper. Based on the numerical analysis of each CPG parameter, the influences of parameters on the locomotion of robot have been investigated. To realize an adaptive motion of the snake-like robot in different environments, the creeping locomotion with an experimental optimization is discussed in a simulated platform. Based on the curvature adaptive principle, the optimal CPG parameters for highest locomotion efficiency under the different friction or the slope have been considered, respectively.

This paper is organized as follows. The structure of the CPG model and its network are presented in Sect. 2. The characteristics of each CPG parameter are obtained and the influences of parameters on the CPG output are analyzed in Sect. 3. A developed simulator is presented and the simulation results to show the effectiveness of the CPG-controlled snake-like robot are given in Sect. 4. Section 5 discusses the adaptive creeping locomotion with the highest efficiency in different environments. Finally, the work of this paper is concluded in Sect. 6.

2 CPG model and network

Original works of Hirose (1993) have given out the mechanism of the snake-like locomotion. During the process of progressing, due to the particular scales cover on the elongated body of snake-like animals, the friction coefficient of the snake in the normal direction with respect to the main axis of the segment is significantly greater than the tangential one. By use of a passive wheel on the snake-like robot we can imitate this biological characteristic. The propelling force of the serpentine motion of a snake-like robot comes from the interaction of the robot with the ground by swinging the joints from side to side. The signals which control the angle of joints should be a series of rhythmic signals with the same phase difference. CPG unit can be taken as the basic oscillator which could generate this kind of rhythmic signal.

2.1 CPG model

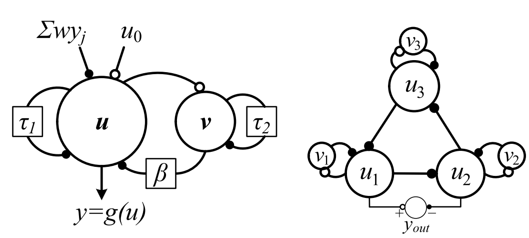
Various models of CPG neuron have been proposed, such as Matsuoka (1985) and Ekeberg (1993). The CPG model proposed by Ekeberg is structurally complicated and difficult to analyze numerically. However, the model of CPG neuron proposed by Matsuoka, has the features of continuous-time and continuous-variable in its simple structure, and can thus be easily implemented to the control of the robot. Moreover, the Matsuoka CPG model has been proven mathematically to generate rhythmic output. Thus this neuron model is adopted into the control of our snake-like robot.

Several neurons are usually included in each CPG model. Through the interaction of neurons between each other, they can provide a group of rhythmic outputs. The structure of the individual neuron model is shown in Fig. 1(a). The mathematical model of each neuron can be expressed as

$$\begin{aligned} &\tau_1 \dot{u} + u = u_0 - \beta v - \sum_{j=1}^{m} w y_j, \\ &\tau_2 \dot{v} + v = y, \\ &y = g(u) = \max(0, u) \end{aligned} \tag{1}$$

where u is the membrane potentials of the neuron; v is the variable that represents the degree of adaptation; y is the output of the CPG neuron, and its value is always positive; u_0 is the tonic driving input; τ_1 and τ_2 are the parameters that specify the time constants for membrane potential and adaptation degree, respectively; β is the adaptation coefficient; w is the weight between neurons; $\sum w y_j$ represents the input from other neurons; m is the number of all the neurons in one CPG model.

Usually, there are several ways to construct a CPG model by connecting different number of neurons, like a dual-neuron model or a tri-neuron CPG model. In our previous study, it has been proven that a cyclic inhibitory CPG model



(a) Structure of one neuron (b) Tri-neuron model

Fig. 1 CPG model composed of neural oscillators with triple neurons is more suitable for a snake-like robot control (Lu et al. 2005). Therefore, we still take this tri-neuron CPG model as our snake-like robot controller, as shown in Fig. 1(b). Since the output of an individual neuron is always a positive value, the output of the CPG y_{out}, which is defined by the subtraction between the output of the first neuron y_1 and that of the second neuron y_2 in the CPG module, is used to get a symmetrical rhythm signal with both positive and negative values.

$$y_{out} = g(u_1) - g(u_2) = y_1 - y_2 \tag{2}$$

2.2 Network of neural oscillator

How the CPG network is implemented to control a snake-like robot is illustrated in Fig. 2. Due to the fact that one joint angle corresponds to one CPG output, a series of successive rhythmic signals with the same phase difference are needed to realize the snake-like locomotion control. Thus, several CPG modules are needed to construct a kind of network for mimicking the neural system of a natural snake.

For simplicity, an open-loop unilaterally connected CPG network has been efficiently employed for the control of the snake-like robot in Inoue et al. (2004) and Lu et al. (2005). However, additional calculation is needed to adjust the irregular output signal of this network. To solve the problems in the unilateral CPG network, a novel closed-loop network with a feedback connection is proposed in this section. The basic concepts of these two networks are shown in Fig. 3.

Based on the mathematical model of a single neuron stated in Sect. 2.1, a CPG network includes n CPG modules which have m neurons in each CPG can be described in

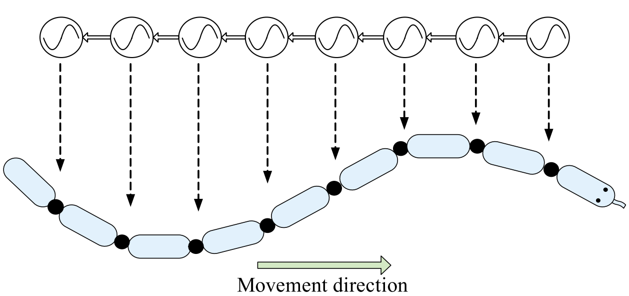


Fig. 2 CPG network implemented to control a snake-like robot

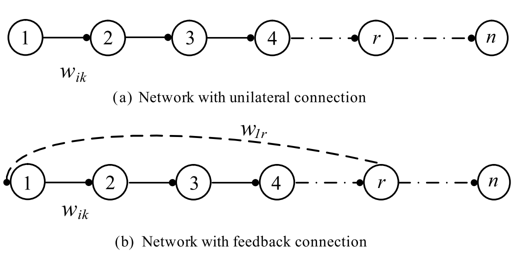


Fig. 3 Networks of neural oscillator

a group of basic equations. Regarding the jth neuron of the ith CPG module, the mathematical model can be described by

$$\begin{aligned}
&\tau_1 \dot{u}_{j,i} + u_{j,i} = u_0 - \beta v_{j,i} - w y_{s,i} + \sum_{k=1}^{n} w_{ik} y_{j,k},\\
&\tau_2 \dot{v}_{j,i} + v_{j,i} = y_{j,i},\\
&y_{j,i} = g(u_{j,i}) = \max(0, u_{j,i}),\\
&y_{out,i} = y_{1,i} - y_{2,i},\\
&i, k = 1, 2, \ldots n,\ i \neq k;\ j = 1, 2, \ldots m;\\
&s = \begin{cases} m, & \text{if } j = 1,\\ j-1, & \text{others} \end{cases}
\end{aligned} \tag{3}$$

where n is the number of CPG modules in the network; m is the number of neurons in one CPG module; s is the serial number of neuron connected to the j-th neuron; $u_{j,i}$ is the membrane potentials of j-th neuron in the i-th CPG module; $v_{j,i}$ is the variable that represents the degree of adaptation; u_0 is the tonic driving input; τ_1 and τ_2 are the time constants; β is the adaptation coefficient; w is the weight between neurons; w_{ik} is the connection weight of the i-th module from the k-th module; $y_{j,i}$ is the output of j-th neuron in i-th CPG module; $y_{out,i}$ is the output of the i-th CPG module.

In the network, all the CPG modules are connected in the direction, from the head to the tail, in which there is a constant connection weight between the neighboring module.

$$w_{ik} = \begin{cases} w_0, & k = i-1,\\ 0, & \text{others} \end{cases} \tag{4}$$

When the weight of the feedback w_{1r} from the r-th module to the first one also adopts the same weight value, given by $w_{1r} = w_0$, it will form a closed-loop network with feedback connection, like in Fig. 3(b).

Rhythmic outputs of six CPG modules with respect to two kinds of network are shown in Fig. 4. It is simulated by use of tri-neuron cyclic inhibitory CPG models, where the 6-th module is selected to provide the feedback to the first CPG module in Fig. 4(b). The set of CPG parameters used in simulation is shown in Table 1. As shown in Fig. 4(a), the amplitude of the CPG outputs in this unilaterally-connected network is not uniform in size, thus it is necessary to make

Table 1 Parameters of the CPG model

Driving input u_0	2.5
Time constant τ_1	2.0
Time constant τ_2	6.0
Adaptation coefficient β	2.5
Connection weight inner neurons w	2.5
Connection weight among CPGs w_0	0.1

adjustments to get suitable rhythmic signals for robot control. Furthermore, it is also difficult to adjust one or more parameters to obtain the desired phase difference of outputs in this network. Compared with the unilaterally-connected network, the network with a feedback connection, generates more uniform outputs with the same amplitude and phase difference in Fig. 4(b). Due to the fact that this network can be applied to the snake-like robot control without giving any additional modification on the output signals of CPG, the system computation cost is decreased dramatically. Moreover, it is convenient to obtain a specific phase difference by feeding selected r-th CPG signal back to the first module (Wu and Ma 2009). This characteristic can be used to control the number of S-shape wave in the snake-like robot locomotion. Therefore, this network with a feedback connection is more suitable for the control of a snake-like robot.

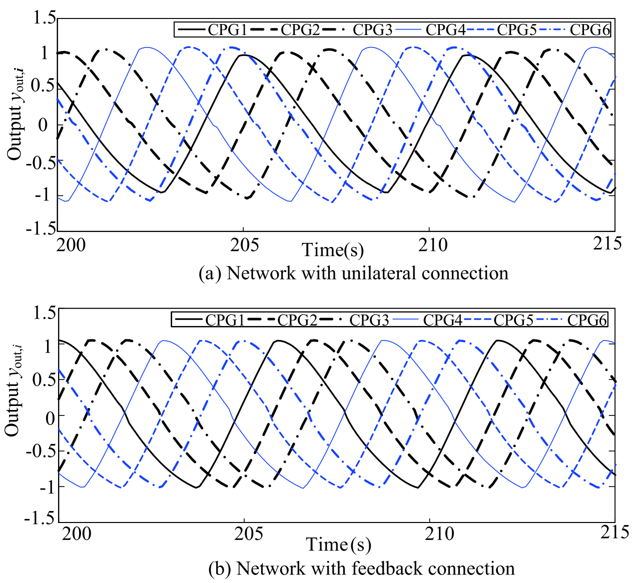


Fig. 4 Rhythmic output of two kinds of network

3 Characteristics of the CPG parameters

To figure out how to implement the CPG network to control locomotion of a snake-like robot, the influence of each CPG parameter on the signal output has to be investigated. To find out the influence of each parameter on the output, the output characteristic is studied with one parameter varied in a certain range while other parameters are fixed. From the mathematical model of the CPG model, the output is mainly determined by several parameters. Influences of these parameters on the amplitude and the period of rhythmic output are primarily investigated. The network with a feedback connection composed of the cyclic inhibitory CPG model is selected to study the influence of parameters, and the numerical results are shown in Fig. 5.

From the numerical results, two important linear relations can be easily found: the output amplitude increases linearly with the driving input u_0; time constant τ_1, τ_2 keeps a linear relation with the period of output while the value of τ_1/τ_2 is a constant. As shown in Fig. 5, the change of the value of τ_1/τ_2 only affects the slope of the line. However, if the value of τ_1/τ_2 is not a constant, the linear relation between them will be broken. The change of parameter u_0 does not influence the period of the output while the change of parameter time constant τ_1, τ_2 with a constant ratio value makes

Fig. 5 Results to show the relation between the CPG parameters and the CPG output

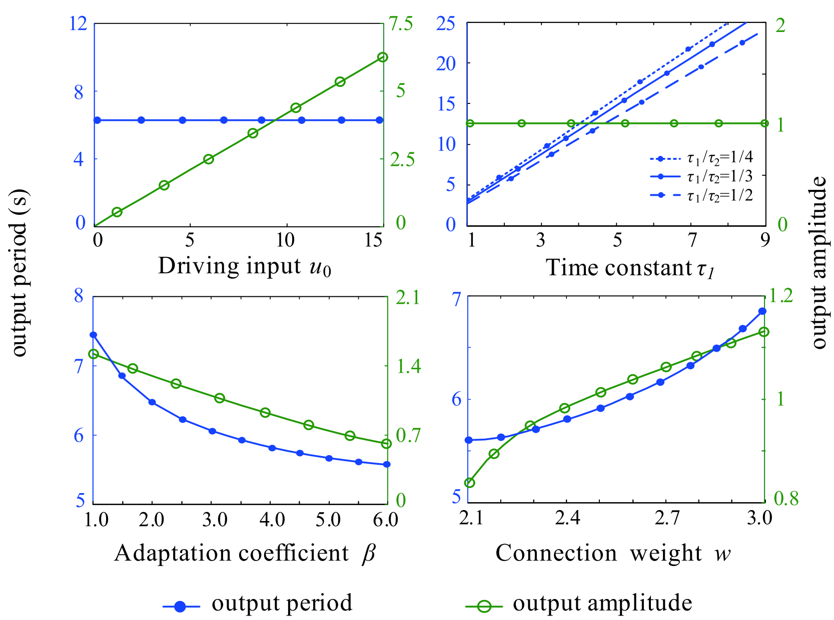


Table 2 Change of the CPG output with respect to each CPG parameter

Parameters increase	Output amplitude	Output period	Wave shape of output
u_0	Linear increase	Unchangeable	Unchangeable
τ_1, τ_2 with constant τ_1/τ_2	Unchangeable	Linear increase	Unchangeable
β	Nonlinear decrease	Nonlinear decrease	Unchangeable
w	Nonlinear increase	Nonlinear increase	Changed

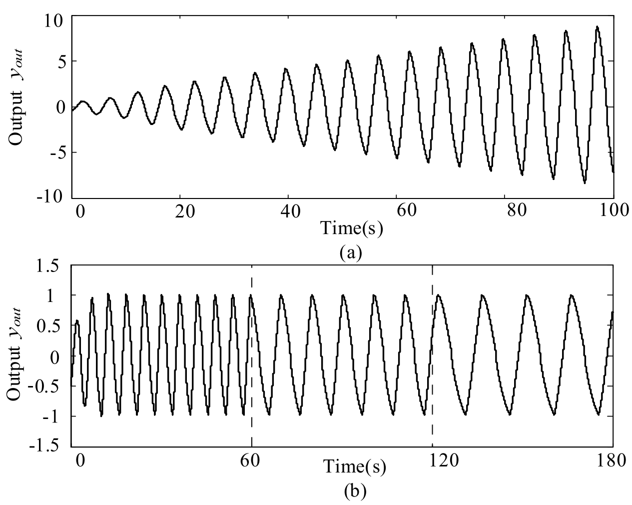


Fig. 6 Oscillation signals changed with respect to driving input and time constant where (**a**) driving input $u_0 = t/5 + 2.5$; (**b**) time constant $\tau_1 = 2.0$, 3.5, 5.0 and $\tau_2 = 6.0$, 7.5, 15.0 for time $t = 0$, 60, 120 (s). Other parameters are the same as Table 1

no influence on the amplitude of the output. Furthermore, the basic shape of the output wave is also not affected by the driving input and time constant. For the parameters of the coefficient β and connection weight w, there are not these advantages. Summarizing these characteristics, a concise conclusion can be obtained in Table 2. Thus, the driving input and time constant can be employed to adjust the CPG output by the two useful linear relations conveniently. Figure 6 shows the signal of oscillator changed corresponding to driving input and time constant respectively.

4 Creeping locomotion of a CPG-controlled snake-like robot

After understanding the influences of the CPG parameters on the output, how to realize the locomotion control of the snake-like robot by the CPG-based system is the next thing needed to resolve. To verify the proposed CPG-based control method, a simulator has been developed in Open Dynamics Engine (ODE) environment, as shown in Fig. 7. In the simulation, the interaction between the robot and the ground is modeled with asymmetric friction by using a larger normal friction coefficient μ_N and a smaller tangential friction coefficient μ_T. To realize this kind of friction model, a passive wheel is utilized for each link of the snake-like robot. The actuators are installed on the joints of the robot to make each joint swing from side to side, like the behavior of a natural snake. The physical parameters of the simulated robot model are given in Table 3.

Table 3 Physical parameters of the simulated robot

Numbers of joints:	Num = 10
Length of link:	$L_{link} = 0.13$ m
Radius of link:	$R_{link} = 0.02$ m
Weight of link:	$M_{link} = 0.2$ kg
Width of wheel:	$L_{wheel} = 0.01$ m
Radius of wheel:	$R_{wheel} = 0.03$ m
Weight of wheel:	$M_{wheel} = 0.08$ kg
Joint angle range:	$\theta = [-45, +45]$ deg

A network with a feedback connection using cyclic inhibitory CPG model is selected as the oscillation generator and the parameters of this CPG model are listed in Table 1. Furthermore, just one S-shape locomotion of the snake-like robot is used in the simulation to analyze in the same level. The output $y_{out,i}$ of the ith CPG is implemented onto the ith joint as the angle input. Each angle of the robot joint θ_i can be calculated by

$$\theta_i = \alpha_i y_{out,i} \tag{5}$$

where α_i is a gain from the control signal to the joint angle.

A natural snake often changes the curvature of its body shape to adapt to different terrains during locomotion, such as a larger locomotion curvature to adapt to a slippy ground. During the simulation, we found that the amplitude of CPG output affects the locomotion curvature of the snake-like robot. Thus, due to the linear relation between the amplitude of CPG output and the parameter driving input u_0, a different locomotion curvature can be obtained by adjusting u_0. As it shown in Fig. 8, it can be easily found that when the driving input u_0 increases, the curvature of the robot will increase correspondingly. From the results of simulation, the snake-like robot with 10 joints can increase its average curvature through enlarging the driving input u_0, as shown in Fig. 9.

The locomotion speed of the robot is mainly affected by the swing frequency of the joints. As stated in Sect. 3, the period of CPG output keeps a linear relationship with time

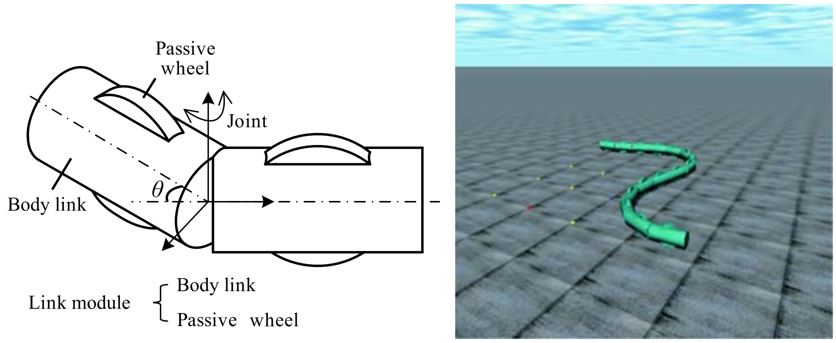
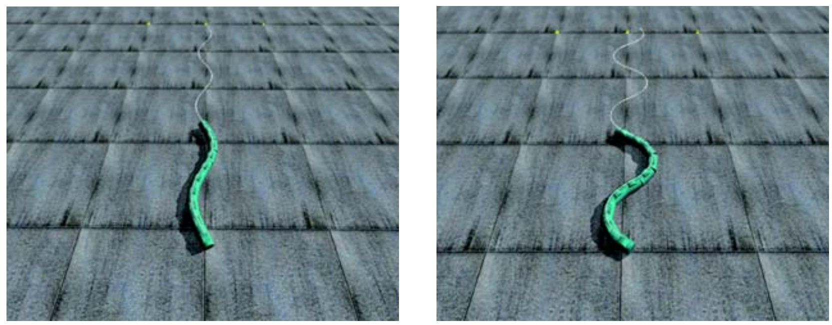


Fig. 7 A simulator for the creeping locomotion of a snake-like robot



(a) Locomotion trajectory when u_0=1.0

(b) Locomotion trajectory when u_0=5.5

Fig. 8 Locomotion of the robot with different body curvatures

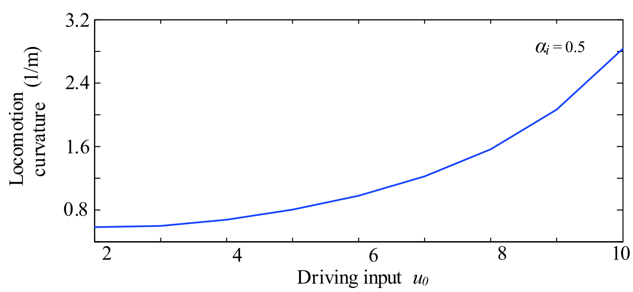


Fig. 9 Curvature with respect to CPG driving input

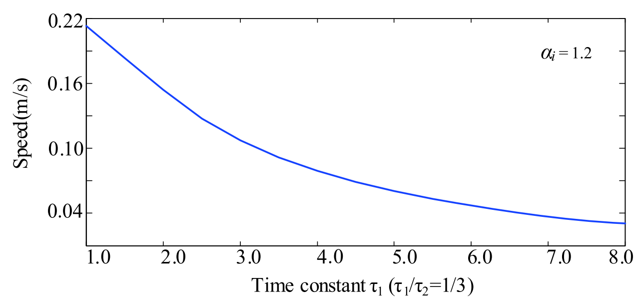


Fig. 10 Motion velocity with respect to CPG time constant

constant. Thus, the locomotion speed of the robot can be controlled by proportionally adjusting the time constant τ_1 and τ_2 while the value of τ_1/τ_2 is a constant. From the result of the simulation shown in Fig. 10, it can be found that the motion speed decreases with the increase of the time constant, since this increment makes the period of CPG output become longer.

The discussion of the locomotion curvature and speed of the snake-like robot is considered when the robot moves forward on a straight-line. Note that, however, turn motion of the snake-like robot can also be achieved by giving certain bias on the amplitude of the angle signals of joints. This can be realized by giving unsymmetrical driving input u_0 in the neurons of the CPG module. The similar experiment results can be found in Inoue et al. (2004).

5 Adaptive creeping locomotion to environmental change

In the previous section, we have verified through simulations that our CPG network is capable of achieving kinds of locomotion by the adjustment of parameters. In the nature the snakes can always keep an adaptive body shape to move on kinds of terrains. In order to figure out which parameters can generate an adaptive motion corresponding to different environments by the CPG-based control, the creep locomotion with the experimental optimization is discussed through simulated experiment. Herein, two typical environments, including slope and horizontal ground with different frictions, are considered to obtain the efficient locomotion of the snake-like robot.

5.1 Curvature adaptive principle

The Coulomb friction model is adopted to describe the interaction between snake-like robot and ground. Detailed analysis about this robot dynamics can be seen in Ma and Tadokoro (2006). The tangential and normal frictions exerted on the pth ($p = 1, 2 \ldots$) module of snake-like robot can be expressed by

$$\begin{aligned} f_p^t &= -\mu_t m_p g \cdot \cos\phi \cdot \operatorname{sign}(\delta^p r^t), \\ f_p^n &= -\mu_n m_p g \cdot \cos\phi \cdot \operatorname{sign}(\delta^p r^n) \end{aligned} \tag{6}$$

where f_p^t and f_p^n are the components of friction in tangential and normal directions, respectively; μ_t and μ_n are the relevant friction coefficients; m_p is the weight of the pth module, which includes both the mass of the link and that of the wheel; ϕ is the inclined angle of slope; $\delta^p r^t$ and $\delta^p r^n$ are the tangential and normal displacements of the pth module at friction point, respectively.

By setting the coordinate system shown in Fig. 11, where the x-axis is taken along or parallel to the forward direction of snake-like robot, the x and y components of the resultant friction force can be calculated by

$$\begin{aligned} f_p^x &= f_p^n \sin\psi_p - f_p^t \cos\psi_p, \\ f_p^y &= f_p^n \cos\psi_p + f_p^t \sin\psi_p, \\ F_x &= \sum_{p=1}^{N} f_p^x, \\ F_y &= \sum_{p=1}^{N} f_p^y \end{aligned} \tag{7}$$

where f_p^x and f_p^y are the components of resultant force in x and y directions, respectively; ψ_p is the rotation angle from x-axis to each link. By taking the snake-like robot as a whole, F_x and F_y are the resultant propellent force from the friction of each link along x-axis and y-axis, respectively.

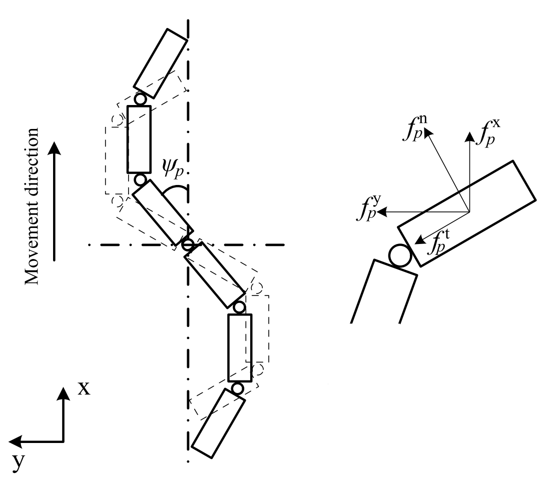


Fig. 11 Curvature adaptive principle

To provide propellent force of the snake-like robot along x-axis, it should have a enough friction to avoid backward slippage. Combining (6) and (7), a positive value of F_x along the forward direction of the robot can be got by an asymmetric friction with μ_n larger than μ_t. However, when the difference between two friction coefficients is not big enough to obtain sufficient F_x, the snake-like robot will swing without effective forward motion. The increment of locomotion curvature with increased ψ_p can enlarge f_p^x to get suitable F_x and solve this problem. From the description of locomotion curvature in Sect. 4, this curvature adaptive principle can be conducted easily by the CPG-based control.

Despite a large locomotion curvature can avoid the skid on the ground, the movement speed along the forward direction will decrease correspondingly. Besides, the force used to drive the robot is also influenced by the locomotion curvature. In order to evaluate the locomotion efficiency of the snake-like robot under different locomotion curvature, we propose a criterion of optimal locomotion, where the ratio between the forward displacement and energy consumption is considered as the target of evaluation. This coefficient of locomotion efficiency can be described as

$$J = \frac{S_T}{\int_0^T \sum_1^n tor_i^2 dt} \tag{8}$$

where S_T is the total forward displacement along the longitudinal direction in one period; tor_i is the torque added on ith joint, thus $\int_0^T \sum_1^n tor_i^2 dt$ is the total square-sum of joint torques in one period; n is the number of robot joints.

Based on the proposed criterion, the effective locomotion curvature can be realized by minimizing the energy consumption and maximizing the forward distance, thus obtaining high efficiency for creeping locomotion of the snake-like robot.

5.2 Ground with different frictions

The normal and tangential frictions play an important role during the creeping locomotion of snake-like robot. As stated above, when the friction changes with respect to different textures of contact surface, the locomotion curvature can be adjusted correctly to get enough propulsion for the robot. Thus, the relevant parameters of CPG network should be modified to get the adaptive motion curvature. As stated in Sect. 4, the driving input u_0 can be used to obtain the desired locomotion curvature of robot.

In the simulation, the interaction between robot and ground is modeled with variable friction environment, where the coefficient of normal friction is set as $\mu_n = 0.5$, and the coefficient of tangential friction μ_t varies from 0.01 to 0.25.

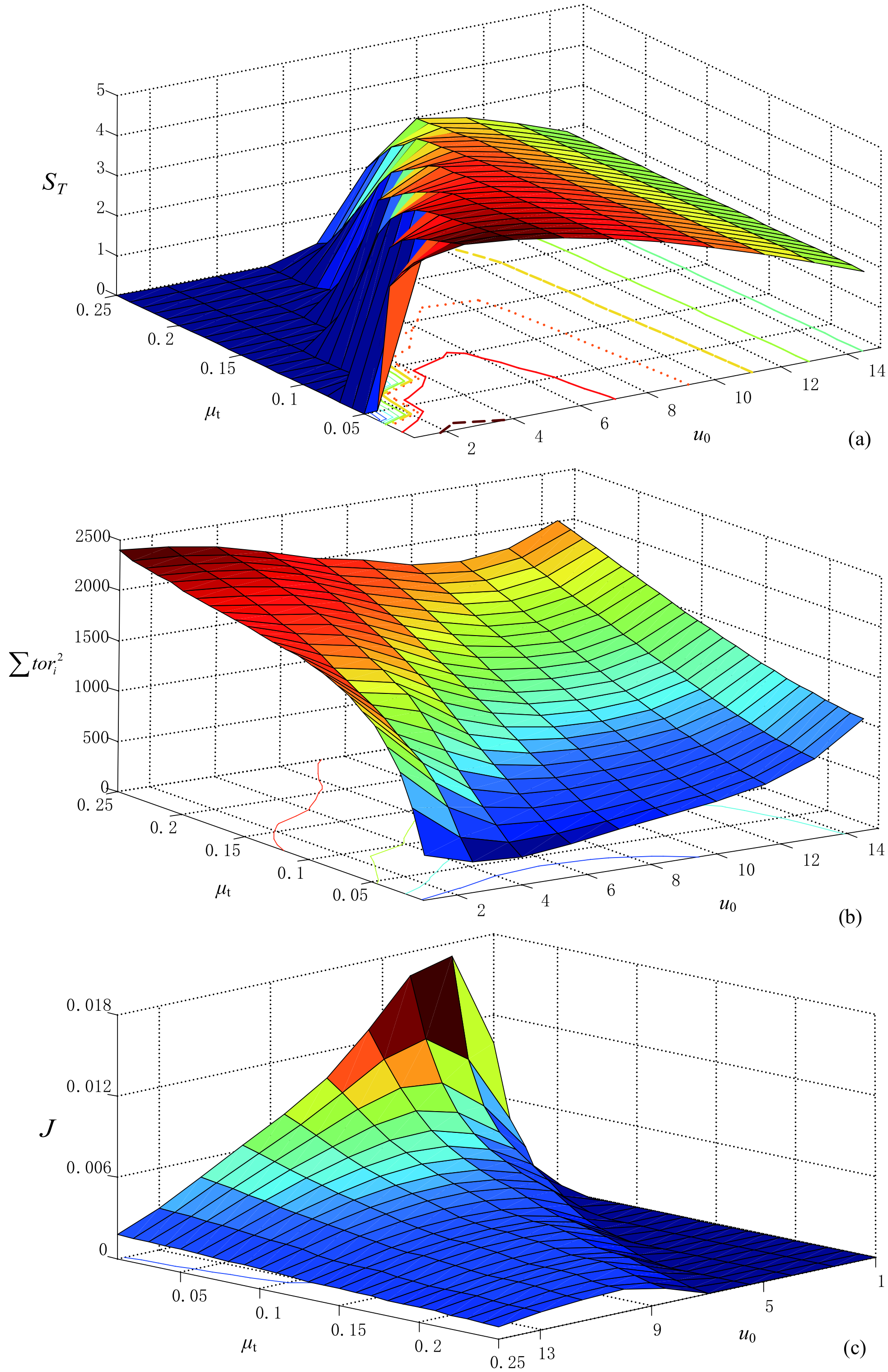


Fig. 12 Simulation results under different friction

Meanwhile, the parameter u_0 is adjusted from 1 to 15 to find the optimal locomotion curvature of the snake-like robot.

The motion displacement along the forward direction and the total square-sum of joint torques in one period, with respect to different friction coefficients and CPG driving input u_0, are illustrated in Fig. 12(a) and (b). Due to the snake-like robot can only swing in the original place with $S_T = 0$ in the blue region of Fig. 12(a), it has a relevant limit inferior for the driving input u_0 to realize forward motion of the snake-like robot under different friction environment. The energy

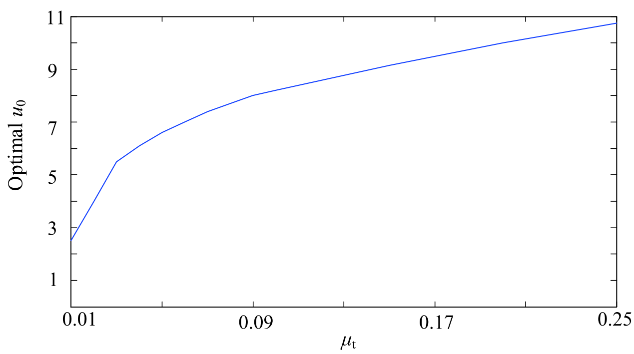


Fig. 13 The relation between optimal u_0 and friction coefficient μ_t

consumption of robot holds a nonlinear U-shape curve with the driving input u_0 in Fig. 12(b). Based on the above proposed criterion, the locomotion efficiency of the snake-like robot with respect to the friction coefficient and CPG driving input is obtained in Fig. 12(c), where the bottom coordinate of illustration is rotated to get a better view of the 3-D surface. For each μ_t, there is a corresponding u_0 to make the robot get the highest efficiency. Therefore, the value of drive input u_0 to generate the highest locomotion efficiency is optimized as shown in Fig. 13, while the coefficient of tangential friction μ_t varies from 0.01 to 0.25 with the interval of 0.02.

When implementing this optimization on the robot, by collecting the friction information of the ground from sensors, the value of the driving input u_0 can be adjusted to follow the data result like that in Fig. 13. Subsequently, the snake-like robot can creep with an adaptive locomotion curvature on the ground correspondingly.

5.3 Slope with different inclined angles

When a snake-like robot creeps on a slope, it has to change its locomotion curvature to avoid slipping from the surface of slope. Thus, by adjusting CPG driving input, the snake-robot can creep on the slope with an adaptive locomotion curvature. As stated above, the locomotion on a slope can be optimized based on locomotive efficiency criterion in the same way as that in Sect. 5.2.

In this simulation, the friction coefficients in tangential and normal directions are set as 0.03 and 0.5, respectively. The range of slope angle ϕ is from 0 to 10 degrees, and driving input u_0 is taken from 1 to 15. Figure 14 illustrates the simulation results, which have the same trend as that in Fig. 12. It also has a limit inferior value of driving input u_0 to take forward motion of the snake-like robot on a certain slope from the blue region of Fig. 14(a).

To get the highest locomotion efficiency for the robot, the relation between optimal driving input u_0 and incline angle ϕ is obtained, as shown in Fig. 15. By sensing the incline angle of the ground, the locomotion curvature of the snake-like robot can be optimized by adjusting the driving input u_0 accordingly as that in Fig. 15. Compared with the simulation result under different friction coefficients shown in Fig. 13, it can be found that both of two relation curves show similar tendency, since the slope is equivalent to the change of ground friction, which can be derived from (6).

5.4 Discussion of ratio μ_n/μ_t

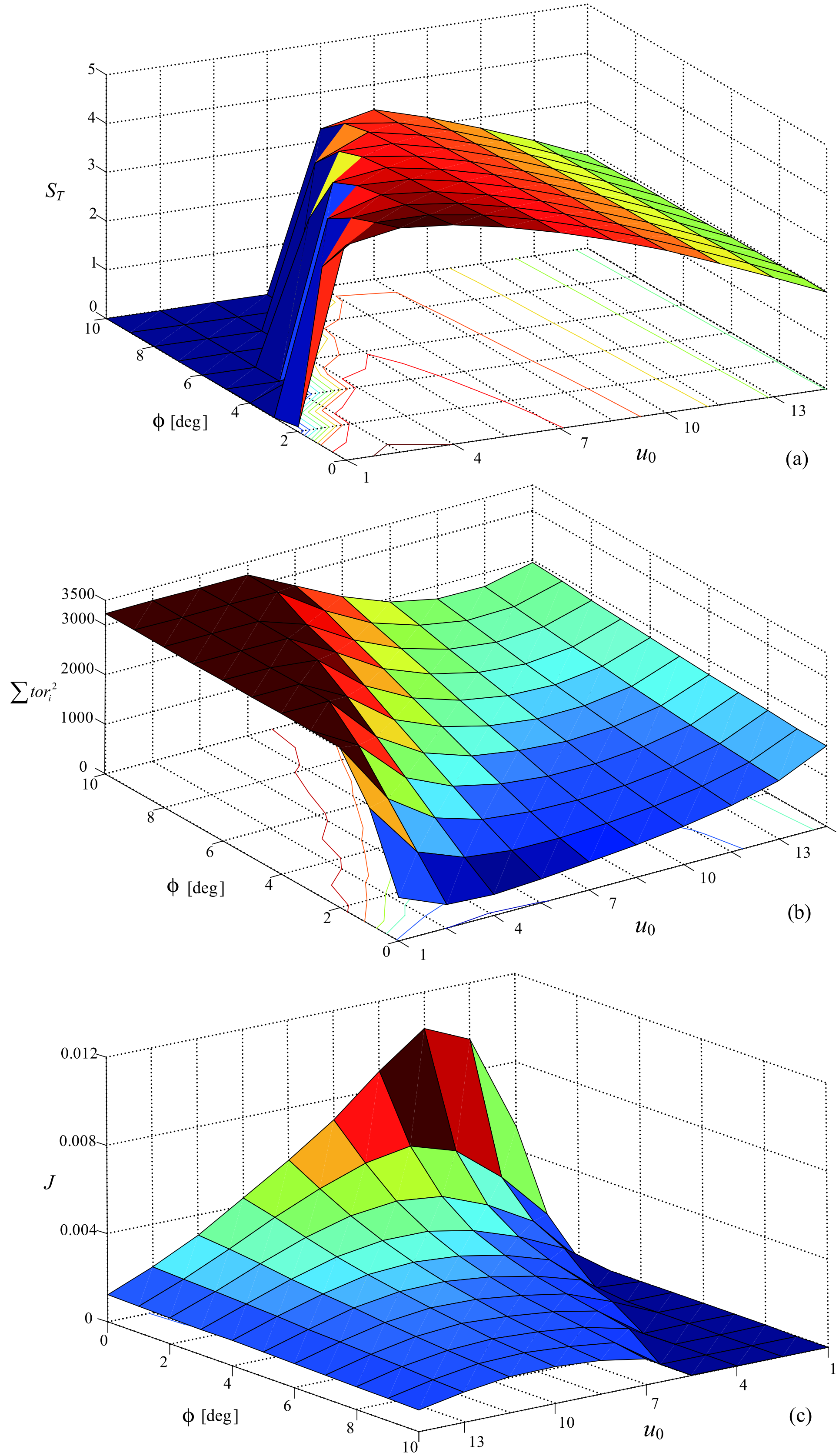
The simulation given in Sect. 5.2 specifies the coefficient of normal friction μ_n as a constant value. To figure out the optimal locomotion when snake robot moves on the ground with different tangential and normal friction, μ_n/μ_t is considered as a variable. We find that the ratio μ_n/μ_t between the normal friction and tangential friction is a primary factor to change locomotion shape of snake-like robot while all of the CPG parameters are constant.

Four groups of μ_n and μ_t such as (2.0, 0.4), (1.5, 0.3), (1.0, 0.2), and (0.5, 0.1) with equal ratio, are employed in simulation. By using identical CPG parameters in four cases, the simulation results in Fig. 16 show that the trajectories of four different combinations of μ_n and μ_t are almost same. More groups of friction environment have been taken into simulation, the results of which have the same trend. The snake-like robot performs similar locomotion curvature when the coefficients of the normal friction and tangential friction have the same ratio, not depending on the coefficient value. Therefore, the value of optimal driving input u_0 which affects the locomotion curvature is mainly determined by the ratio of μ_n/μ_t. To get the highest locomotion efficiency, the driving input u_0 is optimized as shown in Fig. 17 when the ratio μ_n/μ_t varies from 2 to 50 with 25 sample points.

6 Conclusion

In this paper, a bio-inspired system imitating the nervous in the animals has been proposed as the control method of a snake-like robot. The proposed CPG network with a feedback connection can generate uniform outputs with the same amplitude and the specified phase difference without any additional adjustment of CPG output. From the analysis of the characteristic of each CPG parameter, we found that locomotion curvature can be changed by driving input and motion speed can be adjusted by the time constant. Based on the results of simulation, a curvature adaptive principle has been adopted for the locomotion control of the snake-like robot. To evaluate adaptive creeping locomotion of the robot to changed friction or given slope by the curvature adjustment, a criterion of locomotion efficiency has been introduced. Finally, based on the principle and criterion, the creeping locomotion of snake-like robot is optimized in the simulated experiment. Utilizing the relations between the optimal CPG

Fig. 14 Simulation results under different incline angle



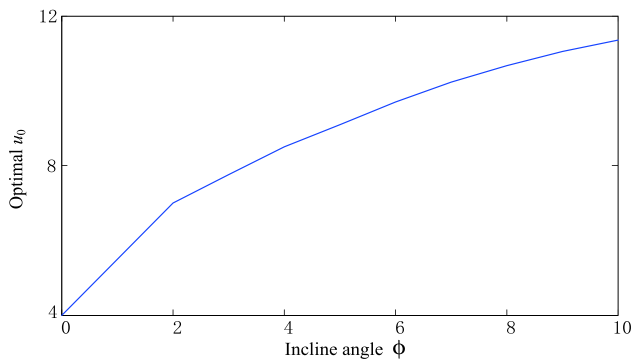


Fig. 15 The relation between optimal u_0 and incline angle ϕ

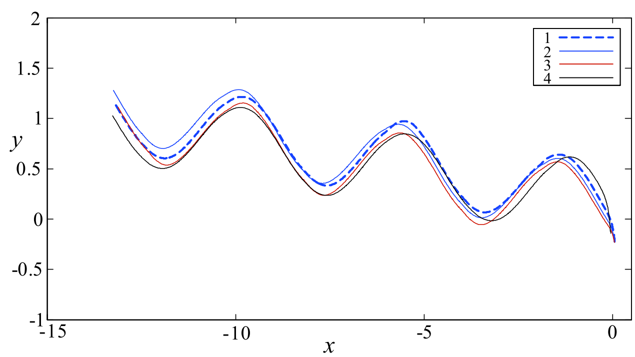


Fig. 16 Trajectories of robot under four different friction

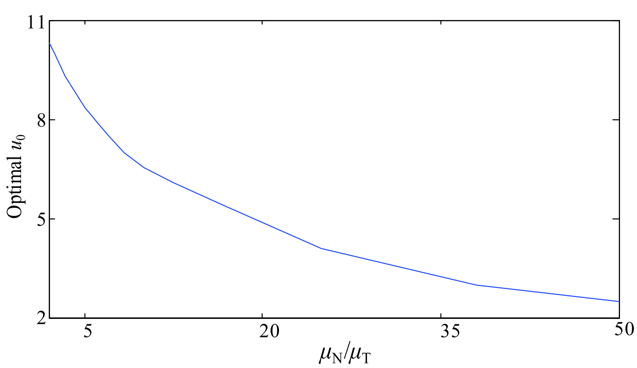


Fig. 17 The relation between optimal u_0 and friction coefficient

parameters and different environment, the most adaptable locomotion can be achieved. However, the discuss in this paper is limited on the planar terrain with varying friction or slope, the problem of how to generate the tremendous adaptability of the snake-like mechanism to more complicated environments still needs further studies in the intersection of biology and engineering.

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