TUM

TECHNISCHE UNIVERSITÄT MÜNCHEN
INSTITUT FÜR INFORMATIK

# A CPG-based Control Architecture for 3D Locomotion of a snake-like robot

Zhenshan Bing, Long Cheng, Kai Huang,
Mingchuan Zhou and Alois Knoll

TUM-I1638

# A CPG-based Control Architecture for 3D Locomotion of a snake-like robot

Zhenshan Bing[1], Long Cheng[1], Kai Huang[1,2], Mingchuan Zhou[1] and Alois Knoll[1]

*Abstract*— **In this paper, a biologically inspired control architecture for a snake-like robot is proposed to achieve 3D locomotion and realize continuously free gait transition. Based on a novel central pattern generator(CPG) model, which is achieved from the perspective of network synchronization, the control architecture integrates three functional parts. First, following the convergence behavior of the gradient system, a new CPG model is presented to adjust the signals' amplitudes and phase differences automatically. Then, the relation characteristics between the CPG parameters and the outputs are investigated, which can be used to optimize the network's efficiency and fault tolerance. Finally, to realize various stable gaits as well as free gait transition for snake locomotion, two kinds of gaits for snake-like robot are present with detailed phase difference parameters. The effectiveness of the proposed control architecture is demonstrated by 3D locomotion simulations and real-life experiments of a snake-like robot. The results show that desired locomotion patterns can be achieved after the CPG parameters are adjusted to corresponding gaits.**

## I. INTRODUCTION

Different from many other kinds of land animals, snake can move in complex environments, like pipes, trees, amphibious ground, and even in water [1]. Therefore, snake-like robots can obtain the advantages of moving well in diverse environments by imitating the robustness and stability of snake locomotion. To meet the growing need for robotic mobility occasions such as disaster rescuing, factory pipes maintenance and terrorism surveillance, a considerable number of snake-like robots have been developed. However, due to the highly redundant degree of freedoms, it is difficult to control the 3D locomotion of the snake-like robots effectively and efficiently, especially those without passive wheels [2].

There are many kinds of bio-logical inspired snake-like robots [3, 4, 5, 6], which show different kinds of mechanism and life-like locomotion. However, they either can only achieve planar locomotion by using passive wheels [7] or lack environmental adaptability due to the complicated model [8]. In addition, few have the ability to transmit the gait conveniently during locomotion. Thus, it is a challenging task for reserchers to increase the snake-like robots' adaptive behaviour and stability in unknown environments.

As a promising solution for the issue, bio-inspired locomotion control method has been widely studied recently. Research on vertebrate animals finds that the *central pattern generator* (CPG), which is located in the spinal of vertebrate animals, functions as the controller of vital movements, such as walking, respiration and excretion[9].

Central pattern generators are a group of coupled neural circuit, which can generate self-induced rhythmic patterned signals without higher-level command or sensory feedback[10]. Therefore, CPG-based control method is admirably suited for gaits modification to adapt to unknown environments, while avoid damaging the robots during gait transition, or control failures caused by inaccurate control model. Another interesting find is, generating self-induced rhythmic signals makes CPG a low-level neural controller which can be stimulated by higher neural controller, such as external sensory feedback information, e.g., vision and external force. Due to these unique advantages in rhythmic locomotion control, which can improve the autonomy and adaptability of locomotion, CPG control methods have been adopted in bio-logical inspired robots.

In this paper, we develop a novel CPG-based control architecture for the 3D locomotion of snake-like robot. The control architecture is proposed by exploring the convergence behaviour of gradient system network. The CPG model parameters are tuned, specific to rolling and sidewinding gaits. To demonstrate the proposed theory, a series of experiments are conducted.

The contributions of this paper are:

- Based on the convergence behaviour of gradient system, a novel CPG model which can modulate the properties of the output wave continuously is proposed. The validity of the model is proved theoretically.
- Based on the proposed CPG model, a control architecture is designed to generate different 3D locomotion gaits and realize a free gait transition.
- Simulations and prototype experiments are conducted to demonstrate the effectiveness of CPG-based control architecture. Expected gaits or gait transitions can be observed both in simulations and experiments.

The rest of this paper is organized as follows: Section II briefly presents related work. The mechanical and electronic hardware of our snake-like robot are generally introduced in Section III. Then the CPG mathematical model and the signals' synchronization are deducted and analyzed in Section IV. In Section V, a series of simulations and experiments are conducted to prove the effectiveness of our proposed architecture. Section VI concludes this paper with the discussion and the presentation of future work.

## II. RELATED WORK

In a global perspective, a considerable number of snake-like robots have been developed in last several decades for

---

Authors Affiliation: [1] Technische Universität München, Fakultät für Informatik. [2] Sun Yat-Sen University.

Email: {bing,chengl,huangk,zhoum,knoll}@in.tum.de

ground locomotion [4], swimming [5] and amphibious enviroments [11]. Those control architectures can be generally classified into three types: serpenoid-based, model-based and CPG-based [12].

The serpenoid-based method [3] is achieved by observing the morphology of real snakes, imitating the serpenoid curves with simple sine-like signals and implemented to control the snake-like robot. Through abundant experiments, the serpenoid-based method has been proven simplicity. H.Choset [13] has came up a parameterized gait equation by simplifying the serpenoid curves to sine functions, which can achieve a variety of gaits. One strength of the serpenoid-based approach is the simplicity, due to the predefine of the significant parameters that influence the gaits, like phase, frequency and amplitude. The limitation is that the snake gait transition may generate jerky movements with the risk of damaging the robot [12], because of the discontinuous jumps of set-points.

Model-based control method requires an accurate mathematica model of the kinematic [14] and dynamic [15] of robot as well as the friction model [7] between the robot and the environment. The advantage of this method is that the robot can make an accurate move based on the torque calculation. While strongly depending on the accurate model, this method lacks the ability of adaptation. The control will fail if the model is not accurate enough, or the snake is in the environment having uncontrolled factors. Therefore, this method does not work well for locomotion in uncertain environment.

CPG based approach is a neural network coupled with nonlinear oscillators(differential equations integrated over time), which can generate the self-adjusted locomotion signals. Those signals have the characters as a limit cycle which means good robust against external disturbance and remain stable in finite time. Therefore, CPG method has become a potential method to cope with redundant degrees of freedom, especially for snake-like robot[1],[11]. However, it is still a challenge to design CPG models with excellent characters. S.Ma[1] used a CPG network with feedback to control the serpentine locomotion of snake-like robot. While, it can not obtain parameters exactly as desired, especially desired phase difference. In this paper, we propose a CPG model based on the gradient system by exploring the synchronization of gradient system. This approach uses the phase differences as a group of state vectors and sets the desired phase differences as the balance point of the gradient system which is shaped by those state vectors. Therefore, we can obtain the a new novel CPG model to build the control architecture. Then, implement it to realize various of gaits and free gait transition.

## III. MECHANICAL OVERVIEW

Our snake-like robot has a modular design consisting seven actuated modules and a head module, which is used to communicate with other modules via I$^2$C and the operator via Wireless. All the output shafts are alternately aligned with the robot's lateral and dorsal planes, thus generating 3D locomotion. The total length of the snake-like robot is 70cm. Every module has three 3D printed shells and an actuated joint, which is connected to the adjacent modules. Each joint allows a full 180° of rotation. The tuning axis of the joint rotates 90° module by module. Including specialized head module, the robot has 7 degrees of freedom (more modules can be appended if necessary).

Each module contains a servo and a set of gears to actuate the joint. The DC servo (DS1509MG) has a maximum torque of 12.8$Kg\cdot cm$ and drives a gearbox with a reduction factor of 3.71. The output axis of the gear is fixed to the connection piece, which is inserted into the next module. For the electronic hardware part, each module has an Arduino Nano board, a printed circuit board and an angle sensor. The Arduino Nano board runs three tasks: controlling the servo, reading the joint angle, and communicating with head module. Besides, a rechargeable Li-Ion battery is built-in to power all the components inside the module such that every module is electrically independent from each other. The battery has a capacity of 850mAh which can power one module for approximately two hours of continuous use in normal condition. Table. I summarizes the technical specifications of our snake robot.

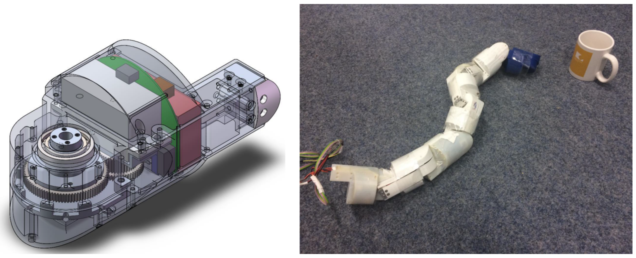


Fig. 1. Module Model and the prototype. The diameter of module is 60mm. Each module has gearbox, servo, circuit board and battery inside. The prototype has 7 actuated modules and a head module with wireless sensor.

TABLE I

OVERVIEW OF SNAKE-LIKE ROBOT SPECIFICATIONS

| | |
|---|---|
| Dimensions | Diameter 60mm<br>Length 70cm |
| Mass | Module 0.3kg<br>Full 2kg |
| Actuation | Max Torque 12.8kg.cm<br>Max Speed 0.07sec/60° |
| Power | Battery 850mAh<br>Current(max): 400mA |
| Communication | I$^2$C Bus<br>Wireless NRF24L01 |
| Sensing | Angular Sensor MLX90316KDC |

## IV. CPG-BASED CONTROL ARCHITECTURE

The CPG-based control architecture can be refined into the CPG model level and the gait generator level and various models of CPG have been proposed. Particularly, the model inspired from lamprey developed by A. J. Ijspeert [11] has the features of adjusting the amplitude and the phase continuously. In Crespi's article, a detailed mathematical derivation about the phase difference is not given, although in the appendix, a simple case of two oscillators is presented. Therefore, we propose a new mathematical model, with detailed derivation, to describe the phase difference based on the convergence behavior of gradient system, which can adjust the output signal's phase difference as desired. The structure of the CPG forms a chain of oscillators coupling the neighbor oscillators as shown in Fig. 2. The chain is designed to generate a travelling wave, from the head to the tail of the robot.

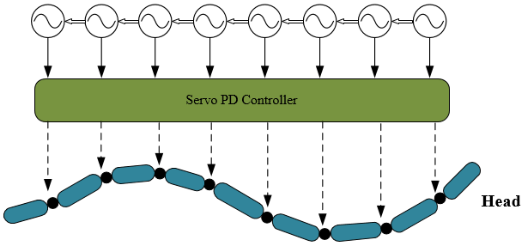


Fig. 2. Sketch of a chain-type CPG network for a snake-like robot.

### A. Mathematical model of CPG network

The propelling force of the serpentine motion of a snake-like robot comes from the interaction between the robot and the ground while the robot is swinging the joints from side to side. The rhythmic signals implements on the joint motors, can be easily generated by a CPG network. Therefore, a series of successive rhythmic signals with certain phase difference are needed to construed a kind of network for mimicking the neural system of a natural snake.

Chain-type CPG network is one of the most common topological structures. Snake-like robot usually implement this open loop unilaterally connected CPG network like[11]. In this chain-type CPG network, each CPG module can transfer the wave in one single direction from the head to the tail. There are two special position, which is the head and the tail, one can just transfer and the other can just receive wave. All the other CPG modules can both transfer and receive wave information from neighbour CPG modules. Due to the asymmetry of the chain-type CPG network, we adopt the 'Gradient System' theory to design the CPG model for the snake-like robot.

The concept of 'Gradient System' is come from gradient field. For any point $M$ in space region $G$, there is a certain scalar function $V(M)$ corresponding to the point $M$, which is called one certain scalar field in space region $G$. If there is a gradient function $gradV(M)$ corresponding to the point $M$, then a gradient field can be determined. It is generated by the scalar field $V(M)$, so that the $V(M)$ is called the potential of the gradient field. In space region $G$, the potential of any point decrease against the direction of the gradient, as shown in Equation.1.

$$\frac{dx}{dt} = -\frac{\partial V}{\partial x}, \vee x \in G \tag{1}$$

If the gradient system has a minimal value $x^*$ in $G$, thus all the vector $x$ will astringe to $x^*$, which satisfies:

$$\left.\frac{\partial V}{\partial x}\right|_{x=x^*} = 0, \left.\frac{\partial^2 V}{\partial x^2}\right|_{x=x^*} > 0 \tag{2}$$

The gradient system has some specific significance in classical mechanics, which means that any initial state $x_0$ will reach to one of the minimal values in the region $G$ during a period of limited time and remain stable since then.

According to the significance of the gradient system, we can design a chain-type CPG network to realize a fixed phase difference among all the CPG modules, which can be used for gait generation. We can consider the phase differences as a group of state vectors, and if there is a global convergence gradient system in the region which is made up by those state vectors, the balance point of the gradient system is just the very target phase difference we desire, thus the system will astringe to the desired phase difference from any position in limited time. Then we can realize the phase lock of the CPG network.

Generally speaking, the chain-type CPG network is composed by $n$ neurons with same parameters. Supposed that, the phase of the $ith$ CPG is $\varphi_i(t)$, and the phase difference between two neighbouring CPGs $ith$, $jth$ is $\theta(t)$, the desired phase difference decided by the gait generator is $\tilde{\theta}_i$, as it is shown in Fig. 3.

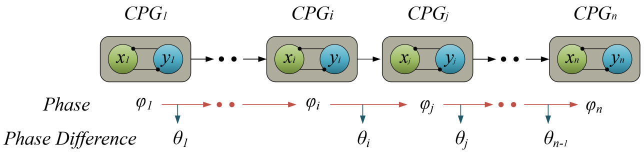


Fig. 3. Parameters setting of CPG net with chain-type.

$$\{a_{i,j}\} = \begin{cases} -1, & \text{from } j \text{ to } i. \\ 1, & \text{from } i \text{ to } j. \\ 0, & i \text{ and } j \text{ are not adjacent.} \end{cases} \tag{3}$$

Considering the chain-type CPG network as a directed graph. We will describe the topological structure of the chain-type CPG network by introducing the Incidence Matrix in graph theory. Set the incidence Matrix as $A = \{a_{i,j}\}_{(n-1)\times n}$

$$A = \begin{pmatrix} 1 & -1 & & & 0 \\ & 1 & -1 & & \\ & & \ddots & \ddots & \\ 0 & & & 1 & -1 \end{pmatrix}_{(n-1)\times n} \tag{4}$$

Thus, the relationship between the phase difference and the phase is as follows:

$$\Theta = A\Phi \tag{5}$$

where phase differences vector is $\Theta = [\theta_1, \theta_2, ..., \theta_{n-1}]^T$; the phase vector is $\Phi = [\varphi_1, \varphi_2, ..., \varphi_{n-1}, \varphi_n]^T$.

In order to design the potential function, we use $\Psi_i$ as the generalized coordinates of the gradient system, which satisfies:

$$\Psi_i = \begin{cases} \varphi_2 - \varphi_1 = -\theta_1, & i\text{=1.} \\ \varphi_{n-1} - \varphi_n = \theta_n, & i\text{=n.} \\ \varphi_{i+1} + \varphi_{i-1} - 2\varphi_i = \theta_{i-1} - \theta_i, & \text{otherwise.} \end{cases} \tag{6}$$

Then the potential function of a parabolic system is as follows:

$$V(\Psi) = \sum_{i=1}^{n} \mu_i (\psi_i - \tilde{\psi}_i)^2 \tag{7}$$

where, $\mu_i$ is the coefficient of the convergence velocity and $\tilde{\psi}_i$ is the generalized coordinates of the desired phase differences. Thus, the gradient system described by the new coordinate $\Psi$ is:

$$\frac{dV(\Psi)}{dt} = -\frac{\partial V(\psi_1, \psi_2, ..., \psi_n)}{\partial(\psi_1, \psi_2, ..., \psi_n)} \tag{8}$$

Transfer the equation into the original coordinate $\Theta$, we can get:

$$\frac{dV(\theta_i)}{dt} = -\frac{\partial V(\Psi)}{\partial \theta_i} = -\sum_{i=1}^{n} \frac{\partial V(\Psi)}{\partial(\psi_i)} \frac{\partial \psi_i}{\partial \theta_i} \tag{9}$$

Then we can express the equation into:

$$\frac{d\theta_i}{dt} = \begin{cases} -2\mu_1(\theta_1 - \tilde{\theta}_1) - 2\mu_2(\theta_1 - \theta_2 - \tilde{\theta}_1 + \tilde{\theta}_2), i\text{=1} \\ 2\mu_{n-1}(\theta_{n-1} - \theta_n - \tilde{\theta}_{n-1} + \tilde{\theta}_n) - \\ 2\mu_n(\theta_{n-1} - \tilde{\theta}_{n-1}), i\text{=n-1} \\ 2\mu_{i-1}(\theta_{i-1} - \theta_i - \tilde{\theta}_{i-1} + \tilde{\theta}_i) - \\ 2\mu_i(\theta_i - \theta_{i+1} - \tilde{\theta}_{i-1} + \tilde{\theta}_{i+1}), \text{otherwise.} \end{cases} \tag{10}$$

Finally, we can get the gait generator model for the chain-type CPG-network as follows:

$$\begin{pmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \vdots \\ \dot{\varphi}_n \end{pmatrix} = \begin{pmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_n \end{pmatrix} + A \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \vdots \\ \varphi_n \end{pmatrix} + B \begin{pmatrix} \tilde{\theta}_1 \\ \tilde{\theta}_2 \\ \vdots \\ \tilde{\theta}_{n-1} \end{pmatrix} \tag{11}$$

where $A$ is,

$$A = \begin{pmatrix} -\mu_1 & \mu_2 & & & 0 \\ \mu_2 & -2\mu_2 & \mu_2 & & \\ & \ddots & \ddots & \ddots & \\ & & \mu_{n-1} & -2\mu_{n-1} & \mu_{n-1} \\ 0 & & & \mu_n & -\mu_n \end{pmatrix}_{n\times n} \tag{12}$$

where $B$ is,

$$B = \begin{pmatrix} 1 & & & 0 \\ -1 & 1 & & \\ & -1 & \ddots & \\ & & \ddots & 1 \\ 0 & & & -1 \end{pmatrix}_{n\times(n-1)} \tag{13}$$

where $\omega = (\omega_1, \omega_2, ...\omega_n,)$ as the integration constants. In order to make the network output signal with same frequency, we set $\omega_1 = \omega_2 = ... = \omega_n$. The convergence rate of the system is decided by the matrix $A$, which increases with the value of $\mu_i$.

Then we can get the phase equation of one single neuron CPG for chain-type network,

$$\dot{\varphi}_i = \omega_i + A\{i,:\} \cdot \Phi + B\{i,:\} \cdot \tilde{\Theta} \tag{14}$$

In summary, combining the amplitude differential equation of A. J. Ijspeert[11], the single neuron CPG model can be written as

$$\begin{cases} \dot{\varphi}_i = \omega_i + A\{i,:\} \cdot \Phi + B\{i,:\} \cdot \tilde{\Theta} \\ \ddot{r}_i = a_i[\frac{a_i}{4}(R_i - r_i) - \dot{r}_i] \\ x_i = r_i \sin(\varphi_i); \end{cases} \tag{15}$$

where $A\{i,:\}$ is the $i$th row vector in Equation.12, $B\{i,:\}$ is the $i$th row vector in Equation.13. $\Phi$ is the vector of the phase of the CPG neurons and $\tilde{\Theta}$ is the vector of the phase difference between the CPG neurons. The state variable $\varphi_i$ and $r_i$ represent, the phase and the amplitude of the $i$th oscillator, respectively. The parameter $R_i$ determines the stable amplitude and $a_i$ is a positive constant. The variable $x_i$ is the rhythmic output signal integrated by the phase $\phi_i$ and the amplitude $r_i$.

After we obtain the CPG mathematical model, the parameters should be analyzed. As it is described before, $\omega_i$ is the frequency of the output signals, while $\theta$ is corresponding to the phase difference, which is important for gait design. In Fig. 4, we plot four CPG outputs by adjusting the parameters with time. From the figure, we can observe how those parameters influence the output wave.

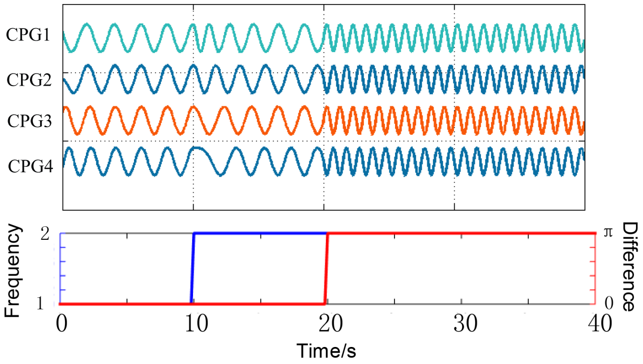


Fig. 4. CPG output with changing parameters. Top: CPG output signals changing with time. Bottom: Frequency changes from 0.5Hz to 1Hz, with $\omega_i$ changes from $\pi$ to $2\pi$, at $t = 10$. Phase difference changes from 0 to $\pi$, with $\theta$ changeing from 0 to $\pi$, at $t = 20$.

The convergence tolerance is also analyzed, which is defined when the phase difference is set as zero as,

$$tolerance = \sum_{i=1}^{n-1} (\frac{1}{n-1} \mid (r_i - r_j) \mid), j = i + 1 \tag{16}$$

where $n$ is the neuron number. As described before, the parameter $\mu$ is related to the speed of the synchronization. Based on the tolerance definition in (16). The relationship between the convergence rate and the parameter $\mu$ is shown in Fig. 5. From the figure, we can conclude that the convergence rate increases with $\mu$.

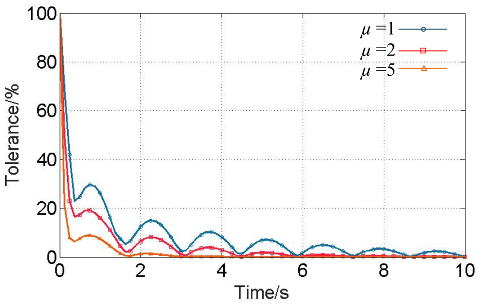


Fig. 5. CPG output synchronization speed changes with the parameter $\mu$. We set the phase at 0, so the signals will reach the peak value at the same pace. Y axis is the tolerance between adjacent CPG. We can observe that the speed of the tolerance reach to zero increase with the parameter $\mu$.

### B. Gait Transitions

Another significant phenomenon during gait generation is called Free Gait Transition(FGT) which means the current gait could freely shift into another gait type in finite time.

As for the snake gaits, we choose two typical gaits, rolling and sidewinding. Rolling gait is a basic gait for snake, consissting of an arc of costant curvature. For our snake robot which has eight modules, the gait generator for the robot is acquired as the neuron number of $n = 8$. The phase difference of rolling is shown in Equation.17 and the CPG signals for joints is is shown in Fig. 6.

$$\vec{\Theta} = (\frac{\pi}{2}, -\frac{\pi}{2}, \frac{\pi}{2}, -\frac{\pi}{2}, \frac{\pi}{2}, -\frac{\pi}{2}, \frac{\pi}{2}), \quad \text{rolling} \tag{17}$$

Besides, sidewinding[16] gait is claimed to be the most efficient and common gait for a snake. The phase difference of sidewinding is presented in (18), as it is shown in Fig. 6.

$$\vec{\Theta} = (\frac{\pi}{2}, 0, \frac{\pi}{2}, 0, \frac{\pi}{2}, 0, \frac{\pi}{2}) \quad \text{sidewinding} \tag{18}$$

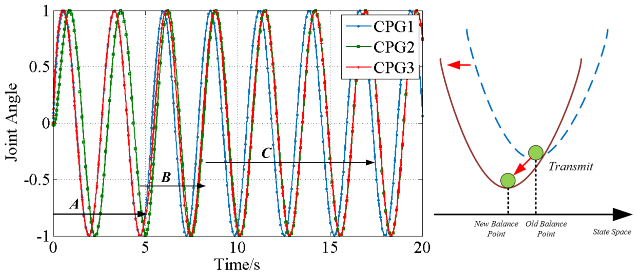


Fig. 6. Process of gait transition from rolling to sidewinding. Left: (A). Signals adjust to the rolling gait, which phase difference is set as Equation.17. (B). Remain rolling until $t = 5$. (C). Signals adjust to the sidewinding gait, which phase difference is set as Equation.18. (D). Remain sidewinding. Right: The physical Meaning of the gait transition, which means the lowest point of gradient system is corresponding to phase difference vector $\Theta$ for one stable gait

## V. EXPERIMENTS

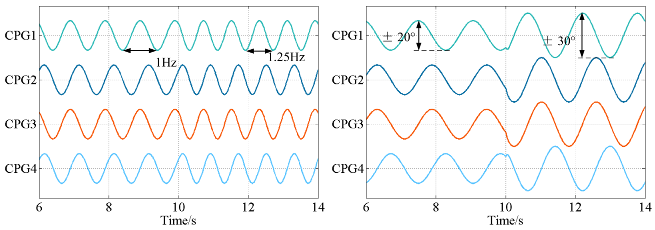
In previous sections, the effectiveness of the presented gait generator has been proved via numerical simulation. Now, we report the results of a set of simulations and experiments conducted on our snake robot to demonstrate the effectiveness of our proposed CPG-based control architecture.

### A. Simulation

A simulator for a snake-like robot has been developed in Virtual Robot Experimentation Platform(V-Rep EDU Version). In the simulation, the interaction between the snake-like robot and the ground is modeled by symmetric friction model with a large friction coefficient $\mu = 1$ to increase the propulsion. The $i$th CPG ouput is implemented on the $i$th servo, located at the $i$th joint of the snake-like robot. The physical properties are obtained from the prototype, for example, the mass or inertia. Inside the V-rep, we choose the bullet as the physics engines and set the time step as 50ms.

The results of the simulation are shown in figures from Fig. 7 to Fig. 10. Fig. 7 shows the generated signals of rolling and sidewinding gaits. Fig. 8 to Fig. 10 present the decomposition diagrams of rolling, sidewinding, and gait transition, respectively.

As Fig. 8 shows, the rolling forward speed of the snake robot is increasing during the process. That is because that we increase the frequency of the CPG output from 1Hz to 1.25Hz at $t = 10s$, which can be observed in Fig. 7(a). Sidewinding gait is shown in Fig. 9. We can observe that the maximum joint angle, which is related to the amplitude, becomes larger after $t = 10s$. The reason is that the amplitude of the CPG output is increased from 20° to 30° at $t = 10s$, as shown in Fig. 7(b). Moreover, the simulation also demonstrate that the desired gaits can be achieved by adopting the generated signals.



(a) (b)

Fig. 7. (a) Rolling gait simulation signals. The frequency is increased from 1Hz to 1.25Hz at $t = 10$. The related parameter in CPG model $\omega_i$ is tuned from $2\pi$ to $2.5\pi$. (b) Sidewinding gait simulation signals. The amplitude is increased from 20° to 30° at $t = 10$. The related parameter in CPG model $R_i$ is tuned from 20 to 30.

Simulation of a free gait transition from rolling to sidewinding is also conducted. We alter the phase differences between adjacent modules of the snake from the set listed in (17) to that in (18), which correspond the two gaits, respectively. Fig. 10 displays several snapshots of the process of gait transition. We can observe that with help of the rapid regulation ability of the CPG network, the snake-like robot takes less than four seconds to finish the gait transition.

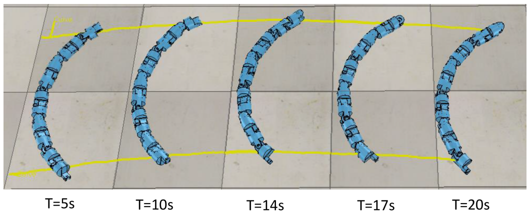


Fig. 8. Snake-like robot rolling with increasing frequency from 1Hz to 1.25Hz. The related signals is shown in Fig. 7 (a). The yellow lines are the trajectories of head and tail.

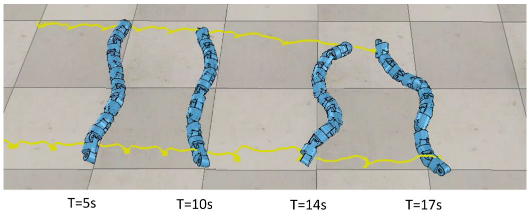


Fig. 9. Snake-like robot rolling with increasing amplitude from 20° to 30° at $t = 10$. The related signals is shown in Fig. 7 (a). The yellow lines are the trajectories of head and tail.

In conclusion, the simulations results shows that: (a) the CPG-based control architecture can adjust the gait parameters continuously and quickly, (b) certain gaits and transition between two gaits can be achieved by adjusting the gait parameters to corresponding sets.

### *B. Prototype Implementation*

The proposed CPG-based control architecture is also implemented on real physical snake-like robot, which is described in Section III. Furthermore, the communication diagram is shown as Fig. 11. The control scheme is implemented partly on a PC which is in charge of calculating the CPG network. Moreover, the PC also runs a ROS node to transmit the command signals to, and receive the feedback joints angles from the wireless-forwarder Arduino board. Then the board forwards the commands to the master board on the head module of the snake-like robot via wireless radio. After parsed by the master board, the commands are sent to the corresponding slaves via $I^2C$ bus. Every slave module runs a PD controller to control the servo such that the joint can reach desired position and feedback the joint angle to the master.

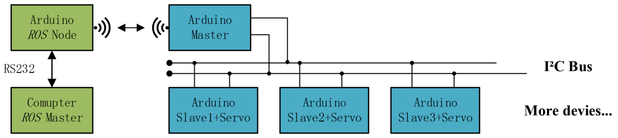


Fig. 11. Design of the communication diagram

In Fig. 14, the snake-like robot moves in the rolling gait. The amplitude and the frequency are is set as 30° and 0.2Hz, respectively. The phase difference is described in (17). From the snapshots we can observe that, rolling gait is consisting of an arc of constant curvature decided by the amplitude.

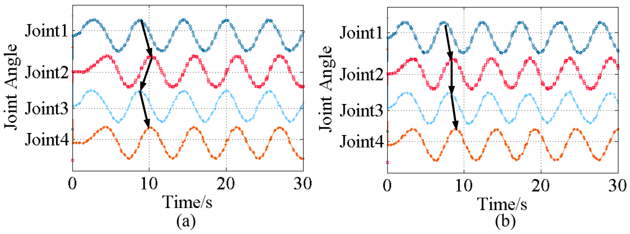


Fig. 12. (a). The feedback angles of rolling gait. The CPG signal parameters: amplitude 30°, frequency 0.2Hz. The phase difference among the four joints are $\frac{\pi}{2}$, $-\frac{\pi}{2}$ and $\frac{\pi}{2}$. (b). The feedback angles of sidewinding gait. The CPG parameters: amplitude 30°, frequency 0.2Hz. The phase difference among the four joints are $\frac{\pi}{2}$, 0 and $\frac{\pi}{2}$.

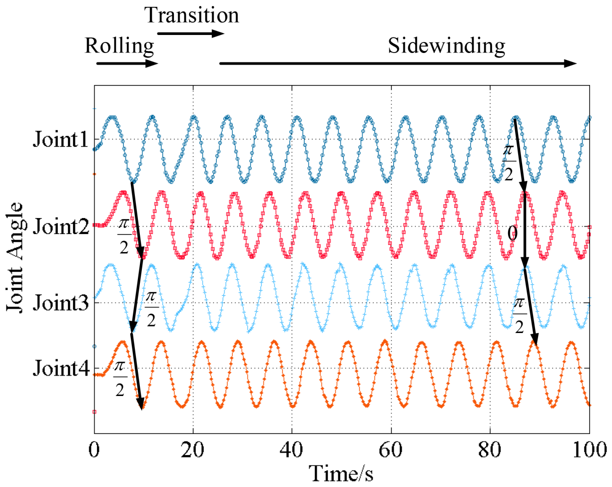


Fig. 13. The feedback angles of gait transition. The robot starts rolling until $t = 15$. The phase differences can be observed from the figure, which is the same as Equation.17. Then the robot starts the transition, during which the signals are self-regulated. At $t = 25$, the robot starts sidewinding, after which the phase differences are same with that in Equation.18.

The rolling speed is related to the sampling frequency. The feedback joint angles of the four modules close to the tail are shown in Fig. 12(a). From the figure, we can observe that the phase differences of the real snake robot agree with those described in Equation. 17.

The snapshots of the experiment of sidewinding are shown in Fig. 15. The amplitude and the frequency are set as 30° and 0.2Hz, respectively. The phase differences between modules described in Equation.18 are used to generator commands for the snake. From the snapshots, a shape of helix can be observed. Driven by the static contact force from the contact points and the ground, the snake-like robot moves its body along the lateral direction. Fig. 12(b) displays the feedback joint angles data of the four modules. As the figure shows, the desired phase differences corresponding to (18) can be observed.

The continuously gait transition from rolling to sidewinding is also shown in Fig. 16. The CPG output signal's amplitude is set as 30°, the frequency is set as 0.2Hz. The phase difference is implemented as Equation. 18. We set the transition starts at $t = 15$s. Form the figure, we can

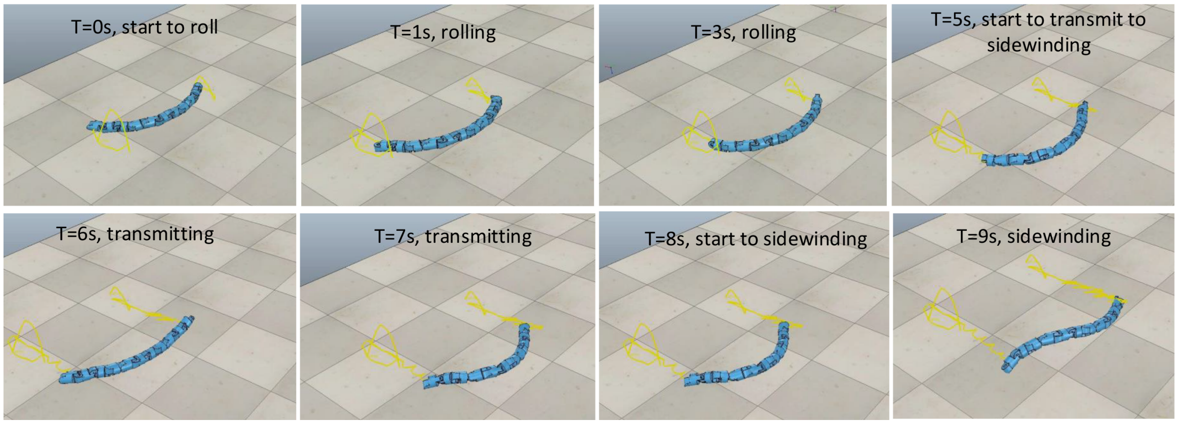


Fig. 10. Snapshots of the snake-like robot achieve gait transition, from rolling to sidewinding at $t = 5$. The yellow lines are the trajectories of head and tail.

Fig. 14. Snapshots of the robot rolling, the CPG parameters: amplitude 30°, frequency 0.2Hz, phase differences are set as Equation.17.

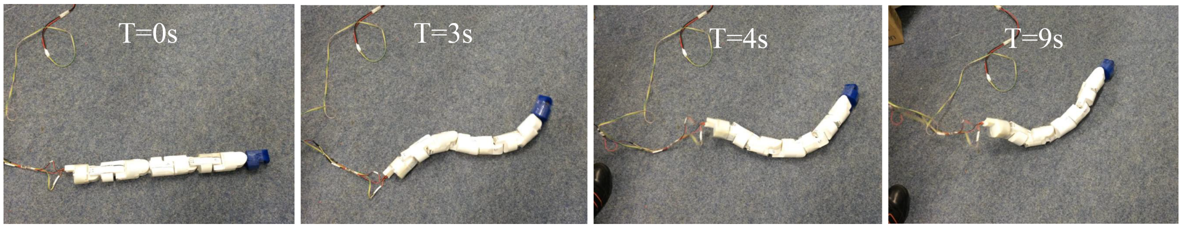


Fig. 15. Snapshots of the robot sidewinding, the CPG parameters: amplitude 30°, frequency 0.2Hz, phase differences are set as Equation.18.

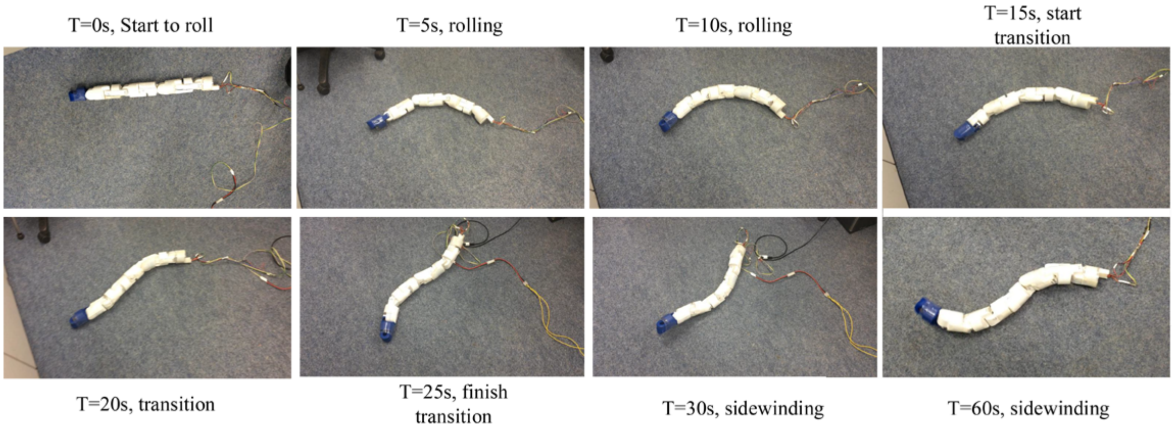


Fig. 16. Snapshots of the gait transition, the CPG parameters: amplitude 30°, frequency 0.2Hz. The phase differences are changed at $t = 15$. Due to Arduino board speed limit, the speed is scaled down to one third of that in simulation.

find that the robot start to roll until $t = 15$s. Then, effected by the CPG signals, the robot changes its gait and finishes the transition at $t = 25$. Finally, the snake-like robot moves in sidewinding gait. The feedback joint angles of the four modules are displayed in Fig. 13. As demonstrated by the figures, the experiments results are closely in agreement with the simulation results.

## VI. CONCLUSIONS AND FUTURE WORK

In this paper, we present a novel CPG-based locomotion control architecture for snake-like robots, which can not only achieve 3D locomotions, but also realize various gaits and continuously gait transition. Based on the convergence behaviour of gradient system, our CPG model can dynamically adjust the phase differences between the neighbouring CPG neurons as desired in a rapid rate. By tuning the parameters in CPG model, the important quantities can be exactly defined, such as, amplitude, frequency and the synchronization rate.

The validity of the proposed architecture had been confirmed via the a series of simulations and real physical robot experiments. The results show that the robot in simulation and experiments behaves as we expected, e.g., holding a certain gait or doing gait transition.

For future work, we plan to optimize the CPG model by integrating the environment sensing, like vision signal, as neuron impulse to control the locomotion of snake-like robot, aiming to improve the adaptive behaviour in unknown environment.

## REFERENCES

[1] X. Wu and S. Ma, "Cpg-based control of serpentine locomotion of a snake-like robot," *Mechatronics*, vol. 20, no. 2, pp. 326–334, 2010.

[2] M. Tanaka and K. Tanaka, "Control of a snake robot for ascending and descending steps," *Robotics, IEEE Transactions on*, vol. 31, no. 2, pp. 511–520, 2015.

[3] S. Hirose, "Biologically inspired robots: Snake-like locomotors and manipulators,(1993)."

[4] M. Mori and S. Hirose, "Three-dimensional serpentine motion and lateral rolling by active cord mechanism acm-r3," in *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, vol. 1. IEEE, 2002, pp. 829–834.

[5] H. Yamada, S. Chigisaki, M. Mori, K. Takita, K. Ogami, and S. Hirose, "Development of amphibious snake-like robot acm-r5," *Proc. ISR2005*, 2005.

[6] D. Rollinson, S. Ford, B. Brown, and H. Choset, "Design and modeling of a series elastic element for snake robots," in *ASME 2013 Dynamic Systems and Control Conference*. American Society of Mechanical Engineers, 2013, pp. V001T08A002–V001T08A002.

[7] Shugen, "Analysis of creeping locomotion of a snake-like robot," *Advanced Robotics*, vol. 15, no. 2, pp. 205–224, 2001.

[8] M. Saito, M. Fukaya, and T. Iwasaki, "Modeling, analysis, and synthesis of serpentine locomotion with a multilink robotic snake," *IEEE Control Systems Magazine*, vol. 22, no. 1, pp. 64–81, 2002.

[9] F. Delcomyn, "Neural basis of rhythmic behavior in animals," *Science*, vol. 210, no. 4469, pp. 492–498, 1980.

[10] S. Grillner, "Neural control of vertebrate locomotion-central mechanisms and reflex interaction with special reference to the cat," in *Feedback and motor control in invertebrates and vertebrates*. Springer, 1985, pp. 35–56.

[11] A. J. Ijspeert, A. Crespi, D. Ryczko, and J.-M. Cabelguen, "From swimming to walking with a salamander robot driven by a spinal cord model," *science*, vol. 315, no. 5817, pp. 1416–1420, 2007.

[12] A. Crespi and A. J. Ijspeert, "Online optimization of swimming and crawling in an amphibious snake robot," *Robotics, IEEE Transactions on*, vol. 24, no. 1, pp. 75–87, 2008.

[13] M. Tesch, K. Lipkin, I. Brown, R. Hatton, A. Peck, J. Rembisz, and H. Choset, "Parameterized and scripted gaits for modular snake robots," *Advanced Robotics*, vol. 23, no. 9, pp. 1131–1158, 2009.

[14] F. Matsuno and K. Suenaga, "Control of redundant 3d snake robot based on kinematic model," in *Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on*, vol. 2. IEEE, 2003, pp. 2061–2066.

[15] J. Ute and K. Ono, "Fast and efficient locomotion of a snake robot based on self-excitation principle," in *Advanced Motion Control, 2002. 7th International Workshop on*. IEEE, 2002, pp. 532–539.

[16] S. M. Secor, B. C. Jayne, and A. F. Bennett, "Locomotor performance and energetic cost of sidewinding by the snake crotalus cerastes," *Journal of experimental biology*, vol. 163, no. 1, pp. 1–14, 1992.