CPG-based Locomotion Control of a Snake-like Robot for Passing through a Variable Width of Path

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In this paper, a biomimetic approach based on central pattern generator (CPG) is utilized to control body shape of a snake-like robot for serpentine locomotion. The CPG model is based on the phase oscillator, in which only one control parameter is used to control the locomotion. The novelty of the approach is the online body shape transition of the snake-like robot which is useful in adapting to various space width especially for rescuing and searching tasks. The major parts of this paper include: 1) a brief introduction of the phase oscillator model and the proposed CPG network, 2) a proposed activation function to control the body shape transition of the snake-like robot, and 3) a turning motion and straight-path motion control strategy. Simulations are used to demonstrate its effectiveness with explanation on setup and control strategy for future experiment on physical snake-like robot.

Key Words: CPG, snake-like robot, phase oscillator, body shape control

1. INTRODUCTION

Research in bio-inspired mobile robots has become attraction to many researchers due to their ability to replace human operations for searching, navigating and rescuing in hazardous environments such as natural disasters, explosions, mining and radiation areas. Several types of bio-inspired robots that have been widely developed are legged robot, wheeled robot, limbless robot, wall climbing robot and amphibious robot.

Locomotion control of a snake-like robot is studied due to its advantages over other types of mobile robots in term of their stability and traverse ability. Moreover, unique locomotion of a biological snake in sneaking into a narrow space, brings a great interest in mimicking it into a snake-like robot, which is useful for rescuing and searching tasks. The main goal is to control body shape of a snake-like robot to move into variable width of path for two different purposes: 1) straight-path motion, and 2) turning motion.

![Axis of locomotion](image)

Fig. 1 Body shape control of a snake-like robot to move into variable width of path: (a) straight-path motion, and (b) turning motion

This paper focuses on the CPG-based control for a snake-like robot to mimic the typical serpentine locomotion of snakes, which is the most efficient among all modes [1]. CPG is neural networks that exist in spinal cords of living animals which are used as activation signal for muscle contractions. It is a neural circuit that can produce a rhythmic pattern without needing any inputs from sensory feedback signal or descending control. Signals from CPG directly control the effector organ such as cilia and legs. From the engineering viewpoint, CPG-based approach uses dynamical systems of coupled nonlinear oscillators or recurrent network to generate traveling waves for desired locomotion. Limit cycle behavior of the traveling waves are achieved by the differential equations integrated over time.

Previous works done for controlling locomotion of a snake-like robot utilizing CPG-based method have either complicated network or complex interneurons connection to produce rhythmic output, which requires high computational cost [2][3][4][5][6]. To overcome the problems, phase oscillator has been adopted as the dynamic model representing our CPG coupled oscillators with a simple unidirectional CPG structure [7]. An interesting aspect of the phase oscillator model is the combination of the simplicity of the sine-based approaches with the robustness of the CPG due to the possesses of limit cycle behavior by the phase oscillator. The parameters of the phase oscillator have explicit relationship to the output, where the frequency, phase, and amplitude are directly influenced the CPG output, which provides easy control.

This paper is organized as follows: Section 2 describes the network of our CPG-based control. Section 3 presents the body shape transition utilizing linear bipolar function. Section 4 explains the straight-path motion and turning motion control strategies. Section 5 shows the simulations and experimental setup. Section 6 is the concluding remarks as well as our future works.

2. NETWORK OF CPG

2.1 Model

Phase oscillator has been adopted as the CPG model. Further explanation of phase oscillator can be referred to [8]. As explained in previous work [7], the phase oscillator has been modified for simplification of control. The modified mathematical model of a phase oscillator is as follows:

\[ \tau \dot{\theta} = 2\pi \nu + \sum w_j \sin(\theta_j - \theta_i - \phi_j) \]  

(1)

The output for each oscillator is defined as follow:
\[ x_i = A \cos \theta_i \]

\[ \text{joint\_angle}[i] = x_i \]  

(2)

where \( x_i \) is the \( i \)-th joint angle. Description of parameters of our CPG model is explained in Table 1.

<table>
<thead>
<tr>
<th>Items</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_i )</td>
<td>Phase of the ( i )-th oscillator</td>
</tr>
<tr>
<td>( \theta_j )</td>
<td>Phase of the ( j )-th oscillator</td>
</tr>
<tr>
<td>( v_i )</td>
<td>Intrinsic frequency</td>
</tr>
<tr>
<td>( A )</td>
<td>Amplitude</td>
</tr>
<tr>
<td>( w_{ij} )</td>
<td>Coupling weights between oscillators</td>
</tr>
<tr>
<td>( \phi_i )</td>
<td>Phase bias</td>
</tr>
<tr>
<td>( x_i )</td>
<td>Rhythmic and positive output signal</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Frequency control</td>
</tr>
</tbody>
</table>

Table 1 Description of the CPG parameters

2.2 Structure of the CPG Network

A simplified CPG structure was proposed in [7], where unidirectional coupling has been designed to control the locomotion of a snake-like robot. Illustration of the proposed CPG structure is shown in Fig. 2. Number of CPG oscillators can be added depending on the number of the actuated joints of the snake-like robot. The interesting feature of the proposed CPG structure is the easy control of parameter \( \phi_i \) where \( \phi_i \) is utilized as the parameter control of the phase difference between the CPGs. In this paper, the value of \( \phi_i \) for all CPG oscillators is set as \( \phi_i = \phi \) (The same value for all oscillators). For forward motion, \( \phi \) is set \( -\phi \) for descending connection and \( +\phi \) for ascending connection. Further explanation on the sign of the \( \phi \) can be referred to [7].

![Fig. 2 Unidirectional coupling of CPG oscillators](image)

Each of the CPG oscillator controls a designated joint angle of the snake-like robot. For example, the first oscillator will control the first actuator of the snake-like robot by inputting the desired joint angle to the joint motor. The goal of this paper is controlling the body shape of the snake-like robot with symmetric S-shape, the phase difference for all joint angles should be the same. This can be achieved using the parameter \( \phi \) of the phase oscillator, which shows a clear relation to the CPG output [20]. With this property, locomotion of the snake-like robot in term of its number of S-shape can be controlled. Using the proposed structure of unidirectional coupling, the total phase difference, \( \phi_{\text{total}} \), is given as follows:

\[ \phi_{\text{total}} = n\phi \]  

(3)

where \( n \) is the number of actuated joints from head to tail of the snake-like robot. To get one S-shape during locomotion, the total phase difference should be equal to \( 2\pi \). Thus, the number of locomotion of S-shape, \( N \) can be given as:

\[ N = n\phi / 2\pi \]  

(4)

By changing the value of \( \phi \), the desired serpentine locomotion of the snake-like robot can be obtained, where (4) can be rearranged as follows:

\[ \phi = 2\pi N / n \]  

(5)

3. BODY SHAPE TRANSITION

Modifying \( \phi \) directly using (5) will result in unstable or discontinuous behavior of the CPG outputs. Thus, an activation function namely linear bipolar has been introduced for producing smooth phase transition, where \( \phi \) increases with time during the phase transition. For further understanding, please refer to our previous work [9]. The proposed linear bipolar is illustrated in Fig. 3(a) and Fig. 3(b).

![Fig. 3. Linear bipolar: (a) \( \phi \) linearly increase, (b) \( \phi \) linearly decrease](image)

3.1 Mathematical Model

Based on (5), a general mathematical model that describes both linearly increasing and linearly decreasing of \( \phi \) with time, is as follows:

\[ \phi = \phi_1 - \alpha(T_1 - t) \]  

(6)

\[ \alpha = \phi_2 (N_2 / N_1)(1 - (N_1 / N_2))(T_2 - T_1) \]  

(7)

From (6), the S-shape locomotion can be easily controlled by changing the value of \( N_2 \). The parameters \( \phi_1 \) and \( N_1 \) are predefined constant value. \((T_2 - T_1)\) is the transition time of the phase difference \( \phi_1 \) to \( \phi_2 \), \( T_1 \) is the trigger time for the phase difference transition. By applying our proposed activation function, a smooth linear change of the CPGs output can be achieved.

![Fig. 4 Behavior of CPGs when \( \phi \) is changed from \( \pi/2 \) to \( \pi/4 \): (a) \( \theta_i \) with respect to time, and (b) output \( x_i \)](image)
3.2 Behavior of CPG Outputs

The behaviors of the CPG outputs for two oscillators are shown in Fig. 4. By applying the activation function in (6), smooth change of $\theta_i$ with respect to time is achieved, and thus results in a smooth change of the CPG output, $x_i$.

In this simulation, we use $\phi_1 = \pi/4$, $\phi_2 = \pi/2$, $n = 8$, and $(t_2 - t_1) = 1$s. Here, $\phi_1$ corresponds to $N_1 = 1$, and $\phi_2$ corresponds to $N_2 = 2$. Thus, the result confirms that the discontinuity or visible cease can be eliminated by incorporating the activation function.

4. LOCOMOTION CONTROL

Using the body shape control model in the previous section, locomotion of a snake-like robot can be achieved in two ways: 1) straight-path motion, and 2) turning motion. These two motions are important for locomotion control of a snake-like robot especially in rescue and searching tasks.

4.1 Straight-path motion

Some situations need a straight-path motion of a snake-like robot, for instance, when moving from a large space into a narrow tunnel as illustrated in Fig. 1(a). If the straight path locomotion cannot be controlled, the snake-like robot may hit the wall.

To overcome this problem, two control strategies for straight path locomotion of a snake-like robot will be proposed using the derived linear bipolar function (6). A method for controlling straight-path locomotion of a snake-like robot is analyzed by manipulating the transition time of the phase transition $(t_2 - t_1)$.

In Fig. 5, the simulation results of the trajectory of a snake-like robot are presented with different $(\phi_2 - \phi_1)$ when $(t_2 - t_1) = 1$s and $(t_2 - t_1) = 3$s. As $(\phi_2 - \phi_1)$ gets larger, the deviation of trajectory becomes apparent. However, the deviation of trajectory can be minimized by manipulating $(t_2 - t_1)$. Thus, two important parameters need to be controlled rigorously i.e., $(t_2 - t_1)$ and $(\phi_2 - \phi_1)$.

4.2 Turning motion

In general, there are two ways for a snake to avoid obstacle; 1) by crawling over the obstacle, and 2) by turning its direction. It depends on the size and shape of the obstacle. For mimicking either method, it is limited on the design of the snake-like robot. In this study, the focus will be on method two which is suitable for wheeled snake-like robot.

Fig. 6 Simulation results of trajectory of a snake-like robot for different value of $(\phi_2 - \phi_1)$ when $(t_2 - t_1) = 1$s

Fig. 7 Different value of $(t_2 - t_1)$ with respect to $(\phi_2 - \phi_1)$

The curves show nonlinear behavior between $(\phi_2 - \phi_1)$ and the deviation angle with different $(t_2 - t_1)$. From this result, desired locomotion control of a snake-like robot can be achieved by selecting $(t_2 - t_1)$ with respect to $(\phi_2 - \phi_1)$.
5. SIMULATIONS AND EXPERIMENT

This section shows verifications of the proposed control strategy for both motions through simulations using Open Dynamic Engine (ODE) platform and experiment setup.

5.1 Simulations

A straight-path motion of a snake-like robot in different space width is shown in Fig. 8, while turning motion is shown Fig. 9.

![Fig. 8 Straight-path motion when moving in different space width](image1)

![Fig. 9 Turning motion for obstacle avoidance](image2)

5.2 Experiment

Verification by experiment is done for body shape control of a snake-like robot to avoid obstacle.

![Fig. 10 Overview of the snake-like robot](image3)

Following Fig. 11 is the flow chart of the control strategy. Communication between each joint motor can be done using inter-integrated circuit (I2C).

![Fig. 11 Flow chart of the control strategy](image4)

6. CONCLUSIONS AND FUTURE WORK

The simplicity in controlling the body shape transition for two purposes: 1) straight-path motion, and 2) turning motion for obstacle avoidance. Using the phase transition method, a smooth body shape transition and continuous input angle can be achieved. It also can achieve turning ability to adapt to the surrounding. Future works are as follows: 1) implementing sensory feedback information for adaptive locomotion, and 2) further implementations on the real snake-like robot.

REFERENCES