2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

CPG-based Locomotion Control of a Snake-like Robot for Obstacle Avoidance

Norzalilah Mohamad Nor[1] and Shugen Ma[2]

***Abstract*— This paper presents a biomimetic approach based on central pattern generator (CPG), to control turning motion of a snake-like robot. One of the interesting features of a biological snake is its ability to avoid obstacles or a barrier by turning its whole body from its trajectory. This special obstacle avoidance motion is different from other types of animal, and thus, it is worth to be analyzed and realized into a snake-like robot. The paper first briefly explains: 1) the phase oscillator model which represents the CPG model and 2) the CPG network. Next, we address several issues related to the existing/typical turning control of a snake-like robot. We then propose the phase transition method utilizing the phase difference control parameter to realize the turning motion of a snake-like robot. We also introduce a new parameter to control the turning of the robot, where it provides a way to incorporate sensory feedback into the CPG model. Simulation results show that the proposed turning method can be used efficiently as an obstacle avoidance method for a snake-like robot.**

***Keywords*-Central pattern generator, turning motion, snake-like robot**

I. INTRODUCTION

One of the main essence of robot's locomotion is their ability to avoid obstacles. For biologically inspired (bio-inspired) mobile robots, mimicking the fundamental locomotions of animals are difficult problems due to their complex body coordination and interactions with the environment. The efficiency of the animals moving adaptively to its surrounding are still beyond the reached of robots.

This paper focuses on the motion control of a bio-inspired snake-like robot for avoiding an obstacle. Different types of bio-inspired mobile robots offer different ways of avoiding obstacles or barrier. For instance, biped hopping robot [1] can utilize its two legs to jump over a barrier. In [2, 3], the quadruped robot crosses an obstacle by lifting up their legs according to the obstacle's height. While in [4], the amphibious robot uses its e-Paddle mechanism combining the wheel-legged gait to move in unstructured environment. All of these bio-inspired mobile robots provide high maneuverability for obstacle avoidance but offer less locomotion's stability.

However, mimicking the motion patterns of limbless animals such as snake and eel-fish into mobile robots's control, are different from the wheeled and legged robots. It is known that from biological snakes, its skeletal structure and scales are the vital parts that contribute to the efficient locomotion [5]. This special features of a snake can be realized into

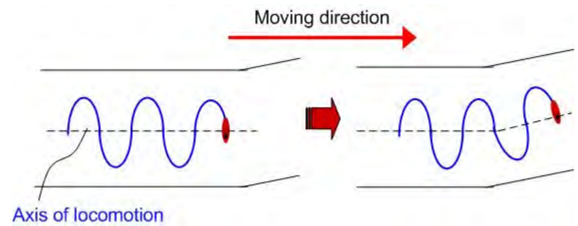

Fig. 1. Turning motion of a snake-like robot when encounters a barrier

a snake-like robot by swinging the body joints from side to side to generate effective forward locomotion [6]. 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 methods, it is limited on the design of the snake-like robot. In this study, the focus will be on method 2 which is suitable for wheeled snake-like robot. Fig. 1 illustrates the turning motion of a snake-like robot when it encounters a barrier.

In previous work [7], we have proposed a neural network based control so-called a simplified central pattern generator (CPG) to control the locomotions of a snake-like robot. The term central means that sensory feedback is unnecessary to produce the rhythmic pattern. Further explanation on CPG can be found in [9-12]. In control point of view, CPG-based control uses dynamical systems of coupled nonlinear oscillators to generate the coordinated patterns of rhythmic output. By manipulating the CPG parameters, different gaits or locomotion patterns of bio-inspired robots such as hexapod, salamander and others can be achieved. However, the ability of the snake-like robot to sneak in narrow space environments and its locomotion stability surpasses the mobility of the conventional wheeled, tracked, and legged robots.

The main focuses of this paper is to produce the turning motion of a snake-like robot based on our proposed CPGs network. The well-known control of turning motion for a snake-like robot is the amplitude modulation method (AMM) [13, 14]. A bias will be added to the output signal where an asymmetric swing of joint will lead to a change in the motion direction. One of the major drawback of the AMM is that, the bias can only be added when the signals is at zero point to avoid sudden change or discontinuity of the output signal during the turning motion. Another turning method proposed by Crespi et al [15], is by varying the offset and the amplitude body's wave of a salamander-like robot. In [16], the authors exploit the obstacles to aid the locomotion of the snake-like

[1]Norzalilah is with the Department of Robotics, Ritsumeikan University, Japan
[2]S. Ma is with the Department of Robotics, Ritsumeikan University, Japan. He is also with School of Electrical Engineering and Automation, Tianjin University, China (`email:shugen.ma@ieee.org`)

978-1-4799-3685-4/14/$31.00 ©2014 IEEE

robot, instead of avoiding it. This method shows a surplus of a snake-like robot locomotion over other types of mobile robot. However, it applies only for some limited situations such as scattered obstacles and round-shape obstacles.

All of the methods for turning motion mentioned previously utilize the amplitude as the control parameter. To the best of our knowledge, there are only few papers that utilize phase difference to control the turning motion: 1) for a fish-like robot [17] and 2) phase modulation method for a snake-like robot [18]. For bio-inspired robot which has independent left and right input control (different actuator) e.g., flapping wings of a fish-like robot [17], the turning control is easy by just inputting different value of the control parameter for both sides. This is different for a snake-like robot, which utilize only one input signal for each joint and dependent to its neighboring unit. In [18], phase modulation method is introduced to control turning motion of a snake-like robot, but results in discontinuity of the input angle. Thus, in this paper, we introduce a simple way to control the turning motion of a snake-like robot which produces continuous input angle using the same control parameter i.e., the phase difference.

This paper is organized as follows: Section II describes the network of our CPG-based control, Section III presents the turning motion analysis, Section IV explains the obstacle avoidance based on the turning control, and Section V is the concluding remarks as well as our future works.

II. NETWORK OF CPG

A. Mathematical model

The mathematical model describing a system of one phase oscillator is as follows:

$$\tau\dot{\theta}_i = 2\pi v_i + \sum w_{ij}\sin(\theta_j - \theta_i - \phi_{ij}) \tag{1}$$

The output for each oscillator is defined as follow:

$$\begin{aligned} x_i &= A\cos(\theta_i) \\ joint\_angle[i] &= x_i \end{aligned} \tag{2}$$

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

TABLE I
DESCRIPTION OF THE CPG PARAMETERS

Items	Details
θ_i	Phase of the *i*th oscillator
θ_j	Phase of the *j*th oscillator
v	Intrinsic frequency
A	Amplitude
w_{ij}	Coupling weights between oscillators
ϕ_{ij}	Phase bias
x_i	Rhythmic and positive output signal
$\dot{\theta}_i$	Determination of the time evolution of the phase θ_i
τ	Frequency control

B. Structure of CPG

In this section, a simple CPG structure to control the snake-like robot locomotion is introduced. Unidirectional coupling has been designed as the CPG structure as shown in Fig. 2. There is an interesting feature of this CPG structure, where we can easily utilize parameter ϕ_{ij} to control phase difference between the CPGs. Note that, in our case, the value of ϕ_{ij} for all CPG oscillators is the same i.e., $\phi_{ij} = \phi$. Throughout this paper, -ϕ for descending connection and +ϕ for ascending connection are used.

Fig. 2. Unidirectional coupling with four CPG oscillators

One CPG will control one joint angle of the snake-like robot. Due to the fact that 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 [1], therefore, it is crucial to control the joint angle with constant phase difference. The parameter ϕ of the phase oscillator shows a clear relation to the CPG output [10]. 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, ϕ_{total} is given as follows:

$$\phi_{total} = n\phi \tag{3}$$

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

$$N = n\phi/2\pi \tag{4}$$

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

$$\phi = 2\pi N/n \tag{5}$$

C. Controlling phase transition

A method that can produce smooth phase transition is introduced in this section: by applying an activation function that makes the ϕ increase with respect to time during the ϕ transition. The mathematical model that describes relationship between ϕ and time, is as follows:

$$\phi = \phi_1 - \alpha(t_1 - t) \tag{6}$$

$$\alpha = \phi_1(N_2/N_1)(1 - (N_1/N_2))/(t_2 - t_1) \tag{7}$$

From (6), the *S*-shape locomotion can be easily controlled by changing the value of N_2. The parameters ϕ_1 and N_1 are all predefined constant value. $(t_2 - t_1)$ is the transition time of the phase difference ϕ_1 to ϕ_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.

III. Turning Motion Analysis

A. Change in locomotion's direction

By using the phase transition to control the body shape of the snake-like robot, the direction of the snake-like robot deviates from its original position i.e., position before the phase transition starts. From our analysis by simulation, there is a small change in the direction of the snake-like robot after the phase transition and it is more apparent when changing ϕ from large to small i.e., decreasing the number of *S*-shape, N for example from 2 to 1. Fig. 3 shows the simulation results by open dynamic engine (ODE).

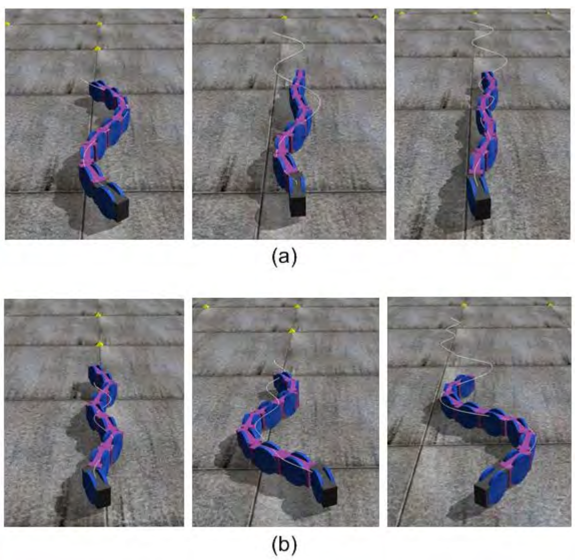

Fig. 3. Deviation of a snake-like robot locomotion: (a) from N = 1 to N = 2, (b) from N = 2 to N = 1

From Fig. 3, as N is changed from bigger to smaller value (refer Fig. 3(b)), the deviation from its original position becomes apparent. From our analysis, the parameter control of the deviation are: 1) control of frequency, v and 2) difference between value of ϕ_1 and ϕ_2. Frequency can be used for controlling locomotion speed of the snake-like robot [19], and thus contributes to the deviation of the trajectory.

B. Turning direction

The superiority of our proposed method for turning control over other methods (for example [14]) is the ability of the snake-like robot to maintain a smooth and continuous change of the joint angles at anytime during the locomotion. The turning motion can be implemented as at any desired time just by controlling the starting of the phase transition, t_1. The control of the direction of the turning can be easily controlled by the positive or negative value of the CPG output, x_i during the start of the phase transition. Thus, in cases where the direction of turning is important, the sign of x_i at t_1 needs to be identified. Fig. 4 shows an example of right and left turning motion with different starting point of phase transition. The small boxes in Fig. 4 are the starting point of the phase transition with the same value of t_1 for two trajectories. Different speed was used by controlling v to get different sign of the CPG output (positive and negative) at the same t_1.

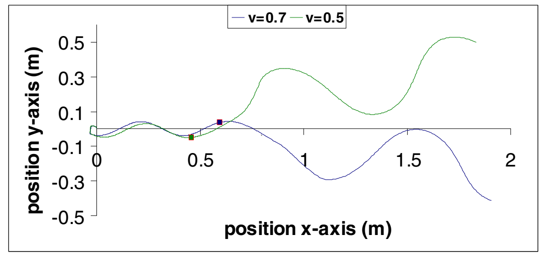

Fig. 4. Direction of turning for left and right

If the output signal is positive, the turning direction will be to the negative of the y-axis, and vice versa. If the right turning is defined at the negative signal of the y-axis, and the left turning is at the positive signal of the y-axis, therefore, it can be concluded that the turning direction of the snake-like robot can be controlled by the positive or negative value of the CPG output, x_i during the start of the phase transition, as follows:

$$\text{Turning direction} = \begin{cases} \text{Right, if } x_i \text{ is positive} \\ \text{Left, if } x_i \text{ is negative} \end{cases} \tag{8}$$

C. Control of the deviation angle

The following Fig. 5 and Fig. 6 show how the deviation are affected by the two control parameters i.e., frequency and difference between value of ϕ_1 and ϕ_2. In these two simulations, the results of the locomotion trajectory are shown by changing value of ϕ from large to small. In Fig. 5, the value of ϕ_1 is $\pi/2$ and the value of ϕ_2 is $\pi/4$. It can be found that different value of frequency, v gives little effect to the deviation angles. The deviation angles are almost the same, which is not suitable to control the turning motion of the snake-like robot.

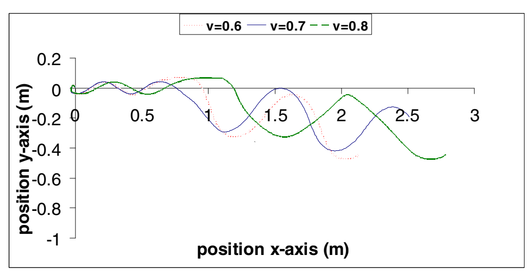

Fig. 5. Analysis of trajectory's deviation with different value of v

Fig. 6, shows the trajectories of the deviation angle while keeping the value of ϕ_1 constant i.e., $\pi/2$ and varying the value of ϕ_2 with v = 0.5, and A = 1.0. The small box in Fig. 6 marks the start of the transition from ϕ_1 to ϕ_2. It shows that the deviation angle becomes more apparent as the difference between (ϕ_1 - ϕ_2) becomes larger. Fig. 7 summarizes the relationship between deviation angle with respect to (ϕ_1 - ϕ_2) where the deviation angle is increasing nonlinearly with the increase of (ϕ_1 - ϕ_2). Thus, the value of (ϕ_1 - ϕ_2) can be increased for producing larger turning angle.

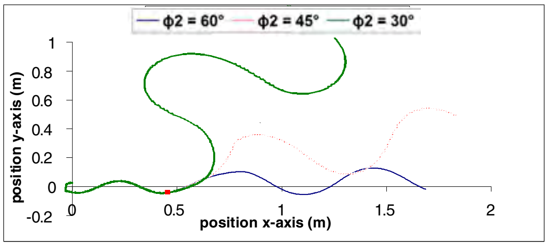

Fig. 6. Analysis of trajectory's deviation with different value of ϕ

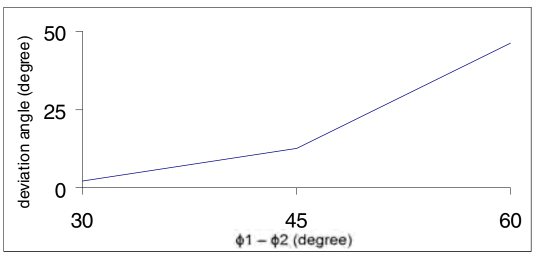

Fig. 7. Deviation angle with respect to (ϕ_1 - ϕ_2)

IV. Obstacle avoidance based on the turning control

We can apply the analysis of turning motion in previous section, into a snake-like robot locomotion control for obstacle avoidance. For instance, IR sensors can be installed at the head of the snake-like robot, or at the side of its body where the trigger of the phase transition is t_1 with appropriate N_2. Currently, deciding a suitable N_2 when encounter an obstacle is still under investigation.

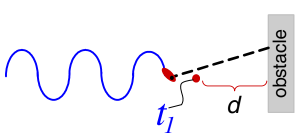

Fig. 8. Schematic of sensor-based obstacle avoidance

It is easy to set the parameter of (6), where $(t_2 - t_1)$ is set to $1s$ (this value is selected based on in depth analysis), where the value is the minimum value to obtain a smooth phase transition without any jerky movement of the snake-like robot. For further clarifications on the analysis, please refer to [22]. In Fig. 8, d is the distance from the obstacle to the starting of the phase transition, t_1. The distance should be in appropriate length to ensure the snake-like robot is totally changed to its final S-shape, N_2. In this paper, the sensor-based experiment is not discussed in details. In the simulation environment, the parameters t_1 and N_2 are calculated directly from the obstacle and the head of the snake-like robot.

A. Simulation setup

Using open dynamic environment (ODE), simulation of a snake-like robot has been conducted to verify the proposed obstacle avoidance based on the turning control. Physical features of the snake-like robot are listed in Table II. To realize the swinging movement from side to side for serpentine locomotion, two passive wheels are installed (to resist lateral movement of the snake-like robot unit) with ground asymmetric friction where the normal friction coefficient μ_N is larger than the tangential friction coefficient μ_T. Each of the snake unit is connected with joint actuator to drive the snake-like robot. The CPG output, x_i is the input signal to the joints.

TABLE II

Physical parameters of simulated snake robot

Items	Details
Snake unit	S_u = 9
Size of snake unit $[m]$	0.05x0.08x0.14
Weight of snake unit	w = 0.1kg
Radius of wheel	r_w = 0.06m
Thick of wheel	t_w = 0.015m
Weight of wheel	w_w = 0.01kg
Friction coefficient	μ_N = 0.5; μ_T =0.01

The angle signal of the robot's joint, *joint_angle[i]* is calculated by

$$joint\_angle[i] = \beta x_i \tag{9}$$

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

B. Body shape adaptation

One of the potential application for obstacle avoidance is the body shape adaptation. Fig. 9 shows the simulation results on how the snake-like robot react when encounters an obstacle by changing its body shape. In the mean time, the appropriate N_2 with respect to the size of the obstacle is still being analyzed. Another option is to move away from the obstacle by changing the robot's direction as shown in Fig. 11 and Fig. 12.

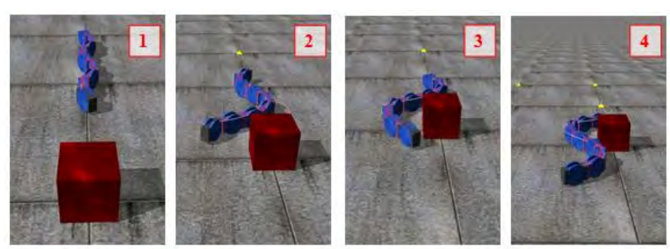

Fig. 9. Head of a snake-like robot encounter an obstacle

C. Motion optimization

Another advantage of our proposed phase transition method is the motion optimization. The propellant force of a snake-like robot can be optimized by controlling the locomotion curvature. Detailed analysis about the interaction between a snake-like robot and ground can be found in [20]. As shown in Fig. 10, increasing the rotation angle, ψ_p will increase the forward force. Adopting Coulomb friction model, the relationship between the forward force and ψ_p are described as follows:

$$
\begin{aligned}
f_p^t &= -\mu_T m_p g \operatorname{sign}(\delta^p r^t) \\
f_p^n &= -\mu_N m_p g \operatorname{sign}(\delta^p r^n)
\end{aligned}
\tag{10}
$$

where f_p^t and f_p^n are the components of friction in tangential and normal directions, respectively, exerted on the pth (p = 1, 2,...) module of a snake-like robot. μ_T and μ_N are the friction coefficients; m_p is the weight of the pth module; $\delta^p r^t$ and $\delta^p r^n$ are the tangential and normal displacements of the pth at friction point, respectively. Based on the coordinate

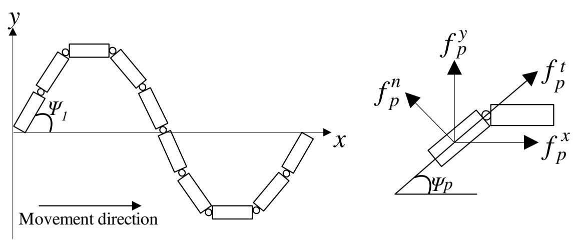

Fig. 10. Relationship between forward force and locomotion curvature

system shown in Fig. 10, where x-axis is set as the forward direction of the snake-like robot, the resultant friction force can be obtained as follows:

$$
\begin{aligned}
f_p^x &= f_p^t \cos\psi_p - f_p^n \sin\psi_p \\
f_p^y &= f_p^t \sin\psi_p + f_p^n \cos\psi_p
\end{aligned}
\tag{11}
$$

where f_p^x and f_p^y are the resultant force in x and y direction, respectively. To avoid backward slippage, sufficient friction needs to be generated along the x direction. There are two ways in obtaining necessary resultant force in the forward direction: 1) asymmetric friction with μ_N larger than μ_T, and 2) with the increasing of ψ_p. The second option can be controlled by our proposed phase transition, where the ψ_p can be increased or decreased by changing the locomotion curvature. Not all cases need to have a large locomotion curvature, for instance, climbing a slope [22], where the most efficient locomotion is when the number of S-shape, N is 2.

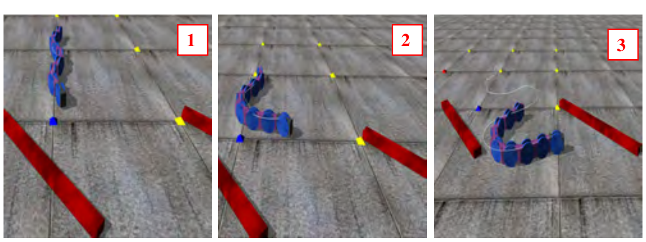

Fig. 11. Locomotion optimization in large space

Another vital point is the body shape adaptation to the surrounding space. This feature of body shape transition is important especially for searching and rescuing tasks. The spaces for instance, after a disaster will be differ with many obstacles surround, thus, an ability of turning motion with body shape transition of a snake-like robot is highly required.

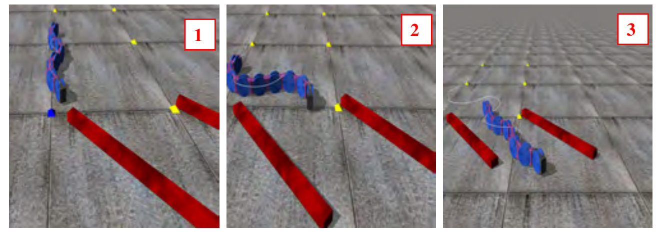

Fig. 12. Body shape adaptivity with limited space

There are two ways in controlling the amplitude of the curvature of a snake-like robot, as shown in Fig. 13: 1) amplitude-controlled, and 2) number of S-shape.

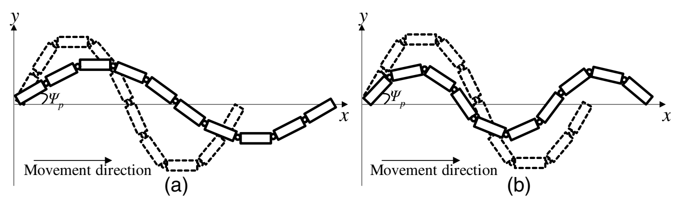

Fig. 13. Control of locomotion curvature: (a) amplitude-controlled, (b) number of S-shape

In Fig. 13(a), we can easily control the amplitude using parameter, A. This work has been done in [13, 23] but using different mathematical model. The superiority of our proposed method of controlling the number of S-shape (Fig. 13(b)) for adaptive locomotion curvature as compared to the amplitude-controlled are: 1) the joint torques is lower and uniformed for all joints (refer Fig. 14), 2) the phase transition controlled can be modified online without needing to stop the robot, and 3) the number of S-shape transition resembles closely the biological snakes when adapting to different space width.

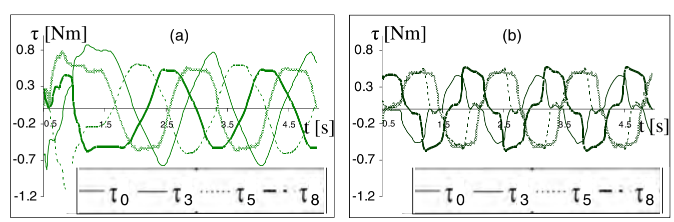

Fig. 14. Joint torques for a snake-like robot: (a) for amplitude-controlled, (b) for number of S-shape

The simulation results in Fig. 14 show examples of joint torques for joint 1, joint 3, joint 5 and joint 8. We can see that there is a fluctuation of the torque for the amplitude-controlled method. Inversely, for the number of S-shape method, the torque profile shows uniform range of torque between ± 0.6 Nm.

Beside energy consumption, another important criteria needs to investigate is the efficiency of forward distance traveled. Based on our analysis through the simulation experiment, the amplitude-controlled method give an advantage of larger forward distance traveled as compared to the number of *S*-shape method, but the difference is not significant. The total forward distance traveled in one period for the amplitude controlled method is approximately 1.101 *m*, while the traveling distance for the number of *S*-shape method in one period is approximately 1.052 *m*. In the simulation, the same setup is used for both methods.

V. Discussion

An ODE simulator has been adopted for testing the feasibility of the proposed turning method for a snake-like robot. The simulation results show a promising approach in controlling smooth and continuous turning motion which can be applied for obstacle avoidance. Even though experimental verifications is not presented yet, the simulation results can still be reliable [18, 20]. The amplitude modulation method proposed in [14, 18] shows several disadvantages such as: 1) the turning radius is big, turning angle is confined to the amplitude of serpenoid curve, and 3) the amplitude can only be modulated when the input angle is at zero. Nevertheless, the advantages of the amplitude modulation are its continuous input angle value when it changes from forward movement to turning movement and its control is simple.

Meanwhile, for the phase modulation method proposed in [18], it also addresses a limitation of the method, where the input angle is discontinuous during the transition from forward motion to turning motion. This results in large sliding of the snake-like robot's motion. By applying our proposed activation function for controlling phase transition, smooth and continuous locomotion of the snake-like robot can be obtained. All of the said drawbacks for amplitude modulation and phase modulation methods have been overcome by our simple method. In addition, our simplified CPG structure with phase oscillator model [7] promise an easy way of integrating a feedback information. Another surplus of the phase transition method for turning motion is the ability to control the number of *S*-shape to adapt to the surrounding.

It should be mentioned that there are many other external causes of the deviation of trajectory such as 1) slippery between the wheel and ground, 2) forward speed, and 3) friction coefficient (surface parameter). Therefore, the exact turning angle may not be accurate and may be different from the results in the simulation environment.

VI. Conclusions and Future Works

The simplicity in controlling the turning and body shape promises a light computational cost, easy implementation, simple control and understandable by readers who may not familiar with CPG-based control. Moreover, another advantage of our proposed phase transition method is the bias to the output signal can be altered at anytime instance for online modification. Using the phase transition method, a smooth body shape transition and continuous input angle can be achieved, with turning ability to adapt to the surrounding. For our ongoing works, we will analyze the followings: 1) the radius of the curvature with respect to ϕ, 2) implementing sensory feedback information into the turning control for adaptive locomotion, and 3) implementation of the control strategy on the real snake-like robot.

References

[1] T. Wang, W. Guo, M. Li, F. Zha, and L. Sun. CPG control for biped hopping robot in unpredictable environment, *Journal of Bionic Engineering*, 9, no.1:29 - 38, 2012.

[2] B. Li, Y. Li and X. Rong. Gait generation and transitions of quadruped robot based on Wilson-Cowan weakly neural networks, *Proceedings of the 2010 International Conference on Robotics and Biomimetics*. Tianjin, China. 2010, pp. 19 - 24.

[3] C. Liu, Q. Chen and D. Wang. CPG-inspired workspace trajectory generation and adaptive locomotion control for quadraped robots, *IEEE Transactions on Systems, Man, and Cybernatics*. 41, 3: 867 - 880, 2011.

[4] Y. Sun, and S. Ma. ePaddle Mechanism: Towards The Development of A Versatile Amphibious Locomotion Mechanism, *IEEE/RSJ International Conference on Intelligent Robots and Systems*. San Francisco, CA, USA. 2011, pp. 5035 - 5040.

[5] J.W. Ayers, J.L. Davis, and A. Rudolph. Neurotechnology for Biomimetic Robots, Massachusetts Institute of Technology, 2002.

[6] S. Hirose. Biologically Inspired Robot: Snake-like locomotors and manipulators, Oxford University, 1993.

[7] N.M. Nor and S. Ma. A Simplified CPGs Network with Phase Oscillator Model for Locomotion Control of a Snake-like Robot, *Journal of Intelligent and Robotic System*. 2013.

[8] F. Delcomyn. Neural basis for rhythmic behavior in animals, Science, 210:492 - 498, 1980.

[9] A.H. Cohen, P.J. Holmes and R.H. Rand. The nature of coupling between segmental oscillators of the lamprey spinal generator for locomotion: a mathematical model, *Journal of Mathematical Biology*, 13:345 - 369, 1982.

[10] S.L. Hooper. Central pattern generators, *Current Biology*, 10, no.5:708 - 716, 2000.

[11] M. MacKay-Lyons. Central pattern generation of locomotion: A review of the evidence, *Journal of the American Physical Therapy Association*, 82:69 - 83, 2002.

[12] A.J. Ijspeert. Central pattern generators for locomotion control in animals and robots:A review, *Neural Networks*, 21:642 - 653, 2008.

[13] X. Wu. CPG-based Neural Controller for Serpentine Locomotion of a Snake-like Robot, *Doctoral dissertation*, Science and Engineering, Ritsumeikan University, 2011.

[14] X. Wu and S. Ma. Autonomous collision-free behavior of a snake-like robot, *Proceedings of the 2010 IEEE International Conference on Robotics and Biomimetics*. Tianjin, China. 2010.

[15] A. Crespi, K. Karakasiliotis, A. Guignard, and A.J. Ijspeert. Salamandra Robotica II: An Amphibious Robot to Study Salamander-Like Swimming and Walking Gaits, *IEEE Transactions on Robotics*, 29, no.2: 308 - 320, 2013.

[16] P. Liljebck, K.Y. Pettersen, o. Stavdahl and J.T. Gravdahl, Hybrid modelling and control of obstacle-aided snake robot locomotion, *IEEE Transactions on Robotics*, 26, no. 5: 781 - 799, 2010.

[17] C. Zhou and K.H. Low. Design and locomotion control of a biomimetic underwater vehicle with fin propulsion, *IEEE/ASME Transactions on Mechatronics*, 17, no. 1: 25 - 35, 2012.

[18] C. Ye, S. Ma, B. Li, and Y. Wang. Turning and Side Motion of Snake-like Robot, *Proceedings of the 2004 International Conference on Robotics and Automation*. New Orleans, LA. 2004, pp. 5075 - 5080.

[19] A. Crespi and A.J. Ijspeert. Online optimization of swimming and crawling in an amphibious snake robot, *IEEE Transactions on Robotics*, 24, no.1: 75 - 87, 2008. 2009, pp. 871 - 876.

[20] S. Ma. Analysis of creeping locomotion of a snake-like robot. *Advanced Robotics*. 15, no.25: 205 - 224, 2001.

[21] S. Ma and N. Tadokoro. Analysis of creeping locomotion of a snake-like robot on a slope. *Autonomous Robot*. 20, no.1:15 - 23, 2006.

[22] N. M. Nor and S. Ma. Smooth transition for CPG-based body shape control of a snake-like robot, *Bioinspir. Biomim.*, 9, 2014. (016003).