Reactive motion for a snake-like robot in a crowded space

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Abstract: Until now, many snake-like robots and its motions have been studied. For example, lateral undulating motion, side winding motion and lateral rolling motion were developed. However, in those motions, the robot's shapes are planned in advance. On the other hand, snake-like robots are expected to be used in a complex, narrow and crowded space such as in a construction of nuclear power plants. In such a complex environment, snake-like robots cannot avoid contacting with the surrounding objects and it is hard to plan the motion in advance. In order to solve the problem, reactive motions for a snake-like robot should be devised. Such a locomotion for a snake-like robot is called as obstacle aided locomotion, and we are also proposing a method of obstacle aided locomotion and conducting its experiments. In this paper, our idea of Reverse Lateral Inhibition is described and simulation results are shown in which energy consumption of the snake-like robot reduced. In addition, a prototype of snake-like robot and experimental results using the prototype robot are shown.

Keyword: snake-like robot; obstacle aided locomotion; lateral inhibition; reverse lateral inhibition

1 Introduction

Biological snakes have a flexible and long body and show many functionality in spite of its simple body structure. For example, the body works as a leg in the case of moving and as an arm in the case of holding somethings. In addition, by using the advantage of its flexibility, biological snakes can enter into a complex and narrow space. Realizing those biological snake's features in robotics will give us many benefit. For example, a robot which can enter into a complex, narrow and crowded space and investigate the inside of structure could be realized. In other words, snake-like robots are expected to use for exploration in rubble of disaster sites and pipes of industrial plants and nuclear power plants.

Hirose had verified that biological snakes utilize difference of frictions in tangential direction and normal direction to move forward with undulatory locomotion and the shape of snake is expressed by serpenoid curve [1]. Based on the Hirose's idea, snake-like robots articulated links serially with passive wheels developed. In addition, we have realized motions for a snake-like robot such as lateral undulating motion, side winding motion, lateral rolling motion and helical rolling motion[2][3]. However, in those motions, the robot's shapes are planned in advance.

On the other hand, snake-like robots are expected to be used in a complex and narrow space such as in a construction of nuclear power plants. In such a situation, snake-like robots cannot avoid contacting with the surrounding objects and it is hard to plan the motion in advance. In order to solve the problem, reactive motions for a snake-like robot should be devised. By observing a biological snake, we can find that it utilizes obstacles in rough terrain to move forward. Such a locomotion for a snake-like robot is called as obstacle aided locomotion [4], and we are also proposing a method of obstacle aided locomotion and conducting its experiments [5] [6] [7].

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In this paper, our idea of reverse lateral inhibition is described and simulation results are shown in which energy consumption of the snake-like robot reduced. In addition, a prototype of snake-like robot and experimental results using the prototype robot are shown.

2 Model for simulation

First, we constructed a snake-like robot by using a simulator ODE (Open Dynamics Engine) and proposing behaviors are implemented to the snake-like robot. The effectiveness of behaviors is verified through the simulation experiment. In this section, the model of the snake-like robot and the environment in the simulator are described.

2.1 Model of snake-like robot

The appearance of the snake-like robot in the simulation environment is shown in Fig.1. In this study, it is assumed that the snake-like robot moves on two dimensional environment and all snake-like robot's links are articulated by yaw joints. Each link is modeled as a shape of capsule, the length of link is 0.07 **m**, the radius is 0.035 **m** and the weight is 0.105 **kg**. Each link is overlapped at semi sphere part to next link, and is connected by a model of hinge joint. The movable range of each joint is set from -60 **deg** to +60 **deg**. The maximum torque of the joints is 3.6 **Nm**. These parameters are based on a prototype of mechanical snake-like robot constructed in our laboratory previously [3]. In this simulation model, mechanical compliance is also introduced at the joints of snake-like robot. The equilibrium point is set at 0 **deg** for each joint's relative angle. The coefficients are 2.5 **N/m** for elastic element and 0.1 **Ns/m** for damper element. These values are decided by trial and error so that the simulated snake-like robot realizes smooth motion.

Three types of sensor are implemented to the snake-like robot model; torque sensor, tactile sensor and distance sensor. The torque sensors are implemented at each joint to measure a torque around each elastic joint. The tactile sensor is located on both sides of each link as shown blue and green objects in Fig.1. The tactile sensor can measure reaction force between the snake-like robot and an obstacle when they contact with each other. The distance sensors are attached at the tip of first link and directed 30 degrees to the heading direction as shown in red line in Fig.1. The distance sensors can detect an obstacle and measure the distance up to 1.0 **m**.

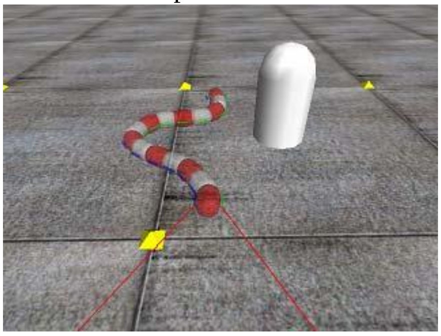

Fig.1 Model of a snake-like robot in simulation environment.

2.2 Model of environment

In this study, piles are located on two dimensional ground as obstacles. The radius of the pile is 0.1 **m**.

The piles are fixed on the ground in order not to move when a snake-like robot contact to the obstacles. Coefficient of kinetic friction for between the snake-like robot and the ground is set as 0.46 for tangential direction to each link, 0.83 for normal direction to each link, which are measured by using a real snake skin mentioned in the literature [1]. Coefficient of kinetic friction and for between the snake-like robot and obstacles is also set as 0.46.

In this study, objects are arranged in square as shown in Fig.2. Distance of objects are set in 0.33, 0.36, 0.39 and 0.42 **m** for each arrange. Of course, objects locate more complex in real environment. In this study, in order to evaluate the efficiency of snake-like robot's locomotion adequately, we arrange the obstacles regularly in the environment. Experiments for more complex environment will be conducted in the future.

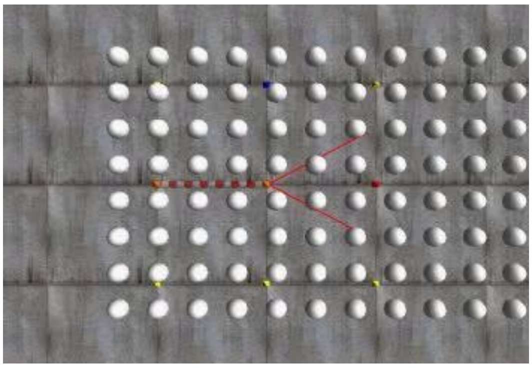

Fig.2 Setting of experimental environment.

2.3 Parameters of model

Parameters of the snake-like robot are defined as shown in Fig.3. Let i be the number of link (i=1, 2, ..., 15) and a joint between link i and link $i+1$ be the joint i.

Let τ_i^{ref} be target torque of joint i, τ_i^m be measured torque of joint i, $\tau_{\max}$ be maximum torque of each joint, ω_i be angular velocity of joint i, ϕ_i^m be measured angle of joint i, ψ be absolute angle of the line which connects robot head tip and goal point, θ be absolute angle of the first link, ℓ_l and ℓ_r be the distance measured by distance sensor attached at the first link on left side and right side respectively.

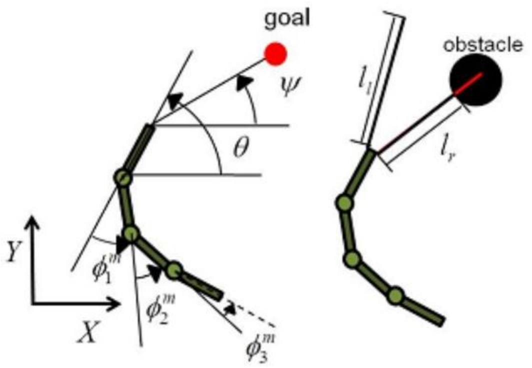

Fig.3 Definition of parameters.

3 Behavior of snake-like robot

In this section, behaviors of snake-like robot, how to decide the value of torque to each joint are described. Note that target angles for each joint are not planned previously. The final given torque is decided by superposing the result of each behavior explained in this section. In the case that the given torque is over the maximum torque, the joint is driven by maximum torque.

3.1 Undulating motion

We have implemented two type of behavior to the snake-like robot. The first one is a behavior which generates undulating motion with heading to a goal position. In this behavior, the snake-like robot is separated into three parts; head part (the first link and the first joint), neck part (the second link and the second joint) and trunk part (the others). For each parts, following role are applied to achieve the motion of undulating and heading to a goal position.

At first, torque for the first joint is given by following equation to avoid obstacles as well as heading the first link to a goal position.

$$\tau_1^{ref} = K_p(\psi - \theta) - \tau_1^m - (1.0 - \ell_l) + (1.0 - \ell_r) \qquad (1)$$

where, the first term of the right side contributes to heading the first link to a goal position, the second term affects to damp down motion of the first joint, and the third and fourth term contributes to avoid obstacles.

To the second joint, following torque is given based on the measured torque of the first and the third joint.

$$\tau_2^{ref} = -\tau_3^m + \tau_1^m \qquad (2)$$

This results that the second link keeps not too much swinging.

To the third joint, maximum torque is given according to the plus and minus sign of the first joint's angle.

$$\tau_3^{ref} = \begin{cases} \tau_{\max} & (\phi_1^m \geq 0) \\ -\tau_{\max} & (\phi_1^m < 0) \end{cases} \qquad (3)$$

After the fourth joints, maximum torque is given according to the plus and minus sign of the previous joint's torque.

$$\tau_i^{ref} = \begin{cases} \tau_{\max} & (\tau_{i-1}^m \geq 0) \\ -\tau_{\max} & (\tau_{i-1}^m < 0) \end{cases} \quad (i = 4,5,\ldots) \qquad (4)$$

As a result of these rule, the snake-like robot generates undulating motion as well as heading the first link to a goal. The snake-like robot have compliance at joint mechanism, such that torque is transferred to later joint with some delay. The snake-like robot also has anisotropy friction between the robot and the ground, difference of friction for tangential direction and normal direction, which results the snake-like robot's propelling forward.

3.2 Reactive motion

3.2.1 Lateral inhibition

Hirose applied the idea of lateral inhibition to the snake-like robot [1]. The idea is that a snake-like robot should change its shape to adapt to the obstacle's shape when the snake-like robot contacts with an obstacle as shown in Fig.4. In order to change the snake-like robot's shape appropriately, a joint where the snake-like robot contact with obstacle rotates with angle θ and the neighborhood joints should change its angle with $-\theta/2$. The effectiveness of original lateral inhibition was verified by experiments using a mechanical snake-like robot that has on-off tactile sensor at each joint. As a result, the snake-like robot emerged a behavior that it automatically coiled up to an obstacle after the obstacle was pushed to the snake-like robot for a while. In addition, by adding shift control to the lateral inhibition, the snake-like robot was able to go through in narrow winding passage.

At the beginning of this study, the original lateral inhibition was implemented in our snake-like robot in the simulation environment. However, a problem was found that the snake-like robot soon comes off an obstacle and repeat contacting on and off, in other words the snake-like robot has the jitters, when they contact each other. In order to keep contact for a while, the obstacle should be pushed toward the snake-like robot. Namely, this is a kind of obstacle avoidance behavior rather than obstacle aided behavior.

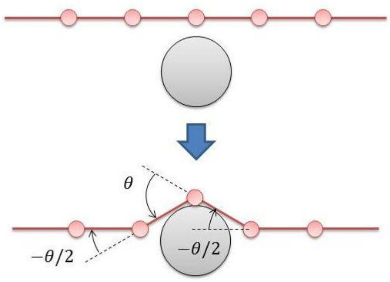

Fig.4 Original idea of lateral inhibition in order to adapt to an obstacle for a snake-like robot.

3.2.1 Reverse lateral inhibition

In this study, a reverse way to the original lateral inhibition is proposed to driven snake-like robot's joints as shown in Fig.5a. A snake-like robot generates a behavior of pushing an obstacle, such that the snake-like robot achieves obstacle aided locomotion. Note that it is assumed that a kind of tactile sensor is mounted not on the joint but on the link, and the command is not joint angle θ but joint torque $\tau \geq 0$. In addition, it is extended so that information of contact affects not only adjacent joints but also several neighboring joints away from a contacting link as shown in Fig.5b. In the Fig. 5b, torques given to the joints are decided by $k_i\tau$, where k_1, k_2, k_3 are constant values and τ is reference torque. In this study, a simple way is taken to set a reference torque as $\tau = \tau^{\max}$, where $\tau^{\max}$ is maximum value of joint torque that depends on a specification of an actuator. Note that minus sign is expressed in the Fig.5b in order to see that the joint is rotate in opposite direction. Actually, the direction is included in the value of k_i and it is taken from the range of $-1 \leq k_i \leq 1$.

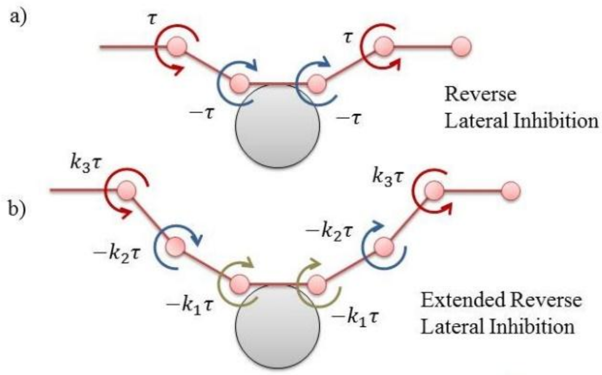

Fig.5 Illustration of, a: reverse lateral inhibition, b: extended reverse lateral inhibition.

4 Simulation result

We have conducted simulation based on the setting described in preivous sections. The snake-like robot is constrcted by connecting 15 links with 14 joints. At initial position, the snake-like robot is located on x axis and its tip of the head is located at (0, 0) .The coodinate of goal position is set at (10, 0) of the environment. We measure time until the snake-like robot reaches at the goal position. We also calcuated energy comsumption from the start position to the goal position by follwing equation.

$$E = \sum_{i=1}^{14} \int_0^T \tau_i^m(t)\omega_i(t)dt \tag{5}$$

Where T is the taking time from start to goal.

In the simulation, we conducted two case of experiment; the snake-like robot only behaves by undulating motion, and the snake-like robot behaves by undulating motion with extended reverse lateral inhibition (denoted as ERLI). In this simulation, the extended reverse lateral inhibition affects former four joints and rear four joint, which means there are four parameter k_i $(i=1,2,3,4)$. Here, each parameter is set as $k_1 = 1$, $k_2 = -1$, $k_3 = -1$, $k_4 = -1$.

As an experimental result, the snake-like robot moves in crowded obstacles to the goal position in both cases. The experimental result of energy consumption is shown in Table 1. The result shows a possibility of that by adding reactive motion the snake-like robot is able to move efficiently in the environment of crowded obstacles. In addition, we can say that the snake-like robot achieved obstacle aided locomotion.

However, we need more experiment to reveal the effectiveness of reactive motion. The behavior caused by our proposed method comes from interaction between the robot and environment, and the resulting behavior shows complex motion. The relationship between the interval of obstacles and the design of robot is not clear so far. It is assumed that the interval is getting shorter, the more the robot contact with obstacles. When the robot contact with obstacles, whether the friction force to the obstacle contributes to the propelling force or not depends on the contacting situation. In the worst case, we observed that the robot stuck in the obstacles. The solution to the stuck problem is discussed in the literature [6].

Table 1 Energy consumption of the snake-like robot

Interval of obstacles [m]	Without ERLI [J]	With ERLI [J]
0.33	25900	10517
0.36	21029	9188
0.39	26301	13475
0.42	28260	11294

5 Prototype of Snake-like Robot

5.1 Mechanism of snake-like robot

Since the robot is necessary to detect contact force, we developed a contact sensor unit. The overview of the snake-like robot and the contact sensor unit are shown in Fig.6. The snake-like robot has length of 594 [mm], width of 150 [mm], height of 335 [mm] and weight of 5000 [g]. The robot has 3 links and 2 joints, and the contact sensor unit are attached on both sides of each link. The actuator (maxon DC motor, 150W, Gear ratio 26:1) is attached to each joint. Passive wheels are attached to each link so that it generates a difference of friction that is necessary in the motion of lateral undulation.

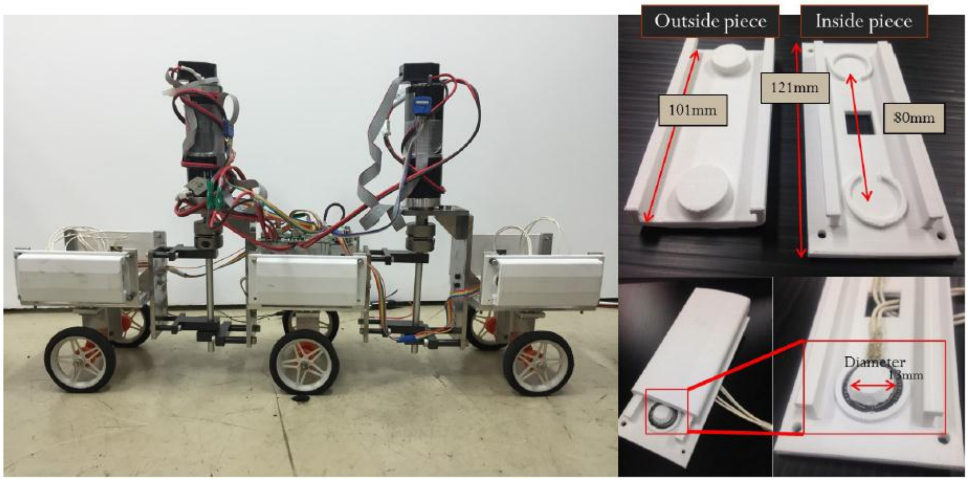

Fig.6 View of prototype snake robot and tactile sensor.

5.2 Contact sensor unit

Contact sensor unit is composed of 2 parts (outside part and inside part) and two force sensors (Interlink Electoronics, Inc. FSR402). When contact force is applied to the contact sensor unit, the force will be transmitted to the force sensor through the outside part. To improve measurement of the force, a cylindrical parts (diameter 13 [mm]) is introduced between the outside part and a force sensor.

5.3 System of snake-like robot

A microcomputer (TITechSH2 Tiny Controller) to control the snake-like robot is mounted on the robot. It does serial communication with control PC. Value of PWM to the joints is calculated in the control PC first, and then it is sent from the control PC to the microcomputer, and then it is sent to the motor driver as PWM signal. Value of force sensor is converted as AD value by the microcomputer, and then it is sent to the control PC.

5.4 Lateral undulation

We have implemented lateral undulation as a basic locomotion method of the snake-like robot. In this paper, we realize lateral undulation by changing duty ratio sinaoidally with phase delay. The value of PWM to the joints is given by following equation. Where, S_i^s denotes the reference of i-th joint's PWM value. Amplitude A, angular velocity ω, phase delay θ are set as A = 0.7, ω = 1, θ = 1.5 in the following experiment. Hereafter, we denote lateral undulation as LU.

$$S_i^s = A\sin(\omega t + (i-1)\theta) \quad (i = 1,2) \tag{6}$$

5.5. Reactive behavior

Hereafter, we denote lateral inhibition as LI and reverse lateral inhibition as RLI. Basically, LI is a behavior to avoid obstacle when snake-like robot contact with obstacles. RLI is reverse movement of joints for the LI and it pushes back the obstacle. To implement the reactive behavior, we give a constant value S_i^h as the duty ratio to each motor. For example, if the left side of the center link is in contact, then S_1^h = S_2^h = a in the case of LI, S_1^h = S_2^h = $-a$ in the case of RLI. Where the constant value a should be taken from 0 $\leqq a \leqq$ 1. In the following experiment, a is set as a = 0.3. We also introduce a threshold to trigger off the behavior. The value of threshold is 200 that is AD value of contact sensor. The robot react only for the stimulation of center link in the following experiment.

6 Experiment

6.1 Experimental set up

We prepare an experimental environment as shown in Fig.7. In the environment, cylindrical obstacles are arranged in regular interval. The diameter of the obstacles is 50 [mm]. The width and depth of interval between obstacles are 190 [mm] and 160 [mm] respectively. Distance from start position to goal position is 1380 [mm], which is from entering the 1st link and to exiting the third link. We have conducted three patterns of robot's behavior, LU, LU+LI and LU+RLI. The symbol '+' means that two behaviors are combined and resulting speed is given to the joints. The target value is given by following equation.

$$S_i^{ref} = S_i^s + S_i^h \quad (i = 1,2) \tag{7}$$

6.2 Experimental result

We conducted an experiment five times for each pattern, measuring the moment time from start position to goal position and power consumption of the motor. The result of average value is shown in Table 2.

As a result, in the case of LU, power consumption is almost the same as the case of LU+RLI and travel time is the longest. On the other hand, in the case of LU+LI, power consumption is the most. In the case of LU+RLI, the travel time is the shortest.

We expected that the snake-like robot can move efficiently by applying a simple reflective behavior. However, we found that the reactive motions are not always effective. We think that this comes from following reason. First, friction force would disturb propelling of snake-like robot. In the case of RLI, the robot pushes obstacles longer time and generates large friction on the surface. The friction not always contribute to propel the snake-like robot forward. Second, the snake-like robot has the jitters by the effect of LI, which is to change the situation of contacting and detaching frequently. The jitters cause unnecessary motion to the robot. Third, the link of the robot is relatively long to the space of obstacles. The robot is sometime stuck for an obstacle at the joint.

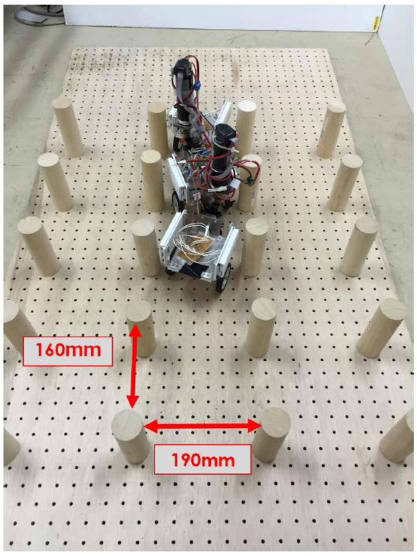

Fig.7 Experimental environment.

Table 2 Energy consumption of the prototype snake-like robot

	LU	LU+LI	LU+RLI
Power consumption [J]	1778	2680	1779
Travel time [s]	87.6	69.1	68.9

7 Conclusion

In this paper, we describes a snake-like robot driven by undulating motion and reactive motion in order to move in uncertain and crowded environment. We propose a new behavior of snake-like robot reverse lateral inhibition that pushes an obstacle when the robot contact with obstacles. We have conducted experiment by simulation and by using a prototype snake-like robot. It is shown that a snake-like robot has possibility to move in crowded environment efficiently by using the reactive motion. However, it is also shown that the reactive motion is not always effective.

Future work will be devoted to change the model of simulation and prototype, and improve the locomotion to be more efficiently in any case. For example, we are considering new behavior that changes motion of the robot according to a direction of friction force between the robot and obstacles.

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References

[1] HIROSE, S.: Biologically Inspired Robots (Snake-like Locomotor and Manipulator), Oxford University Press, 1993

[2] MORI, M., and HIROSE, S.: Development of Active Cord Mechanism ACM-R3 with Agile 3D mobility, IEEE RSJ International Conf. on Intelligent Robots and Systems, Vol.3, pp.1552-1557, 2001.

[3] KAMEGAWA, T., HARADA, T., and GOFUKU, A.: Realization of cylinder climbing locomotion with helical form by a snake-like robot with passive wheels, IEEE International Conf. on Robotics and Automation, pp.3067-3072, 2009.

[4] ANDREAS, A., REMCO, T., LEINE, I., GLOCKER, C., PETTERSEN, K. Y., and LILJEBACK, P.: Snake-like robot Obstacle-Aided Locomotion: Modeling, Simulations, and Experiments, IEEE Transactions on Robotics, 2008, 24 (1), 88-104.

[5] KAMEGAWA, T., KUROKI, R., TRAVERS, M., and CHOSET, H.: Proposal of EARLI for snake-like robot's obstacle aided locomotion, IEEE International Symposium on Safety, Security and Rescue Robotics, 2012.

[6] KAMEGAWA, T., KUROKI, R., and GOFUKU, A.: Evaluation of Snake-like robot's Behavior Using Randomized EARLI in Crowded Obstacles, IEEE International Symposium on Safety, Security and Rescue Robotics, 2014.

[7] WATANABE, T., EN, S., KAMEGAWA, T., and GOFUKU, A.: Development of Snake-like robot with Obstacle Aided Locomotion by Reverse Lateral Inhibition, Second International Workshop on Functional Modelling for Design and Operation of Engineering Systems, 2015.