Design of Neural Circuit for Sidewinding of Snake-like Robots*

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***Abstract*— This paper presents a kind of biomimetic neural circuit for simulating and implementing sidewinding of a snake-like robot. Biologically inspired by the neural circuit diagram in the spinal cord of lampreys, we propose a neural oscillator model and a chained inhibitory neural circuit. A set of leaky integrator type and sigmoid type interneurons is incorporated into the design of the neural diagram for rhythmic signal generation. The model provides explicit parameters for output modulation, including the modulation of amplitude, period, phase difference and offset. By classifying a snake-like robot into a pitch and a yaw group of modules, a sidewinding circuit is further designed to satisfy the requirement of sidewinding. Through simulation and on-site experiment, the effectiveness of the proposed model is verified in realizing sidewinding motion.**

***Index Terms*— Sidewinding, Central pattern generator, Snake-like robot, Limbless locomotion.**

I. Introduction

Limbless animals have a wide range of locomotive capabilities taking advantage of the features of limbless locomotion, such as a low center of gravity, a large contact area and a distributed mass. Due to the loss of legs, they have to undulate their bodies to propagate flexural waves along their bodies, so as to generate forces between them and the surrounding environment to propel them forward.

The best known of limbless animals are snakes. Snakes can use different limbless gaits depending on the environmental surface. When moving on soft surface such as sand or mud, some snakes will perform a special gait called sidewinding, as shown in Fig. 1. Sidewinding is derived from lateral undulation, but differs in the pattern of bending. First, the head is lifted off the ground and laterally set down again a short distance away. Then the body follows the path of the head. During the following phase, the head begins a new round of lateral movement while the rear part of the body completes the old track. The movement has only two segments in contact with the ground during the movement, which prevents the snake from overheating due to excessive

Fig. 1. A sidewinding snake, adopted from [1].

contact with the desert sand. The resulting movement leaves a series of disconnected tracks on the surface [2].

In the field of robotics, inspired by the limbless animals, a variety of snake-like robots have been developed in the last few decades [3]. Researchers not only focus on replicating the mechanical structure from snakes, but also are interested in imitating diverse locomotion patterns of snakes. In particular, as the unique locomotion pattern of snakes, sidewinding has been implemented using different approaches. From the control point of view, these approaches can be classified into two categories. The first one is model-based method. As a classic control method, kinematic or dynamic models of snake-like robots are used to analyze the locomotion pattern and design control strategies. The purpose is to find an expression of the equations of motion for a given robot with known kinematic constraints for gait generation. Related work refers to references [4]. However, this method excessively relies on the model of the robot and is not flexible enough to change the behavior of the robot especially when dealing with a complex environment.

The sine-based method is another alternative to realize sidewinding. This method takes simple sine-based functions as the generator of rhythmic movement. It usually contains explicit parameters that are used for the modulation of frequency, amplitude, phase difference and offset, respectively. To generate sidewinding, all sine-based generators should have a unified amplitude and frequency, as well as a fixed phase difference. As a result, they can oscillate synchronously

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and produce traveling waves along the body of the robot. There has been a lot of related work, such as the work by Gonzalez-Gomez et al. [5] and Tesch et al. [6]. Although this method features simplicity and the ability of modulation, it cannot produce smooth modulation and provide simple way for sensory feedback integration .

Even though there are many valuable contributions on sidewinding implementation, seldom efforts were focused on realizing sidewinding using biomimetic approach. Our ongoing project aims to do so by developing a novel Central Pattern Generator (CPG) model as the controller of the robot for achieving adaptive limbless locomotion. The research motivation is as follows: (1) The CPG-based method is a model-free control method, which requires no prior knowledge about the model of the robot; (2) Due to the neuron level design of the CPG model, neurons described by differential equations guarantee the smooth modulation of output signals. In this paper, we concentrate on developing the CPG model for realizing sidewinding. More details of the CPG model are presented in [7].

II. Related work

A. Analysis of Sidewinding

Sidewinding is a relatively efficient mode of sideways locomotion. From Fig. 1, it is obvious that the tracks on the ground are roughly diagonally relative to the direction of sidewinding motion. This indicates that sidewinding is a superposition of two body waves: one ventral and one horizontal along the body of the snake. In addition, the head part of the snake starts a new lateral movement before the rear part finishes the vertical movement in the last round. This implies that the propagation of the two body waves along the body of the snake are out of phase.

The principle of sidewinding can be summarized as follows [8]:

- Sidewinding includes two orthogonal body waves.
- The two body waves propagate in the same direction and with the same period.
- The two body waves maintain a fixed phase difference.

B. CPG based Control of Snake-like Robots

In biology, through neurobiological studies rhythmic locomotion is generated in the spinal cord by a group of neural circuits called Central Pattern Generators (CPGs). A lot of rhythmic activities e.g. walking, breathing and chewing, are all controlled efficiently by CPGs [9].

In robotics, CPG based control method is considered an elegant solution for online trajectory generation [10]. CPG-based controllers have already been successfully developed and applied on snake-like robots for generating serpentine gait [11], swimming gait [12], caterpillar-like gait [13] and worm-like gait [14], etc. However, there are no CPG-based controllers that are used for mimicking sidewinding. In the next section, we will present a novel CPG model involving the sidewinding principle to achieve the sidewinding motion.

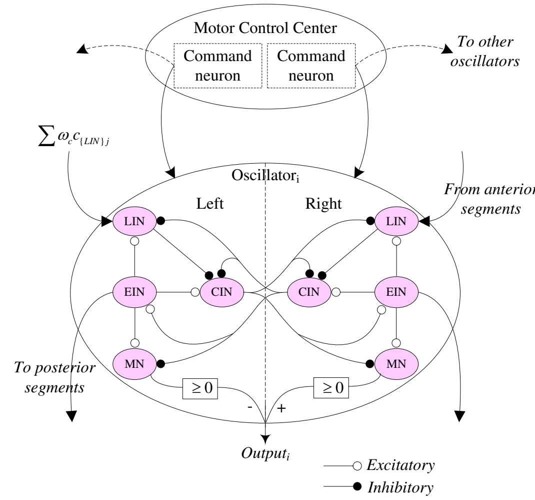

Fig. 2. The oscillator model.

III. Locomotion Controller Design

Although the underlying mechanisms of the CPG circuits are not yet fully understood, several simple creatures, such as the lamprey, have been extensively studied to learn the neural circuits in the spinal cord [15]. Inspired by the neural circuit in the spinal cord of lamprey, we propose a novel CPG model that features the following characteristics:

- Rich dynamics of oscillatory activities;
- Explicit control parameters for output modulation;
- Simple sensory integration via sensory neurons.

A. Single Oscillator Design

The topology of the neural circuit is adapted from [15] but with modification of synapses. Fig. 2 shows the modified CPG circuit containing one motor control center and one oscillator. The motor control center behaves as the brainstem of the CPG circuit, and descends motor commands through command neurons to modulate the output signal of the oscillator. The oscillator is responsible for rhythmic output generation. It is composed of two symmetric parts: the left part and the right part. Each part contains four types of interneurons, including Crossed InterNeurons (CIN), Lateral InterNeurons (LIN), Excitatory InterNeurons (EIN) and MotoNeurons (MN).

To generate rhythmic signals, the four types of interneurons are synaptically connected: each CIN emits inhibitory synapses to all the other interneurons except the EIN at the contra-lateral side; each EIN emits excitatory synapses to all the other three types of interneurons on the same side; and each LIN sends an inhibitory synapse to the CIN on the same side. The two MNs from both sides are combined together

TABLE I
SYNAPSE WEIGHTS OF THE OSCILLATOR MODEL

Presynaptic neuron	Postsynaptic neuron	Type	Value
EIN	CIN	Excitatory	1
EIN	LIN	Excitatory	1
EIN	MN	Excitatory	0.1
CIN	CIN	Inhibitory	-1
CIN	EIN	Excitatory	1
CIN	LIN	Inhibitory	-1
CIN	MN	Inhibitory	-1
LIN	CIN	Inhibitory	-1

after signal filtering, which finally generate the output signal of the oscillator.

Besides internal coupling synapses, one oscillator also emits inhibitory synapses to other oscillators through the EINs and receives inhibitory synapses from other oscillators via the LINs.

The dynamics in one oscillator are designed as:

$$\tau\dot{x}_{\{CIN\}i} = -x_{\{CIN\}i} + \sum \omega_s s_{\{CIN\}i} \tag{1}$$

$$\tau\dot{x}_{\{LIN\}i} = -x_{\{LIN\}i} + \sum \omega_s s_{\{LIN\}i} + \sum \omega_c c_{\{LIN\}j} \tag{2}$$

$$\tau\dot{x}_{\{MN\}i} = -x_{\{MN\}i} + \sum \omega_s s_{\{MN\}i} + \beta A \tag{3}$$

$$x_{\{EIN\}i} = \frac{A}{1+e^{x_{\{\overline{CIN}\}i}}} - \frac{1}{2}A \tag{4}$$

$$output_i = max(x_{\{MN\}i}, 0) - max(x_{\{\overline{MN}\}i}, 0) \tag{5}$$

where x_i is the state of each interneuron, and the overline on the subscript of x represents the state of the interneurons on the opposite side of the same oscillator. Parameters τ, A and β are tunable parameters to modulate the oscillator's period, amplitude and offset, respectively. s_i represents the synapses received from the other interneurons in the same oscillator, and c_j represents the synapses received from other oscillators. The variable $output_i$ stands for the oscillator's output.

Compared to the original topology, the synapses emitted from CINs to EINs are changed from inhibitory to excitatory. The purpose is to comply with the new designed dynamics of the oscillator to give rise to oscillation. Note that the dynamics of the EIN type of interneurons in (4) is different from other types of interneurons. They are described by sigmoid function instead of leaky integrator. The sigmoid function is indeed a key element for oscillatory generation. Since the EINs activate the other types of interneurons on the same side, the sigmoid function helps these interneurons to switch internal state alternately. Meanwhile, the leaky integrator helps them to achieve the desired state monotonically. Thus, the sigmoid function together with the leaky integrator forms the self-sustaining mechanism.

TABLE II
INITIAL VALUES OF THE OSCILLATOR MODEL

Interneurons	Value	
	Left side	Right side
$x_{\{CIN\}}$	0.01	0.010001
$x_{\{EIN\}}$	0	0
$x_{\{LIN\}}$	0	0
$x_{\{MN\}}$	0	0

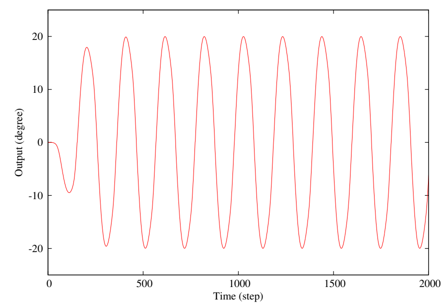

Fig. 3. The output of a single oscillator. The oscillator succeeds to oscillate by using the synaptic weights in Table I and the initial values in Table II, with parameters $\tau = 0.2$, $A = 20$ and $\beta = 0$.

As for the synaptic weight, the parameter ω is designed to be positive for excitatory synapses, and negative for inhibitory synapses. All the synaptic weight parameters in one oscillator representing as ω_s are fixed and form a symmetric matrix, as listed in Table I. To create a rhythmic and smooth output, all the ω_s have an absolute value of 1.0, except for the synapse from EIN to MN, whose weight parameter's value is 0.1. The purpose for the decrease of the synaptic weight from EIN to MN is to guarantee the output in the range of ± 90 degrees.

In addition, the initial values of the interneurons also play important roles in the start of rhythmic oscillation, as it has been found that a slight initial asymmetry between the two CINs on both sides can give rise to self-sustained oscillations. Table II shows an example of initial values for the interneurons in an oscillator. By using these initial values, the oscillator is able to achieve rhythmic pattern. Fig. 3 illustrates the corresponding oscillatory behavior from the initial state to a steady oscillatory state.

B. Chained Inhibitory CPG Circuit

Based on the single oscillator design, CPG circuits can be further constructed by means of the connection between oscillators. Oscillators in CPG circuits are no longer isolated, but interconnected with one another. Therefore, to some extent, the connectivity among oscillators determines the behaviors of CPG circuits.

In order to make the appearance of CPG circuit more concise, interneurons and synapses in the oscillator are simplified, as shown in Fig. 4. 'L' and 'R' represent four

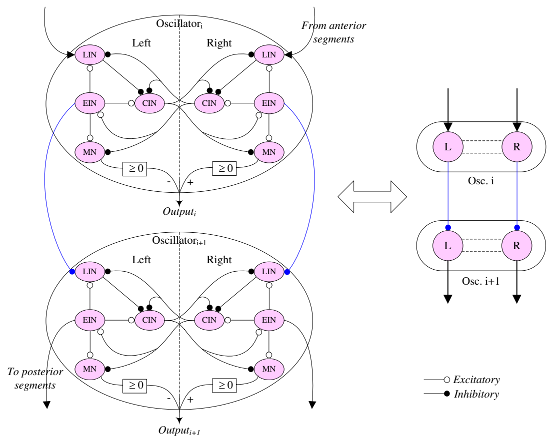

Fig. 4. The unidirectional connection between two oscillators and its simplification.

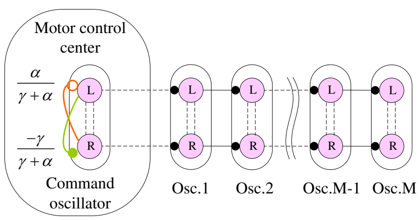

Fig. 5. The chained topology of oscillators.

TABLE III

PARAMETERS AND CONTROL RANGE OF THE CPG CIRCUIT

Symbols	Value	Description	Control Range
A	(0,90]	Amplitude	(0, 90][degree]
τ	[0.2,0.8]	Period	[135,535][steps]
α	(0,1]	Phase difference	(45, 145][degree]
β	[-1,1]	Offset	$[-A,A]$[degree]

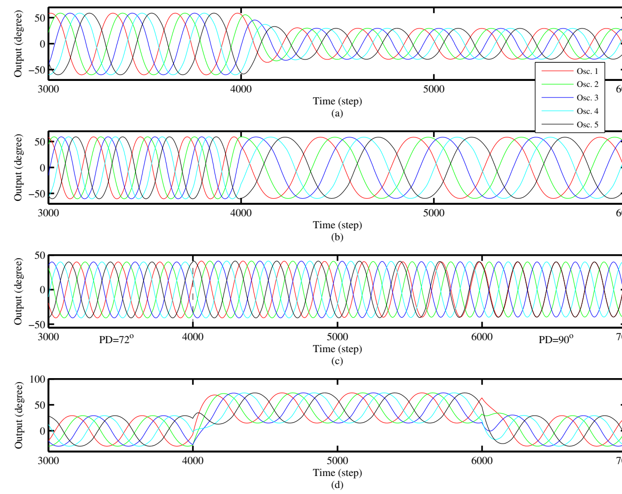

Fig. 6. Parameter modulation. (a) Amplitude modulation. (b) Period modulation. (c) Phase difference modulation. (d) Offset modulation.

interneurons together with their synaptic connection on the left and right part, respectively. The dashed lines between 'L' and 'R' in the oscillator indicate the mutually connection between the left and right part.

Fig. 5 shows the design of the chained inhibitory CPG circuit. For each oscillator, unidirectional inhibitory synapses are emitted to its adjacent oscillator. The inhibitory synaptic weights ω_c between oscillators are all assigned to a value of -1, aiming to maintain a fixed phase difference between these oscillators.

In addition to the normal oscillators, there is a special oscillator in the circuit. A command oscillator belonging to the motor control center emits inhibitory synapses to the first oscillator of the chained topology. As shown in Fig. 5, two additional synapses, one for excitatory synapse and the other for inhibitory synapse, are self projected to the command oscillator, which are used to modulate the phase difference among these oscillators. It has been tested that if the two synapses have relative small values of synaptic weights, such as in the range of (-1, 0) and (0, 1), respectively, they can shift the phase difference sensitively. Moreover, if the two synaptic weights are interrelated, such as by artificially setting the sum of their absolute values to a constant, the variation of phase difference becomes monotonous and smooth with respect to the two synaptic weights.

Based on the investigation, the two additional synapses are defined as follows:

$$\omega_{excitatory} = \frac{\alpha}{\gamma + \alpha} \tag{6}$$

$$\omega_{inhibitory} = \frac{-\gamma}{\gamma + \alpha} \tag{7}$$

where $\omega_{excitatory}$ and $\omega_{inhibitory}$ are the weights of the two synapses; α and γ, with a range of (0, 1], are control parameters that play a role in phase difference modulation. To simplify the control, γ is fixed ($\gamma = 0.2$). Thus, only α is responsible for phase difference modulation.

Numerical simulations are performed to study the modulation of the output of the chained CPG circuit using the tuneable parameters A, τ, α and β. In each simulation, only one parameter is tuned within an acceptable range while the other parameters are fixed. Numerical results show that parameters A, τ and β are directly proportional to the amplitude, period and offset, respectively, whereas the parameter α is inversely proportional to the phase difference. Table III summarizes the acceptable range of these tuneable parameters, as well as their corresponding control range with respect to the oscillatory characteristics.

Fig. 6 shows an example of how the output of the chained inhibitory CPG circuit is affected by these tuneable parameters. For simplicity, the output of 5 oscillators is shown here.

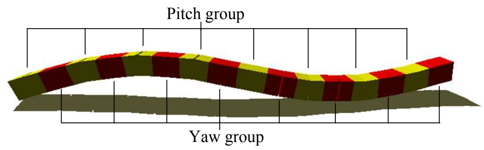

Fig. 7. A pitch-yaw connected snake-like robot.

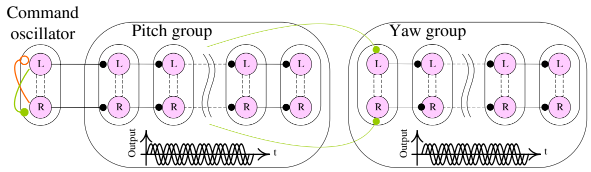

Fig. 8. CPG circuit of sidewinding.

Through numerical study, the chained inhibitory CPG circuit is verified to have rich dynamics and be capable of explicitly modulating amplitude, period, phase difference and offset.

IV. Implementation of Sidewinding Gait

In this section, we utilize the chained inhibitory CPG circuits to implement the sidewinding type of locomotion.

A pitch-yaw connected robot is constructed in the Open Dynamic Engine [16] environment as the test bed of our approach. The modules of the robot are categorized into two groups: the pitch group and the yaw group, as shown in Fig. 7. For the design of the sidewinding gait, two chained inhibitory CPG circuits are utilized for the pitch and yaw grouped modules, respectively, as shown in Fig. 8. The purpose is to generate two traveling body waves along the modular robot. For the pitch group, an additional command oscillator is used for generating phase differences between the oscillators. For the yaw group, there is no additional command oscillator. Instead, an inhibitory synapse emitted from one oscillator in the pitch group is projected to the first oscillator in the yaw group.

The inhibitory synapse between the two groups has two functions. First, it makes the oscillators in the yaw group have the same phase difference as the one in pitch group, which therefore enables the pitch and yaw grouped modules to propagate body waves in the same direction. Second, since it is emitted from one oscillator in the pitch group, the two groups of oscillators maintain a phase difference. This makes all the modules not in contact with the ground at the same time, and results in the body shape looking like a flattened coils of a helix.

The phase difference for the two groups of oscillators is defined as the phase difference between the head oscillators in pitch and yaw groups, respectively. Since the inhibitory synapse between the two groups is projected to the first oscillator in the yaw group, therefore the phase difference for the two groups is related to the position where the inhibitory synapse emits. In this paper, we suppose that the phase difference for the two groups is close to $90°$. Thus, the emitted position of the inhibitory synapse pos can be calculated as:

$$pos = \lfloor \frac{90}{pd} \rfloor \tag{8}$$

where pd represents the phase difference among the oscillators in the pitch group.

A simulated example is executed with parameters $A = 25$, $\tau = 0.3$ and $\alpha = 1$ and $\beta = 0$ in the sidewinding circuit. A phase difference of $45°$ among oscillators is obtained according to Table III. Therefore, according to (8), it is the second oscillator in the pitch group that emits the inhibitory synapse to the first oscillator in the yaw group.

Fig. 9 shows the simulated process of sidewinding, where the robot is shifting its body laterally. During the locomotion process, only two supporting segments remain in contact with the ground. The dashed lines show the trajectory of the supporting segments. This gait is similar to the locomotion pattern used by a snake when moving in desert. The trajectory of sidewinding is shown in Fig. 10. There is slippage happening when the robot starts from a standstill, resulting in a slight change of the forward direction at the beginning. In spite of this, after several periods of sidewinding movement, the gait becomes stable and the forward direction is no longer changed.

Simulation results show that the sidewinding circuit can generate the sidewinding gait that is similar to the locomotion pattern of sidewinding snakes in nature.

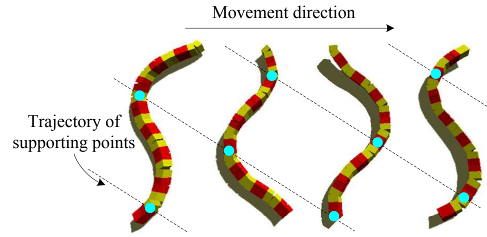

Fig. 9. Simulation of sidewinding.

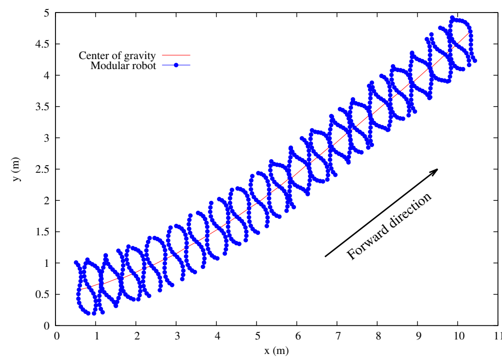

Fig. 10. The trajectory of sidewinding.

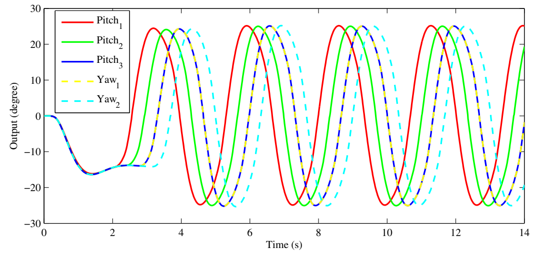

Fig. 11. Angle variation of the snake-like robot for sidewinding.

V. SIDEWINDING EXPERIMENT

An on-site experiment was carried out to demonstrate the effectiveness of the proposed sidewinding circuit. we connected five GZ-I modules in a pitch-yaw connected manner [17]. The GZ-I module weighs around 0.15 kg and has a length×width×height of $72mm \times 56mm \times 56mm$. The GZ-I module is equipped with a RC servo (Futaba s3003) as the actuator of the module, which provides a maximum speed of 1.45 rad/s and a maximum torque of 0.314 Nm. By actuating the servo, the GZ-I module can rotate in one degree of freedom within $\pm 90°$.

The modular robot is controlled by a PC via a cable. The control is an open loop. It works as follows: First, the desired angle of each module, i.e. the output of the corresponding oscillator is continuously calculated online by the PC. Then, all the desired angles are encoded as a command and sent to the servo controller with an empirical sampling time period of 80 ms. Finally, the servo controller decodes and executes the command, driving the robot to achieve the desired posture. By using such real-time control, sidewinding is realized with parameters $A = 25$, $\tau = 0.3$ and $\alpha = 1$ and $\beta = 0$. Fig. 11 illustrates the variation of the desired angle of each module with respect to time. Fig. 12 shows a series of pictures taken from a video recorded during the sidewinding experiment, which is consistent to the simulation result, as well as the locomotive pattern the snake moves on the sandy surface.

VI. CONCLUSION

This paper emphasizes the design of a neural circuit to realize sidewinding motion. A neural oscillator model biologically inspired by the spinal cord diagram of lampreys is designed at the neural level. Based on the oscillator model, a chained inhibitory neural circuit is constructed to generate entrainment among oscillators. Taking advantages of two traveling waves along the body of the snake and a phase difference between them, a sidewinding circuit is further designed by applying two chained inhibitory neural circuits to the pitch and the yaw modules of the snake-like robot, respectively. Simulation and on-site experiment results show the effectiveness of the proposed approach in realizing sidewinding motion.

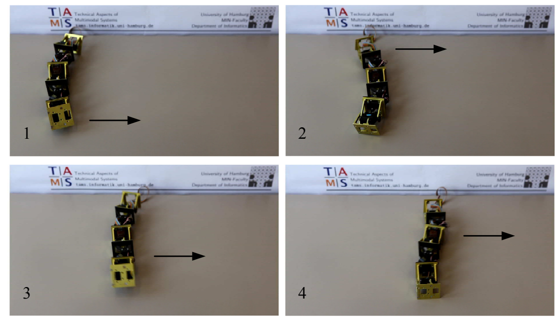

Fig. 12. On-site sidewinding experiment.

Future work will focus on: (1) investigating how these tuneable parameters affect the behavior of sidewinding; (2) Integrating sensory feedback into the model to achieve adaptive sidewinding in natural environment.

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