Bio-inspired Locomotion Control for UBot Self-reconfigurable Modular Robot

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***Abstract*— This paper first presents a mathematic CPG (central pattern generator) model which has been developed based on the characteristics of a self-reconfigurable modular robot (UBot)'s modules with universal joints. Then, a bionic motion neural control network based on the CPG is proposed to solve the problem of multi-mode locomotion control problem in the complex environment. The bionic network is composed of perceptual neurons, CPG phase modulation network and motor neurons, so it can coordinate the walking and creeping gait of the modular robot before and after deformation, and adapt to autonomous movement in the complex environment with challenging features, such as steps, slopes and obstacles. Finally, the proposed motion control algorithm is verified by experiments.**

Keywords—modular robot; self-reconfiguration; bionic locomotion control network, autonomous locomotion

I. Introduction

The key advantage of modular self-reconfigurable robots is that they can adapt to different environment conditions and operational requirements by changing their configurations and emerging new locomotion mode as well as different functions. In recent years, they have been widely researched and developed. Many typical SRR systems [1][2], including CEBOT [3], TTRO [4], crystalline [5], M-TRT [6], SMORES [7], PolyBot [8], SuperBot [9], YaMor [10], Roombot [11], [12] etc.

Motion control is a research challenging issue for the modular robots. The biological movement ability is superior to the function of any artificial machinery so far [13]. The method from simulating the biological nerve motion control mechanism can not only generate the bionic gait, but also can adapt to the biological environment, and have more advantages such as learning and evolution capabilities [14]. In the study on the organism movement mechanism, as the basic level regulatory mechanism of the movement control of spinal cord animals, the principle of the central pattern generator (CPG)) in the spinal cord is widely used and studied to robotics motion control[15]. The CPG motion control principle is to generate a rhythm signal through a nonlinear coupled oscillator with a limit cycle state to drive the robot. For the self-reconfigurable robot, a motion control method of CPG was developed by T. Kamimura et al [16][17] and used in their M-TRT system. Tuke Jan Ijspeert's research group of Swiss federal Institute of Technology in Lausanne (EPFL)[18][19][20] has used the CPG model of nonlinear coupling oscillators in YaMor and RoomBot system, and the model's parameters are optimized by the Powell method. They also used CPG method to control the salamander's locomotion of both swimming and terrestrial stepping [21]. Bernstein Center for Computational euroscience applied the CPG method to a hexapod robot with multiple sensors [22][23]. The CPG method has been combined with chaos theory to integrate various information from the sensors, so that the robot can automatically adjust its motion according to the changes in the environment. Since the bionic locomotion control has been widely used in the limbless robot such as snake-like robot [24][25], and in the limbed robot such as bipedal [26], quadruped [27], insect-like robot [28], it must can be used in the motion control of the self-reconfigurable robot system which has multi-mode configurations and multi-mode locomotion modes.

II. Design Principle of UBot System

The UBot modular robot is shown in Fig.1. Each module is cubic structure consisting of two parts, which can rotate from -90° to 90° around independent joints J10 and J00 respectively, just like a universal joint. Each module has four connecting surfaces (F00, F01, F10 and F11), which can be connected and

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disconnected with adjacent modules. This paper mainly focuses on the bionic quadruped configuration constructed by 16 UBot modules, as shown in Fig. 2, where LF, RF, LH, RH represent the left front, right front, left hind and right hind leg, respectively. Each leg has three modules, namely the hip joint module which is connected with the torso module, the knee joint module in the middle of the leg, and the ankle joint module in contact with the ground. Micro switches (as the touch sensors) are installed on the end of the foot modules. The head module in robot is a sensor module, with infrared sensors, acceleration sensors, vision sensors, etc., to detect the environmental changes and motion status itself during the movement. Ts shown in the right of Fig. 2, the quadruped configuration can be changed to a forward H configuration that can creep along the direction of the torso, and a lateral H configuration that can creep in the direction laterally relative to the torso.

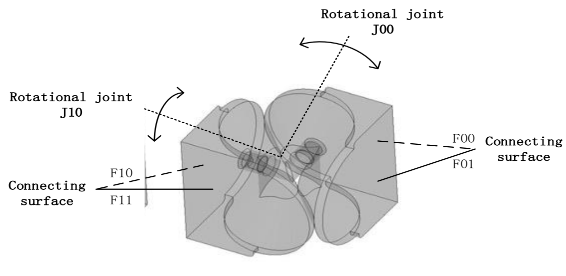


Fig. 1. Concept model of UBot module

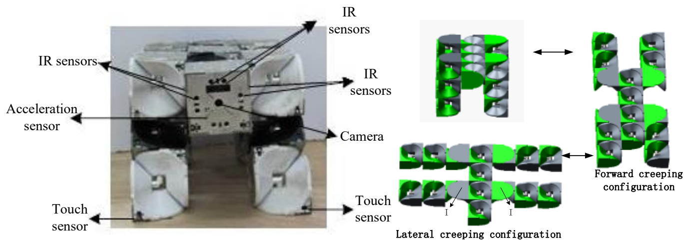


Fig. 2. Three topology types conversion for bionic quadruped configuration

III. BIONIC LOCOMOTION CONTROL NETWORK

A. Two-outputs CPG oscillator for UBot module

The UBot module has two rotational degrees perpendicular to each other. Its two parts cannot be rotated from the zero position to the same side of the module at the same time, that means the joint angles α_{J10} and α_{J00} of the two joints J10 and J00 should meet the following condition:

$$\alpha_{J10} \times \alpha_{J00} \geq 0 \qquad (1)$$

Tccording to the mutual restriction feature of the two joints, based on Kimura's CPG model [29], the two-output CPG oscillator has been designed as follows:

$$\begin{cases} T_r \dot{u}_{\{e,f\},i} + u_{\{e,f\},i} = -w_0 y_{\{f,e\},i} - \beta v_{\{e,f\},i} + u_e + feed_{\{e,f\},i} + a \cdot \sum_j weight_{ij} u_{\{e,f\},j} \\ T_a \dot{v}_{\{e,f\},i} + v_{\{e,f\},i} = y_{\{e,f\},i} \\ y_{\{e,f\},i} = \max(0, u_{\{e,f\},i}) \\ i = 0, \cdots N-1 \\ output_i = -m_1 y_{e,i} + m_2 y_{f,i} \\ output'_i = -m'_1 y_{e,i} + m'_2 y_{f,i} \end{cases} \qquad (2)$$

where, e, f represent the two neurons in the oscillator, extensor and flexor neuron, respectively; T_r and T_a are the rising time constant and adaptation time constant of the oscillator, respectively; N represents the number of the CPG oscillators; u is the inner state of the neuron; v is the degree of self-inhibition effect in the neuron; y is the output of the neuron; u_e is a constant of the neuron's external input, which can provide the energy for the neuron to vibrate; w_o is the connection factor between the extensor and flexor neurons. β is the adjustment coefficient; $feed_i$ is the feedback from the external environment in the motion; $output_i$and $output_i'$ are the control signals for the J00 joint and J10 joint of the ith module. a is the influence coefficient from the other CPG oscillators, W=($weight_{ij}$) is the connection matrix of the CPG network. In the CPG model, quantities which need to be controlled are $weight_{ij}$, $feed_i$, and N.

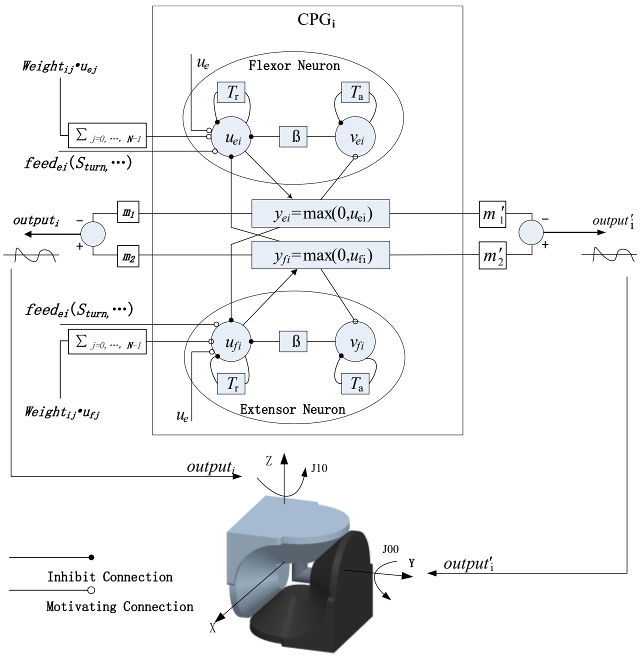


Fig. 3. Two-output CPG oscillator structure

Tccording to the feature of an UBot module, the output equation needs to satisfy one of the following conditions:

- When one joint of the UBot module stops at zero position, the other joint can rotate arbitrarily.
  If $m_1' \cdot m_2' = 0$, $m_1' = 0$ & $m_2' = 0$.
- If none of the two joints stops at the zero position, the oscillations for controlling the two joints should be the

same both in the frequency and direction, and the joints should pass through the zero position at the same time.

If $m_1' \cdot m_2' \neq 0,\ m_1/m_2 = m_1'/m_2'$.

B. Motor neurons

1) Hip joint motor neuron

The neuron output y_h to control the hip joint consists of three parts: CPG rhythm signal y_{CPG}, joint offset signal $offset_h$, and sensor signal S_h in Fig. 4. The offset signal is the joint angle value of the initial state of the hip joint movement, that is, the balance point of the leg's swing state; The sensor signal is sent by the sensory neurons, which is 0 during the normal motion, but it can be stimulated when the movement encounters a sudden situation, and resulting in the phenomena such as flexor responses.

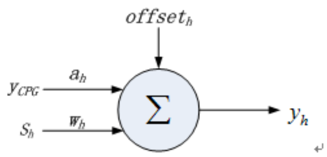


Fig. 4. Motion neuron for hip joint

The output function of the hip motor neuron is:

$$y_h = a_h \cdot y_{CPG} + offset_h + w_h \cdot S_h \qquad (0)$$

2) Knee joint neuron

In the leg-lifting action, the knee joint is bent inward to increase the height from the ground to the leg. When the leg is in the supporting state, the knee joint does not rotate. In this way, in the process of transmitting CPG signals to the knee joints, an activation function is required to change the signal transmission coefficient through judging the leg state. The structure of the neuron for the knee joint is as shown in Fig. 5. in which the CPG signal for the knee joint is determined by the logical operation function shown in Eq. (3), and the output of the knee motor neuron is given in Eq. (4).

$$\phi_1(\bullet) = \begin{cases} -1, (dy_{cpg}/dt \geq 0 \ \text{且} \ y_{CPG} \geq 0) \\ 0, (dy_{cpg}/dt < 0) \\ 1, \ (dy_{cpg}/dt \geq 0 \ \text{且} \ y_{CPG} < 0) \end{cases} \qquad (3)$$

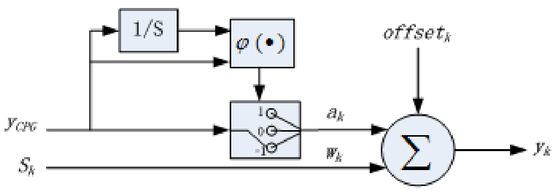


Fig. 5. Motion neuron for knee joint

The output function of the knee motor neuron for is:

$$y_k = y_{CPG} \cdot a_k \cdot \phi_1(\bullet) + w_k \cdot S_k + offset_k \qquad (4)$$

3) Ankle joint motor neuron

In order to avoid the module damage in the motion process of colliding with the ground, at the moment of landing, the module should land at an angle in parallel to the ground to ensure the minimum pressure. Therefore, the rotation of the ankle joint is affected by the hip joint, the knee joint and the inclination angle of the ground, the structure of the ankle neuron is shown in Fig.6, and the function is as follows:

$$y_a = -(y_h + y_k) + w_a \cdot S_a + offset_a \qquad (5)$$

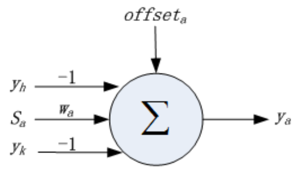


Fig. 6. Motion neuron for ankle joint

C. CPG phase modulation network

The bionic control network for the quadruped configuration is shown in Fig.7, in which the phase modulation controller formed by the coupling of four CPG oscillating units is located in the center of the control network, which is equivalent to the CPG of the quadruped animal. The network can generate four self-excited oscillation signals of phase interlocking. These four original signals can be converted into the angle control signals for all joints of the four legs through the motor neurons we aforementioned in the motor neurons.

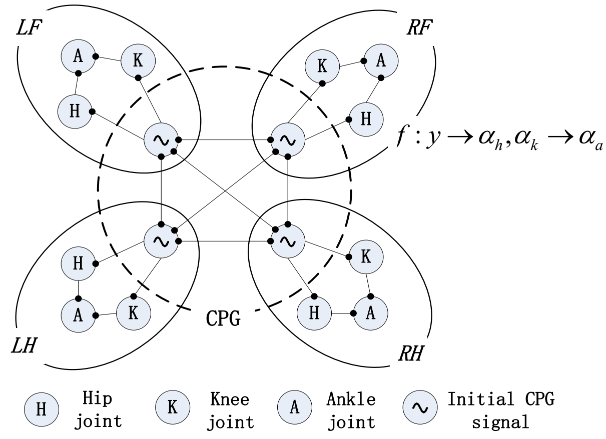


Fig. 7. Bionic control network for quadruped configuration

The trot gait is used for normal walking in the quadruped configuration, the CPG network connection is in Fig.8, the four CPGs are connected in a fully symmetrical manner. For the forward H configuration and the lateral H configuration, the network in Fig. 9. The output signal of the CPG acts on the hip joint, and the signal acts on the corresponding knee joint and ankle joint after a delay Δt, so that the limbs can move in a sine wave.

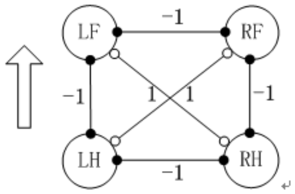


Fig. 8. CPG connection for trot motion

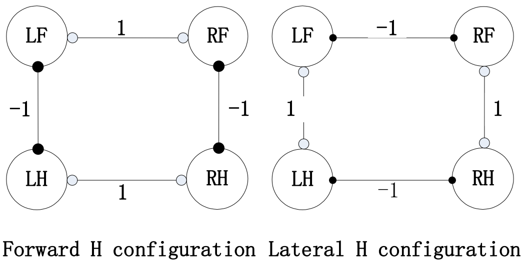


Fig. 9. CPG network for peristalsis H-configuration

D. *Bionic Locomotion Control Schematic*

Learning from the biological nervous system, the two-output CPG phase modulation controller is used to simulate the spinal cord of the biological motion control nervous system to generate a stable phase sequence and combined with sensory neurons, inter-neurons, and motor neurons to form a bionic motion control network in Fig. 10.

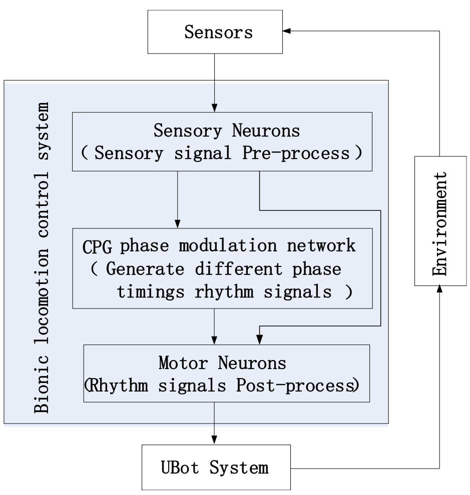


Fig. 10. Bionic Motion Control System Schematic

In the network, the sensory neurons are used to receive the external feedback information from the sensors and pre-process the sensory information into the simulation signal. Motor neurons are used to transform the numerical signal from the CPG phase modulation controller to the angle signal of the modules' joints. The bionic motion control system can control modular robots' multi-mode motion, and realize the coordinated change of motion mode and configuration deformation, and generate autonomous motion behaviors adapted to the environment.

Ⅳ. Information Feedback and Autonomous Behavior

A. *Obstacle avoidance mechanism*

The flexor reflex phenomenon enables animals to remove a limb from a noxious stimulus instinctively. The autonomous obstacle-crossing sensing neurons are established. The collision information is obtained through the touch switch at the front of the ankle joint module. Tfter the collision information is processed by the sensing neuron in the bionic control network, it is directly transmitted to the motor neurons of the hip and knee joints, so that the leg can be rapidly bent and lifted to cross the obstacle. Tfter the stimulation signal end, the leg recovers to normal motion status. The autonomous obstacle crossing is shown in Fig. 11.

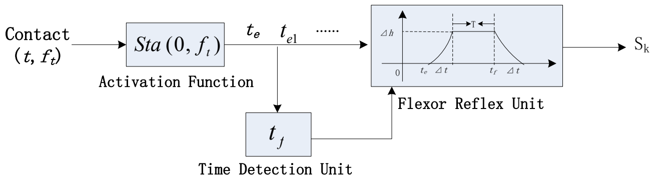


Fig. 11. Autonomous obstacle crossing sensory neuron

Contact signal which contains the touch signal received by the touch switch and the corresponding time when the contact occurs has been transmitted to flexor reflex unit through the activation function. The signal is a group of the discrete time point t_e、t_{e1}、$\cdots t_{en}$ when collisions occur. Tt the moment t_e, the first time of the collision, the flexor reflex unit is activated, and the output can be flexibly increased from 0 to Δh in Δt time through cubic interpolation. If after t_{ei}, there has been T time that no contact signals have been received, which means the obstacle has been crossed, the time detection unit will send a signal t_f to control the output of the flexor reflex unit to flexibly recover from Δh to 0 through cubic interpolation. The output of the neuron acts directly on the knee motor neurons, which control the change of the swing amplitude of the knee joint.

B. *Attitude adjustment mechanism*

During the movement, the robot may encounter a slope, which may result in slippage or tipping over. For this situation, the pose-sensing neurons have been studied. The acceleration sensor has been used to detect the abnormal motion and judge the tilt angle α of the robot. The pose-sensing neuron is designed as S_{slope}=Kα, in which K is the adjustment coefficient, the neuron is to control the robot posture through adjusting the balance angle of hip and knee motor neurons.

TABLE I. JOINT EQUILIBRIUM POSITION FOR QUADRUPED CONFIGURATION'S SLOPE WALKING GAIT

Parameters	Hip Joint $Offse_{th}$	Knee Joint $Offes_{tk}$
Front leg	$0.262+K_h{\cdot}S_{slope}$	$-1.047-K_k{\cdot}S_{slope}$
Back leg	$-0.262+K_h{\cdot}S_{slope}$	$1.047-K_k{\cdot}S_{slope}$

C. *Obstacle avoidance mechanism*

Beside the flexor reflex phenomenon, when the animals see the obstacles, they can adjust the motion route to avoid them in advance. The obstacle avoidance neuron is developed to simulate this. The infrared sensors on the head module of the quadruped configuration are used to sense the obstacles in the measurement range. The three infrared sensors T, B and C are arranged at -67.5 ° 、 0 ° 、 67.5 ° angles, the sensor measurement range is shown on the left of Fig. 12.

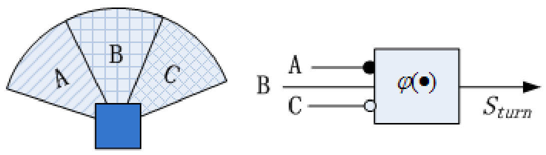


Fig. 12. Sensor measurement range and obstacle avoidance perception neuron

If sensor B detects the obstacle signal, but sensor T and C do not, which means the obstacle is in front of the robot, the sensing neuron will send the left turn signal S_{turn}= -1 by default, and the robot turns left; If B and C sensor detect the obstacles, that means the obstacle is on the right front of the robot, the neuron will also send the left turn signal; If T and B sensor detect the obstacle signal, that means the robot should turn right, the neuron will thus send the right turn signal S_{turn}= 1. the signal S_{turn} with the turning coefficient λ directly acts on the CPG oscillator which controls the movement of the leg modules. Through adjusting the amplitude of the CPG output signal, the swing range of the corresponding legs are adjusted, so the walking direction can be changed.

$$T_r\dot{u}_{\{e,f\},i}=\begin{cases}-u_{\{e,f\},i}-w_0y_{\{f,e\},i}-\beta v_{\{e,f\},i}+u_e+a\cdot\sum_j weight_{ij}u_{\{e,f\},j}+\lambda\cdot S_{turn}(i\in LF,LH)\\ -u_{\{e,f\},i}-w_0y_{\{f,e\},i}-\beta v_{\{e,f\},i}+u_e+a\cdot\sum_j weight_{ij}u_{\{e,f\},j}-\lambda\cdot S_{turn},(i\in RF,RH)\end{cases}.$$

D. *Complex deformation motion*

Sometimes the robot cannot avoid the obstacle by changing the motion direction, the deformation property of the modular robot should be used. If all the three infrared sensors T, B and C in Fig. 12. receive the blocking signals, which means the robot has been completely blocked in the moving direction, then the deformation mechanism will be triggered. The robot deforms to the forward-H-configuration first, if B=0, that means there are no blocks in front of the robot, the robot can creep forward; if B≠0, the new deformation mechanism will be trigged, the robot deforms to the lateral-H configuration, and creeps laterally until it finds the exit, where B=0. Then the robot can deform to the forward-H configuration again to creep forward.

Ⅴ. EXPERIMENTS

Tn experiment scenario has been built as shown in Fig. 13. The length of the environment is about 3800mm. T series of obstacles are arranged in the scenarios, including steps, uphill, downhill, obstacle and arched doors. The entire walking process is shown in Fig. 14. The special obstacles faced by the quadruped configuration and the corresponding actions during the experiment are shown in order in the following table:

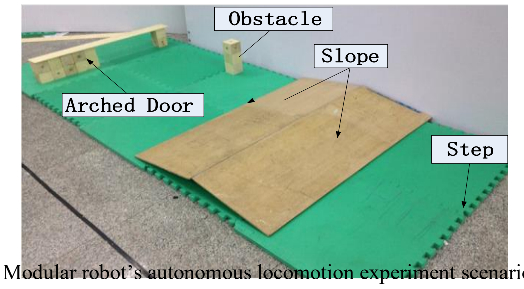
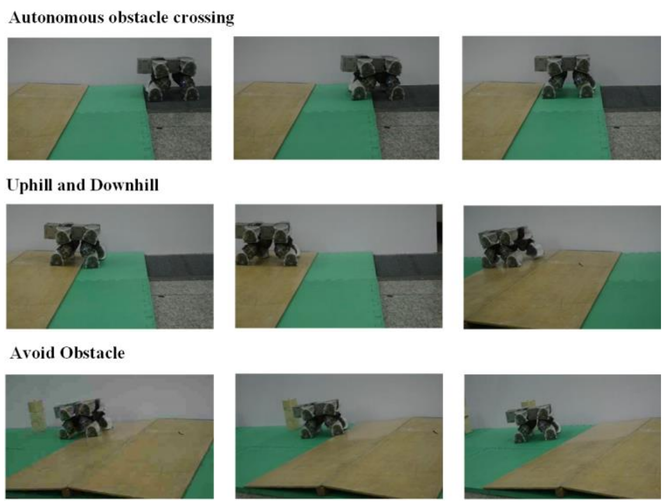


Fig. 13. Modular robot's autonomous locomotion experiment scenarios

TABLE II. LIST OF DIFFERENT BEHAVIORS AND CORRESPONDING ACTION METHODS IN THE EXPERIMENT

Environment Type	Sensors	Excitation methods	Corresponding locomotion mode
Step	Touch switch	Flexor reflex phenomenon	Tutonomous obstacle crossing
o stimulus	--	--	Trot motion
Slope (uphill)	Tccelerometer S_{slope}	Motor neuron: Pose-sensing neuron	Tttitude adjustment: front low back high
Slope (downhill)	Tccelerometer S_{slope}	Motor neuron: Pose-sensing neuron	Tttitude adjustment: front high back low
Obstacle	Infrared sensor S_{turn}	The obstacle avoidance neuron: acts on the CPG phase modulation network	Turn to avoid obstacle
Completely Blocked	Infrared sensor S_{stop} or SR	Complex deformation motion mechanism	Deformation to creep or stop



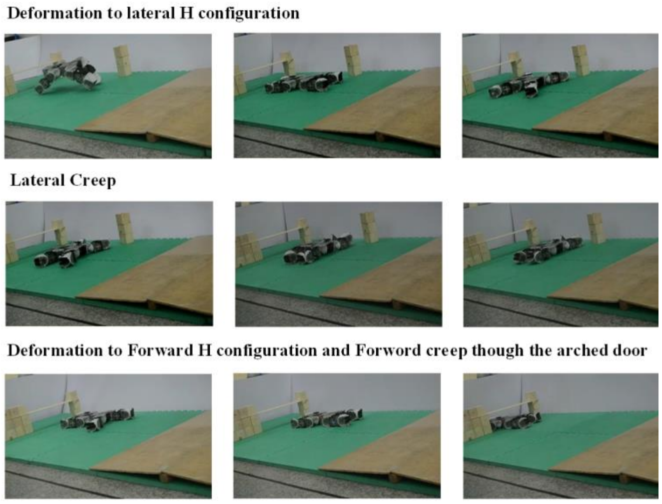


Fig. 14. Autonomous locomotion experiment in complex environment

CONCLUSION

In this paper, we have established the bionic locomotion system for the modular self-reconfigurable robot which is based on the CPG model designed for the UBot module with universal joints. The system can adjust the multi-mode motion and deformation features of the modular robot and can also adjust the external environment. In the future, we need to improve the CPG oscillator model with fewer parameters and wider application range, adopt the autonomous learning process in the bionic control network, and finally realize to control the multi-mode locomotion in any movable configurations.

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