

# **An Approach for Adaptive Limbless Locomotion using a CPG-based Reflex Mechanism**

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## **Abstract**

Animals' free movement in natural environments has attracted many researchers to explore control methods for bio-inspired robots. This paper presents a novel reflex mechanism based on a central pattern generator (CPG) for adaptive locomotion of limbless robots. First, inspired by the concept of reflex arc, the reflex mechanism is designed on a connectionist CPG model. Since the CPG model inspired by the spinal cord of lampreys is developed at the neuron level, it provides a possible natural solution for sensory reflex integration. Therefore, sensory neurons that bridge the external stimuli and the CPG model, together with the concept of reflex arc, are utilized for designing the sensory reflex mechanism. Then, a border reflex and a body reflex are further developed and applied on the ends and the middle part of a limbless robot, respectively. Finally, a ball hitting scenario and a corridor passing scenario are designed to verify the proposed method. Results of simulations and on-site experiments show the feasibility and effectiveness of the reflex mechanism in realizing fast response and adaptive limbless locomotion.

**Keywords:** sensory reflex mechanism; reflex arc; central pattern generator; limbless locomotion

## 1 Introduction

Bio-inspired robotics has been a hot research topic in the last few decades. Nature has inspired the design of diverse robots, such as legged robots <sup>[1]</sup>, crawling robots <sup>[2]</sup>, swimming robots <sup>[3]</sup> and flying robots <sup>[4]</sup>. The result of animal evolution guarantees that bio-inspired design offers good locomotor skills to robots, allowing them to move in complex and changing environments. More importantly, the underlying mechanisms that enable animals to generate free movements are an elegant and efficient solution for achieving adaptive locomotion of bio-inspired robots.

In nature, animals can produce rapid involuntary responses to external stimuli for their survival, such as moving towards for foods or mates, and moving away from predators. Reflex actions govern the majority of behaviors by simple animals, while complex animals use reflex actions to regulate bodies to achieve free movements. Reflex actions are simple but efficient. Given the role of reflex actions in animals' locomotion, we have a great interest not only in modelling the reflex mechanism, but also in developing reflex based adaptive locomotion for bio-inspired robots.

From a contemporary biological viewpoint, animals' locomotion consists of inherent locomotion patterns and reflex actions. On the one hand, rhythmic movements are generated in the spinal cord by a group of neurons, called a central pattern generator (CPG) <sup>[5]</sup>. CPG can produce rhythmic signals that control muscular activity to generate rhythmic patterns, such as serpentine creeping, peristaltic crawling, and anguilliform swimming. On the other hand, reflex circuits interact with proprioceptive and exteroceptive information, and coordinate and influence the activity of locomotion patterns <sup>[6]</sup>. The coupling between CPG and the reflex circuits is strong. In particular, reflex circuits are able to affect the activity of CPG at two levels <sup>[7]</sup>. If the reflex circuit is beneath the CPG, the reflex circuit generates higher priority signals to the locomotor system, guaranteeing the locomotion safety and reliability. Otherwise, the reflex circuit serves as an indirect indicator of CPG modulation, which integrates sensory feedback into CPG to alter the pattern of locomotion. In either case, reflex circuits help animals to adapt to environmental changes.

To date, designers of bio-inspired robotics domain have adopted the concept of reflex control

at the aforementioned two levels. For example, Bekey and Tomovic defined an artificial reflex using the biological reflex as reference<sup>[8]</sup>. The artificial reflex arc can reproduce the desired functional motion to mimic the reflex of human motion. Espenschied et al. proposed behavior based strategies to formulate reflex control<sup>[9]</sup>. They applied three types of postural reflexes on a hexapod robot and verified that the robot could effectively deal with irregular terrain with no prior knowledge. Asif and Iqbal presented similar work in a foothold reflex control method to achieve reflex-based gait generation<sup>[10]</sup>. Huang and Nakamura developed a control system for humanoid walking, where different sensory reflexes are designed to cope with different unexpected situations<sup>[11]</sup>. Dirk and Kirchner proposed a hybrid bio-inspired approach that combines posture control with CPG-based control and reflex control for locomotion control of multipods<sup>[12]</sup>. They designed a simple reflex model that has an input-, activation-, and a response-function. Experiments showed that the hybrid approach enables a robot to move through complex terrains, such as rock fields, asphalt, sand, gravel and grass. Kimura et al. explored adaptive quadruped walking using CPGs and reflexes<sup>[13]</sup>. They defined a reflex as joint torque generation and assumed that reflexes have a higher priority to joints than CPG outputs have. Followed the research line of Kimura's group, Liu et al. studied adaptive quadruped walking with an AIBO robot<sup>[14]</sup>. They combined a vestibular reflex with a CPG model and implemented slope-adaptive walking.

Besides legged robots, other types of robots such as manipulators<sup>[15, 16]</sup> and mobile robots<sup>[17, 18]</sup> have used reflex control. Nevertheless, the study of reflex control on limbless robots is seldom seen<sup>[19, 20]</sup>. Furthermore, due to the topology difference between legged robots and limbless robots, the aforementioned methods for applying existing reflex mechanisms on limbless robots may result in somewhat stiff and unnatural resultant behaviors. Our research aims to develop a hierarchical control architecture for bio-inspired modular climbing caterpillar robots, including a reflex level, CPG with biological locomotion features and a learning algorithm for sensor-servo-based behavior control and active perception of the environment. In this paper, we propose a new CPG-based reflex mechanism in a natural manner to realize adaptive locomotion for limbless robots. The contribution of this paper is threefold. First, a connectionist CPG model based reflex mechanism is proposed, with an emphasis on the design of sensory reflex pathway on

the neural level. Second, reflex mechanisms that take advantage of the concept of reflex arc are designed. Third, the feasibility and effectiveness of the proposed control mechanism are verified through simulation and real on-site experiments.

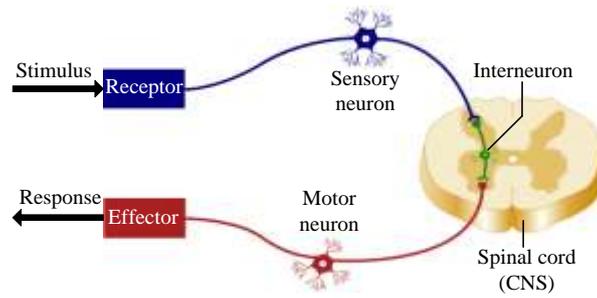
## **2 CPG-based reflex mechanism**

In this section, we propose a CPG-based reflex mechanism for adaptive limbless locomotion. The reflex mechanism allows robots to self-modulate behaviors by changing body shapes adapting to the environmental changes.

### **2.1 Reflex arc**

In neuroanatomy, it has been found that the response of an animal to external stimuli is coordinated by its central nervous system (CNS) [21]. The CNS contains the majority of the nervous system and consists of the brain and the spinal cord. Animals' response time is determined by the speed of information processing, which is further related to the number of neurons involved in a task. If it is a conscious stimulus-response procedure, which involves multiple brain areas and many neuron connections, the elapsed time from perception to the response behavior is relatively long. Nevertheless, if the safety of an animal demands a very quick response, such as rapid withdrawal from dangerous stimuli, the signals may directly generate instant and unconscious action. This is a reflex action.

Reflex actions in animals are usually controlled by the reflex arc, which involves only a few neurons. As shown in Fig. 1, a reflex arc is a neural pathway that makes a fast, automatic response possible [6]. In the reflex arc, the entire signaling sequence, from sensing to processing to response, is handled by the spinal cord without the need to wait for instructions from the higher brain regions. First, a receptor detects a painful stimulus and relays this information along an afferent fiber. The information is carried all the way from the receptor to the interneurons within the spinal cord by a single sensory neuron without any other intervening synaptic connections. These interneurons, in turn, pass the information along an efferent fiber to a motor neuron. As the efferent fiber ends in an effector, the effector is stimulated by the activated motor neuron and its reaction is the response.



**Fig. 1** Reflex arc. It consists of a receptor, a sensory neuron, a reflex center (spinal cord), a motor neuron and an effector.

Nevertheless, CNS involvement of the interneurons in the spinal cord along the pathway is not always necessary. A reflex arc may only consist of a sensory neuron and a motor neuron, namely, the monosynaptic reflex, which allows reflex actions to occur relatively quickly by activating the two neurons without the delay of routing signals through the CNS. The knee jerk reflex is the most common and classic example of the monosynaptic reflex arc [22]. There are no CNS interneurons in the pathway taking part in the reflex arc. Instead, the sensory neuron directly sends the nerve impulse to a motor neuron, causing the leg to suddenly jerk forward.

In light of the reflex arc in the knee jerk, a CPG-based reflex mechanism is designed at the neural level. The following sections introduce the method in detail.

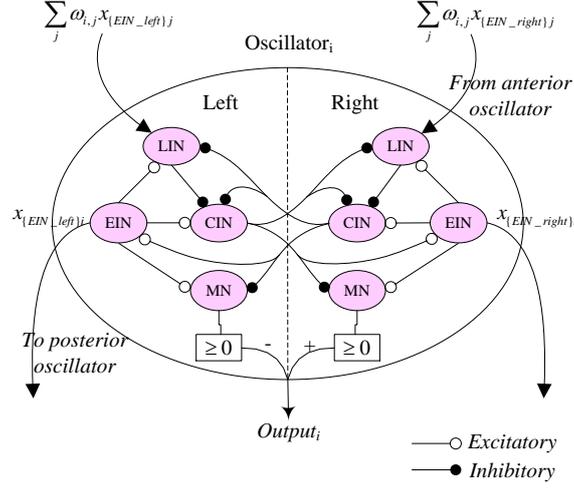
## 2.2 Single neural oscillator

Here, we select the CPG model in [23] — a connectionist model as the basic controller. The CPG model is a plausible biological model, which is inspired by the neuronal circuit diagram in the spinal cord of swimming lampreys. Although the model is simplified for engineering development, it features the following characteristics:

- It has a rich dynamic of oscillatory activities. Besides the normal oscillatory activity, it also exhibits other oscillatory phenomena, such as synchronization and maintenance activities.
- It provides explicit control parameters for output modulation, including the modulation of amplitude, period, phase difference, and offset.
- It provides interfaces for realizing reflex mechanisms at the neural level.

Here we only give a brief introduction to this CPG model before the explanation of sensory reflex integration. For more details, please refer to [23].

The topology of the neural oscillator is adapted from [7] but with modification for reflex mechanism integration. As shown in Fig. 2, the neural oscillator is composed of two symmetric parts: the left part and the right. Each part contains four types of interneurons: Crossed InterNeuron (CIN), Lateral InterNeuron (LIN), Excitatory InterNeuron (EIN) and MotoNeuron (MN).



**Fig. 2** The neural oscillator model.

To generate rhythmic activity, the four types of interneurons are synaptically connected. The CINs project inhibitory synapses to CIN, LIN and MN but excitatory synapses to EIN on the contralateral side. The LINs only emit inhibitory synapses to the ipsilateral CINs, while the EINs only emit excitatory synapses to the other three types of interneurons on the same side. The two MNs determine the output of the oscillator, where they merge after signal filtering.

Note the CINs project both inhibitory and excitatory synapses. This may be not true in biological systems. For engineering design, the inconsistency between the neural oscillator and its original diagram is ignored. In addition to the synaptic connections within one neural oscillator, the oscillator can also project and receive synapses to/from other oscillators through EINs and LINs, respectively. In most cases, the synapses between oscillators are ipsilateral and symmetric.

The dynamics of an oscillator is described as a set of equations, with each type of interneurons corresponding to one of the equations:

$$\tau x'_{\{CIN\}i} = -x_{\{CIN\}i} + \sum \omega_s s_{\{CIN\}i} \quad (1)$$

$$\tau x'_{\{LIN\}i} = -x_{\{LIN\}i} + \sum \omega_s s_{\{LIN\}i} + \sum \omega_c c_{\{LIN\}j} \quad (2)$$

$$\tau x'_{\{MN\}i} = -x_{\{MN\}i} + \sum \omega_s s_{\{MN\}i} + \beta A \quad (3)$$

$$x_{\{EIN\}i} = \frac{A}{1 + e^{x_{\{CIN\}i}}} - \frac{1}{2} A \quad (4)$$

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

where  $x$  represents the state of each interneuron, and its subscript stands for the type of interneuron. Parameters  $\tau$ ,  $A$  and  $\beta$  are tunable parameters that are responsible for the oscillator's period, amplitude and offset, respectively. The CINs, LINs and MNs are described as leaky integrators. For CINs,  $s_{\{CIN\}i}$  represents any other interneurons in the oscillator projecting onto the CINs, and  $\omega_s$  is their synaptic weight. Similar  $\omega_s$  and  $s$  appear in Eq. (2) and (3). For LINs, the last term indicates the coupling from other oscillators, where  $c_{\{LIN\}i}$  is the state of the EIN interneuron of connecting oscillator and  $\omega_c$  is its synaptic weight. For MNs, the last term implies the amount of offset. For EINs, their states are controlled by sigmoid functions. Note the overline on the CIN represents the state of CIN at the contralateral side of the oscillator. *output* is the oscillator's output, which is the combination of the two MNs after their non-negative filtering.

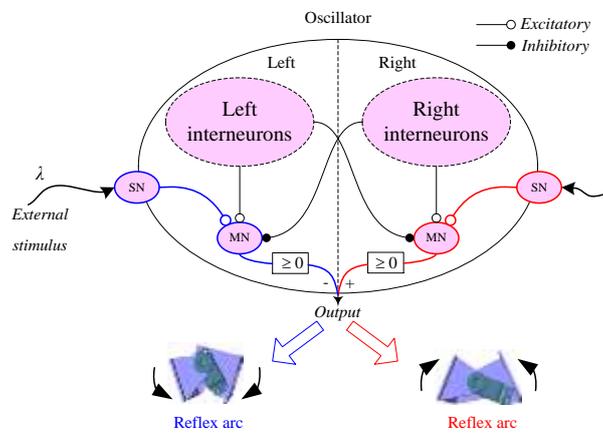
In the oscillator, the sign of the synaptic weight  $\omega_s$  is dependent on whether the synapse is excitatory (+) or inhibitory (-). To regulate the output in the range of  $\pm 90$  degrees, all the synaptic weights are fixing to the absolute value of 1.0, except for the synapse from EIN to MN, whose weight parameter's value is 0.1. In addition, a slight initial asymmetry between the two CINs on both sides is essential for the generation of self-sustained oscillation. In this paper, by initializing the two CINs a value of 0.01 and 0.010001, respectively, together with the rest of interneurons a zero value, the oscillator achieves a rhythmic pattern.

### 2.3 Sensory neuron integration

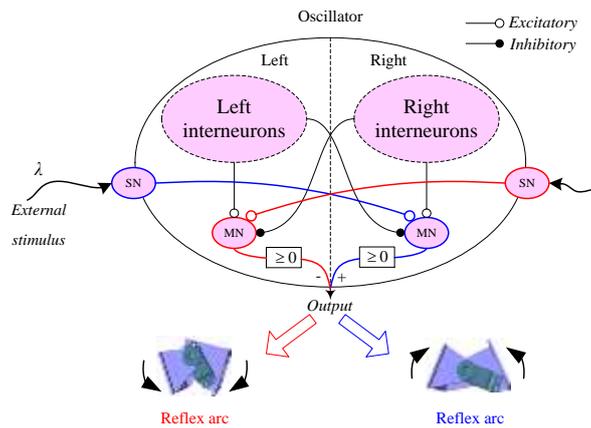
In the field of biology, lampreys are found to have sensory neurons (SNs) that are located within the spinal cord and activated by external stimuli [7]. The SNs on each side of the spinal cord are considered as part of the reflex circuit. Following this fact, we took the concept of reflex arc into account and designed two types of sensory reflex, called border reflex and body reflex, respectively.

Fig. 3 illustrates the border reflex with two monosynaptic reflex arcs integrated. To make the diagram more concise, the oscillator shown in detail in Fig. 2 is lumped together on each side,

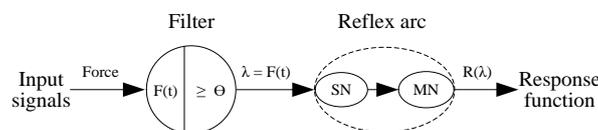
with a substitution of “interneurons”. Each of the monosynaptic reflex arcs is made up of an SN and a motoneuron (MN) on the ipsilateral side. Because of the signal filtering on the MN, the excitatory synapse from the SN to the MN would exacerbate the external stimulus and thus force the CPG model to generate a fast response output. The body reflex is another type of reflex mechanism. As shown in Fig. 4, it also contains two integrated monosynaptic reflex arcs. In contrast to the border reflex, the monosynaptic reflex arc in the body reflex consists of an SN and a contralateral MN. This means opposite response behaviors would happen to the body reflex compared to the border reflex.



**Fig. 3** Border reflex.



**Fig. 4** Body reflex.



**Fig. 5** Reflex model.

In this study, an SN is directly correlated with sensors such as a force sensor. A simple reflex model illustrates how the sensory reflex works, as shown in Fig. 5. First, input signals measured from the force sensor are handled by a filter. To avoid disturbance caused by sensor noise, the filter activates the reflex arc only if the measured force exceeds a pre-defined threshold. The reflex model takes the measured force as the afferent stimulus and sends it to the reflex arc. Then, the SN propagates the external stimulus along the reflex arc and serves to reinforce the MN. The MN further affects the output of the oscillator and finally generates the response behavior. In contrast to the canonical assumption that sensory reflexes are fixed reactions, the reflex model associates the response function with the value of the measured force. Therefore, it is able to generate non-fixed response behaviors.

The dynamic of the SN is given by the following piecewise function:

$$\begin{cases} \tau_1 x'_{\{SN\}i} = -x_{\{SN\}i} + p\lambda & \text{if } \lambda > \Theta \\ \tau_2 x'_{\{SN\}i} = -x_{\{SN\}i} & \text{otherwise} \end{cases} \quad (6)$$

where  $\tau_1$  and  $\tau_2$  are time constants that control the response and the recover speed of the state of the SN, respectively;  $p$  is a proportional constant and  $\Theta$  is a threshold for activation;  $\lambda$  indicates the external stimulus, which equals the absolute value of the force received by the touch sensor on the robot.

When the force  $\lambda$  on the touch sensor exceeds the pre-defined threshold  $\Theta$ , the external stimulus  $p\lambda$  is afferent and transmitted to one of the SNs. Then, the SN affects the output by means of the reflex arc, resulting in a quick reaction at the corresponding joint. If there are no stimuli afferent into the reflex model after the reaction, according to the Eq. (7), the SN will gradually eliminate the influence on the modified joint and finally recover it to the normal state. That completes the reflex response.

### 3 Reflex behavior under CPG network

Based on the single neural oscillator, CPG network can be further constructed by means of the connection between oscillators. However, this is not the focus of this paper; we only show the CPG network in brief. The reflex behaviors based on the CPG network are more concerned, which will be introduced thereafter.

### 3.1 Chained inhibitory network

The chained inhibitory network is designed to generate linear movement for limbless robots. The oscillators are connected by unidirectional inhibitory synapses. The inhibitory synaptic weights  $\omega_c$  between oscillators are all set to -1, so that a fixed phase difference could be maintained between oscillators. A special command oscillator is used in this network, which plays a role in phase difference modulation. It not only projects inhibitory synapses onto the chained network, but also emits two synapses, one excitatory and one inhibitory, to itself. Here we use parameters  $\alpha$  within the range of  $[0, 1]$  as the tunable parameter for phase difference modulation. Numerical study shows that the phase difference among oscillators decreases with the growth of  $\alpha$ , being available in the range of  $[45^\circ, 145^\circ]$ .

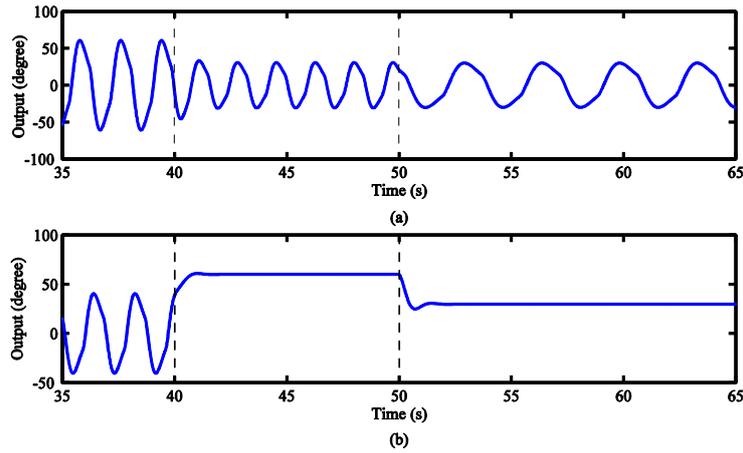
The chained inhibitory network is capable of explicitly modulating amplitude, period, offset and phase difference. Table 1 summarizes the tuneable parameters, as well as their acceptable range.

**Table 1** Parameters of the chained inhibitory network

Symbol	Value	Description
$\omega_s, \omega_c$	$\pm 1$	Synaptic weight
$A$	$(0, 90]$	Amplitude parameter
$\tau$	$[0.2, 0.8]$	Period parameter
$\alpha$	$(0, 1]$	Phase difference parameter
$\beta$	$[-1, 1]$	Offset parameter

### 3.2 Cyclic inhibitory network

Another way of connecting oscillators is to use mutually inhibitory synapses. Instead of producing phase difference between oscillators, the mutually inhibitory synapse forces connected oscillators to generate unified behaviors. A cyclic-connected inhibitory network is constructed to extend the oscillatory activity. It consists of a loop of cyclic connected oscillators. Within the oscillator loop, inhibitory synapses are emitted to the oscillators on the ipsilateral side bilaterally. By adjusting the synaptic weight  $\omega_c$  among oscillators, the cyclic inhibitory network can exhibit two interesting oscillatory phenomena: synchronization and maintenance.

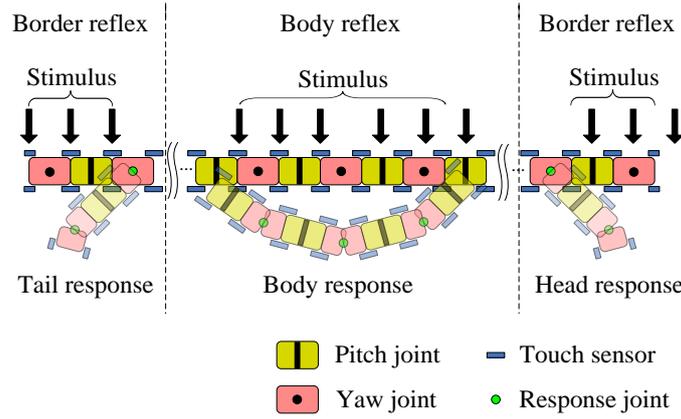


**Fig. 6** Synchronization and maintenance activities. (a) Synchronization:  $\omega_c = -0.1$ . Amplitude modulation: the amplitude is reduced by half at 40s by tuning  $A$ . Period modulation: the period is doubled at 50s by tuning  $\tau$ . (b) Maintenance: assigning  $\omega_c = -0.1$  and  $A = 60$  at 40s causes the maintenance behavior. Modulation takes place at 50s, where the maintained value is smoothly reduced by one half.

Fig. 6 illustrates the phenomena of synchronization and maintenance, as well as their modulation. The synchronization occurs only when a small inhibition, e.g.  $-0.2 \leq \omega_c < 0$ , is applied among oscillators in the cyclic inhibitory network. As shown in Fig. 6a, the oscillators will not only produce the same amplitude and period, but also keep in-phase oscillation. Note that tuning parameters  $A$  and  $\tau$  will make the modulation of the amplitude and period of the synchronized oscillation still available. If a strong inhibition, e.g.  $\omega_c < -0.2$ , is applied among the oscillators in the network, a maintenance phenomenon occurs, where all the output of the oscillators will be held at the same value, as shown in Fig. 6b. Through numerical simulation, it has been found that the outputs of all the oscillators are equal to the value of parameter  $A$ . Moreover, modifying parameter  $A$  can also result in a change of the maintained value.

### 3.3 Response behaviors

As mentioned before, the border reflex and the body reflex have opposite response behaviors due to the different composition of the monosynaptic reflex arcs. In general, the border reflex is supposed to be used for these oscillators on the border of the CPG network, while the body reflex is utilized for the non-boundary oscillators in the CPG network.



**Fig. 7** Reflex behavior.

Taking a pitch-yaw connected modular robot with touch sensors on both sides as an example, the top view of the robot is shown in Fig. 7. We apply chained inhibitory network on pitch modules and cyclic inhibitory network on yaw modules. Since the pitch modules are responsible for linear gait generation and should not be interrupted by external stimuli, we assume the reflex mechanism is only applied to the yaw modules of the robot. When external stimuli act on the border modules of the robot and activate their border reflexes, these border modules are designed to bend to the opposite direction compared to the direction of the afferent stimuli. In contrast, if external stimuli happen to the internal modules of the robot and activate their body reflexes, these modules are designed to respond in an opposite way, namely, to bend toward the direction of the afferent stimuli.

As a result, the resulting response behaviors always seek to make the robot bend correctly and get rid of external stimuli, so as to avoid potential damages to the robot.

#### 4 Sensory reflex experiments

Numerous simulations and experiments have been carried out to validate the feasibility and effectiveness of the proposed model in realizing the sensory reflex mechanism.

On the one hand, a pitch-yaw connected modular robot mounted with force sensors on both sides of its body is configured in the ODE environment <sup>[24]</sup>, as shown in Fig. 8. On the other hand, a real pitch-yaw connected modular robot with five aluminum modules is constructed for on-site experiments. Each end of the module is surrounded by six touch switches. The specification for the module is shown in Table 2.

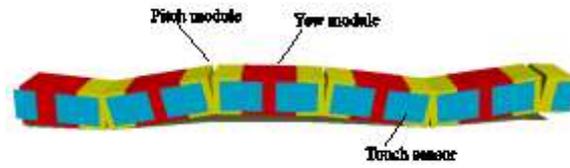


Fig. 8 The simulated limbless robot with touch sensors on both sides.

Table 2 Specification of the aluminum module

Specification	Value
Size (mm)	$90 \times 52 \times 52$
Weight (kg)	0.12
Actuator	RC servo motor (Futaba s3003)
Touch sensor	On-off touch switch (Omron D2MQ)
Position sensor	Built-in sensor of Futaba s3003

We employed a turning gait for both simulation and experiments, where a chained inhibitory CPG network and a cyclic inhibitory CPG network are applied on the pitch and the yaw joints of the robot, respectively. Table 3 lists the parameters that are used to generate this gait. The control of the robot, including calculating CPG outputs, sending joint angles and receiving sensory information, is done by a PC via Bluetooth devices. Note that the reflex mechanism is only integrated into the yaw joints to produce reflex turning behaviors under external stimuli. Border reflexes are applied on the two yaw joints at both ends of the robot, while body reflexes are utilized on the rest yaw joints. The rotating speed of pitch joints is determined by the difference of the desired angle and the real angle within an interval of 100 ms, which enables the real angle to follow the desired angle without losing accuracy, as shown in Fig. 9. However, more interest lies in the response of the yaw joints rather than the pitch joints in the reflex experiments. Therefore, only the yaw joints and the touch sensors are discussed in the following two experiments.

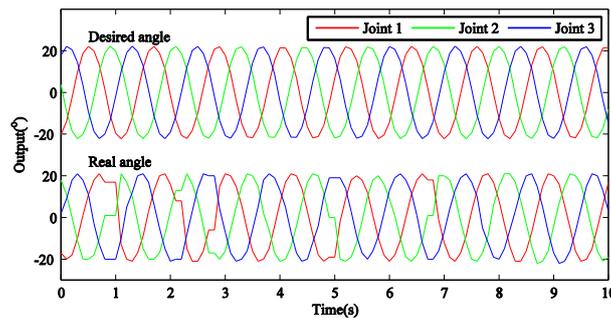
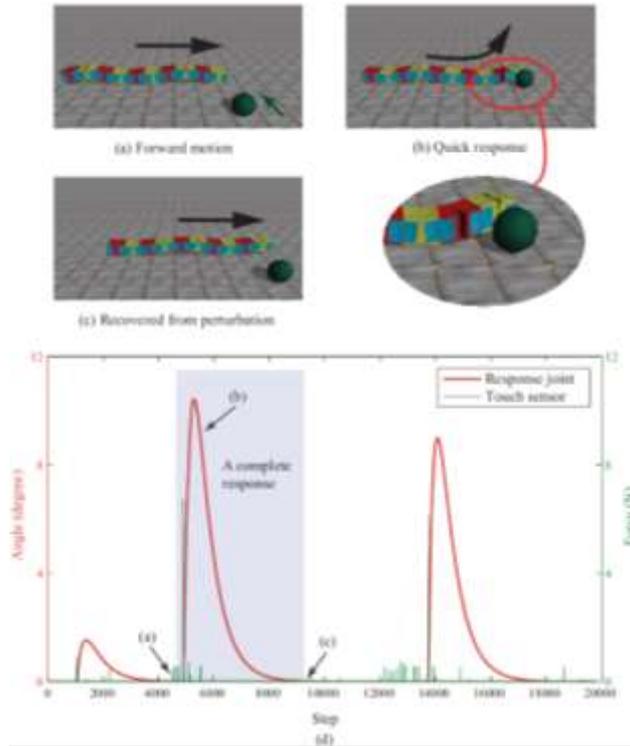


Fig. 9 Angle variation of pitch joints.

**Table 3** Parameters for turning gait generation

Parameters	Pitch joint	Yaw joint
$A$	22	0
$\tau$	0.4	0.4
$\alpha$	0.06	--
$\beta$	0	0

#### 4.1 Ball hitting experiment

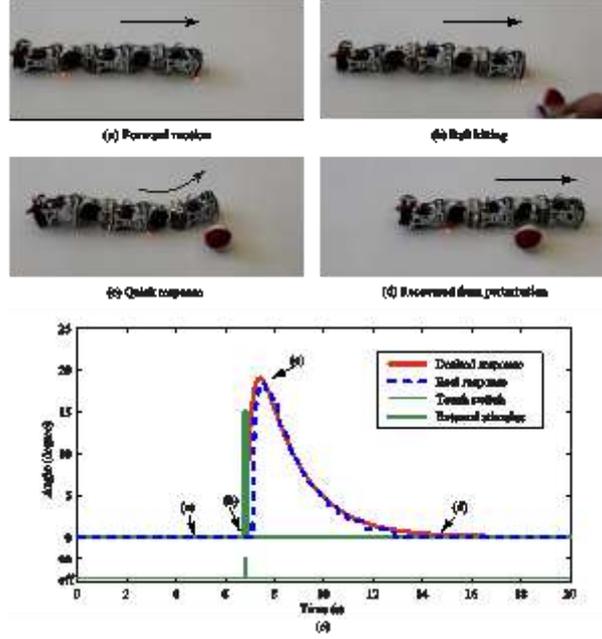


**Fig. 10** Ball hitting simulation. (a) A ball is hitting the robot in forward motion. (b) The force on the touch sensor over a threshold activates the afferent stimulus and makes the robot respond quickly. (c) The robot recovers since there is no further afferent stimulus. (d) The force on the touch sensor and the response angle of the corresponding joint.

As mentioned above, the ball hitting experiment is carried out to check whether the robot is able to respond correctly to external stimuli. In the simulation, we set  $\Theta=1$ ,  $p=2$ ,  $\tau_1=0.4$  and  $\tau_2=6$ . This setting would make the reflex mechanisms not only sensitive to external stimuli, but also generate fast response, slow recover behaviors.

A small ball, similar to the hammer in the knee jerk experiment, is utilized here as the source of external stimuli. A complete reflex process is shown in Fig. 10a-c. The procedure is as follows: the robot was suddenly hit on the head by the ball during forward motion, and it made a quick

response by using the first yaw joint to turn to avoid the ball. When the ball no longer hit the robot, the turning behavior gradually disappeared and the robot recovered from the external perturbation and resumed its forward motion. Fig. 10d illustrates the afferent stimulus as well as the response angle of the corresponding joint.



**Fig. 11** On-site ball-hitting experiment. (a)-(d) Scenes of the experiment. (e) The state of the touch switch on the right side of the head and the response of the first yaw joint.

The on-site experiment also successfully exhibits the response and recovery behaviors, as shown in Fig. 11a-d. The only difference lies in that the real robot uses touch switches as touch sensors instead of force sensors. Thus, the dynamic of SN in Eq. (6) and (7) should be rewritten as:

$$\begin{cases} \tau_1 x'_{\{SN\}i} = -x_{\{SN\}i} + \Delta t \cdot p \lambda_0 & \text{if switch is pressed} \\ \tau_2 x'_{\{SN\}i} = -x_{\{SN\}i} & \text{otherwise} \end{cases} \quad (8)$$

$$(9)$$

where  $\lambda_0$  is a constant that indicates the afferent speed of the external stimulus ( $\lambda_0=15$  in this experiment) and  $\Delta t$  is a period of time which depends on the state of the touch switch. Here  $\Delta t$  is defined as:

$$\Delta t = t - t_0 \quad (10)$$

The variables  $t$  and  $t_0$  represent the current time and the moment when the touch switch is pressed, respectively. Note that the longer the duration of time when the touch switch is pressed, the larger the amount of external stimuli  $\Delta t \cdot p \lambda_0$  that will be generated at the corresponding joint.

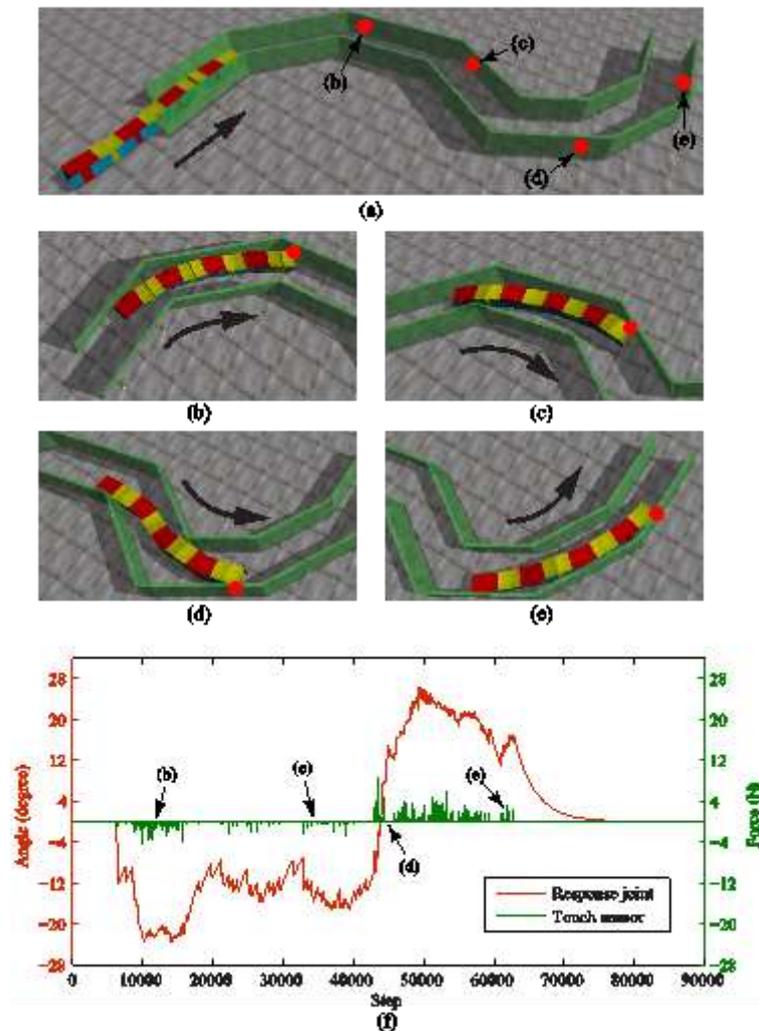
Fig. 11e illustrates the relationship between the state of the touch switch on the right side of the head and its corresponding response on the first yaw joint. At time 6.8s, the touch switch on the right side of the head was hit by the ball. At the same time, an external stimulus generated by Eq. (8) was afferent to the corresponding sensory neuron in the oscillator at the first yaw joint. Along the reflex arc, the output of the oscillator was forced to modulate to respond the external stimulus. As long as there is no longer any perturbation, the oscillator resumes its maintenance activities. That is why from time 7.3s to 15s, the angle of the first yaw joint gradually got back to normal state. Compared to Fig. 10d, the result shows that the touch switch plays the same role as the force sensor in the reflex of external stimuli. Through the ball-hitting experiment, the feasibility of the integrated sensory reflex mechanisms is validated.

#### **4.2 Corridor passing experiment**

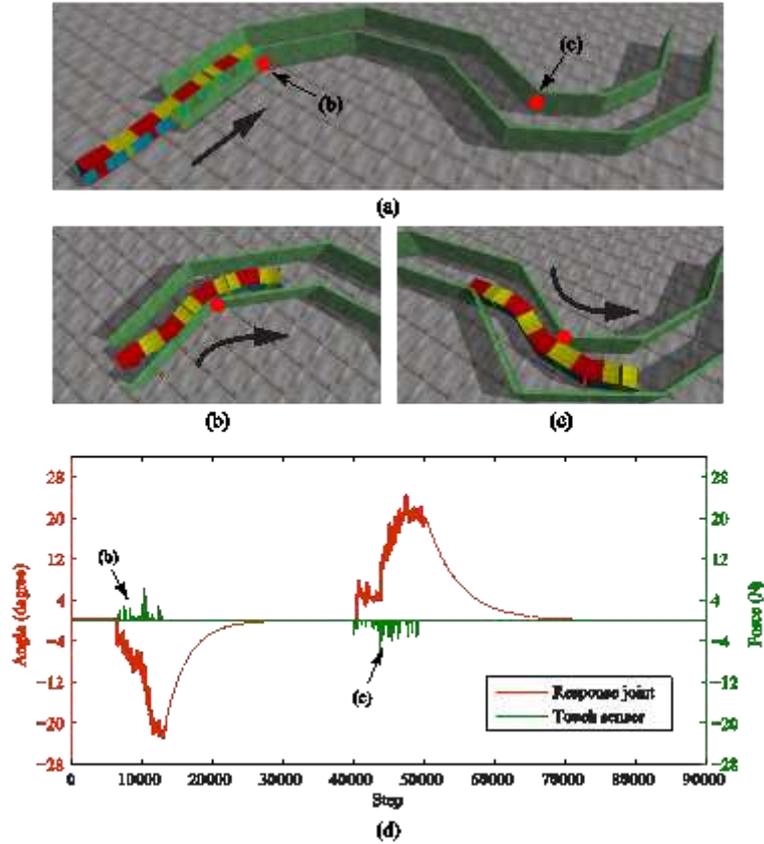
A more complicated scenario is an application of the reflex mechanisms, which requires the robot with a forward motion to pass through a narrow and winding corridor. Two response strategies are involved in this experiment. First, when a collision on the head or tail is detected, the border reflex is activated. External stimuli will be transmitted to its corresponding yaw joint and initiate an opposite turning behavior. Second, if body collision occurs, the body reflex is enabled. External stimuli will cause the corresponding yaw joint to bend away from the collision point. Since too many collisions occur when the robot is crossing the corridor, only the touch sensors on the head and on the middle, as well as the response of the first yaw joint and the middle yaw joint, are considered.

In the simulation, the corridor is designed to have a length of 2500 mm and a width of 130 mm, which is about 3.5 times as long and 2.5 times as wide as the robot used in this experiment, as shown in Fig. 12a. The red points indicate the sampled head collision positions corresponding to the points in Fig. 12b-e. Since the corridor is curved, collisions inevitably occur on the head of the robot, especially when the robot moves toward each corner in the corridor. To guide the robot to pass the corridor, the border reflex is applied on the head of the robot, which helps the robot to turn the head in the opposite direction to avoid further collisions. Fig. 12f illustrates the reaction of the head reflex, namely the variation of the first yaw joint over all the time steps. For the forces measured from touch sensors, a negative value indicates the force measured by the touch sensor

on the left side, while a positive value represents the force caused by the touch sensor on the right side. For the angle of the response yaw joint, a negative value implies a right turning of the module, while a positive value means a left turning of the module. The force detected by touch sensors on both sides not only affects the values of the bending angle, but also determines the bending direction. From this figure, it can be seen that the detected forces always result in response angles with the same sign. This means the response direction is opposite to external stimuli, which is consistent with the function of the border reflex.



**Fig. 12** Border reflexes in the corridor passing simulation. (a) Overview of the corridor. (b)-(e) Different head turning reactions based on the border reflex. (f) The angle variation of the first yaw joint and the force detected by its corresponding touch sensors on the head.

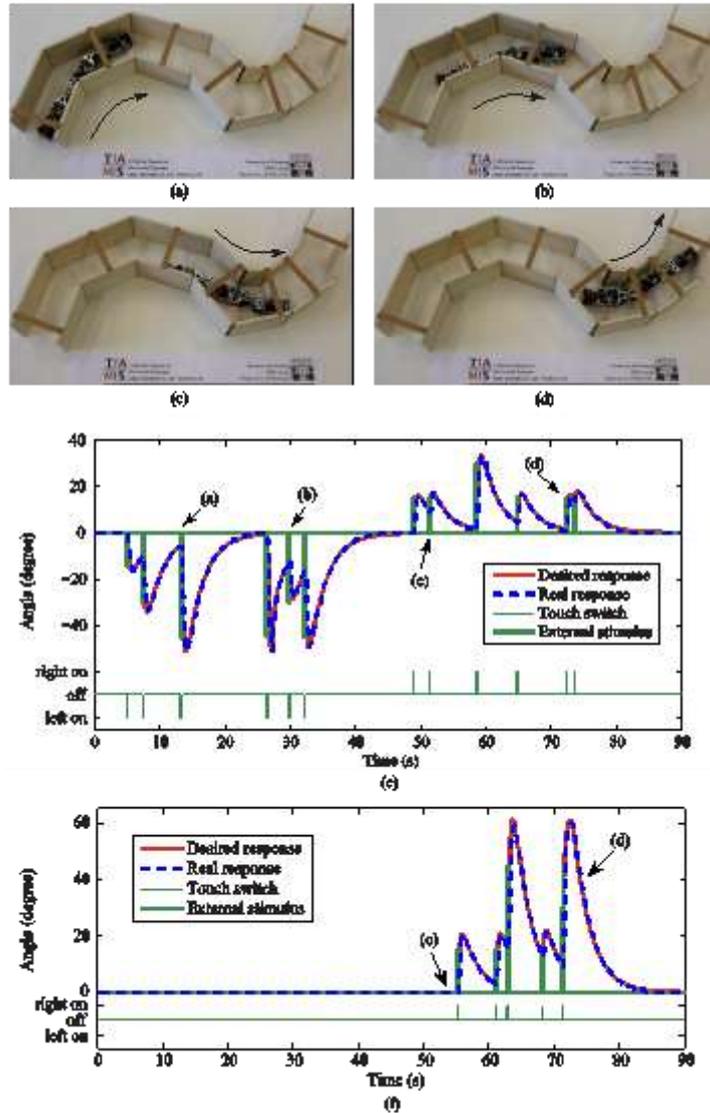


**Fig. 13** Body reflexes in the corridor passing simulation. (a) Overview of the corridor. (b)-(c) Different body turning reactions based on the body reflex. (d) The angle variation of the second yaw joint and the force detected by its corresponding touch sensors.

Fig. 13 shows the reaction on the body of the robot. Likewise, the red points shown in Fig. 13a are the positions where the body collision occurs, which corresponds to the positions in Fig. 13b-c. The body reflexes appear much less than the border reflexes. This is because body collisions happen only when the robot moves to a sharp corner and passes half of its body. In such a situation, collisions usually first occur on the head of the robot, resulting in border reflexes. Then the border reflexes change the turning of the head. Due to the momentum, the consequence of the head response also shifts the body of the robot, which finally leads to the body collisions. Fig. 13d illustrates the reaction of the body reflex, including the variation of the second yaw joint and its corresponding sensor information. During the body reflex, it can be found that the sign of the detected forces are opposite to the sign of the response angles. Compared to Fig. 12f, the response behavior of the body reflex is totally the opposite of the response behavior of border reflex. That exactly complies with the expectation of the two types of reflexes.

A similar on-site experiment is carried out using the same response strategies, as shown in

Fig. 14a-d. During the experiment, the robot responds quickly at the yaw joints where collisions are detected by their touch switches, allowing the robot to behave adaptively to the curving of the corridor. Furthermore, in a similar manner to the ball-hitting experiment, the yaw joints that had responded to external stimuli can swing back to their initial state gradually, which helps the robot to recover normal linear motion. By alternating between the response and recover states during the forward motion, the robot successfully passes through the corridor.



**Fig. 14** Border reflexes in on-site corridor passing experiment. (a)-(d) Scenes of the experiment. (e) Head reflex. (f) Tail reflex.

Note that the real robot has only two yaw modules, one used for head responses and the other for tail responses. The body reflex was not used. Hence, we only analyze the border reflex here. Fig. 14e illustrates the state of touch switches on the head, as well as the reaction of the first yaw joint. Compared to Fig. 12f, the trend of their responses on the first yaw joint is almost equivalent.

During the first half of the experiment, both angles of the first yaw joint were negative, while in the second half, they became positive. However, the number of reflexes occurring in Fig. 12f is found to be much larger than that of reflexes in Fig. 14e. The reason is that the touch switch in the real world is not as sensitive as the force sensor in simulation. Although the number of reflexes decreases in the on-site experiment, the result shows that it does not influence the robot to cross through the corridor. Fig. 14f shows the angle variation of the yaw joint at the tail side, together with the touch states detected by its corresponding touch switches. The tail reflex only occurs in the latter half of the experiment. It regulates the behavior of the yaw module at the tail side so that the robot manages to cross through the last corner of the corridor.

As a result, we conclude that the integrated sensory reflex mechanisms work well with our CPG model to respond to external environment stimuli.

## **5 Conclusion**

This paper emphasizes the design of sensory reflex mechanisms based on a lamprey spinal generator that can realize fast response and achieve adaptive limbless locomotion. In light of the reflex actions in nature, we present a CPG-based reflex mechanism. A CPG model biologically inspired by the spinal circuit of lampreys is used, which not only features explicit output modulation, but also extends the activity of oscillation, including synchronization and maintenance. The highlight of this CPG model is the capability of integrating the sensory reflex mechanism. Thus we designed a sensory reflex mechanism at the neural level. First, sensory neurons are added into the CPG model. The idea of reflex arc is also utilized to form short pathways to bridge external stimuli and the CPG model. Then, a border reflex and a body reflex are developed for adaptive limbless locomotion. Due to the inverted structure of reflex arcs in the two types of reflexes, they can generate opposite response behaviors. This design helps limbless robots to respond reasonably to external stimuli. Through a ball hitting and a corridor passing experiments, the proposed reflex mechanism based on the CPG model is verified effectiveness in realizing fast response and adaptive locomotion for limbless robots.

Currently, we are designing new robot modules with different kinds of sensors. Future work will focus on two aspects. First, more types of sensory information will be considered so as to generate more reasonable response behaviors. Second, the reflex mechanism will combine with a

high-level controller to form a complete control system for limbless robots, which would enhance their terrainability in unconstructed environments.

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