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Adaptive Walking of a Quadrupedal Robot Based on Layered Biological Reflexes

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Abstract: A multiple-legged robot is traditionally controlled by using its dynamic model. But the dynamic-model-based approach fails to acquire satisfactory performances when the robot faces rough terrains and unknown environments. Referring animals' neural control mechanisms, a control model is built for a quadruped robot walking adaptively. The basic rhythmic motion of the robot is controlled by a well-designed rhythmic motion controller(RMC) comprising a central pattern generator(CPG) for hip joints and a rhythmic coupler (RC) for knee joints. CPG and RC have relationships of motion-mapping and rhythmic couple. Multiple sensory-motor models, abstracted from the neural reflexes of a cat, are employed. These reflex models are organized and thus interact with the CPG in three layers, to meet different requirements of complexity and response time to the tasks. On the basis of the RMC and layered biological reflexes, a quadruped robot is constructed, which can clear obstacles and walk uphill and downhill autonomously, and make a turn voluntarily in uncertain environments, interacting with the environment in a way similar to that of an animal. The paper provides a biologically inspired architecture, with which a robot can walk adaptively in uncertain environments in a simple and effective way, and achieve better performances.

Key words: legged robot, motion control, central pattern generator (CPG), biological reflex

1 Introduction

A control system for an autonomous legged robot must perform many complex tasks, integrating different sensor information that are required to stimulate different functions in terms of real time and complexity. How a robot control system integrates large numbers of sensory inputs and actuator outputs so as to achieve an excellent locomotivity in unstructured environment is a controversy as well as a big challenge in the fields of robotics and artificial intelligence(AI). According to Brooks[1], two approaches have been developed for legged robots to achieve satisfactory performances in unstructured environment. Traditional AI approach modularizes perception, modeling, planning, and execution. Behavioral responses emerge from the interplay of the planner with a given goal and the particular world model that have been constructed from the sensory data. Robotic soccer game and map-based navigation are two typical applications of this approach. However, it falls far from ideal in handling an unpredictable and changing environment owing to slow reasoning and complexity of representing a dynamic real world.

Behavior-based approach is another choice, where many individual modules are involved, each incorporating its own perceptual, modeling, and planning requirements to directly generate some part of the behavior of the robots and respond quickly to the changes in the world. Brooks programmed a six-legged robot, Genghis, to walk over rough terrain, using this approach[2]. He designed the subsumption architecture with augmented layers of behaviors, implementing the abilities to stand up, walk without feedback, adjust for rough terrain and obstacles by means of force feedback, and modulate for this accommodation based on pitch and roll inclinometers. The robot successfully navigated rough terrain with very little computation. Behavior-based approach is more like the way that organisms interact with the world. However, this approach is unprincipled and does not scale well to some extent. How a concept becomes a practicable procedure remains a tough work, as it is difficult to layer behaviors properly or to build a reasonable relationship between them.

Imitating animals is an effective way to design and control a mobile robot. However, the key problem is how to translate a complex biological neural system into a plausible physical control system. Central pattern generator (CPG)-based approach[3] is a successful example, which derives its model from biological neural system for rhythmic movement control of the robots. CPG has been built as different models by many scientists and researchers[4–10]. However, modeling reflexes and organizing them into the

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CPG-based control system has no solid methodology. Kimura developed two ways to introducing sensory information into control system: “response” named the feedbacks introduced into the CPG modulating the CPG phase, and “reflex” named the one introduced into the joint PD controller generating joint torque. They built many reflexes to control a quadrupedal robot walking dynamically in a mid-irregular terrain. Different representations are developed for different reflexes, and the representations and parameters in the control system are obtained experimentally for their best performance[11–13]. Taga built a control system, including a rhythmic generator (RG) and a discrete generator(DG), for a simulative human biped. RG is responsible for generating basic motion pattern, while DG modifies the basic motion based on sensory information. Real-time adaptability can be realized through global entrainment between neuro-musculoskeletal system and the environment[14–15].

Even though CPG-based approach exhibits some attractive features when used for robot control, designing the control architecture and handling the interaction between the CPG and reflexes as well as between the reflexes themselves is a tough work. It can be a big trouble in complex environment where a lot of reflexes or feedbacks need to be handled. In this paper, we have proposed a clear control architecture for a quadrupedal robot to walk adaptively, in which the basic rhythm motion is controlled by rhythmic motion controller(RMC) comprising a CPG for the hip joints and a rhythmic coupler (RC) for the knee joints. Multiple biological reflex models are organized, and thus interact with the CPG in three layers. Each reflex is accommodated into different layers of architecture according to its function complexity and real-time requirements. Reflex modules are isolated from each other. Under this architecture, we have modeled flexor reflex, postural reflex, and turning reflex by patterning their behaviors after a cat, and applied them to a quadrupedal robot to perform in an environment with unknown obstacles and slope.

2 Biologically Inspired Motion Control Architecture

To design an effective motion control system, we investigated the physiological structure of the neural system of the vertebrates. We presumed that some clues could be obtained from the investigation as a reference when designing the control system for a physical robot.

2.1 A layered neural system

The neural system structure of a vertebrate can be approximately divided into three layers, as shown in Fig. 1. The central nerve system (CNS) is composed of many motion nerve centers, which monitors and regulates the body movements and activities on a top-down basis. CPG is the core of the rhythmic movement, capable of generating rhythmic outputs in the absence of inputs from outside or higher centers. The sensory passages bring the information from the body postures and environments back to different neural layers.

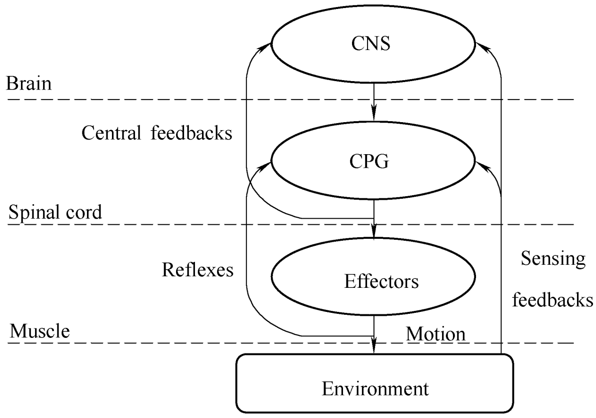


Fig. 1. Biological neural system of motion control (revised from Ref. [16])

It is generally accepted that animals’ walking is mainly generated at the spinal cord by a combination of CPG and reflexes. CPG outputs can be changed by outside inputs, namely biological reflexes[17]. Animals adapt themselves to environments by various reflexes, such as flexor reflex, tendon reflex, postural reflex, etc.

2.2 Designing a rhythmic motion controller

The basic motion of a legged robot for locomotion is rhythmic motion. We designed an RMC that could generate the rhythmic position signals for hip joints and knee joints of the quadrupedal robot. The RMC consists of a CPG and RC.

2.2.1 CPG model

In the RMC, the CPG is the core part responsible for generating rhythm for the whole system. We used the CPG model presented by Matsuoka[18–19]. Matsuoka’s oscillator consists of two reciprocally inhibited neurons that correspond to a flexor neuron and an extensor neuron in animals. The CPG model can be represented in a vector equation set as Eq. (1). The subscripts i, n, m, f and e indicate The ith oscillator, number of oscillators, number of sensing inputs, flexor neuron, and extensor neuron, respectively.

$$\begin{cases} T_{\mathrm{r}}\dot{\boldsymbol{U}}^{\mathrm{f,e}}+\boldsymbol{U}^{\mathrm{f,e}}=b\boldsymbol{V}^{\mathrm{f,e}}+a\boldsymbol{Y}^{\mathrm{e,f}}+\boldsymbol{W}\boldsymbol{Y}^{\mathrm{f,e}}+\boldsymbol{S}\boldsymbol{G}^{\mathrm{f,e}}+c\boldsymbol{E}, \\ T_{\mathrm{a}}\dot{\boldsymbol{V}}^{\mathrm{f,e}}+\boldsymbol{V}^{\mathrm{f,e}}=\boldsymbol{Y}^{\mathrm{f,e}}, \\ y_i^{\mathrm{f,e}}=\max(u_i^{\mathrm{f,e}},0), \\ \boldsymbol{Y}=p(\boldsymbol{U}^{\mathrm{f}}-\boldsymbol{U}^{\mathrm{e}}), \\ \boldsymbol{U}^{\mathrm{f,e}},\boldsymbol{V}^{\mathrm{f,e}},\boldsymbol{Y}^{\mathrm{f,e}},\boldsymbol{Y}\in\mathrm{R}^n,\boldsymbol{W}\in\mathbf{R}^{n\times n},\boldsymbol{S}\in\mathbf{R}^{n\times m},\boldsymbol{G}\in\mathbf{R}^m, \\ \boldsymbol{E}=[\underbrace{1,1,\cdots,1}_{n}]^{\mathrm{T}},i=1,2,\cdots,n, \end{cases} \tag{1}$$

where $\boldsymbol{U}$—Neuronal states,

$\boldsymbol{V}$, b—Internal adaptability and an adaptive coefficient respectively,

T_r—Rising time constant that determines the oscillation period,

T_a—Adaptability time constant that characterizes the delay of the adaptability effect,

c—Constant tonic input from higher levels, which linearly determines the output amplitude,

p—Regulating gain that makes the output amplitudes equal to c,

$\boldsymbol{Y}^{f,e}$, a—Neuronal outputs and an inhibition coefficient of the neuron–neuron coupling term, respectively,

$\boldsymbol{W}$—Gait matrix of the oscillator–oscillator coupling term, which represents the walking pattern of a legged robot,

$\boldsymbol{S}$, $\boldsymbol{G}$—Sensing inputs and reflex gains of the feedback term respectively,

$\boldsymbol{Y}$—Set of stably oscillating outputs of the CPG, which are used as angular position control signals for the hips of a quadrupedal robot.

2.2.2 RC model

The quadrupedal robot has eight DOFs, that is, four hip joints and four knee joints. Generally, motion control becomes more complex with increasing DOFs for a robot walking dynamically with high speed. Moreover, it is crucial to ensure a uniform and steady rhythm over the course of the whole motion for rhythmic walking. To simplify multi-DOFs control, we designed an RC, which is a mapping connection between the hips and the knees. As shown in Fig. 2, the four hips are controlled by the CPG, and each knee is controlled by a function f, whose value is calculated from the hip variable in the same leg. The hip-to-knee mapping function f is represented, after a cat's motion, as Eq. (2):

$$\begin{cases} y_k(t) = \begin{cases} \operatorname{sgn}(\psi)(A_h - |y_h(t)|)d(t) & (\dot{y}_h \geqslant 0, \quad \text{Swing phase}), \\ 0 & (\dot{y}_h < 0, \quad \text{Stance phase}), \end{cases} \\ d(t) = d_0\left(1 + \dfrac{|y_h(t)|}{A_h}\right), \\ d_0 = A_k / A_h, \\ \psi = \begin{cases} 1 & (\text{Elbow}), \\ -1 & (\text{Knee}), \end{cases} \end{cases} \tag{2}$$

where y_h, y_k—Angular positions of the hip and knee, respectively,

A_h, A_k—Angular amplitudes of the hip and knee, respectively,

d—Variable gain,

$\operatorname{sgn}(\psi)$—Sign function, is used to indicate two types of joints in the quadrupeds as well as in some legged robots (knee-style and elbow-style), which rotate in opposite directions at their hips and knees.

The RC turns the hip control signals to knee control signals over time, so as to couple the hip's motion and knee's motion at the same rhythm.

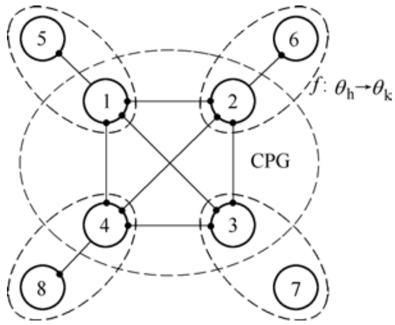


Fig. 2. Rhythmic coupling connection between the hips and knees

1, 2, 3, 4—Hip joints; 5, 6, 7, 8—Knee joints

f—Knee mapping function; θ_h, θ_k—Hip and knee angular position

2.3 Three-level biological reflexes

Animals survive themselves in a complicated world, where they must accommodate various environmental conditions encountered during everyday activity. The efficiency and flexibility of operation and robustness to contingency and damage that animals exhibit can be attributed to the affluent sensory system and delicate reflex mechanisms. The sensorimotor interactions in animals are real-time, reciprocal, and widespread in local muscle, CPG, and cerebral cortex[20]. To employ the biological reflex mechanisms to improve the adaptability of robots, we need to find approaches to engineer the reflexes and develop interaction between the CPG and reflexes. A well-structured framework can provide simple, clear, and practicable approaches to integrate the sensory information to the locomotor control system, dealing with various tasks of different complexity and response-time requirements. We suggest a three-level reflex modeling framework derived from the real biological reflexes' neural system, as shown in Fig. 1. Each task that handles an environmental change is regarded as a basic module. The framework provides layered routes to organize all modules and encode each module.

2.3.1 Organizing the modules

By referring to vertebrate's neural system of motion control, we present a biological reflex modeling framework of three levels: lower reflex (LR), intermediate reflex (IR), and higher reflex (HR), as shown in Fig. 3.

LR organizes the reflex module under CPG, that is, modifying the CPG outputs to produce a proper reflex act towards the direction of eliminating a stimulus. Here, a well-designed fixed motion form emerges and replaces the ongoing rhythmic movement of the robot in case if LR is triggered. With short connections between the sensors and actuators, LR is advantageous to stimuli requiring quick treatment. It serves simple and high real-time behaviors, such as knee jerk or flexor reflex.

IR is in charge of behaviors involving multilimb coordination, such as postural reflex. It organizes the reflex module within the CPG by introducing sensory inputs to the CPG model via the feedback term in Eq. (1), which we represent as the product of $\boldsymbol{S}$ and $\boldsymbol{G}$. The sensing information matrix $\boldsymbol{S}$ accommodates the feedback signals, as

$$\boldsymbol{S}=\begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1m} \\ s_{21} & s_{22} & \cdots & s_{2m} \\ \vdots & \vdots & & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nm} \end{pmatrix},$$

where the columns indicate the legs and the rows indicate all kinds of feedback signals.

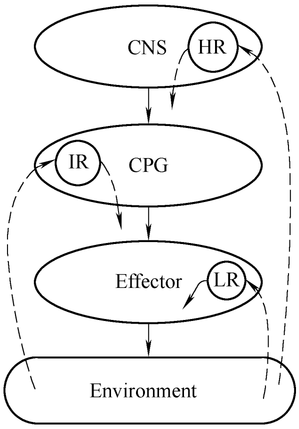


Fig. 3. Three-layer biological reflex modeling framework

Each feedback signal is integrated into the CPG by the corresponding element in the reflex gain vector $\boldsymbol{G}$. We define $\boldsymbol{G}=[g_1, g_2,\cdots,g_m]^{\mathrm{T}}$, $g_i^{\mathrm{e}}=-g_i^{\mathrm{f}}$, based on the fact that extensor and flexor is a pair of antagonistic muscles. By introducing sensory inputs into the multioscillator-coupled CPG, IR produces coordinated motion among the legs of a robot. A reflex act triggered by a single source evolves to be a collective act owing to the entrainment among the oscillators. Such expression of the feedbacks can fuse various kinds of sensory information to exhibit a global behavior of the robot.

HR organizes the reflex module within the CNS that has affluent neurons. Unlike the involuntary LR and self-organized IR, HR is conscious, that is, cerebrum engages in its response so that much more information can be processed and more complicated behavior can be produced, such as visual reflex or audio reflex.

When a reflex is required for the robot to adapt to a specific environmental change, proper level is chosen to model the reflex depending on the task's complexity, response time, etc., and then the detailed reflex motion is designed, which we have termed as encoding a function.

2.3.2 Encoding a function

Evolution has shaped the breathtaking abilities of animals. Their adaptability, flexibility of motion, and great variety of behaviors has made them the benchmarks for robot performance. When it comes to designing a concrete reflex function for a robot, we aim to make the robot interact with its environment in a way similar to that of an animal. Therefore, we investigate a cat's behaviors, emulate and formalize its reflex acts under specific conditions, and reconstruct its targets of control on its robotic counterpart. The robot acquires the most natural performance by means of the reflex motions and the basic rhythmic movement combined in a harmonious way.

3 Adaptive Movements of a Quadrupedal Robot Using Layered Biological Reflexes

3.1 Quadrupedal robot

A quadrupedal robot (Fig. 4), Biosbot (Biologically Inspired Robot), is constructed as a platform to test the control architecture. Each leg of the robot had three joints: hip, knee, and ankle, with one pitching degree of freedom. Hips and knees are active joints driven by DC motors. Ankles are passive joints with spring damper. All the joints can rotate up to 180°. The robot is equipped with the following sensors: a photo encoder on each joint, contact switches on the toe of each leg to detect obstacles, and pitch and roll inclinometers on the trunk to acquire inclination of the terrain and sense the smoothness of the performance. The robot has dimensions of 400 mm$\times$320 mm$\times$300 mm, and a mass of 5.7 kg.

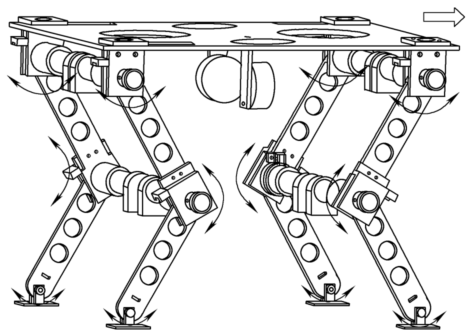


Fig. 4. Mechanical draft of the quadrupedal robot, Biosbot

The experimental environment is arranged as a long bar with cross-section of 20 mm$\times$20 mm as an obstacle, a continuously changing slope with a maximum pitch angle of up to around 12°, and a 1.2 m-high wall. The profile parameters of the terrain are unknown to the robot in advance.

3.2 Clearing obstacle using LR flexor reflex

Flexor reflex in animals refers to the retraction response of a limb caused by a harmful stimulus. Animals use flexor reflex to escape or clear an obstacle when their limb bump into it. We employ the flexor reflex to make a quadrupedal robot to clear obstacles in its environment autonomously. To simplify the flexor reflex modeling and acquire a natural reflex motion, we investigate a cat's clearing-obstacle act and emulate it on the quadrupedal robot.

3.2.1 Flexor reflex behavior of a cat

A cat's flexor reflex behaviors are investigated by using a digital camera to record its motion, with the cat's eyes covered by a piece of cloth to avoid the vision influence. A wooden bar is put before it as an obstacle. We found that the cat performed dependently when its leg bumped the bar. When bumping the bar during anterior swing(AS), with adequate time to respond, the bumping leg somewhat retracts back, and then lifts up higher to clear the bar. If bumping the bar during posterior swing(PS), the leg retracts back a little more and touches down on the ground, because the rest of the swing time is too short to carry out a complete stepping-over. This indicates that the flexor reflex is phase-dependent, i.e. it has different effects depending on the timing within a locomotor cycle.

The acts used by the cat to step over an obstacle are as follows: flexing its bumping leg like a scissor, much more than normal, to get a higher foot clearance.

3.2.2 Flexor reflex model

From the cat's behaviors, it can be concluded that the flexor reflex requires fast response to avoid further damage, and usually involves only single leg; hence, we chose to model it in the LR layer. We design the robot's flexor reflex motion according to the cat's behaviors as follows:

(1) Treating dependently on the bumping-phase location;

(2) Flexing the leg much more to clear the obstacle;

(3) Only the bumping leg reflexes and the other legs maintain their normal motion, to keep the whole rhythm unchanged in the robot.

3.2.2.1 Determining the bumping-phase location

If a swinging leg encounters bumping at time, t_0, then the hip output of the leg, y_0, is recorded. y_0 is compared with a prestored list of swing-phase data of the CPG to determine whether the bump occurred in AS or PS, which are segmented by zero. The reflex time, T_{ref}, is calculated as the rest of the swing time.

3.2.2.2 Bumping during AS

When a leg bumps into an obstacle during AS, then the reflex time is divided into three stages as follows: retracting back, stepping over, and touching down, namely, AS-pattern, only for the bumping leg.

(1) Retracting back: the hip output decreases linearly to make the leg retract back, while the knee output increases for elbow-style joint or decreases for knee-style joint, to ensure that the hip and knee flex like a scissor to lift up the foot.

(2) Stepping over: the hip output increases linearly to make the leg swing forward, while the knee remains unmoving, to step over the obstacle.

(3) Touching down: the hip keeps swinging and the knee returns back to its normal swing-to-stance phase-switch position.

The AS-pattern can be represented discretely as Eq. (3). The subscripts h, k, sw, st indicate hip joint, knee joint, swing phase and stance phase respectively.

$$
\begin{aligned}
&y_{\text{h}}(x+1)=\begin{cases} y_{\text{h}}(x)+\dfrac{Q_{\text{h}}}{T_1}\Delta t & (t_0<t\leqslant t_0+T_1),\\ y_{\text{h}}(x)+\dfrac{A_{\text{h}}-(y_0+Q_{\text{h}})}{T_{\text{ref}}-T_1}\Delta t & \\ \qquad (t_0+T_1<t\leqslant t_0+T_{\text{ref}}), & \end{cases}\\
&y_{\text{k}}(x+1)=\begin{cases} y_{\text{k}}(x)+\dfrac{Q_{\text{k}}}{T_1}\Delta t & (t_0<t\leqslant t_0+T_1),\\ y_{\text{k}}(x) & (t_0+T_1<t\leqslant t_0+T_1+T_2),\\ y_{\text{k}}(x)+\dfrac{0-(y_0+Q_{\text{k}})}{T_3}\Delta t & \\ \qquad (t_0+T_1+T_2<t\leqslant t_0+T_{\text{ref}}), & \end{cases}\\
&Q_{\text{h}}=-\gamma_{\text{h}}A_{\text{h}},\quad Q_{\text{k}}=\operatorname{sgn}(\psi)\gamma_{\text{k}}A_{\text{k}},\\
&t=x\Delta t,\quad T=T_{\text{sw}}+T_{\text{st}},\quad T_{\text{sw}}=(1-\beta)T,\\
&T_{\text{ref}}=T_{\text{sw}}-T_0=T_1+T_2+T_3,\quad T_1=\lambda_1T_{\text{ref}},\quad T_2=\lambda_2T_{\text{ref}},
\end{aligned}\tag{3}
$$

where x —Sequence number,
y—Joint output,
Q—Retracting change,
γ—Retracting change gain,
β—Duty factor,
Δt—Calculating step,
T—Current time,
t_0—Bumping time,
y_0—Hip output of the bumping leg at t_0,
T—Cycle time of the walk, i.e. the period of the CPG,
T_{ref}—Period of reflex time,
T_0—Period from the former stance-to-swing phase-switch point to t_0,
T_1—Period of retracting back,
T_2—Period of stepping over,
T_3—Period of touching down,
λ_1—Proportion of retracting-back stage to reflex time,
λ_2—Proportion of stepping-over stage to reflex time.

3.2.2.3 Bumping during PS

When bumping into an obstacle during PS, the leg retracts back and touches down directly on the ground instead of stepping over the obstacle, which is considered as PS-pattern. The motion form can be designed as follows: the hip of the bumping leg decreases linearly to the normal stance-to-swing phase-switch point during the reflex time, then remains unmoving until the beginning of the next swing. The knee does not reflex. The PS-pattern is represented discretely as follows:

$$
y_{\text{h}}(x+1)=\begin{cases} y_{\text{h}}(x)+\dfrac{-y_0-A_{\text{h}}}{T_{\text{ref}}}\Delta t & (t_0<t\leqslant t_0+T_{\text{ref}}),\\ y_{\text{h}}(x) \quad (t_0+T_{\text{ref}}<t\leqslant t_0+T_{\text{ref}}+T_{\text{st}}), & \end{cases}\tag{4}
$$

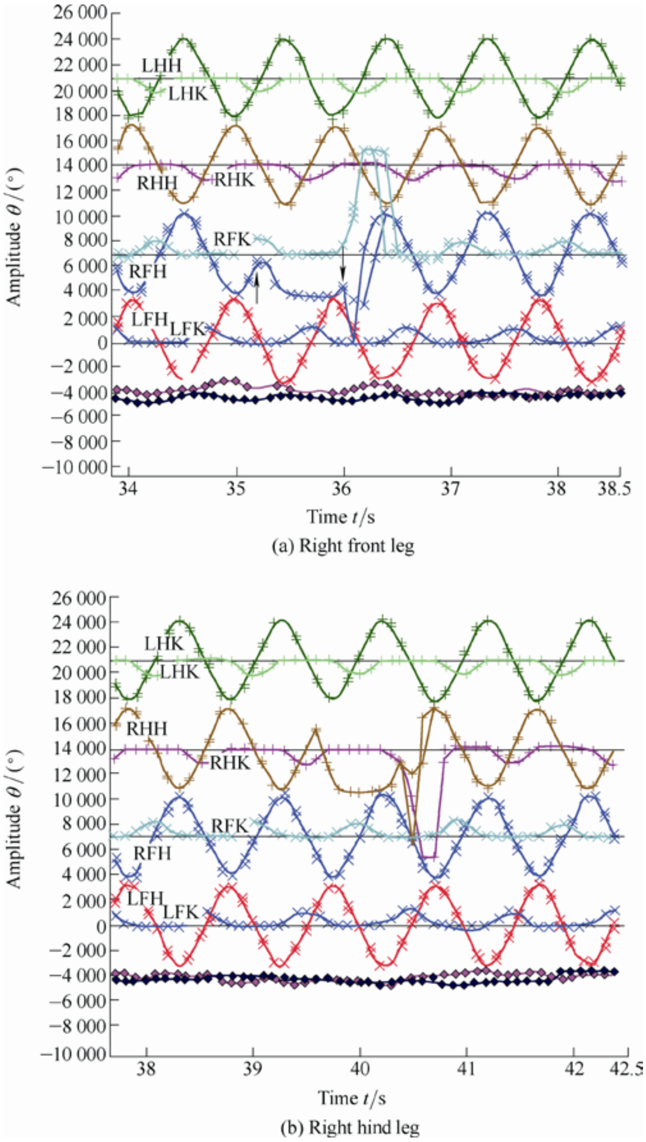
where T_{st} is the stance time, which is equal to the swing time for trot gait with a duty factor of 0.5.

3.2.3 Clearing-obstacle experiments

A long bar with a cross-section of 20 mm×20 mm is placed in the experimental environment as an obstacle. The location of the bar is unknown to the robot, so that the swinging leg can bump on it at any phase location. The quadrupedal robot walks in trot gait[21]. We control Biosbot by combining the flexor reflex model with the basic rhythmic generator and the hip-to-knee mapping function. The parameters are shown in Table 1. As shown in Fig. 5(a), Biosbot executes proper flexor reflex when its right front leg (Leg RF) bumps into the bar under two different situations. At t = 35.2 s, Leg RF bumps into the obstacle during PS, and a PS-pattern is triggered to output a fixed motion in the very leg. With its hip output decreasing and its knee output unchanged, Leg RF retracts back and touches down on the ground. At t = 36.0 s, Leg RF bumps into the obstacle again, but during AS, an AS-pattern is triggered. With its hip output decreasing and its knee output increasing, Leg RF retracts back and lifts up its foot to step over the obstacle (Fig. 6(a)). Similar flexor reflex and clearing obstacle on right hind leg under the two situations are shown in Fig. 5(b) and Fig. 6(b). The labels indicate as follows—LFH: left front hip; RFH: right front hip; RHH: right hind hip; follows: LHH: left hind hip; LFK: left front knee; RFK: right front knee; RHK: right hind knee; LHK: left hind knee.

Table 1. Parameter values used in the paper

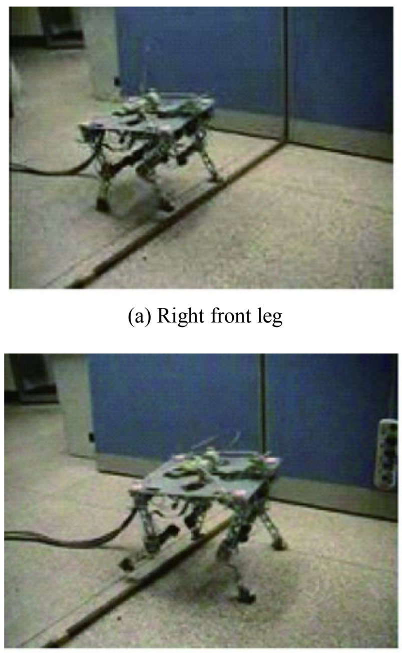
Variable	Value
Gait matrix $\boldsymbol{W}$	$\begin{pmatrix} 0 & -1 & 1 & -1 \\ -1 & 0 & -1 & 1 \\ 1 & -1 & 0 & -1 \\ -1 & 1 & -1 & 0 \end{pmatrix}$
Inhibition coefficient a	−1.0
Adaptive coefficient b	−2.0
Constant tonic input $\boldsymbol{c}$/rad	A_h
Regulating gain p	0.18
Rising time constant T_r	0.08
Adaptability time constant T_a	0.80
Cycle time of the walk T/s	1.6
Calculating step Δt/s	0.012
Angular amplitudes of the hip A_h/(°)	13.4
Angular amplitudes of knee A_k/(°)	10; 5
Joints type sign ψ	−1, 1
Duty factor β	0.5
Retracting change gain of the hip γ_h	5.0
Retracting change gain of the knee γ_k	6.0
Proportion of retracting-back stage to reflex time λ_1	1/3
Proportion of stepping-over stage to reflex time λ_2	1/3
Hip feedback gain for the postural reflex δ	0.25
Knee feedback gain for the postural reflex δ_k	0.06
Joint mid-position θ_0/(°)	30
Body length L/mm	400
Leg length l/mm	150
Hip amplitude modifying coefficient μ	0.2
Increment of the joint mid-positions $\Delta\hat{\theta}$/(°)	10



(a) Right front leg

(b) Right hind leg

Fig. 5. Actual reflex output curves of Biosbot clearing an obstacle


(a) Right front leg

(b) Right hind leg

Fig. 6. Biosbot clearing an obstacle

From Fig. 6, it can be noted that the foot clearance of the bumping leg is much higher than that of the bar. This implies that the robot can clear a bar higher than 20 mm, whereas the control experiments with no flexor reflex employed show that the robot fails to clear an obstacle 20 mm high.

By limiting the flexor reflex only to the bumping leg and other legs moving as usual, the robot maintains its normal body movement during the stepping-over and does not fall down owing to the swift response of an LR reflex. The flexor reflex, behaving based on phase locations, ensures a stable rhythm in the whole system by avoiding the reflex act conflicting with the basic rhythmic movement.

3.3 Walking uphill and downhill using IR postural reflex

Slopes are common terrain in the real world. Walking uphill and downhill requires animals dealing with possible slipping or falling down caused by the offset of center of gravity (COG) of their body. An animal walking on the slope benefits from its postural reflex that adjusts the animal's posture by changing its legs' movement depending on its body's postural information sensed by the vestibular organ in the inner ear and other proprioceptors. Similarly, we investigate the cat's postural reflex behaviors and emulate them on the quadrupedal robot, to make it walk uphill and downhill smoothly in a changing slope.

3.3.1 Postural reflex behavior of a cat

By recording the cat's walking uphill and downhill behaviors using a camera with no special preparations for the cat, we find that the cat adjusts its body posture to counteract COG offset and maintain the balance by changing its legs' extension. When walking on a flat terrain, the cat is found to have its backbone parallel to the supporting plane. When walking uphill and downhill, the backbone is found neither to be parallel to the supporting plane nor to the horizontal ground. During uphill walking, the height from the supporting front feet to the backbone is lesser than the height from the supporting back feet to the backbone. During downhill walking, the height from the supporting front feet to the backbone is greater than the height from the supporting back feet to the backbone.

3.3.2 Postural reflex model

From the cat's motion, we observe that the postural reflex requires all the legs to coordinate with one another to change the body's posture harmoniously in response to the changing terrain in real time. Hence, we choose to model it in IR layer, and design the robot's postural reflex motion according to the cat's behaviors as follows:

(1) All legs need to coordinate to obtain a proper posture by changing the amount they extend, i.e., their motion range.

(2) The front legs flex more than the hind legs for uphill walking, and flex less than the hind legs for downhill walking.

3.3.2.1 Adjusting the posture for a quadrupedal robot on slope

The quadrupedal robot's posture can be adjusted by changing its leg extensions, i.e. the leg motion ranges. This is realized by modifying the mid-positions of the hips and knees while keeping their amplitude unchanged, as shown in Fig. 7. The dotted lines are the preadjusted positions. α is the pitch angle of the slope and $\Delta\theta$ is the mid-position increment of the legs. When the quadrupedal robot with four knee-style joints is walking uphill, a positive angular displacement is added to the normal mid-positions of the front hips, while adding a negative angular displacement to the normal mid-positions of the hind hips. The knees rotate oppositely in angles similar to those of the hips of the same legs, to maintain their current absolute angles. Thus, the posture of the robot is adjusted to have a higher head and lower tail. In contrast, when walking downhill, the changes in the hips and knees are opposite to those when walking uphill, to adjust the posture to have a lower head and higher tail. To adapt to a slope with changing inclination, the value of the hips' mid-position increment is acquired based on the inclination of the slope using a pitch inclinometer attached to the robot's trunk.

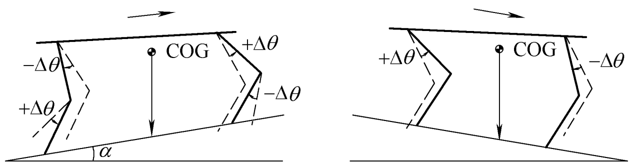


Fig. 7. Postural adjustment of the quadrupedal robot when walking uphill and downhill

3.3.2.2 Introducing postural reflex to the CPG

To model the postural reflex in IR, the pitch angle of the slope is introduced to $\boldsymbol{S}$ and $\boldsymbol{G}$ in the CPG model as a linear function:

$$\begin{cases} sg = F(\alpha), \\ F(\alpha) = \delta\alpha, \end{cases} \tag{5}$$

where s—Element of sensing input matrix $\boldsymbol{S}$,
g—Element of the reflex gain vector $\boldsymbol{G}$,
α—Pitch angle of the slope,
δ—Feedback gain for the postural reflex.

As shown in Fig. 7, the two front hips and the two hind hips produce opposite changes in their mid-positions, and the front hip changes have the same sign as that of the slope pitch angle**.** Inhibiting each other, the flexor neurons and extensor neurons have positive and negative gains, respectively. Thus, the postural reflex can be represented as follows:

$$\begin{cases} \boldsymbol{S} = \begin{pmatrix} \alpha & 0 & 0 & 0 \\ \alpha & 0 & 0 & 0 \\ -\alpha & 0 & 0 & 0 \\ -\alpha & 0 & 0 & 0 \end{pmatrix}, \\ \boldsymbol{G}^{\mathrm{f}} = [\delta \quad 0 \quad \cdots \quad 0]^{\mathrm{T}}, \\ \boldsymbol{G}^{\mathrm{e}} = [-\delta \quad 0 \quad \cdots \quad 0]^{\mathrm{T}}. \end{cases} \tag{6}$$

Additionally, the knees change by an angle opposite to the mid-position increment of the hips, to complete the quadrupedal robot's postural adjustments:

$$\Delta\boldsymbol{\theta}_{\mathrm{k}} = -\Delta\boldsymbol{\theta}_{\mathrm{h}} = \begin{pmatrix} -\delta_{\mathrm{k}}\alpha \\ -\delta_{\mathrm{k}}\alpha \\ \delta_{\mathrm{k}}\alpha \\ \delta_{\mathrm{k}}\alpha \end{pmatrix}, \tag{7}$$

where $\Delta\boldsymbol{\theta}_{\mathrm{k}}$ —Knee increment,
$\Delta\boldsymbol{\theta}_{\mathrm{h}}$ —Hip increment,
δ_{k}—Inherent coefficient determined by $\Delta\boldsymbol{\theta}_{\mathrm{h}}$ and α through the CPG model.

3.3.3 Walking uphill and downhill experiments

Biosbot is controlled by introducing the postural reflex model into the CPG, adding knee adjustments to the hip-to-knee mapping function, and extending the walking period by increasing T_{r} and T_{a}. Biosbot walks around in an environment that includes flat terrain and a man-made slope. The slope location and profile is unknown to Biosbot. When Biosbot walks on the flat surface, the controllers exhibit normal output curves (Fig. 8(a)) and Biosbot's trunk is horizontal (Fig. 9(a)). When walking uphill, depending on the pitch angles of the slope, the output curves of the two front hips move gradually upward, that is, their mid-positions increase continuously, and the output curves of the two front knees move correspondingly downward. At the same time, the output curves of the two hind hips move downward with their mid-positions decreasing, and the output curves of the two hind knees move upward (Fig. 8(b)). Thereby, Biosbot obtains a posture in which the head is lower than the tail, to maintain its balance and counteract slipping (Fig. 9(b)). When walking downhill, the exactly opposite changes occur to all joints, as shown in Fig. 8(c), so that the head is higher than the tail to counteract falling down (Fig. 9(c)). The data from the roll inclinometer, shown as the curves labeled "RI" in Fig. 8, quantify the inclination of the body in the roll plane, and exhibit the robot walking steadily both uphill and downhill, using the control algorithms discussed earlier. Control experiments with no postural reflex show that the robot fails to walk uphill because of serious slipping, and walks downhill with a dangerous unsteadiness, as well as the likelihood of falling under inclinations larger than what we use in the experiments with the postural reflex model. The labels PI and RI indicate pitch inclinometer and roll inclinometer.

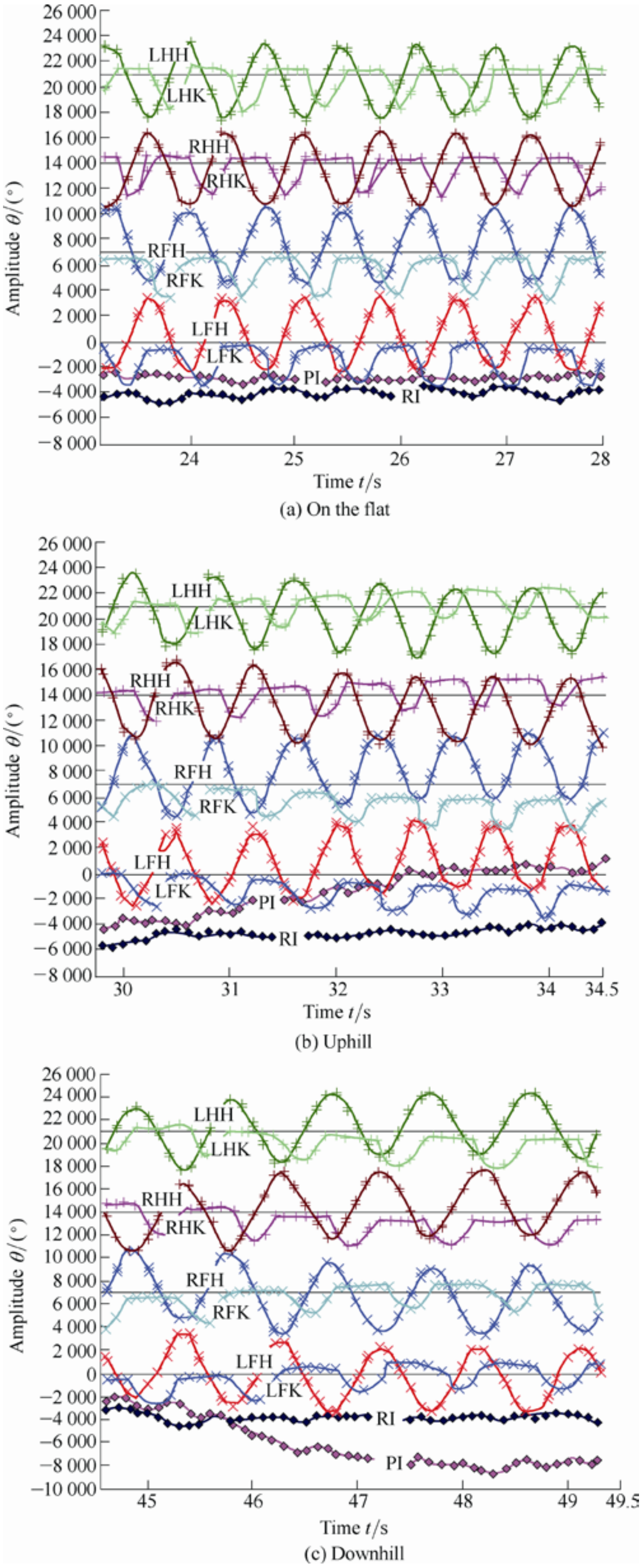


Fig. 8. Actual reflex output curves of Biosbot walking uphill and downhill.

3.4 Turning using an HR reflex

In this three-layer reflex model, the HR layer is simulated as a brain to accommodate advanced functions, i.e. functions that cannot be coped with by LR and IR. The HR layer, with its strong computing ability, could process complicated information or deal with multiple sensory inputs, such as visual data and distance sensors signals, to understand its surroundings clearly, so as to let the robot make an active response to avoid upcoming danger.

(a) On the flat

(b) Uphill

(c) Downhill

Fig. 9. Biosbot walking uphill and downhill

A turning experiment is designed for Biosbot to demonstrate HR layer's modeling ability. Biosbot could not clear a wall if it used only the lower flexor reflex. However, Biosbot, based on its sensory information, chose to make a turn to avoid colliding with the wall. The function consisted of two modules: one is the sensory module of recognizing the wall and the other is the action module of making a turn. For the sensory module, we used a video camera and ultrasonic distance sensors to acquire the surrounding images and the distance between the robot and the wall. This task is executed in a PC where the HR layer is present (this part is not explained in this study). After acquiring necessary information, a command signal is sent to trigger the action module, making Biosbot to turn left or right.

3.4.1 Turning reflex model

Biosbot has no yaw joints. Its turning action is achieved by adjusting the strides of its left and right legs to be different. The stride difference between the left and right sides subsequently lead to a change in the moving direction. The stride adjustments are achieved by changing two parameters, the swing amplitudes and the mid-positions of the left and right legs, represented as Eq. (8):

$$\begin{cases} \hat{y}_{\mathrm{h}}(t) = [1+\operatorname{sgn}(\varepsilon)\mu]y_{\mathrm{h}}(t) + \operatorname{sgn}(\varepsilon)\operatorname{sgn}(\psi)\Delta\hat{\theta}, \\ \hat{y}_{\mathrm{k}}(t) = y_{\mathrm{k}}(t) - \operatorname{sgn}(\varepsilon)\operatorname{sgn}(\psi)\Delta\hat{\theta}, \\ \varepsilon = \begin{cases} 1 & \text{(Left/right legs when turning right/left)}, \\ -1 & \text{(Left/right legs when turning left/right)}, \end{cases} \end{cases} \tag{8}$$

where $y_{\mathrm{h}}, y_{\mathrm{k}}$—Original angular positions of the hips and knees, respectively,

$\hat{y}_{\mathrm{h}}$, $\hat{y}_{\mathrm{k}}$—Actual turning inputs of the hips and knees, respectively,

$\Delta\hat{\theta}$—Increment of the joint mid-positions,

μ—Hip amplitude modifying coefficient,

ε—Turning direction flag.

3.4.2 Turning experiments

When the turning reflex module is triggered by a turn-left command, the left hips subtract $\Delta\hat{\theta}$ from their mid-positions and the left hips' amplitudes decreased, while the right hips add $\Delta\hat{\theta}$ to their mid-positions and the right hips' amplitudes increase. Each knee changes its mid-position opposite to the hip in the same leg, as shown in Fig. 10. Thereby, the left legs become shorter and swung less than the right legs, making Biosbot turn to the left to avoid a big board at its right side, as shown in Fig. 11. A similar process is carried out when turning to the right.

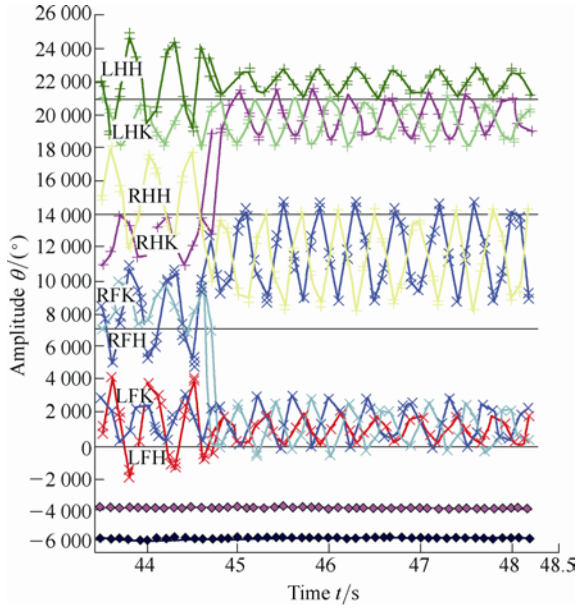


Fig. 10. Actual reflex output curves of Biosbot turning left

Fig. 11. Biosbot turning left

4 Discussions

A frequently used approach for legged-robot motion control is based on classical kinematics and dynamics, i.e. planning feet trajectories first, and then solving to joints inversely. If environments change drastically, a considerable computation is involved owing to slow reasoning and complexity of representing a dynamic real world. However, animals do not use this approach. Their motion behaviors and corresponding neural networks are hierarchical. Different motion controls are executed in different neural layers according to their requirements of complexity and response time to the tasks. Hence, they have higher efficiency. Nevertheless, how to use the biologically inspired approach? In our opinion, the core is designing a proper RMC, which can coordinate multiple DOFs and guarantee a uniform and steady rhythm in the whole system. Moreover, reflexes are introduced and combined with RMC in appropriate ways, that is, they are capable of modulating RMC outputs, but not disturbing the fixed rhythm of the RMC.

In this paper, we have designed a proper RMC that consists of a CPG and RC. The CPG is responsible for generating rhythm of the whole system and for hips control, and the RC is responsible for knees control. The RC relates the knees and hips in one and only rhythm via a hip-to-knee mapping function. Consequently, a uniform and steady rhythm over the course of the whole motion is ensured. To introduce reflexes in appropriate ways, we have designed a three-layer modeling framework. According to the requirements of complexity and response time to the tasks, reflexes can interact with the RMC under CPG, within CPG, or within CNS via HR, MR, or LR respectively. They do no harm to the stability of the rhythm of the RMC, and stable rhythmic activities occur owing to global entrainment among the CPG, robot, and environment. Furthermore, these reflexes regulate the RMC outputs and ensure the robot walking adaptively in uncertain environments and irregular terrain.

The presented approach has the potential for improving control efficiency based on the following facts. With three functionally divided layers to bridge the sensorimotor pathways, the functions are distributed in different layers, and the central controller, usually a computer (similarly brain), can be released to execute more complex computation. Moreover, combining RC with CPG for multiple DOFs control dramatically reduces the dimensionality of the descending control signals because the knees acquire their control signals from the hips indirectly. Furthermore, reflex modules are isolated from one another. Adding new functions to the robot is easier and does not impair the response time of the control system, when compared with using the traditional trajectory-planning approach, which requires re-planning of the whole trajectory every time when a new function module is added.

5 Conclusions

(1) A motion control architecture, abstracted from vertebrate neural system, is presented in this paper, which includes an RMC for basic rhythmic motion and layered reflexes to carry out complex sensorimotor tasks for adaptive motion. RMC consists of a CPG model and RC. Reflexes are organized in three layers of the neural system, under CPG, within CPG, and within CNS, to meet different requirements of complexity and response time to the tasks. The biologically inspired architecture makes the robot to interact with the environment in a way similar to that of an animal.

(2) When designing the motion pattern of a specific reflex function, useful clues are drawn from a cat's behaviors, to simplify the trajectory plan and achieve natural performances.

(3) Based on the layered biological reflex architecture, a quadruped robot is constructed, which can clear obstacles and walk uphill and downhill autonomously, and make a turn voluntarily in uncertain environments, by employing a lower-level flexor reflex, an intermediate-level postural reflex, and a higher-level turning reflex, respectively.

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