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LOCOMOTION CONTROL OF QUADRUPEDED ROBOTS BASED ON WORKSPACE TRAJECTORY MODULATIONS

Chengju J. Liu,^{*} Danwei W. Wang,^{*,**} and Qijun J. Chen^{*}

Abstract

Designing an effective motion control for legged robots is a challenging task. Inspired by biological concept of central pattern generator, this paper proposes a locomotion control system consisting of a workspace trajectory modulator and a motion engine. The modulator adjusts swinging phase and supporting phase of a leg by adjusting toe positions on a predesigned workspace trajectory, while motion engine generates accurate joint control signals. With body attitude feedback, the modulator adjusts the durations of swinging phase and supporting phase in real time through mutual entrainment. This proposed control system ensures that the robot locomotion is adaptive to various terrains and environments. Extensive experiments using an AIBO robot validate the proposed control scheme and the AIBO adapts its walking patterns according to environmental properties.

Key Words

Central pattern generator, workspace trajectory modulator, locomotion control, quadruped robot

1. Introduction

Creating effective locomotion for legged robots has attracted increasing attention with more research efforts [1]–[4]. Up to now, most research works focus on trajectory-based methods [5], [6]. With predesigned foot trajectories and relative gait, trajectory for every joint can be calculated via inverse kinematics such that robots can walk and keep balance simultaneously. The predesigned trajectories can be acquired by experience or some offline optimization methods. However, such trajectories are sensitive to ground conditions and variations.

Animal walking is an inspiration to the locomotion control of legged robots [7], [8]. In biology, neurobiologists confirmed that locomotion central pattern generators (CPGs) exist in the spinal cords of vertebrates [9]–[11]. CPGs consist of neural circuits to produce rhythmic sequence signals for controlling legs' movement. Moreover, sensory inputs from lower level central nervous system and signals from higher level central nervous system can modulate the activity of CPGs [12]–[15]. Inspired by this, the CPG concept is finding its way to biped robots to realize environmental adaptability and motion pattern diversities [16]–[21]. CPG-inspired control methods present interesting properties: (1) Limit cycle behavior: an oscillatory pattern is robust against transient perturbations and asymptotically return to the limit cycle. This makes CPG-inspired control methods well suited to deal with environmental perturbations. Furthermore, the limit cycle can be modulated by some parameters and thus it is possible to smoothly modulate gait (*e.g.*, increase frequency and/or amplitude) or even to induce gait transitions. (2) Synchronization: synchronization allows strong coupling between robot and environment. Moreover, CPG network for control policy generation can reduce the dimensionality of the control problem, since only simple parameters like frequency, amplitude and coupling weights have to be chosen to generate high-dimensional coordination policies.

Two CPG-inspired methods are commonly used in applications: the first is that one CPG unit is assigned to one degree of freedom in joint space, and the distributed CPGs can generate complex coordinated multi-dimensional control signals for coordinated locomotion. This method is referred to as “CPG-joint control method” [22]–[27] and this method comes with two limitations: (1) For legged robots, such as quadruped or humanoid robots, joint control signals are more complex than the current CPG models can generate directly. (2) The stability of a walking robot is usually realized by adjusting CPG parameters to generate coordinated joint control signals. Many CPG units are required for multi-degrees of freedoms and, thus, too many parameters need to be modulated. Another control approach is to assign the oscillators to the periodic variables which can reflect the characteristics of walking gait during locomotion [28]–[33], which can reduce the

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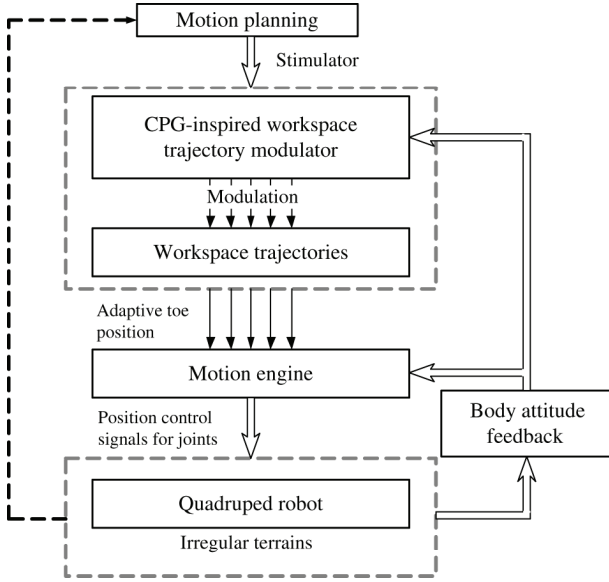


Figure 1. Architecture of control system.

number of the parameters of the control system and the feedback pathway can be easily designed.

For legged animals, toe tips reflect gait patterns. Task space based study of animal's walking mechanism can be an efficient way for CPG-inspired locomotion control of legged robots. Results in [28]–[33] had developed some motion control schemes in task space. Paper [33] uses CPGs to generate toe trajectories online for a robot to realize adaptive walking of quadruped on various terrains, referred to as “CPG-workspace control method”. In this work, a novel CPG-inspired control method that combines the advantages of trajectory-based methods and the CPG concept is presented. Different from our previous work in [33], this paper uses CPGs to modulate predefined workspace trajectories for a robot online rather than to generate workspace trajectories. The main works of this paper are as follows: (1) A workspace trajectory modulator is designed based on CPGs to modulate the predefined three-dimensional (3D) workspace trajectories online for a legged robot. (2) Through the mutual entrainment of modulator with the feedback of robot body attitude, adaptive walking patterns for legs' swinging phase and supporting phase can be generated corresponding to environmental properties. (3) A motion engine is designed to map workspace to joint space to generate accurate joint control signals for legs. (4) The proposed control architecture is validated using a quadruped robot.

2. Overview of Control Architecture

The proposed CPG-inspired control architecture for a quadruped robot is shown in Fig. 1. It consists of a workspace trajectory modulator and a motion engine. The modulator involves a CPG network composed of oscillators corresponding to the trajectory of each toe. The network can generate a set of rhythmic signals with particular phase relationships. Output signals act like clocks to modulate toe positions on predefined workspace trajectories.

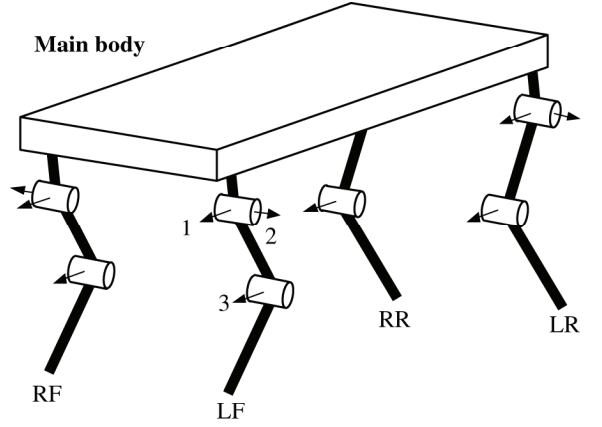


Figure 2. Schematic model of a quadruped robot.

Because the output signals are sensitive to network parameters, the modulation signals can be adjusted in real-time by modulating CPG parameters. Moreover, through coupling, the oscillators with the feedback signals of body attitude, the toe positions with environmental adaptability on the predefined trajectories can be set under the control of modulator. Through inverse kinematics, the accurate adaptive joint control signals can be calculated. Thus, all leg joints can be driven to realize the desired motion.

Consider a quadruped robot shown in Fig. 2, which has a main body and four legs. Each leg consists of links of thigh and tibia being connected to each other through a knee joint which controls forward movements. Each leg is connected to the main body through a rotary joint which controls the forward movements and a shoulder joint which controls the side movements.

3. CPG-Inspired Workspace Trajectory Modulator

In this section, a trajectory modulator is designed to adaptively adjust the toes' positions of a robot at the workspace. The modulator is based on CPGs for two main reasons: (1) CPGs can generate stable rhythmic patterns with different phase relationships, which are ideal for controlling robot gait patterns; (2) CPGs can integrate sensory feedback signals to modulate the output signals. Thus, with the feedback information from robot–environment interaction, adaptive modulation signals can be expected.

3.1 CPG Model

Phase oscillator is probably the simplest type of oscillator, where the radius is neglected and only the phase is retained. In this paper, a modified phase oscillator is used as CPG model as follows:

$$\dot{\theta}_i = 2\pi v_i + \sum_{j=1}^N \lambda_{ij} \sin(\theta_j - \theta_i - \Delta\phi_{ij}) \quad (1)$$

$$\ddot{a}_i = \mu_i^2 (A_i - a_i) - 1.5\mu_i \dot{a}_i \quad (2)$$

$$r_i = a_i \sin(\theta_i) + c_i + f_i \quad (3)$$

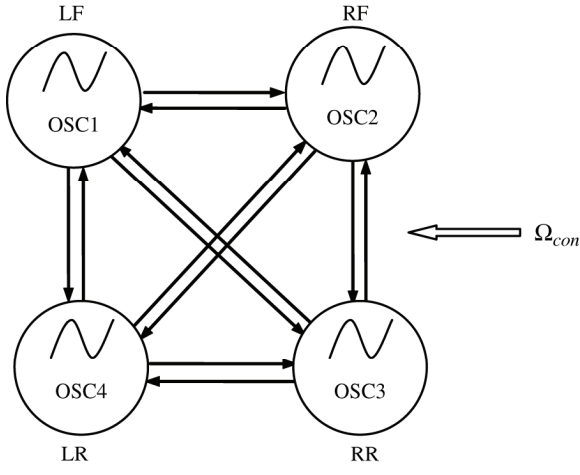


Figure 3. CPG network.

Equation (1) is the model of a population of N coupled phase oscillators which evolves from Kuramoto model [34] and is used to generate oscillation signals. Variable θ_i is the phase of the i th oscillator and v_i is the frequency parameter. Each oscillator in (1) runs independently at its own frequency, while the coupling term λ_{ij} tends to synchronize it to all the others [34]. Variable $\Delta\phi_{ij}$ denotes the desired phase shift between oscillator i and j . Equation (2) ensures that the amplitude of the output signals will asymptotically and monotonically converge to A_i . So the amplitude of oscillations can be smoothly modulated. μ_i is a positive constant determining the speed of state a_i converges to A_i . Equation (3) is the transform of instantaneous internal phase to external angle signal. A compensation variable c_i is superimposed to the output r_i , which makes r_i no longer a zero-axial symmetric oscillatory signal. This asymmetric property will be used in the design of the trajectory modulator. Parameter f_i is the feedback signal and is used to couple the feedback information to CPG network to generate adaptive modulation signals.

Such a CPG model has limit cycle behaviour and its outputs can be adjusted by explicit parameters. Parameters v_i and A_i determine the intrinsic frequency and amplitude of a signal oscillator. Variables λ_{ij} and $\Delta\phi_{ij}$ determine the connections among oscillators, ultimately the structure of the CPG network. Given these parameters, the oscillation signals of oscillators are generated and the behaviour properties of the CPG network are determined.

3.2 CPG Network Architecture

In this work, a network is constructed by four inhibitory connected phase oscillators as shown in Fig. 3. One oscillator corresponds to one toe. Coordination of four toes is achieved by entraining oscillators mutually and allowing them to oscillate in the same period and with a fixed phase difference. Using the output signals of network with different phase relationship to modulate the predesigned workspace trajectories of legs can realize corresponding gait patterns of robot. For quadruped robots, walking and trotting patterns are the basic gait patterns.

Table 1
Values of the Parameters of CPG Network

Parameter	Values
v_i, A_i	1.8, 1.0
λ_{ij}	4.0
c_i, f_i	0, 0
$\Omega_{con.walk}$	$\begin{bmatrix} 0 & \pi & \pi/2 & 3\pi/2 \\ -\pi & 0 & -\pi/2 & \pi/2 \\ -\pi/2 & \pi/2 & 0 & \pi \\ -\pi/2 & -\pi/2 & -\pi & 0 \end{bmatrix}$
$\Omega_{con.trot}$	$\begin{bmatrix} 0 & \pi & 0 & \pi \\ \pi & 0 & \pi & 0 \\ 0 & \pi & 0 & \pi \\ \pi & 0 & \pi & 0 \end{bmatrix}$

The parameters are fixed as shown in Table 1. Parameter settings are mainly according to the experimental platform. Here, the same frequency parameter $v_i = 1.8$ is used for all CPG units. The coupling parameters are set as $\lambda_{ij} = 4.0$ and $\Delta\phi_{ij} = 0$ for all $i = j$ (*i.e.*, there are no self-couplings). There is no feedback and compensation term in the simulation, so $f_i = 0$, $c_i = 0$. The interlinked connection matrix $\Omega_{con} = [\Delta\phi_{ij}]_{4 \times 4}$ is a gait matrix of the oscillators' coupling term, which can represent the gait patterns of a legged robot. As shown in Fig. 4(a) and (b), by designing Ω_{con} , two basic pattern phase relationships can be realized easily. Moreover, as Fig. 4(c) shows, by changing Ω_{con} , gait transitions between various gait patterns can be realized.

3.3 3D Workspace Trajectory

As shown in Fig. 5, a 3D workspace trajectory is designed as:

$$l^2 z = -4h \cdot x^2 + l^2 h \quad (4)$$

A complete walking cycle of a leg consists of a swinging stage and a supporting stage. In the designed workspace trajectory, the segment from posterior extreme position (PEP) to A to anterior extreme position (AEP) corresponds to the swinging phase. It is composed by the swinging up phase (PEP-A) and swinging down phase (A-AEP). To improve the stability during locomotion, a compensatory variable γ is introduced for the center of gravity (CoG) in supporting stage (*i.e.*, the segment from AEP to B to PEP). Thus, the supporting stage divided into two parts: supporting front phase (AEP-B) and supporting back phase (B-PEP). The validity of this workspace trajectory can be seen in Fig. 6. The distance from the

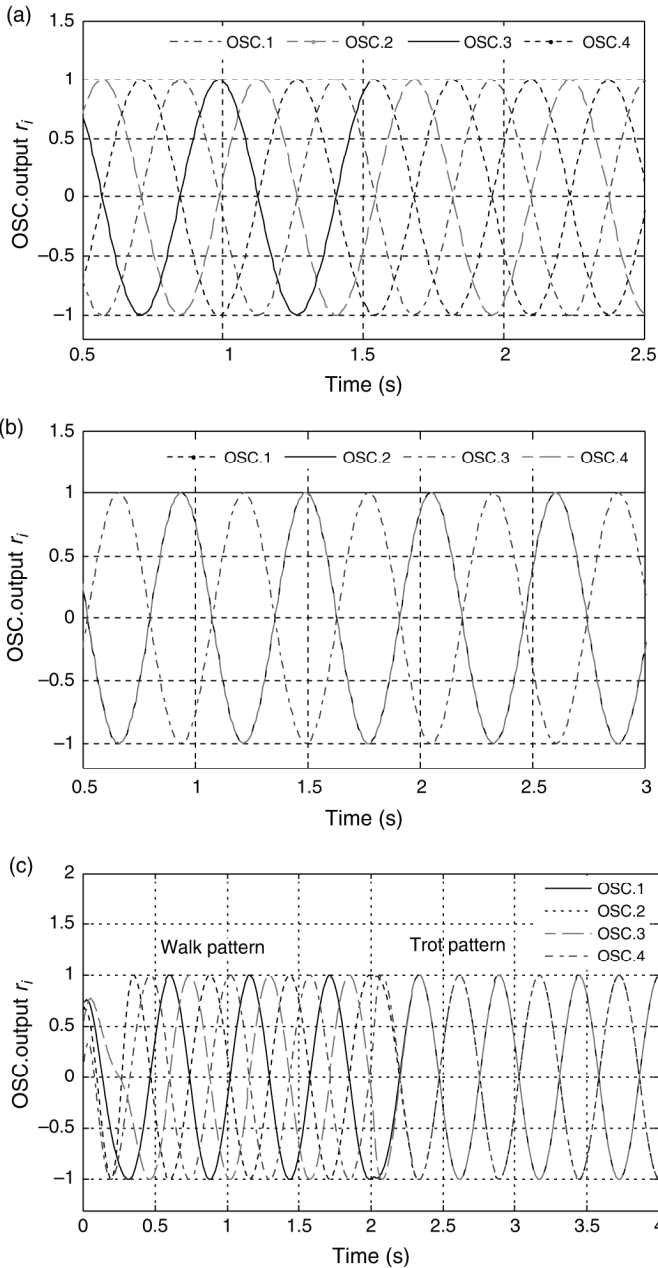


Figure 4. Phase relationships between the four CPG units designing by the connection matrix Ω_{con} : (a) walking pattern with $\Omega_{con} = \Omega_{con.walk}$; (b) trotting pattern with $\Omega_{con} = \Omega_{con.trot}$; and (c) walk-to-trot gait pattern transition.

projected point of the CoG to the edges of the polygon constructed by the projected points of legs with γ is larger than without γ , indicating that the designed 3D workspace trajectory has wider stability margin.

3.4 Modulation Function

The position of each toe on the predesigned 3D workspace trajectory is given as functions of the state of the corresponding oscillator r_i . Take walking pattern as an example, the offset term $c_i = -1.0$, the other parameters of network are set according to Table 1. The output of the oscillator corresponding to left front leg is shown in Fig. 7.

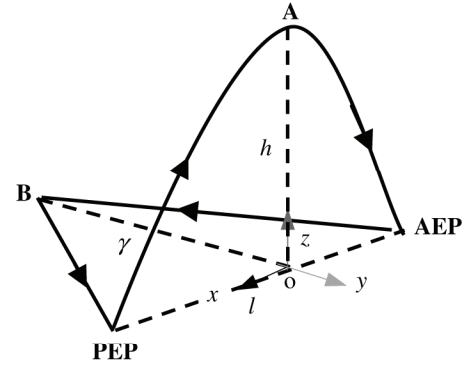


Figure 5. 3D workspace trajectory.

Parameters A_{pi} and A_{ni} are the absolute values of the maximum and minimum amplitudes of the steady-state output waveform.

The trajectory modulation process is divided into two parts:

1. Toe trajectories modulation in swinging phase ($r_i > 0$)
The swinging phase of a leg movement consists of a swinging up phase and a swinging down phase. The modulation function is designed as:

$$\begin{aligned} x_{Locus}(i) &= \mp(h/2) \cdot ((A_{pi} - r_{i(index)})/A_{pi}) \\ y_{Locus}(i) &= 0 \\ z_{Locus}(i) &= -(4h/l^2) \cdot (x_{Locus}(i))^2 + h \end{aligned} \quad (5)$$

where $x_{Locus}(i)$ is negative for swinging up phase and positive for swinging down phase. $index$ represents the frame of the modulation signal, which acts like the pointer of the modulation process. $r_{sw(index)}$ is the value of the CPG output corresponds to the frame of the modulation process.

2. Toe trajectories modulation in supporting phase ($r_i \leq 0$)
The supporting phase of the leg movement is composed by a supporting front phase and a supporting back phase. The modulation function is designed as:

$$\begin{aligned} x_{Locus}(i) &= \pm(l/2) \cdot (A_{ni} + r_{i(index)})/A_{ni} \\ y_{Locus}(i) &= \pm\gamma \cdot (l/2 - |x_{Locus}(i)|)/(l/2) \\ z_{Locus}(i) &= 0 \end{aligned} \quad (6)$$

where $x_{Locus}(i)$ is positive for supporting front phase and negative for supporting back phase, $y_{Locus}(i)$ is negative for left legs and positive for right legs.

Through the designed modulation function, the toe positions on the predesigned 3D workspace trajectories are controlled by the modulation signals. Thanks to the dynamic properties of the CPGs, by modulating the parameters, the cyclic periods, the ratios of swinging phase and supporting phase and even phase relationships can be adjusted online conveniently. Thus, for a robot, the gait patterns and the durations of swinging phases and supporting phases of legs can be adjusted in real time. This is an important condition to realize environmental adaptability locomotion on irregular terrains.

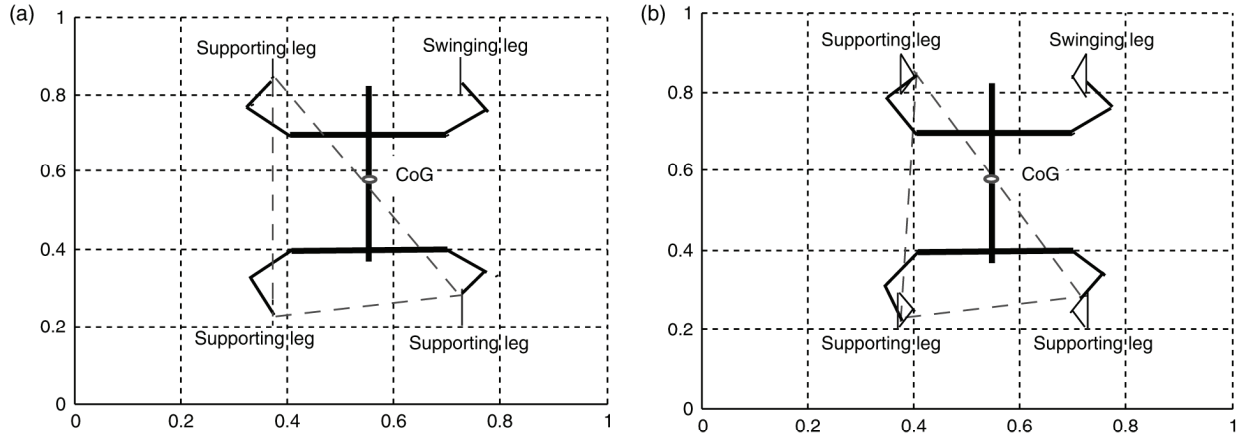


Figure 6. Validity of the new 3D workspace trajectory: (a) without γ ; and (b) with γ .

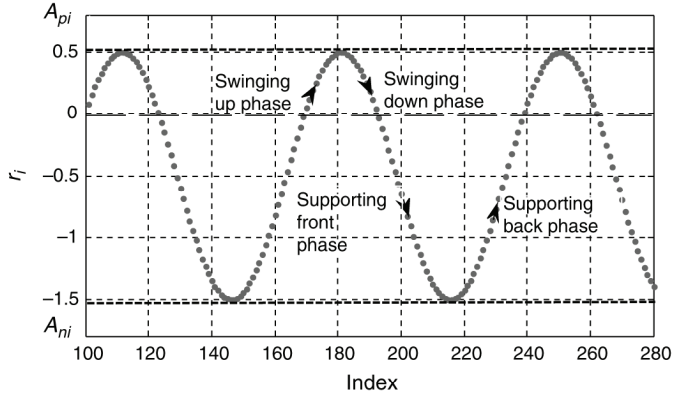


Figure 7. Modulation signal for the left front toe.

4. Experiments

AIBO ERS-7 robot [35] is utilized as the robot platform to validate the proposed control method. This robot has the similar structure with the constructed quadruped robot (Fig. 1). In this work, the 12 degrees of freedom relevant to locomotion on four legs are studied in detail to illustrate the proposed CPG-inspired control method. The motion engine is to generate a set of joint control signals to realize the desired walking pattern [33].

4.1 Variables and Constants

The modulation signals are sensitive to the parameters of the CPGs. Parameter v_i influences the frequency of the modulation signals, thus adjusting this variable can change the cyclic period of the locomotion, which can adjust the walking speed. The parameter c_i can adjust the ratios of swinging phase and supporting phase. Connection matrix Ω_{con} can influence the phase relationships of the modulation signals, so by changing this matrix, different gait patterns can be realized. Parameter f_i is the feedback term which can couple the environment feedback information to adjust the modulation signals. The other parameters in the network are set constants in the following experiments independent of terrains (Table 1).

4.2 Performance of Walking on Flat Terrain

By applying the proposed workspace trajectory modulator, locomotion with adaptive walking speed or with various gait patterns can be realized. Take the gait transitions between walking gait and trotting gait for example. The experiment is conducted for 16 s, and the results of experiment are shown in Fig. 8. At 8 s (*index* = 1,000), the connection matrix Ω_{con} is switched from $\Omega_{con.walk}$ to $\Omega_{con.trot}$, and this induces a rapid gait transition to the higher speed trotting pattern as Fig. 8(a) shows. Figure 8(b) shows the modulation process, in the walking pattern, the legs move a quarter period out of turn. In the trotting pattern, diagonal legs move together. Figure 8(c) shows the control signals for four knee joints of AIBO, under the modulator with walking and trotting patterns, the control signals for the knee joints are also with the expected phase relationships.

4.3 Slope-Adaptive Walking

To validate the adaptive feature of the proposed control method, the vestibular reflex mechanism of animals is simulated to realize slope adaptive walking. In this work, the body attitude state of AIBO is used as input sensory information to the CPGs. Using the acceleration sensor, the body attitude angle θ_{pitch} can be calculated. According to the characteristic of slope terrain, the average attitude angle θ_{Pitch_DC} is coupled to CPGs and the parameters of kinematic model are also modified in real time by θ_{Pitch_DC} to generate slope-adaptive joint control signals.

1. Feedback via the kinematic model

The purpose is to adjust body height and extension range of legs in supporting surface according to attitude perception, so as to reduce the high CoG and improve the stability during locomotion. Feedback to kinematic model is expressed as:

$$\begin{cases} 100 \leq L_f = 120 - 3 \times |\theta_{Pitch_DC}| \\ 110 \leq L_r = 130 - 3 \times |\theta_{Pitch_DC}| \\ S_f = 40 + 1.5 \times |\theta_{Pitch_DC}| \leq 60 \\ 30 \leq S_r = 40 - 1.5 \times |\theta_{Pitch_DC}| \end{cases} \quad (7)$$

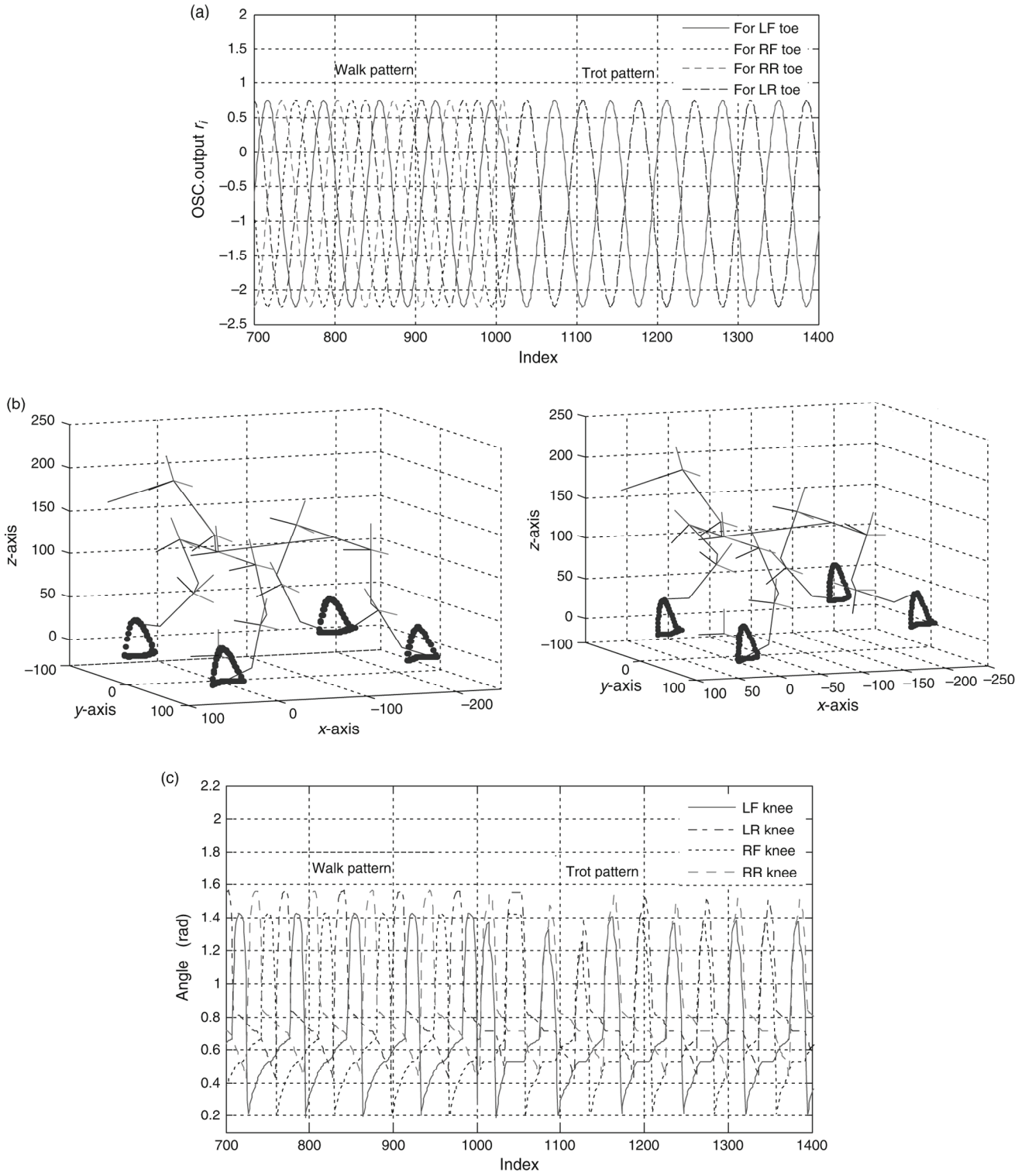


Figure 8. The simulation results of walk-to-trot gait transition on flat terrain: (a) CPG output modulation signals; (b) workspace trajectories modulation during walking and trotting processes; and (c) joint control signals for the four knee joints.

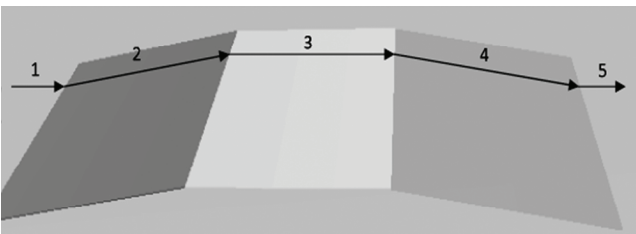


Figure 9. The simulated slope terrain environment.

2. Feedback via CPG network

The purpose of this feedback is to use the attitude perception to adjust the duty factors of the swinging phase and supporting phase of a leg in real time. That is an essential condition to realize adaptive locomotion on irregular surfaces. Feedback to CPG is expressed as:

$$\begin{cases} f_i = K_f \times \theta_{Pitch_DC} \\ f_i \leq |f_{limit}| \end{cases} \quad (8)$$

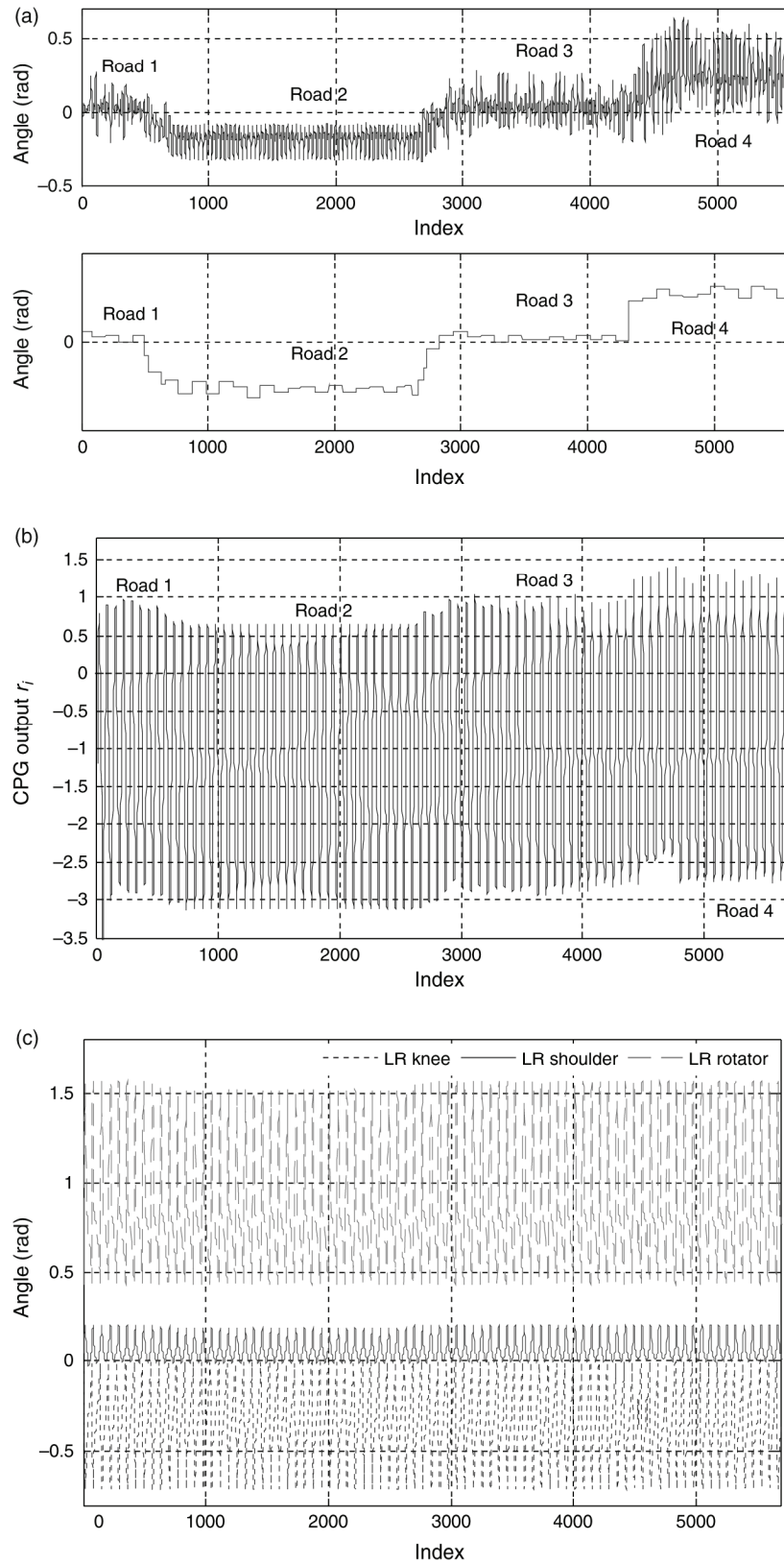


Figure 10. Experiment results of walking on a slope of about 10° with the vestibular reflex: (a) θ_{pitch} and θ_{pitch_DC} ; (b) modulation signals for left rear leg; and (c) joint control signals for left rear leg.

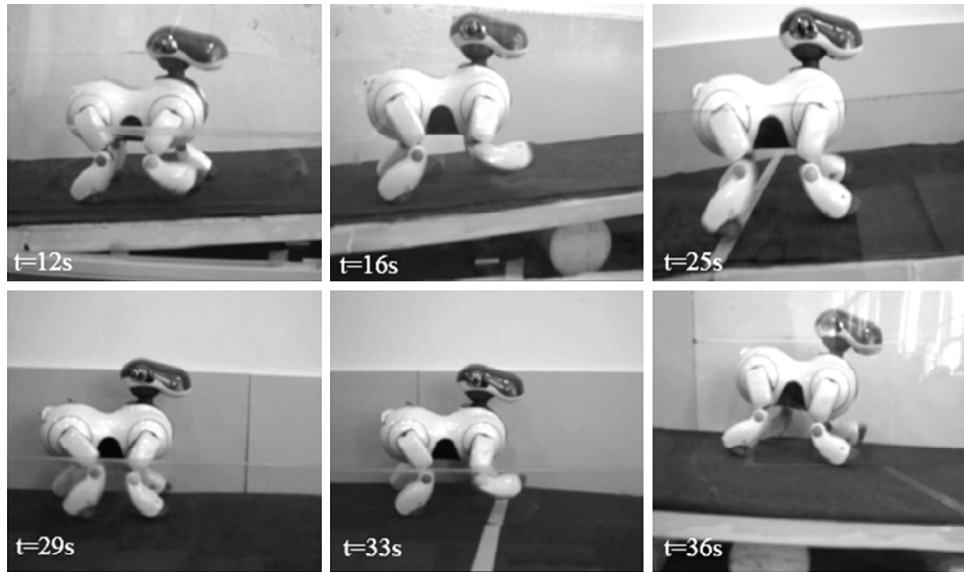


Figure 11. Screenshots during slope terrain walking.

where K_f is a feedback gain. f_{limit} is a restriction on feedback signal to prevent r_i totally with positive or non-positive values, which is the non-working state of workspace trajectory modulator.

The experiment environment is shown in Fig. 9. Road 2 and 4 are about 10° slopes. Road 1, 3 and 5 are all plain surfaces.

Figure 10 shows the results of the slope terrain experiment. The effect of the feedback signal on the output of CPGs can be seen in Fig. 10(b), coupled with the perceived θ_{Pitch_DC} , when walking up the slope, the feedback signals to the neural oscillators in walking up the slope make the swinging phase of the modulator become shorter, so the supporting phases of the legs are longer in comparison with those in walking on flat surface. Thus, when walking up a slope, the supporting stage is long enough for the robot to maintain the motion stability to avoid slip. In the same way, the feedback signals to the neural oscillators in walking down the slope make the swinging phase of the modulator become longer, so during walking down a slope, the supporting stage is decreased to increase the swinging stage and walking speed to prevent overturning. With the vestibular reflex mechanism, AIBO succeeds in walking up and down a slope of about 10° much more stably and smoothly. Slope-adaptive walking experiment is conducted for 44 s, and the snapshots of the experiment are shown in Fig. 11.

The proposed control method in this paper has several advantages against the CPG-joint space control method mentioned in [33]: (1) Allocation of CPG units in the workspace to modulate the pre-designed 3D workspace trajectories simplifies the oscillator connections and feedback pathways. Adjustment of walking speed and walking patterns of the quadruped is easier to realize than the CPG-joint space control method. (2) This method can substantially reduce the number of CPGs and require less tuning parameters.

5. Conclusion

In this study, a locomotion control system has been presented for a quadruped robot which consists of a workspace trajectory modulator and a motion engine. Using the proposed control system, the gait pattern modulations and adaptive walking on slope terrain can be realized. It is noted that the gait transitions and walking pattern changes were realized only by modifying a few parameters of the CPGs. This work validates the potential of the CPG concept in the study of the dynamic walking of legged robots. The proposed control scheme is a combination of the biological concept and traditional control strategy. This method sheds the light on a new direction for adaptive locomotion control of legged robots. By referring to the neural system of legged animals, the more adaptive dynamic walking on irregular terrains using more reflexes is being studied.

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