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Satoshi Ito · Hideo Yuasa · Zhi-wei Luo · Masami Ito
Dai Yanagihara

Adaptive locomotion to periodic perturbation. Adaptation mechanism with coupling of oscillator and link dynamics

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Abstract Quadrupeds can acquire new gait patterns with respect to environmental changes. Yanagihara et al. have demonstrated this adaptability by experiments on a decerebrate cat. These experiments indicate that quadrupeds gradually adapt to their environment by repeating locomotion in a steady environment, and that the acquired gait pattern is persistently memorized after the locomotion. Our research aims at formulating a mathematical model of these cats' behavior and constructing a quadrupedal walking robot to realize such adaptive behavior. To date, we have proposed a mathematical description of adaptation at the level of gait pattern generation using neural oscillators. In this paper, we extend it to take into account limb dynamics. We study how to design the interaction of the oscillator and limb dynamics.

Key words Quadrupedal locomotion · Gait pattern · Adaptation · Periodic perturbation · Coupled oscillators · Limb dynamics

Introduction

Adaptation in quadrupedal locomotion can be observed in experiments on decerebrate cats. As a result of adaptation, the gait pattern changes to another steady one. Yanagihara et al.[1,2] have demonstrated this adaptation process using a specially designed treadmill (Fig. 1). Their treadmill consists of three moving belts. Each belt can be driven independently with different speeds. Firstly, they drove all the treadmill belts at the same low speed. After some training, the decerebrate cat naturally showed the same "walking" gait as intact cats. Next, they changed the speed of one treadmill belt (on which the cat placed its left forelimb) to 1.7 times faster than the others, and observed the cat's behavior in three trials. Each trial includes 60–100 steps, and the interval between each trial was a few minutes. In the first trial, the gait pattern of the cat did not converge to a steady one, but in the second trial, it converged to a new gait pattern after a few steps. In the last trial, the cat showed the acquired new gait pattern from the beginning of the locomotion experiment.

In order to examine the stability of the gait pattern, it is necessary to impulsively disturb the locomotion. However, under the environment of nonregular perturbation, a new gait pattern cannot be acquired, and the gait pattern soon goes back to the original one owing to its stability. In the experiments by Yanagihara et al., the cat's locomotion is perturbed whenever it places its left forelimb on the treadmill belt. This means that the locomotion is perturbed periodically. It is under such periodic perturbation that the new gait pattern was generated.

In this paper, we formulate a mathematical model of the cats' behavior to construct a quadrupedal walking robot. We have previously proposed a mathematical description for the adaptation using neural oscillators.[3] Here, we extend it to take into account the limb dynamics. Then the coupling of oscillator and limb dynamics becomes an important problem.

Adaptation mechanism

The experimental results in Yanagihara et al. provide us with several ideas. Firstly, the cat had memorized the walking gait for a normal environment. When the speed of the treadmill belt changed, this walking gait was not suitable to

S. Ito (✉) · Z. Luo · M. Ito
Bio-Mimetic Control Research Center (RIKEN), Anagahora, Shimoshidami, Moriyama-ku, Nagoya 463-0003, Japan
Tel. +81-52-736-5870; Fax +81-52-736-5871
e-mail: satoshi@bmc.riken.go.jp

H. Yuasa
Graduate School of Engineering, Nagoya University, Nagoya Japan

D. Yanagihara
Brain Science Institute (RIKEN), Saitama, Japan

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the changed environment. Accordingly, the cat adjusted the memorized gait pattern into a new one by repeated locomotion. The fact that the new gait pattern emerged at the beginning of the third trial of the experiment implies that the cat had memorized the new locomotion pattern.

We formulate this adaptation process as follows (Fig 2). Firstly, when we think about the gait pattern, we focus on the relative phases of movement of the four limbs. Although each limb movement is dynamic and periodic, the relative phases will be constant if the gait pattern becomes steady. Then, we can regard the gait pattern as a fixed point in relative phase space. Using the potential function for simplicity, the steady gait pattern corresponds to the minimum point of the potential function in the relative phase space.

Initially, the cat walked on the treadmill with a "walking" gait. Accordingly, the cat memorized the walking gait for normal conditions (i.e., all the treadmill speeds the same). So we can first represent the walking gait as the minimum point of the potential function. From the characteristic of the potential function, the memorized motion pattern is stable; in other words, it is an attractor in relative phase space. Even though locomotion is perturbed impulsively, its pattern will soon come back to the original one. However, if perturbation becomes periodic, the next perturbation will disturb the motion pattern again before the original motion pattern completely returns. Consequently, the perturbation and gradient force of the potential will balance each other where the relative phase is different from the memorized one.

Note that the gradient force is a force which tends to realize the memorized motion pattern. Even though such a gradient force is always working, it fails to produce the memorized pattern. This means that the memorized motion pattern is not suitable to the environment. Therefore, the memorized pattern should be adjusted so that the gradient force can achieve it. In other words, the attractor in the motion pattern should be adjusted to decrease the gradient force. We consider this adjustment process to be "adaptation."

Formulation of adaptive behavior

Assumptions

Our final goal is to realize the adaptive behavior of the decerebrate cat by a quadrupedal walking robot. In a previous paper, we formulated the adaptation mechanism with a mathematical expression.[3] In this study, we extend it to include the limb dynamics. Here, the coupling of the oscillator and the limb dynamics, i.e., how to design the interaction of two dynamics, becomes an important problem. Figure 3 is a sketch for the quadruped model examined in this study. We summarize our main assumptions below.

- The walking motion is restricted within the sagittal plane.

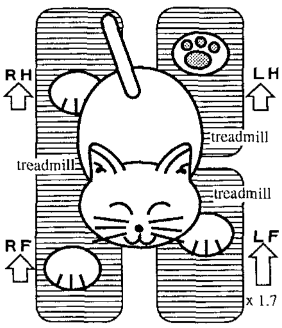

Fig. 1 Experiment with a decerebrate cat

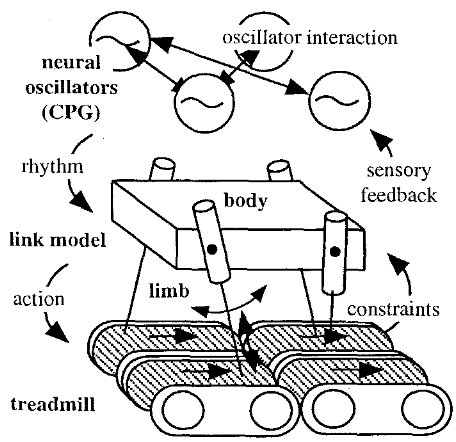

Fig. 3 A model of adaptive behavior in cat locomotion

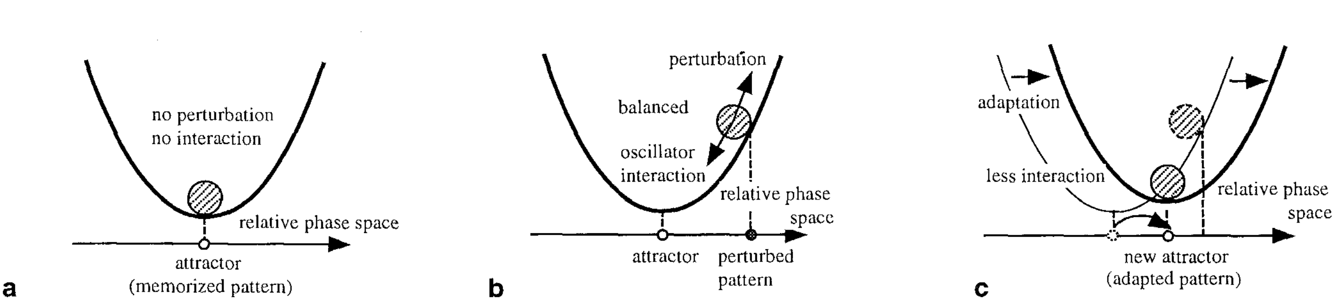

Fig. 2 Mechanism of adaptation in perturbed locomotion. **a** Normal locomotion; **b** perturbed locomotion without adaptation; **c** perturbed locomotion with adaptation

- The balance of the body is not considered, i.e., the body is supported at a fixed position on the treadmill.
- The four limbs have the same structure and perform 2 DOF of the motion: the rotation of the joint between the body and the limb (α_i), and the contraction/extension of the limb (r_i).
- The step length is constant ($\alpha_{sp\_s} \leq \alpha_i \leq \alpha_{sp\_f}$) for each limb with no relation to the walking speed.
- The ground reaction force from the treadmill is detectable.

The CPG (central pattern generator) is a spinal neural oscillator responsible for the generation of the rhythm of locomotion. In our model, each limb motion is mainly controlled by the neural oscillator model assigned to the limb.

We need to define both the control law for the limb and the oscillator dynamics separately in the swing phase and the support phase. This is because that the nature of the limb movement is essentially different in these two phases. In addition, we must define the dynamics of the adaptation process to achieve an adaptive behavior. Therefore, three dynamics are important: the support phase dynamics, the swing phase dynamics, and the adaptation dynamics.

Preparations

We express the phase of the oscillator by the variable $\theta_i (i = 0, 1, 2, 3)$. The phase space becomes the one-dimensional torus space. We split the phase space into two regions: the region satisfying $\cos\theta_i > \cos\pi\beta = \gamma$ and the remainder, as shown in Fig. 4. The constant parameter β controls the duty factor which denotes the ratio of the support phase in one locomotion step.

The limb has a two-link structure attached to the body, as shown in Fig. 5. We express its dynamics as

$$M_l(q_i)\ddot{q}_i + H_l(q_i, \dot{q}_i) + G_l(q_i) = \tau_i + J^T(q_i)F_i \quad (1)$$

where i represent the number of the limb (i = 0, 1, 2, 3), $q_i = [\alpha_i, r_i]^T$ is a joint angle (superscript T denotes the transpose), τ_i is a joint torque, M_l is an inertia matrix, H_l denotes the Coriolis and centrifugal force, G_l denotes the gravitational force, F_i is a reaction force from the treadmill, and J is a Jacobian matrix.

Support phase dynamics

In the support phase, the limbs support the body, and their movements are constrained by the treadmill. The limb has to generate a large force in the gravitational direction while following the treadmill movement in the horizontal direction. Accordingly, we apply impedance control such that the mechanical impedance is high in the gravitational direction and low in the horizontal direction. We can compute the joint torque τ_i so that the response to the ground reaction force F_i becomes

$$M_d\ddot{X}_i + D_d(\dot{X}_i - \dot{X}_{di}) + K_d(X_i - X_{di}) = F_i \quad (2)$$

where X_i is the position of the toe in absolute coordinates, X_{di} is its desired position, and M_d, D_d, and K_d are matrices denoting the desired inertia, viscosity, and elasticity, respectively.

In order for the CPG to generate the locomotion rhythm appropriately with respect to the environment, the position or moving velocity of the limb should be fed back to the CPG. Therefore, we changed the oscillator phase in the support phase according to the limb movement. We assumed that the step length of the limb movement is constant ($\alpha_{sp\_s} \leq \alpha_i \leq \alpha_{sp\_f}$) as well as the range of the support phase in the oscillator phase space ($\theta_{sp\_s} \leq \theta_i \leq \theta_{sp\_f}$), as shown in Figs. 4 and 5. It provides the initial and final conditions for the relation between the phases of the oscillator and limb movement. Under these conditions, we composed some continuous mapping from the limb position to the oscillator phase,

$$\theta_i = P(\alpha_i) \quad (3)$$

such that,

$$\theta_{sp\_s} = P(\alpha_{sp\_s}), \qquad \theta_{sp-f} = P(\alpha_{sp\_f}) \quad (4)$$

Here, we focused on the joint angle α_i between the body and the limb when considering the phase of the periodic limb movement (Fig. 5). Using the above equation, we define the oscillator dynamics in the support phase as

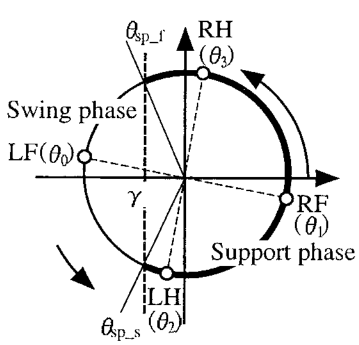

Fig. 4 Stance phase and swing phase. In this case, only the LF (θ_0) is in the swing phase and the others (LH, RF, RH) are in the stance phase

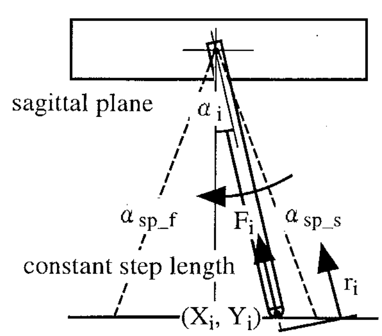

Fig. 5 The structure of the limb. Each limb has 2 DOF: rotation (α_i) and contraction/extension (r_i). F_i is a ground reaction force

$$\dot{\theta}_i = \frac{\partial P(\alpha_i)}{\partial \alpha_i}\dot{\alpha}_i \tag{5}$$

Swing phase dynamics

In the swing phase, the limb is released from the constraint of the treadmill and can move freely. The timing of limb movement, in other words, the relative phases of limb movement, can be modified in this swing phase. So, in the swing phase, CPG governs the dynamics of the limb movement. We can calculate the desired value of α_i, i.e., α_{di} from the oscillator phase θ_i because, as is the case for the support phase, we already know the initial and final conditions for the relation between θ_i and α_i. We control the limb movement so that it follows this desired value α_{di}.

The CPG, on the other hand, must produce the oscillation pattern, i.e., the phasic relation of the four oscillators, which should be memorized as the preferred gait pattern. Using the method proposed by Yuasa and Ito,[4] we can control the relative phases $\phi_0 = \theta_1 - \theta_0$, $\phi_1 = \theta_2 - \theta_1$, and $\phi_2 = \theta_3 - \theta_0$ to their desired values D_0, D_1, and D_2 by the potential function defined in the relative phase space,

$$V = \frac{1}{2}\tau_\theta\left[\left(\phi_0 + \phi_1 - D_0 - D_1 + \frac{\omega_0}{\tau_\theta}\right)^2 + \left(-\phi_2 + D_2 + \frac{\omega_2}{\tau_\theta}\right)^2 + \left(-\phi_0 + \phi_2 + D_0 - D_2 + \frac{\omega_1}{\tau_\theta}\right)^2 + \left(-\phi_1 + D_1 + \frac{\omega_3}{\tau_\theta}\right)^2\right] \tag{6}$$

According to this potential function, the dynamics of the relative phase become the gradient system

$$\dot{\phi}_j = -\frac{\partial V}{\partial \phi_j}, \qquad (j = 0, 1, 2) \tag{7}$$

Further calculation provides the following oscillator dynamics:

$$\dot{\theta}_i = \omega_i + f_i, \qquad (i = 0, 1, 2, 3) \tag{8}$$

Here, ω_i ($i = 0, 1, 2, 3$) denotes the natural frequency of the neural oscillator, and fi ($i = 0, 1, 2, 3$) are oscillator interactions given as

$$f_0 = \tau_\theta(\theta_1 + \theta_3 - 2\theta_0 - D_0 - D_1) \tag{9}$$

$$f_1 = \tau_\theta(\theta_0 + \theta_2 - 2\theta_1 + D_0 - D_2) \tag{10}$$

$$f_2 = \tau_\theta(\theta_1 - \theta_2 + D_2) \tag{11}$$

$$f_3 = \tau_\theta(\theta_0 - \theta_3 + D_1) \tag{12}$$

Note that the memorized pattern is described not only by the desired relative phases D_0, D_1, and D_2, but also by the natural frequency of the neural oscillator ω_i.

Adaptation dynamics

At the normal locomotion, CPG produces the walking gait using the potential function in Eq. 6 for the appropriate D_j ($j = 0, 1, 2$) and ω_i ($i = 0, 1, 2, 3$). Then, from the characteristics of the potential function, the oscillator interaction does not work because the walking gait is a minimum point of the potential function. However, if the treadmill speed increases, the perturbations push away the motion patterns from the minimum point, and a steady pattern emerges at different points from the minimum point. Consequently, oscillator interaction always works to realize the memorized pattern.

Then, as mentioned in the previous section, we adjust the memorized motion pattern so that the oscillator interaction decreases. We prepare two type of evaluation function,

$$F_i = \int_T f_i dt \tag{13}$$

and

$$V_d = \int_T \sum_{i=0}^{3}\left\{\frac{1}{2\tau_\theta} f_i^2\right\} dt \tag{14}$$

To decrease Eq. 13, we can derive the dynamics

$$\omega_i^{(n+1)} = \omega_i^{(n)} + \tau_\omega \int_T f_i dt \qquad (i = 0, 1, 2, 3) \tag{15}$$

while for Eq. 14, we can obtain the following equations:

$$D_0^{(n+1)} = D_0^{(n)} + \tau_D \int_T (f_0 - f_1) dt \tag{16}$$

$$D_1^{(n+1)} = D_1^{(n)} + \tau_D \int_T (f_0 - f_3) dt \tag{17}$$

$$D_2^{(n+1)} = D_2^{(n)} + \tau_D \int_T (f_1 - f_2) dt \tag{18}$$

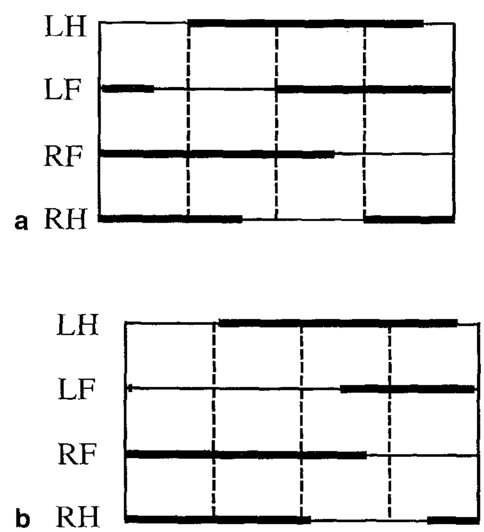

Fig. 6 The gait pattern results of the computer simulations. **a** Normal condition; **b** perturbed condition

where n denotes the number of step cycles, T is the duration of one step cycle, and τ_ω and τ_D are parameters that influence the convergence of ω_i and D_j, respectively.

These parameters should be adjusted slowly, because we cannot adjust them until we know their evaluation. Therefore we define the adaptation dynamics discretely at every locomotion cycle. In addition, we set the time constants τ_D and τ_ω smaller than the oscillator dynamics, i.e., τ_θ.

Simulation

We executed the computer simulation according to the defined dynamics. Firstly, we confirmed that the CPG certainly produced the walking gait in a normal environment. The gait pattern obtained in this simulation is shown in Fig. 6a.

Next, we increased the parameter corresponding to the treadmill speed for the left forelimb to 1.7 times faster than the others. Then, the effect of treadmill movement was reflected in the oscillator dynamics through each limb motion, and the adaptation dynamics played the role of adjusting the memorized gait pattern. The gait pattern finally obtained in this simulation is shown in Fig. 6b. This pattern is similar to the experimental result with a decerebrate cat.

Conclusions

In this study, we extended our mathematical model of adaptive behavior in cat locomotion to include actual limb dynamics. Results similar to those of the experiment can be obtained from the computer simulations.

Future work will examine a quadrupedal walking robot on the treadmill, and make the robot move adaptively on the treadmill as a real cat does.

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