Proc. of Third Int. Symp. on Artificial Life, and Robotics (AROB III' 98), Oita, Japan, 19-21, January, 1998,

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 the environmental changes. Yanagihara et al. have demonstrated this adaptability by experiments of a decerebrate cat. These experiments indicate that quadrupeds gradually adapt to their environment by repeating locomotion in the steady environment, and that the acquired gait pattern is persistently memorized after the locomotion.

Our research aims at formulating the mathematical model of these cats' behaviors and constructing a quadrupedal walking robot to realize such an adaptive behavior. By now, we have proposed a mathematical description for adaptation at the level of gait pattern generation using the neural oscillators. In this paper, we extend it to take into account the limb dynamics. We study on how to design the interaction of the oscillator and limb dynamics

key words : quadrupedal locomotion, gait pattern, adaptation, periodic perturbation, coupled oscillators, limb dynamics

1 Introduction

Adaptation in quadrupedal locomotion can be observed in the experiment of 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 the different speed. Firstly, they drove all the treadmill belts with the same low speed. After some training, the decerebrate cat naturally showed the 'walk' gait as the intact cats. Next, they changed the speed of one treadmill belt (on which the cat places its left forelimb) 1.7 times faster than the others, and observed the cat's behavior through three trials. Each trial includes 60 to 100 steps, and the interval between each trial was about a few minutes. At the first trial, the gait pattern of the cat did not converge to the steady one. But at the second trial, it converged to a new gait pattern after some steps. At 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 efficient to impulsively disturb the locomotion. However, under the environment of the non-regular perturbation, a new gait pattern can not be acquired: The gait pattern soon goes back to the original one due to its stability. In the experiments by Yanagihara et al., the cat locomotion is perturbed whenever the cat places its left forelimb on the treadmill belt. It means that the locomotion is perturbed periodically. It is under such periodic perturbation that the new gait pattern was generated.

In this paper, we aim at formulating the mathematical model of these cats' behaviors for constructing a quadrupedal walking robot. We have already proposed a mathematical description for adaptation using the neural oscillators [3]. Here, we extend it to take into account the limb dynamics. Then, the coupling

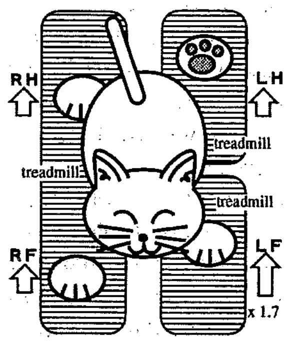
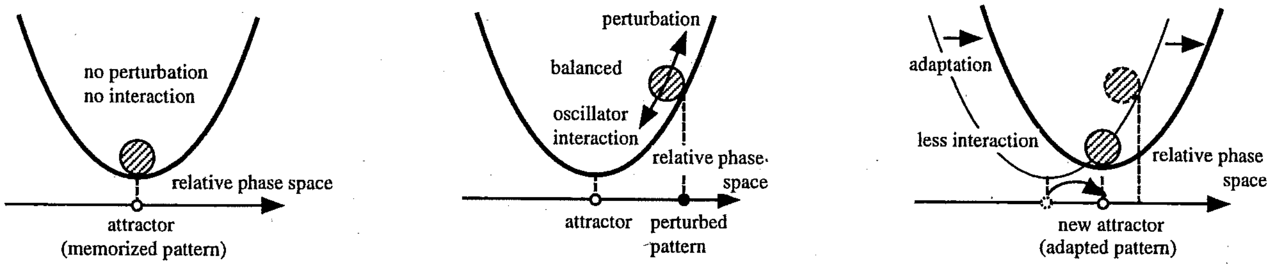


Figure 1: Experiment with a decerebrate cat.



(a) Normal locomotion.

(b) Perturbed locomotion without adaptation.

(c) Perturbed locomotion with adaptation.

Figure 2: Mechanism of adaptation in perturbed locomotion.

of oscillator and limb dynamics becomes an important problem.

2 Adaptation mechanism

The experimental results by Yanagihara et al. provides us the following ideas: Firstly, the cat had memorized the walk gait for the normal environment. When the speed of the treadmill belt changed, this walk gait was not suitable to the changed environment. Accordingly, the cat adjusted the memorized gait pattern into a new one by repeating locomotion. The fact that the new gait pattern emerged at the beginning of the third trial of experiment implies the evidence that the cat memorized the new locomotion pattern.

We formulate this adaptation process as follows: Firstly, when we think about the gait pattern, we focus on the relative phases of four limbs' movements. 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 the 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 the 'walk' gait. Accordingly, the cat memorized the walk gait for the normal conditions (i.e., all the treadmill speed is the same). So, we can firstly represent the walk gait as the minimum point of the potential function. From the characteristic of 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 comes back to the original one. However, if perturbation becomes periodic, the next perturbation will disturb the motion pattern again before the motion pattern completely comes back. Consequently, the perturbation and gradient force of 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, this gradient force fails to produce the memorized pattern. It 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 motion pattern should be adjusted to decrease the gradient force. We consider this adjustment process as 'adaptation'.

3 Formulation of adaptive behavior

3.1 Assumptions

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

- The walking motion is restricted within the sagittal plane.
- The balance of the body is not considered, i.e., the body is supported at the fixed position on the treadmill.

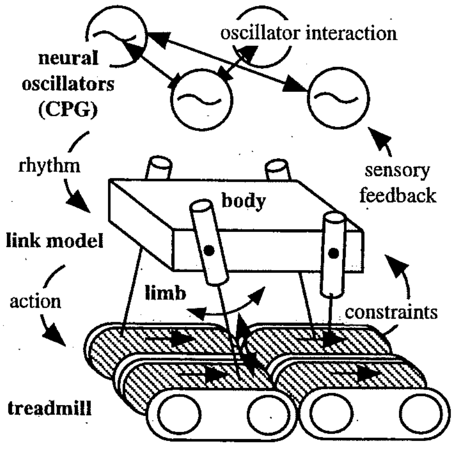


Figure 3: A model of adaptive behavior in the cat locomotion.

- Four limbs have the same structures and perform 2 DOF of the motion: the rotation of the joint between body and 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 reacting force from the treadmill is detectable.

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

We should 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 adaptation process to achieve an adaptive behavior. Therefore, three dynamics are important: the support phase dynamics, the swing phase dynamics and the adaptation dynamics.

3.2 Preparations

We express the phase of 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 to two regions: the region satisfying $\cos\theta_i > \cos\pi\beta = \gamma$ and the remainder, as shown in Fig. 4. The constant parameter β, which denote the ration of the support

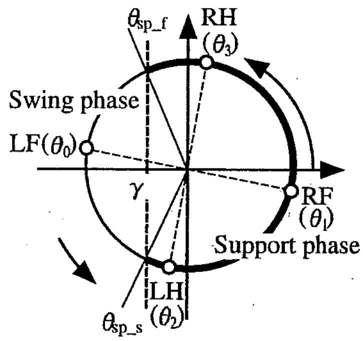


Figure 4: Stance phase and swing phase. In this case, only the LF (θ_0) is in the swing phase and the others (LH, RF, RH) are in the stance phase.

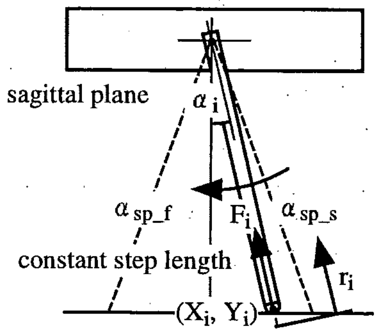


Figure 5: The structure of the limb. Each limb has 2 DOF: rotation (α_i) and contraction/extension (r_i). F_i is a ground reacting force.

phase in the one locomotion step, can control the duty factor.

The limb has two link structure attached the body, as shown in Fig. 5. We express its dynamics for it 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 reacting force from treadmill, and J is a Jacobian matrix.

3.3 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 the large force along the gravitational direction while follow the treadmill movement along the horizontal direction. Accordingly, we apply the impedance control such that high-impedance in the gravitational direction and low-impedance in the horizontal direction. We can compute the joint torque τ_i so that the response to the ground reacting 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 the absolute coordinate, X_{di} is its desired position, M_d, D_d and K_d are matrices denoting the desired inertia, viscosity and elasticity.

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 CPG. Therefore, we change 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 for the support phase in the oscillator phase space ($\theta_{sp\_s} \leq \theta_i \leq \theta_{sp\_f}$), as shown in Fig. 4 and Fig. 5. It provides the initial and final condition to the relation between the phases of the oscillator and limb movement. Under this condition, we compose some continuous mapping from the limb position to oscillator phase,

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

such that,

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

Here, we focused on the joint angle α_i between body and 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,

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

3.4 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. It is because that, as is the case of the support phase, we have already known the initial and final condition for the relation between θ_i and α_i. we control the limb movement so that the limb movement follows this desired value α_{di}.

The CPG, on the other hand, must produce the oscillation pattern, i.e., phasic relation of 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 value D_0, D_1 and D_2 by the potential function defined in the relative phase space,

$$V = \frac{1}{2}\tau_\theta[(\phi_0 + \phi_1 - D_0 - D_1)^2 + (-\phi_2 + D_2)^2 + (-\phi_0 + \phi_2 + D_0 - D_2)^2 + (-\phi_1 + D_1)^2]. \quad (6)$$

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

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

Further calculation provides the following oscillator dynamics:

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

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

$$f_0 = \tau_\theta(\theta_1 + \theta_3 - 2\theta_0 - D_0 - D_1), \quad (9)$$

$$f_1 = \tau_\theta(\theta_0 + \theta_2 - 2\theta_1 + D_0 - D_2), \quad (10)$$

$$f_2 = \tau_\theta(\theta_1 - \theta_2 + D_2), \quad (11)$$

$$f_3 = \tau_\theta(\theta_0 - \theta_3 + D_1). \quad (12)$$

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

3.5 Adaptation dynamics

At the normal locomotion, CPG produces the walk gait using the potential function eq.(6) for the appropriate $D_j (j = 0, 1, 2)$ and $\omega_i, (i = 0, 1, 2, 3)$. Then, from the characteristics of the potential function, the oscillator interaction does not work, because the walk gait is a minimum point of potential function. However, if the treadmill speed increase, the perturbation push away the motion pattern from a minimum point, and the steady pattern emerges at the different point 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 decrease. We prepare two type of evaluation function,

$$F_i = \int_T f_i dt, \quad (13)$$

and

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

To decrease eq. (13), we can derive the dynamics

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

while for the eq. (14), we can obtain the following equations:

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

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

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

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 can not adjust them is until we know the evaluation for these parameters. Therefore we define the adaptation dynamics discretely at every locomotion cycle. In addition, we set the time constant τ_D and τ_ω smaller enough than that of oscillator dynamics, i.e., τ_θ.

4 Simulation

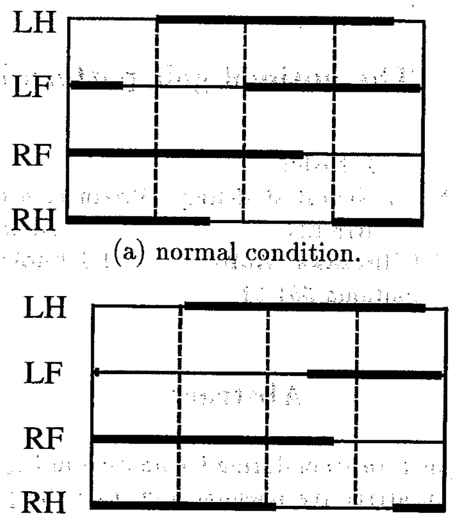
We executed the computer simulation according to the defined dynamics. Firstly, we confirm that the CPG certainly produce the walk gait at the normal environment. The gait pattern obtained in this simulation is shown in Fig. 6 (a).

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

5 Conclusion

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

As the future works, we will practically examine a quadrupedal walking robots on the treadmill, and make the robot to move adaptively on the treadmill as a real cat.



(a) normal condition.

(b) perturbed condition.

Figure 6: The gait pattern results of the computer simulations.

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