Adaptive Behavior of Quadruped Walking Robot under Periodic Perturbation

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Abstract

Adaptive behavior of animals can be observed in the locomotion, as the variations of gait patterns. Physiological experiments demonstrated that decerebrate cats can adapt to periodic perturbation applied by the treadmill, and change their gait pattern with respect to the environmental changes. Based on this fact, we regard the adaptation as the process that adjusts memorized motion patterns to be more appropriate for the changed environments. Following this idea, we describe the adaptive behavior of decerebrate cat locomotion using a central pattern generator (CPG) model. We also take into account of the coupling of oscillators and limbs dynamics, and propose an adaptive control approach for the limb movements.

1. Introduction

Adaptation is one of the most interesting abilities in animal behavior. It was difficult to realize it by machines artificially. Usually, machines were designed to move under the specific conditions in the restricted environments. If these conditions vary, machines can not always act in the desired manner. Conversely, animals can adapt to the variations of environments or task requirements, and achieve their intended tasks successfully. An example of such adaptive behaviors can be found in animal locomotion. For example, if a animal lost the function of one leg, it can acquire a new walking pattern under this constraint and finally become to walk automatically with the new pattern. However, in the case of conventional walking machines, the locomotion might be impossible unless we teach the new method to walk.

Throughout this paper, we consider the adaptation in animal locomotion from the viewpoint of the gait variations, i.e., the changes of the rhythms for the leg movements. These types of the rhythms are reproducible. Thus, it is considered that locomotion rhythms are memorized as programs in the rhythm generators, i.e., central pattern generators (CPG) (Grillner, 1975; Delcomyn, 1980), and the CPG generate the rhythms in a feedforward manner. In our opinion, the adaptation in locomotion is equal to the change of memorized rhythm patterns with respect to the environmental variations.

The experimental paradigm for adaptive locomotion satisfying the above conditions has been proposed (Yanagihara and Kondo, 1996). According to their reports, cats were gradually acquiring a new gait pattern with repeating the locomotion on the treadmill, although the cats could not walk with the steady gait patterns initially (see Sect. 2). In this paper, we aim at realizing the above adaptive behavior of decerebrate cats by machine.

2. Adaptive locomotion of cats

Concerning the adaptive locomotion of quadrupedal animals, the following experimental results were reported by Yanagihara et al. (Yanagihara and Kondo, 1996) who elucidated that a neural transmitter nitric oxide (NO) plays an essential role in learning mechanism of cerebellum. They designed such a special treadmill as shown in Fig. 1. This treadmill consists of three moving belts, each of which can be driven independently at the different speed. The left forelimb (LF) and left hindlimb (LH) of the cat are separately placed on the different belts, whereas the right forelimb (RF) and right hindlimb (RH) are placed together on the other belt. If the speed of each treadmill are different, the movement of the limb is periodically disturbed whenever the cat places the limbs on the treadmill belt.

Firstly, they drove all treadmill belts normally with the same low speed (normal condition), and trained de-

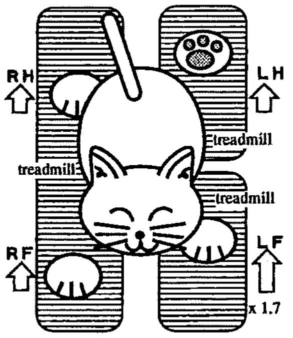
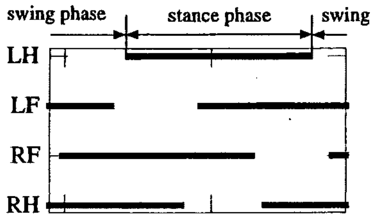
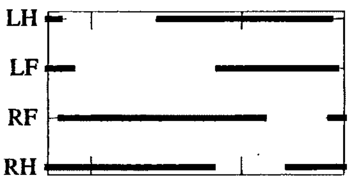


Figure 1 Experiment with a decerebrate cat.



(a) Gait pattern in normal condition.



(b) Adapted gait pattern in perturbed condition.

Figure 2 Gait diagrams of cat locomotion. Thick lines denote support phase, and only one step cycle is expressed. The gait pattern changes according to adaptation.

cerebrate cats[1] to walk on such a treadmill. Then, decerebrate cats can walk on this treadmill with the same gait pattern 'walk' (Fig. 2(a)) 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 (perturbed condition), and observed the cat's behavior through three trials. Each trial includes 60 to 100 steps A few minutes of intervals were taken between each trial. At the first trial, any steady gait patterns can not be observed. However, at the second trial, the decerebrate cat obtained a new gait pattern (Fig. 2(b)) after some steps. At the last trial, the cat showed the new pattern acquired at the second trial from the beginning of the locomotion experiment.

[1] The decerebrate cat is a cat whose high nerve systems such as cerebral cortex are surgically cut at the midbrain. The locomotion of decerebrate animals means that the high nerve systems do not influence the control and the rhythm generation in locomotion.

3. Mathematical modeling of adaptive locomotion

3.1 Adaptation mechanism

We interpret the experimental results by Yanagihara et al. as follows: Firstly, the cat had memorized the walk gait for the normal condition. When the speed of the treadmill belt changed, the walk gait had become less appropriate to the changed environment. Accordingly, the cat adjusted the memorized gait pattern 'walk' into a new one by repeating locomotion. The fact that a new gait pattern appeared at the beginning of the third trial in the perturbed condition implies that the cat had memorized this new locomotion pattern.

In order to explain our concept of adaptation mechanism schematically, we use the potential function in Fig. 3 for a while (see also (Ito et al., 1997)). Although each limb movement is dynamic and periodic, the relative phases of four limb movement will be constant if the gait pattern is stationary. Therefore, the gait pattern can be treated as fixed point, i.e., the minimum point of the potential in a relative phase space. Note that gradient expresses the forces which effect to realize the memorized motion pattern. Accordingly, at the minimum point, any forces do not work since the gradient of the potential vanishes.

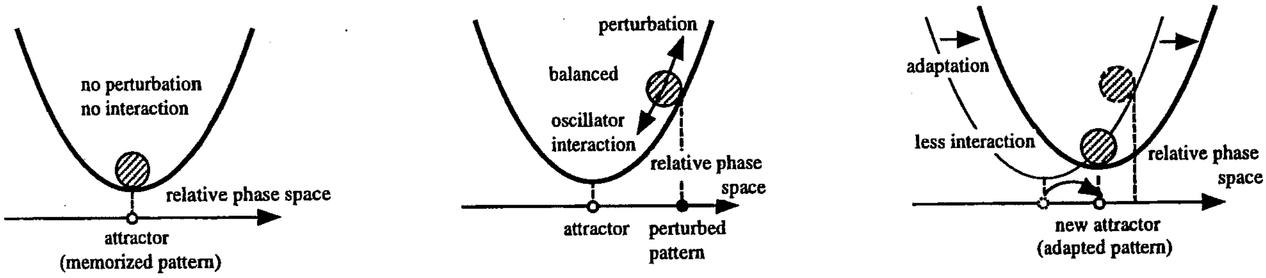
In the case of decerebrate cats, the walk gait initially becomes the minimum point (Fig. 3(a)). From the characteristic of potential function, the memorized motion pattern is stable, in other words, corresponds to an attractor. Even though locomotion is perturbed in an impulsive-like manner, it will soon regain its original gait pattern.

However, if the perturbation becomes periodic, the next perturbation will disturb the motion pattern again before the motion pattern is completely regained. Consequently, the perturbation and gradient force of potential will balance each other, as shown in Fig. 3(b). As mentioned above, the gradient force is force which realizes the memorized motion pattern. In Fig. 3(b), the memorized motion pattern is not realized even though this force is always working, which means that the memorized motion pattern is not appropriate to the changed environment.

Therefore, the memorized pattern, i.e., an attractor in motion pattern should be adjusted so that the gradient force can achieve it. This is equivalent to adjusting the minimum point of the potential in order to decrease the gradient force, as shown in Fig. 3(c). We consider this adjustment process as 'adaptation'.

3.2 Rhythm generator dynamics

Figure 4 shows a model of CPG. It is composed from four coupled oscillators. We assume that the oscillator phase θ_i $(i = 0, 1, 2, 3)$ directly represents the phase of the periodic limb movement. The coupling in Fig. 4 may



(a) Normal locomotion.

(b) Perturbed locomotion without adaptation.

(c) Perturbed locomotion with adaptation.

Figure 3 Adaptation mechanism in perturbed locomotion.

not always coincide with the actual oscillator connections in animals. This is only for mathematical convenience. A different coupling may also generate the same rhythm pattern mathematically.

Each limb moves in either swing phase or support phase. The character of limbs movements is essentially different in each phase. Before defining a rhythm generator dynamics, we divide the phase space of oscillators into two regions and assign them to the swing phase and the support phase, respectively. As shown in Fig. 5, we set the support phase to the region $\cos\theta_i \geq \gamma$, while the swing phase to the region $\cos\theta_i < \gamma$. Here, we determine γ by

$$\gamma = \cos \pi\beta. \tag{1}$$

where β is duty factor that denotes the proportion of the support phase in one step cycle. From Fig. 2(a), we set $\beta \cong 2/3$.

In the support phase, limbs are always in contact with the treadmill and cannot move freely. Thus, we describe the dynamics of the supporting limbs as

$$\dot{\theta}_i = \rho_i \quad (i = 0, 1, 2, 3), \tag{2}$$

where ρ_i $(i = 0, 1, 2, 3)$ is a variable representing the speed of the treadmill belt. Equation (2) means that the limb movement is forced by the treadmill.

In the swing phase, limbs can move freely. Thus, it is possible to adjust the phase of limb movement according to interactions among oscillators.

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

Here ω_i $(i = 0, 1, 2, 3)$ denotes a natural angular velocity of oscillator. As the limbs shows the same movements in normal condition, we initially set them as follows:

$$\omega_0 = \omega_1 = \omega_2 = \omega_3 = \omega. \tag{4}$$

In addition, f_i $(i = 0, 1, 2, 3)$ denotes the interaction term. According to Yuasa and Ito (Yuasa and Ito, 1990),

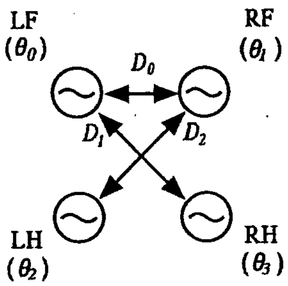


Figure 4 Connection of oscillators in our CPG model (LF: left forelimb, RF: right forelimb, LH: left hindlimb, RH: right hindlimb). D_0, D_1, D_2 are the desired values of each relative phase.

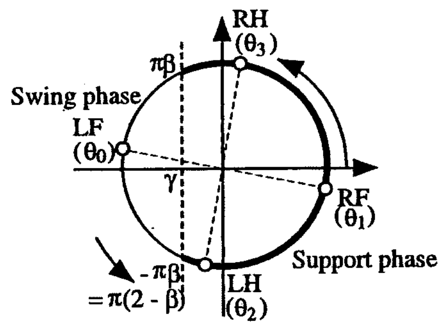


Figure 5 Swing phase and support phase. In this case, only the LF (θ_0) is in the swing phase and the others (LH, RF, RH) are in the support phase.

we can control relative phases to any values with a potential function in relative phase space. Using this method, f_i $(i = 0, 1, 2, 3)$ is given as follows:[2]

$$f_0 = \tau_\theta(\theta_1 + \theta_3 - 2\theta_0 - D_0 - D_1) \tag{5}$$

$$f_1 = \tau_\theta(\theta_0 + \theta_2 - 2\theta_1 + D_0 - D_2) \tag{6}$$

$$f_2 = \tau_\theta(\theta_1 - \theta_2 + D_2) \tag{7}$$

[2] These oscillator interactions can be calculated with local information, in other words, each oscillator should know only the phase of coupled oscillators. Therefore, phases of all the oscillators, i.e., global information are not necessary.

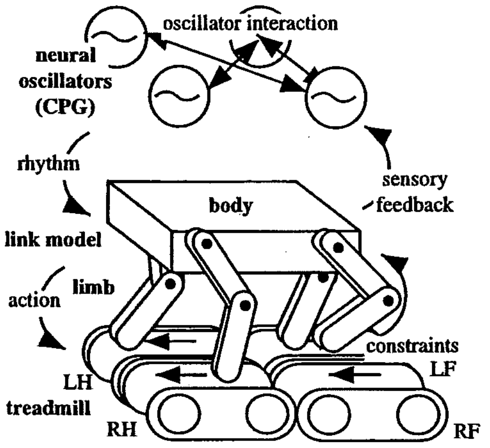


Figure 6 A model of adaptive behavior in the cat locomotion.

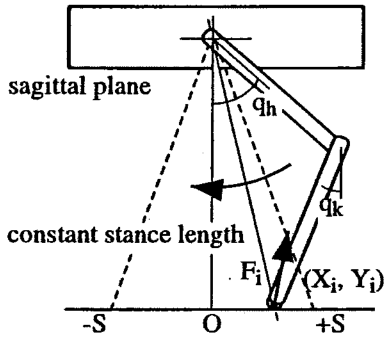


Figure 7 The structure of the limb. Each limb has 2 DOF: hip joint (q_f) and knee joint (q_k). F_i is a ground reacting force.

$$f_3 = \tau_\theta(\theta_0 - \theta_3 + D_1), \qquad (8)$$

Here, τ_θ is a constant parameter which determines the magnitude of oscillator interaction, D_0, D_1 and D_2 are desired value of relative phases. For example, if we want to generate the walk gait in Fig. 2 (a), we should set them as

$$D_0 = \pi, D_1 = \frac{3}{2}\pi, D_2 = -\frac{1}{2}\pi. \qquad (9)$$

We show the potential function in Appendix A.

3.3 Adaptation dynamics

The parameters which determine the minimum point of the potential function are ω_i $(i = 0,1,2,3)$ and D_j $(j = 0,1,2)$. Adaptation dynamics change them to decrease the oscillator interactions. As the cost functions we choose the integrated value of interaction f_i for one cycle,

$$F_i = \int_T f_i dt \quad (i = 0,1,2,3), \qquad (10)$$

and the integration of the squared sum of interaction f_i

$$V_D = \int_T \sum_{i=0}^{3} \left\{ \frac{1}{2\tau_\theta} f_i^2 \right\} dt. \qquad (11)$$

The resultant adjustment rules are given as

$$\omega_i^{(n+1)} = \omega_i^{(n)} + \tau_\omega \int_T f_i dt \quad (i = 0,1,2,3), \qquad (12)$$

$$D_0^{(n+1)} = D_0^{(n)} + \tau_D \int_T (f_0 - f_1) dt, \qquad (13)$$

$$D_1^{(n+1)} = D_1^{(n)} + \tau_D \int_T (f_0 - f_3) dt, \qquad (14)$$

$$D_2^{(n+1)} = D_2^{(n)} + \tau_D \int_T (f_1 - f_2) dt, \qquad (15)$$

where n denotes the number of step cycles, T is the duration of one step cycle, f_i $(i = 0,1,2,3)$ is the force given by eqs. (5)–(8), and τ_ω and τ_D are parameters that influence the convergence of ω_i and D_j, respectively. We show in Appendices B and C the derivation of this dynamics from the cost functions. This dynamics should be slower than that of locomotion.

4. Control of limb movements

4.1 Assumptions

We extend the mathematical expression in the previous section to include the limb dynamics. Then, the coupling of the oscillator and limb dynamics, or the design of the interaction between two dynamics, becomes an important problem. Figure 6 shows a sketch of our quadruped model.

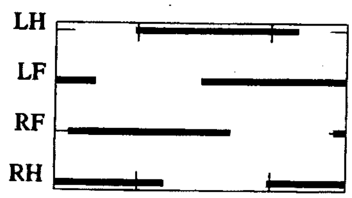
For the simplicity, we make the following assumptions to focus on the coupling of the two dynamics.

- 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.
- As shown in Fig. 7, each of four limbs has the same structure with 2 degrees of freedom of the motion: the hip joint (q_h), and the knee joints (q_k).
- The stance length for each limb is constant from $-S$ and $+S$ with no relation to the walking speed.
- The ground reacting force from the treadmill is detectable.

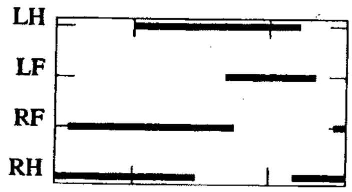
From the second assumption, we can treat the motion equations of the limbs separately in each four limbs. Then we can obtain four decoupled motion equations of two link systems.

4.2 Control in support phase

In the support phase, the oscillator dynamics should follow the limbs dynamics. It is because the limb movements are under constraint of the treadmill movements and are reflected to the oscillator phases. The limbs have to generate the large force along the gravitational direction, while following the movement of treadmill along the horizontal direction. Accordingly, we apply the



(a) Gait pattern in normal condition.



(b) Adapted gait pattern in perturbed condition.

Figure 8 Simulation result of gait change by adaptation dynamics.

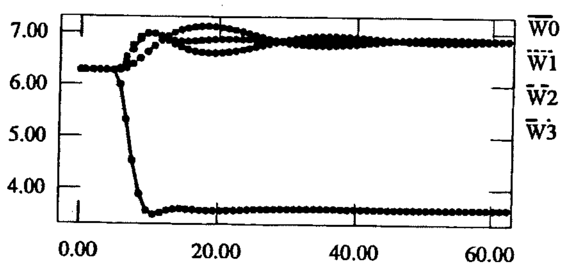


Figure 9 Change of ω_i $(i = 0, 1, 2, 3)$ due to adaptation.

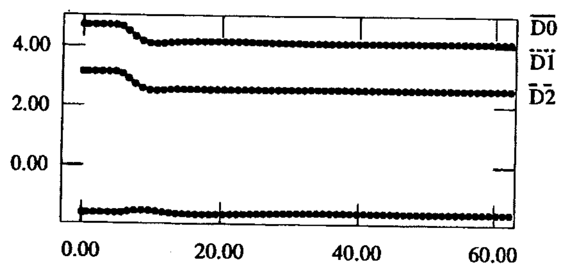


Figure 10 Change of D_j $(j = 0, 1, 2)$ due to adaptation.

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

$$M_d\ddot{X}_i + D_d(\dot{X}_i - \dot{X}_{di}) + K_d(X_i - X_{di}) = F_i \quad (16)$$

where $X_i = [x_i, y_i]$ 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. We design X_{d_i} to follow the treadmill belt as

$$x_i = \hat{\omega}_i t, \quad y_i = H_{sp}. \quad (17)$$

Here, $\hat{\omega}_i$ is an estimated speed of treadmill, and H_{sp} is a desired height of the toe in the support phase. To contact with the treadmill at any time, we set $H_{sp} < 0$.

In the support phase we change the oscillator phase according to the position of the toe. The toe moves along the horizontal direction from $+S$ to $-S$ (Fig. 7), while phase evolves from $-\pi\beta$ to $\pi\beta$ (Fig. 5). If we assume that the phase evolves at the constant rate when the toe moves at the constant horizontal speed, we can compose the following continuous mapping from the toe position to the oscillator phase,

$$\theta_i = -\frac{\pi\beta}{S} X_i. \quad (18)$$

The oscillator dynamics becomes

$$\dot{\theta}_i = -\frac{\pi\beta}{S} \dot{X}_i. \quad (19)$$

This equation must replace eq. (2) if we consider the limb dynamics.

4.3 Control in swing phase

In the swing phase, on the other hand, the oscillator dynamics govern the limb movement dynamics. Followed by the oscillator rhythms, the timing of limb movements, i.e., the relative phases are adjusted.

At first, we calculate the desired trajectory of toe from the oscillator phase θ_i. In the swing phase, phase evolves from $\pi\beta$ to $\pi(2-\beta)$ (Fig. 5), while toe moves along the horizontal direction from S to $+S$ (Fig. 7). Under the similar condition in the support phase, we can generate the desired toe position as follows:

$$x_{di} = \frac{S}{\pi(1-\beta)}(\theta - \pi), y_{di} = H_{sw}. \quad (20)$$

Here, H_{sw} is a desired height of the toe in the swing phase. Then, we determine the joint torques,

$$\tau_i = J^T(q_i)[D(\dot{X}_{di} - \dot{X}) + K(X_{di} - X)] \quad (21)$$

to follow this trajectory, where D and K are respectively the velocity and position feedback gain. Note that, in swing phase, there is no reaction force form the treadmill, i.e., $F_i = 0$

5. Simulations

We executed the computer simulation including the limbs dynamics. At 5.0(s) after the simulation started, we switch the treadmill speed 1.7 times faster. We set time constants as $\tau_\theta = 2.0$, $\tau_\omega = 0.25$ and $\tau_D = 0.045$.

Fig. 8 shows the simulated gait diagram, which is very similar to the experimental result of the decerebrate cat of Fig. 2. Figure 9 and Fig. 10 show the adjustment of angular velocity ω_i and the desired relative phase D_j. These show that the minimum point of potential function, i.e., memorized gait pattern is gradually changing.

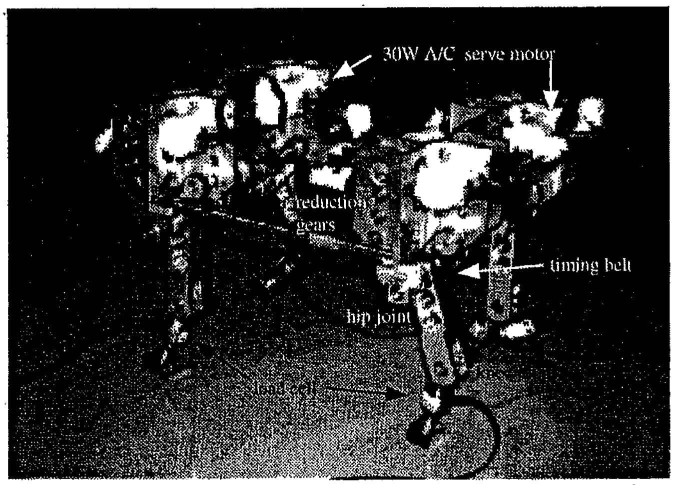


Figure 11 A quadrupedal walking robot.

6. Conclusion

We have successfully simulated the gait change with the treadmill speed. As the future works, we will experimentally examine it with a quadrupedal walking robots shown in Fig. 11. The experimental results of robot will be presented at the conference.

Appendices

A Dynamics of relative phases

Using eqs. (3) to (8), we can calculate the dynamics of relative phases, $\phi_0 = \theta_1 - \theta_0$, $\phi_1 = \theta_3 - \theta_0$, $\phi_2 = \theta_2 - \theta_1$ as:

$$\begin{aligned}\dot{\phi}_0 &= \omega_1 - \omega_0 + \tau_\theta(-\phi_0 + \phi_2 + D_0 - D_2) \\ &\quad -\tau_\theta(\phi_0 + \phi_1 - D_0 - D_1), \qquad (22)\end{aligned}$$

$$\dot{\phi}_1 = \omega_3 - \omega_0 + \tau_\theta(-\phi_1 + D_1) - \tau_\theta(\phi_0 + \phi_1 - D_0 - D_1), \quad (23)$$

$$\dot{\phi}_2 = \omega_2 - \omega_1 + \tau_\theta(-\phi_2 + D_2) - \tau_\theta(-\phi_0 + \phi_2 + D_0 - D_2). \quad (24)$$

It is obvious that they are gradient dynamics with the potential function given as follows:

$$\begin{aligned}V &= \frac{1}{2}\tau_\theta[(\phi_0 + \phi_1 - D_0 - D_1 + \frac{\omega_0}{\tau_\theta})^2 \\ &\quad +(-\phi_0 + \phi_2 + D_0 - D_2 + \frac{\omega_1}{\tau_\theta})^2 \\ &\quad +(-\phi_2 + D_2 + \frac{\omega_2}{\tau_\theta})^2 \\ &\quad +(-\phi_1 + D_1 + \frac{\omega_3}{\tau_\theta})^2)]. \qquad (25)\end{aligned}$$

In fact, eq. (22) to (24) can be derived from $\dot{\phi}_0 = -\partial V/\partial\phi_0$, $\dot{\phi}_1 = -\partial V/\partial\phi_1$ and $\dot{\phi}_2 = -\partial V/\partial\phi_2$.

B Adjustment of angular velocity in the swing phase

The dynamics of the oscillator in the swing phase are given by

$$\dot{\theta}_i = \omega_i + f_i \quad (i = 0, 1, 2, 3). \qquad (26)$$

Integrating them during the swing phase, we obtain

$$\Delta\theta_i = \theta_i(t_f) - \theta_(t_s) = \omega_i T_{sw} + F_i, \qquad (27)$$

where

$$F_i = \int_{T_{sw}} f_i dt, \qquad (28)$$

and $T_{sw} = t_f - t_s$ is the duration of the swing phase. If $F_i > 0$ (or < 0), then θ_i is accelerated (or decelerated). In order to reduce the interaction F_i, we adjust ω_i in proportion to F_i as

$$\omega_i^{(n+1)} = \omega_i^{(n)} + \tau_\omega F_i \quad (i = 0, 1, 2, 3). \qquad (29)$$

If $F_i = 0$, then we do not change ω_i.

Since interactions do not work in a support phase, we can change eq. (28) as follows:

$$F_i = \int_T f_i dt \quad (i = 0, 1, 2, 3). \qquad (30)$$

C Modification of desired relative phase

When the cost function is given by eq. (11), we can adjust the minimum of the potential function D_j as

$$\frac{dD_j}{dt} = -\tau_{D'}\frac{\partial V_D}{\partial D_j} \quad (j = 0, 1, 2). \qquad (31)$$

It can be expressed in the discrete form as

$$\begin{aligned}D^{(n+1)} &= D^{(n)} + \tau\frac{dD_j^{(n)}}{dt} \\ &= D^{(n)} - \tau_D\frac{\partial V_D}{\partial D_j}. \qquad (32)\end{aligned}$$

Thus, eqs. (13)–(15) can be derived from eqs. (5) – (8).

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