Learning scheme of multiple-patterns in quadruped locomotion using CPG model

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Abstract: Quadrupeds show several locomotion motion patterns adapting to environmental conditions. An immediate transition among walk, trot, and gallop implies an existence of the memory for locomotion patterns. In this paper, we postulate that the motor patter learning necessitates the repetitive presentation of the same environmental conditions, and aim at constructing a mathematical model for new pattern learning. The model construction deals with a decerebrate cat experiment where only the left forelimb is driven at the higher speed by the belt on the treadmill. A CPG model that adaptively generates locomotion pattern and qualitatively describes the decerebrate cat behavior has already proposed. Developing this model, we introduce a memory to retain locomotion patterns. Here, the memory is represented as the minimal point of the potential function whose gradient system describes recollecting process, and new minimal point is generated by the bifurcation from already-existed minimal point. The process where two minimal points are generated based on the repetitive presentation of the same environmental condition is described.

Keywords: Learning, Adaptation, Pattern generation, Quadruped locomotion, CPG

1. INTRODUCTION

Some automatic motions such as locomotion are periodic, and the rhythm of these periodic motions are produced at the spinal cord[1]. The neural circuits for these rhythm generation are called CPG (central pattern generator). These days, the CPG model is utilized to the walking robot controller[2-4]. In this controller, the entrainment [5] of the oscillator rhythm in controller and legs' rhythmic motion is the most important factor for stabilizing the locomotion. Although the effectiveness of such controller are demonstrated by the robot motion, the design methods for such CPG controllers have not been established yet.

The CPG rhythms in biological systems are acquired by the learning through the motion. The variation of the rhythms with respect to the environment can be observed as the gait pattern changes in the decerebrate cat experiment[6]. In this paper, we consider a new motion pattern learning based on the following hypothesis: if some environmental conditions are repetitively presented, a motion pattern is memorized as a distinct one for each condition. Followed by this hypothesis, we propose a mathematical model in which a new motion pattern is learnt with keeping the originally-stored pattern in the memory.

2. MOTION PATTERN LEARNING

2.1 An adaptive behavior of decerebrate cat

Yanagihara et al.[6] make a decerebrate cat walk on the special treadmill where the belt for left forelimb can be driven at the different speed from the others. At first, all the belt is driven at the same speed (normal condition). Then, the cat walked with the "walk" gait as shown in Fig. 1(a), which is the same one as the intact cat. Next, the belt for the left forelimb is driven 1.7 time as fast as the others (disturbed condition). At the first trial (one trial contains 60 -100 steps), the locomotion pattern is only disturbed, but at the second trial, the steady locomotion pattern is observed. In addition, at the third trial, the cat walk with the steady locomotion pattern at the beginning of this trial.

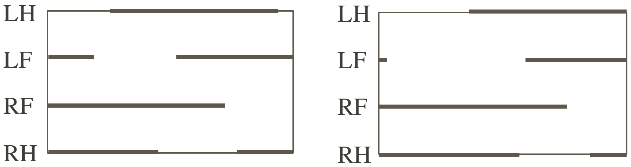
For this cat that had adapted to the environment where the left forelimb is driven faster, this belt speed was returned to the initial condition, i.e., driven at the same speed as the others. Then, the cat could not walk with the walk gait at the beginning of this trial. Namely, some training is required to regain the coordination between forelimbs.

2.2 A hypothesis on motion pattern learning

The experimental results presented at the previous section allow us to conclude the motor pattern learning as follows:

- An appropriate locomotion pattern for the current environment can be acquired with performing motions.
- The acquired locomotion pattern is memorized.
- In this experimental condition, both the gait pattern "walk" and another gait pattern acquired in the disturbed condition are not memorized simultaneously.

The second item originates from the inference that, if the motion pattern had not been memorized, the stable gait pattern could not have been observed at the beginning of the third trial. The last item is inferred from the fact that the re-adaptation was required at the trial re-



(a) normal gait (b) adapted gait

Fig. 1 Gaits of a decerebrate cat.

presenting the normal condition after disturbed condition even though the steady gait pattern was observed at the first normal condition.

By the way, quadrupeds can immediately change the gait pattern among walk, trot and gallop with respect to the environmental conditions. Such an immediate switching, in our opinion, requires the memorization and the selective recollection of the appropriate pattern in the memory. This idea supports the memorization of the multiple motion patterns, although it contradicts the last item in the above. In fact, humans can utilize different motion patterns, walk and run, depending on the situation, and thus the multiple-pattern memorization seems to be valid. A reason why the decerebrate cat can memorize only one gait pattern would be the less-frequent presentation of the environmental condition: if both the normal condition and disturbed condition are repetitively presented in the experiment, the decerebrate cat would learn the both gait pattern simultaneously.

Based on this idea, we set a hypothesis on the motion pattern learning as follows:

- If some environmental conditions are repetitively presented, animals can memorize a motion pattern as a distinct one for each condition.

According to this hypothesis, if the normal and disturbed condition are repetitively presented, the cat is expected to learn two gait patterns together. In the remainder of this paper, we propose a mathematical model that realize our expectation. At this time, we assume the following scenario:

1. A pattern with which the locomotion is enabled is inherently stored in memory. This pattern does not change, i.e., is stored undisturbedly as a basic pattern.
2. With respect to a new environmental condition, the memorized patterns are made modification.
3. When the same environmental condition is repetitively presented, an appropriate pattern for this environment is newly memorized as a distinct pattern to immediately cope with this condition.

As for the locomotion pattern generation and its adaptation, we have already proposed a mathematical model[7]. In this paper, we add a memorization mechanism to it to retain multiple motion patterns.

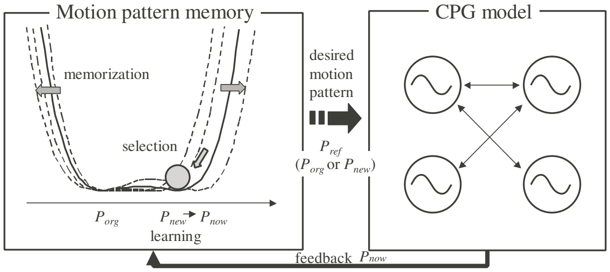


Fig. 2 Controller containing CPG model and gait pattern memory.

3. A LEARNING MODEL OF MULTIPLE MOTION PATTERN

3.1 locomotion pattern generation, adaptation, and learning

The model in the previous paper is used for locomotion pattern generation and adaptation. This is a CPG model consisting of oscillators. At first, the model is briefly explained. Next, introducing the concept on the memorization, the learning of two locomotion patterns is tried to be modeled. Then, a locomotion pattern memory is adopted at the higher level of the CPG. Patterns for new environmental conditions are being stored to this memory. In addition, this memory provides to the CPG a locomotion pattern that is supposed to be appropriate to the current environmental conditions.

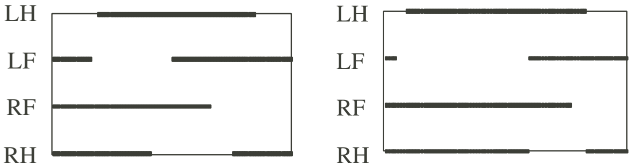
Here, we used words, “adaptation” and “learning”. In this paper, we distinguish between them as follows: suppose a new pattern is generated to the environmental conditions. If this pattern is memorized by adjusting the originally-memorized pattern, we say, this pattern generation is caused by “adaptation”. On the other hand, if this pattern is memorized as a new pattern and the original pattern remains as it is in the memory, we call it “learning”. Namely, our definition is: the adaptation refines a memorized motion pattern, while the learning creates a new reference pattern in memory.

3.2 Adaptive rhythm generation of CPG model [7]

3.2.1 locomotion pattern generation

The locomotion consists of the periodic motion of each limb. The quadruped locomotion is characterized by relative phases among the periodic motion of four limbs as well as the duty factor that denotes the ratio of the stance phase period in one locomotion cycle. Thus, to each limb, one oscillator is assigned. The state of the limb motion is represented by the phase of the oscillator. In addition, the phase space of oscillator is divided to two region, a region of the swing phase and one of the support phase. The duty factor is represented as the ratio of the time in which the oscillator phase passes in the latter region against one cycle.

The representation of the locomotion pattern using oscillator phase requires the relative phase control: The relative phases should be controlled to their desired values. A method based on the gradient dynamics in the relative



(a) normal gait (b) adapted gait

Fig. 3 Gaits obtained by a mathematical model.

phase space[8] makes it feasible. In this paper, we utilized this method and define the oscillator dynamics as follows:

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

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

$$f_1 = \tau_\theta(\theta_0 + \theta_2 - 2\theta_1 - D_0 - D_2) \quad (3)$$

$$f_2 = \tau_\theta(\theta_1 + \theta_2 + D_0) \quad (4)$$

$$f_3 = \tau_\theta(\theta_0 + \theta_3 + D_1) \quad (5)$$

Here, θ_i denotes the oscillator phase which represents the state of the limb motion, $i = 0, 1, 2, 3$ distinguish the limb, i.e., right forelimb, left forelimb, right hindlimb and left forelimb, in this order. ω_i are natural frequencies of the oscillator and f_i are interactions among oscillators. According to these dynamics, the relative phases $\phi_0 = \theta_1 - \theta_0$, $\phi_1 = \theta_3 - \theta_0$ and $\phi_2 = \theta_2 - \theta_1$ converge to their desired values D_0, D_1 and D_2.

Based on the above control method of relative phases, we describe the decerebrate cat behavior. Then, we must re-define oscillator dynamics in CPG since the nature of the limb dynamics is inherently different between swing and support phase. In the support phase, the limbs are forced to be driven by the treadmill belt. So, the oscillator dynamics in the support phase are defined as the forced oscillation by the treadmill:

$$\dot{\theta} = \rho_i (i = 0, 1, 2, 3) \quad (6)$$

where ρ_i denote the belt speed of the treadmill. In the swing phase, on the other hand, the limbs can move freely without constraints. The relative phase adjustments are feasible only in this phase. Therefore, the oscillator dynamics is defined as the gradient dynamics in the above. In these dynamics, the natural frequencies ω_i and relative phase are the parameters of the locomotion pattern, while ρ_i is those of the environment.

3.2.2 Adaptation dynamics

The oscillator phases are controlled to their desired values followed by the oscillator interactions f_i. The interactions corresponds to the gradient of the potential function that defines gradient dynamics in the relative phase space. The minimum point of the potential function becomes the steady state. By selecting the parameters, we can make the oscillator interaction to be zero at the steady state of the normal condition. If the relation of the relative phases have effected from the instantaneous disturbance, they will return to the desired values because of its stability.

In the decerebrate cat experiment, however, the locomotion pattern is disturbed whenever the left forelimb is placed on the faster treadmill belt. In this case, the disturbance becomes stationary, i.e., periodic. The locomotion is disturbed before the pattern returns to the desired one, which produces the situation such that the disturbance and interaction is balanced in the timescale of locomotion cycle.

In this situation, the pattern is maintained by the permanent oscillator interactions. But, the interaction originally works so that the desired pattern could emerge. The permanent interaction implies that the desired pattern is not appropriate to the given environmental conditions. Therefore, the adjustment of the desired pattern is introduced. This adjustment corresponds to the displacement of the minimum point of the potential function in the gradient dynamics. From the context, this adjustment should be defined so that the oscillator interactions become small. Because the desired locomotion pattern is represented by the natural frequencies and relative phases, the parameters to be adjusted should be them. These parameters are adjusted in each step followed by these adaptation dynamics:

$$\omega_i^{(n+1)} = \omega_i^{(n)} + \tau_\omega \int_T f_i dt \ \ (i = 0, 1, 2, 3) \quad (7)$$

$$D_0^{(n+1)} = D_0^{(n)} + \tau_D \int_T (f_0 - f_1) dt \quad (8)$$

$$D_1^{(n+1)} = D_1^{(n)} + \tau_D \int_T (f_0 - f_3) dt \quad (9)$$

$$D_2^{(n+1)} = D_2^{(n)} + \tau_D \int_T (f_1 - f_2) dt \quad (10)$$

Here, n is the number of the locomotion step, and τ_ω and τ_D are parameters that changes the speed of the above adaptation dynamics.

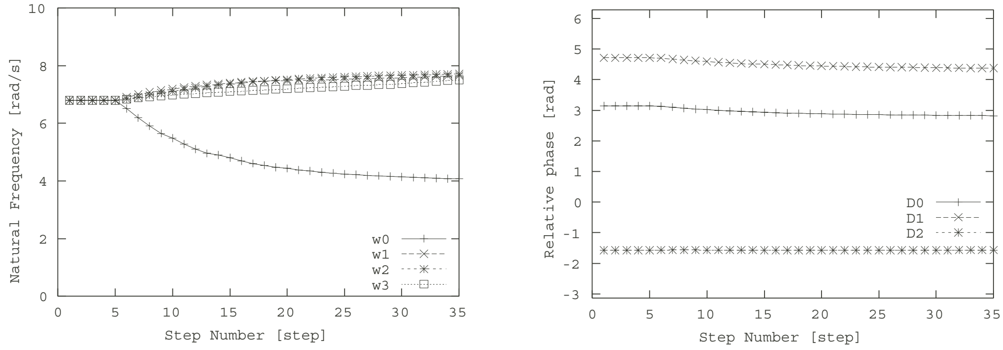
3.2.3 Simulation playback

The computer simulation was performed according to the previous paper [7]. The parameters are: $\omega_i = 6.8$, $\rho_i = 6.8$, $D_0 = \pi$, $D_1 = 3\pi/2$, $D_2 = -\pi/2$, $\tau_\theta = 2.0$, $\tau_\omega = 0.25$ and $\tau_D = 0.02$. In the disturbed condition, the ρ_0 is set 1.7 times as large as the above value. Fig. 3 shows the gait patterns obtained from this simulations, which is similar to the cat shown in Fig. 1.

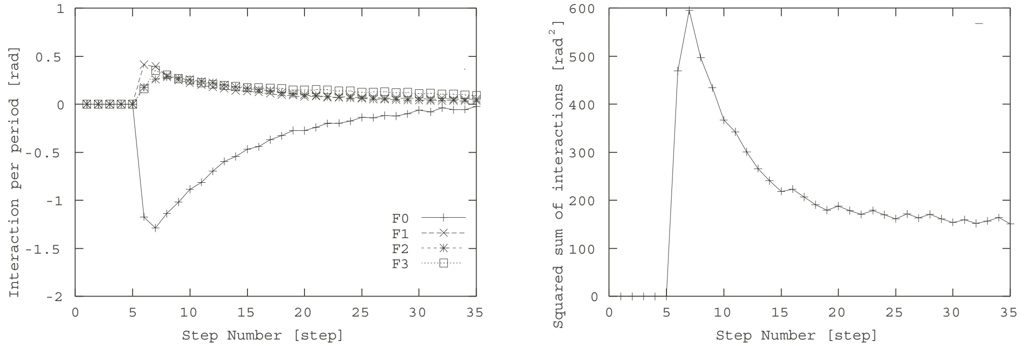
3.3 A locomotion pattern memory

3.3.1 Pattern registration and recollection

The locomotion pattern produced by the CPG model would changes with the environmental conditions according to the adaptation dynamics. This adaptation adjusts the desired locomotion pattern for the CPG. Now, suppose the same environmental condition would be presented again. The adjusted pattern could be generated immediately if it were stored in memory. This is why the memory for the adjusted pattern is adopted, as shown in Fig. 2. The role of this memory is described as the registration process and recollection process.



(a) Natural frequencies (b) Relative phases



(c) Interaction integrated during one step period (d) Squared sum of integrated interactions

Fig. 4 Simulation results for disturbed condition (disturbed condition).

In the registration process, the motion pattern that is currently set as the desired pattern according to the adaptation dynamics is memorized based on the feedback from the CPG model. Then, the environmental condition should be registered together. As the recollection process will be described as the dynamical process at the latter section, the memorized pattern must be represented as an attractor. To make this representation easy, the memorized pattern is expressed as a minimum point of the potential function which is defined in the parameter space of the locomotion pattern. The main subject of this paper is to make additions of distinct motion pattern to the memory which already has possessed the memorized pattern. Using the potential function, this subject is represented as the deformation process of the potential function: it originally has one minimum point. By the registration, a new minimum point bifurcates from the original minimum point. As the result, the function that has multiple minimum points are generated.

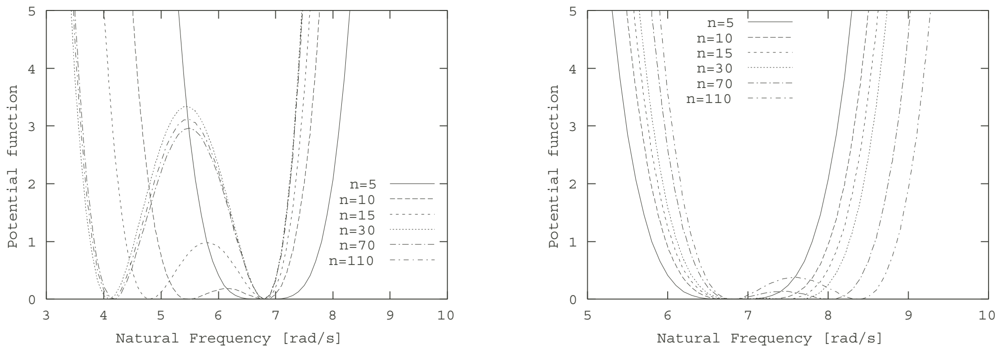
In the recollection process, on the other hand, an appropriate pattern is selected, whose result is outputted to CPG as the desired pattern. This is only the moment when the desired pattern adruptly changes by the command from the memory. The discontinuous change of the desired pattern triggers the switching of the locomotion patterns with respect to the environmental conditions. Here, the pattern selection is supposed to be optimization process based on some criteria. Thus, it had better be described as the dynamical process since the dynamical process could give solutions by the repetitive computation and so generally be used for the complex calculation problem. If the memorized pattern is represented as the minimum point of the potential function in the registration process, the recollection process is described as the minimization process of the potential function.

3.3.2 Formulations

The locomotion pattern is represented as seven parameters, i.e, the natural frequencies and the relative phases. These are denoted here by the variables $p^{(j)} (j = 1, \cdots, 7)$. The potential function in the memory is defined in this seven dimensional space. The problem in this paper is that one new pattern is added to the memory in which the "walk" gait has been originally stored. Thus, restricting the number of memorized pattern in two, the potential function is defined as the four-order polynomial that can possesses two minimum points:

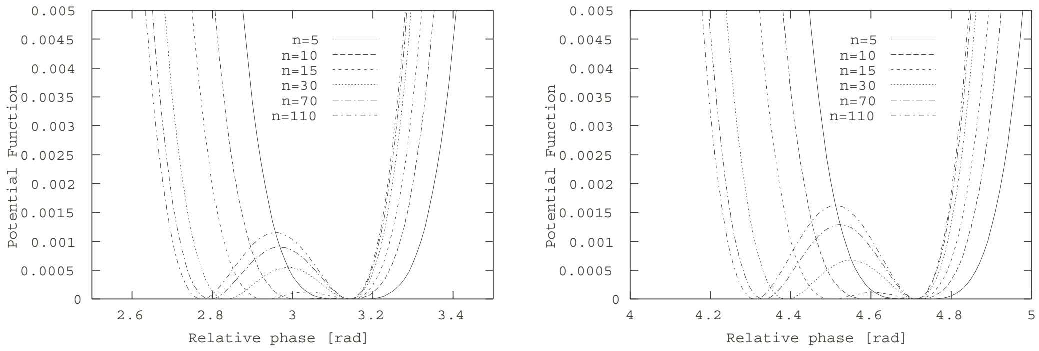
$$V_P = \sum \left(p^{(j)} - p_1^{(j)}\right)^2 \left(p^{(j)} - p_2^{(j)}\right)^2 \qquad (11)$$

Here, $p_1^{(j)}$ and $p_2^{(j)}$ denotes the memorized patterns P_1 and P_2, which are the minimum point of potential function. At first, there is only the walk gait (P_1) in the memory. This situation is expressed as the function with single minimum point where two minimum points are duplicated ($P_2 = P_1$). When the environment varies, a new locomotion pattern is generated followed by the adaptation dynamics in CPG. The pattern acquired by the adaptation dynamics should be memorized in order to immediately



(a) Potential function with respect to ω_0

(b) Potential function with respect to ω_0



(c) Potential function with respect to D_0

(d) Potential function with respect to D_1

Fig. 5 Deformation of potential function by learning.

generate it when the same environmental condition is presented again. Here, the current desired pattern P_{now} in the CPG model is sent to the memory and registored according to the following dynamics.

$$\dot{p}_2^{(j)} = \tau_\beta (p_{now}^{(j)} - p_2^{(j)}) \tag{12}$$

This registration produces the potential function with two minimum points, "walk" gait $(= P_1)$ and $P_{now} (= P_2)$. The recollection process can be described as a gradient system of the potential function V_P:

$$\dot{p}^{(j)} = -\tau \frac{\partial V_P}{\partial p^{(j)}} \tag{13}$$

4. SIMULATIONS

In the simulation, the decerebrate cat experiment in section 2.1 is taken as examples. The conditions are: (i) All the treadmill belts are driven at the same speed (normal condition), (ii) The left forelimb is driven 1.7 time as fast as the others (disturbed condition), (iii) The normal condition and the disturbed condition are presented alternately. The parameter in this simulation is the same as the previous paper and in section 3.2.3 and the remaining parameters are set as $\tau_\beta = 0.5$, $\tau = 8.0$. These parameter setting makes oscillator interaction zero at the steady state of the normal condition. Although the results are not shown, zero oscillator interaction is confirmed in the simulation, where the desired pattern, i.e., the natural frequencies and relative phases, keep still.

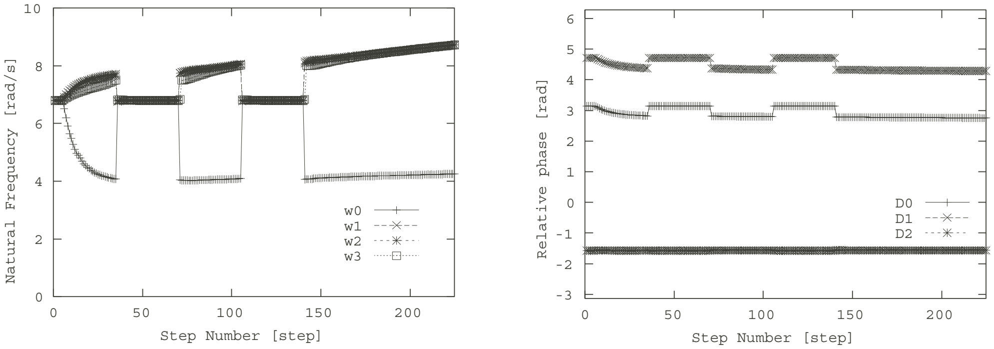
The recollection dynamics started at the moment that the oscillator interaction of the left forelimb went over the pre-defined threshold. The initial value of the recollection dynamics are set so that the relation between the locomotion parameters in memory and its environmental conditions can be linearly interpolated.

$$p(0) = \frac{p_2^{(j)} - p_1^{(j)}}{\rho_2 - \rho_1}(\rho_{now} - \rho_1) + p_1^{(j)} \tag{14}$$

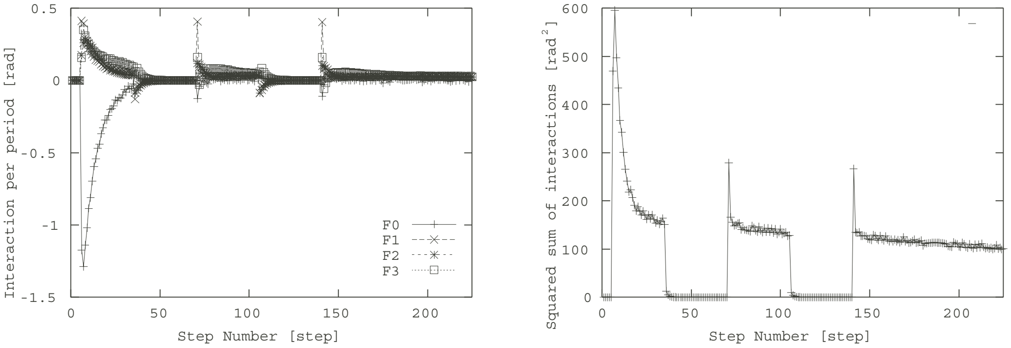
The value of the recollection dynamics after one locomotion cycle was outputted to the CPG as the desired locomotion pattern.

The simulation results for the case (ii) are shown in Fig. 4. These graph illustrates the time course of the following variables: (a) natural frequencies, (b) desired relative phase, (c) oscillator interactions integrated in one locomotion cycle, and (d) integrated squared sum of interactions in one cycle. The horizontal axis in all the four graphs represents the number of the steps in the locomotion. The natural frequencies and relative phases were adjusted, which made oscillator interactions to decrease. The gait pattern obtained from this simulation is shown in Fig. 3(b). This pattern was sent to the locomotion pattern memory and registered there as a new pattern. The transection of the potential function along the ω_0, ω_1, D_0 and D_1 axis are shown in Fig. 5. The single minimum point bifurcates and the double minimum point are produced.

Finally, the simulation results for the case (iii) are shown in Fig. 6. In the simulation, the environmental



(a) Natural frequencies (b) Relative phases



(c) Interaction integrated during one step period (d) Squared sum of integrated interactions

Fig. 6 Simulation results where the environmental conditions alter.

condition was switched from normal condition to disturbed condition at the 10 steps. After that, the condition was alternately switched in each 35 steps between two. The locomotion pattern immediately changed at the moment when the environment became the normal condition. When the environment became disturbed condition, the locomotion pattern under learning was selected to the desired pattern and the adaptation proceeded from this pattern.

5. CONCLUSION

In this paper, we considered a new motion pattern learning under the repetitively-presented environmental conditions. Then, the following hypothesis was set: If some environmental conditions are repetitively presented, a motion pattern is memorized as a distinct one for each condition. Followed by this hypothesis, we proposed a mathematical model of the new pattern learning. Computer simulations based on the experimental result of the decerebrate cat show that the new pattern are reginsterd with keeping the original memorized pattern in the memory. As the future works, we must extend this model so that the physical dynamics are included.

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