Novel Control Principle
Based on the Discrepancy Function

By

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Abstract

Animals can locomote slickly and sinuously in a complex environment, whereas the most advanced robots are unable to do so. This is because animals have a large number of degrees of freedom, and they can control them in a well-coordinated manner. Our objective is to understand how animals attain such elegant motion. Autonomous decentralized control (ADC) is a key concept that facilitates the control of a large number of degrees of freedom under uncertain conditions in real time. First, we focus our attention on a single-cell organism, i.e., plasmodium of *Physarum polycephalum*. We extract the simple form of ADC from this organism, which is termed as *discrepancy control*; then, we test it by implementing it in various types of robots. In this article, we report the present status of our study.

§ 1. Introduction

Animals are capable of moving in a supple and adaptive manner under uncertain real-world conditions by orchestrating the large number of degrees of freedom embedded in their bodies. Our objective is to understand this ability of animals. We tackle this problem by performing biological experiments, constructing mathematical models, and designing robots. The key concept is *autonomous decentralized control* (ADC).

It is known that animals control their large number of degrees of freedom in a well-coordinated manner by means of distributed neural networks called central pattern generators (CPGs) [1, 2], which generates rhythmic signals. Taga et al. presented a framework in their pioneering work [3], in which biped walking is expressed by the limit cycle in the product space of the body, controller, and environment. The formation of this limit cycle is known as *global entrainment*, and it guarantees stability of locomotion against small perturbations to the body, controller, or environment. Adopting CPG as a controller seems to be an advantageous approach to realizing ADC in robots; however, its design principle has not been established thus far. Our strategy for obtaining the design principle of ADC is to learn from animals, especially from the most primitive living system, i.e., *true slime mold*. The plasmodium of true slime mold is a large single-cell amoeboid organism with multiple nuclei. The pressure gradient caused by mechanochemical oscillators distributed in its body generates a flow of protoplasm, and consequently induces locomotion. Because it is a single-cell organism, it has neither a nervous system nor a central organ for information processing. Therefore, it can be interpreted as a system in which ADC works in the purest form.

Kobayashi et al. proposed a model for the motion of true slime mold in [4], which involved two important ideas linked to the present study. One is a spring whose natural length changes, and the other is feedback to the oscillator based on the *discrepancy function*. Let us introduce this model briefly.

Actine-myosin filaments are distributed in the gel layer of the plasmodium, and they exhibit contractile oscillation causing a change in the body thickness. In order to express this oscillation using a mathematical model, imaginary springs were introduced, whose natural lengths were controlled by oscillators; they yielded a force proportional to the difference between the actual length and the natural length. In this mathematical model, the springs and controllers (oscillators) are coupled and distributed in a two dimensional region, and the pressure p is given by the force generated by the springs. Then, the protoplasmic sol is assumed to stream at a rate proportional to the pressure gradient, i.e., Darcy's law. (See Fig.1.)

The imaginary spring introduced in this model was independently developed as a real elastic actuator by Ishiguro's group, and it was termed as a realtime tunable spring (RTS). This device changes its natural length by winding up a part of the spring using a DC motor (Fig.2). *Backdrivability* of the actuators (muscles) is important for the animals to make sinuous movements. This is because it enables soft and safe interaction between the animal's body and its surroundings; moreover, it enables animals to easily obtain mechanical information from their own bodies. We often make use of the RTS in models and real robots because it has several advantages despite its simple structure: (i) it has both of active and passive characters, (ii) backdrivability is guaranteed at the
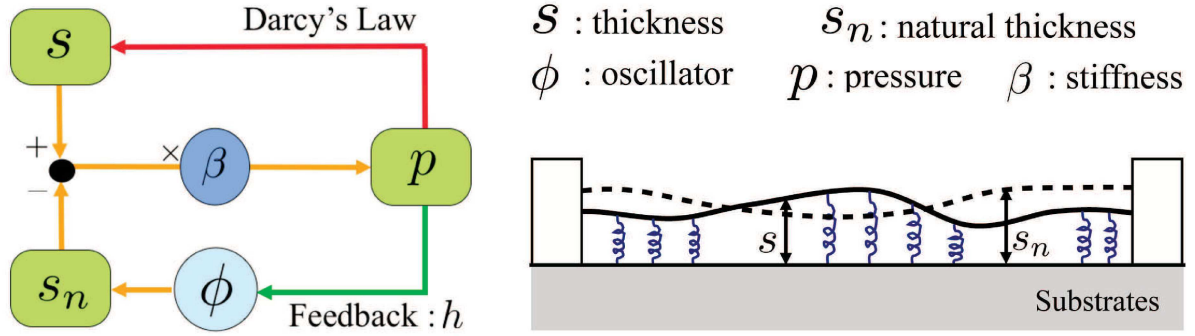
Figure 1. Model of plasmodium : Natural thickness s_n and the pressure p are given by the formula $s_n = \bar{s}(1 - a\cos\phi)$ and $p = \beta(s - s_n)$, respectively. Phase oscillator ϕ receives a feedback signal through the pressure.

hardware level, and (iii) stiffness can be controlled easily.

Figure 2. RTS(Realtime Tunable Spring)

In the model, it was assumed that the feedback signal shifts the phase of the oscillators so as to decrease p^2 by taking the feedback signal $h = h(\phi, p)$ as

$$(1.1) \qquad h(\phi, p) = -\partial_\phi \left(\frac{\sigma}{2} p^2 \right).$$

Pressure p is a result of the actuator's force, and it can also be interpreted as an index of the difference between the actual state of the actuator and the target state of the actuator, which is required by the controller. Thus, the strength of the pressure is termed as *discrepancy* (in this case, it is expressed by $\frac{\sigma}{2} p^2$), and we assumed that the feedback to the controller decreases the *discrepancy*. It should be noted that a *discrepancy* is not to be eliminated like an error. Actually, the controller continues to produce a *discrepancy*, and it drives the motion. From the viewpoint of ADC, this feedback signal should be generated only by locally available information. Actually, $h(\phi, p)$ can be calculated locally because $p = \beta(s - s_n)$ and $s_n = \bar{s}(1 - a\cos\phi)$.

In the motion of the plasmodium, a key property is the conservation of protoplasmic sol that connects local and global behavior. This conservation law generates global interactions, and consequently induces an anti-phase oscillation instead of an in-phase oscillation, thereby producing a coherent protoplasmic flow. Another key property is the stiffness of the body (gel layer), whose non-uniformity determines the direction

of motion. Actually, the plasmodium extends a softer part of its body to perform locomotion. These key properties are utilized in the design of the robot "Slimy", which will be presented in section 3.

§ 2.   A simple model of a discrepancy control

§ 2.1.   Two RTSs model

In this section, we present a very simple model that consists of two RTS's with control signals derived from the *discrepancy function*. Let us consider two RTSs connected serially, with both ends anchored to the walls, as shown in Fig.3. The equation of motion of the mass point is

$$(2.1) \qquad m\ddot{x} + \alpha\dot{x} = T_2 - T_1$$

where T_i is a tension of the i-th spring. Tension T_i is expressed using the real length ℓ_i, the natural length L_i as follows.

$$(2.2) \qquad T_i = \kappa\left(\frac{\ell_i}{L_i} - 1\right) \qquad (i = 1, 2)$$

where $\ell_1 = L_0 + x$, $\ell_2 = L_0 - x$. The parameter κ determines the elastic property of the material composing springs. It is assumed that the natural length L_i of the i-th spring is controlled by a phase oscillator ϕ_i in the following manner.

$$(2.3) \qquad L_i = \bar{L}(1 + a\sin\phi_i) \qquad (i = 1, 2)$$

We also assume that each phase oscillator is driven at a constant rate and simultane-
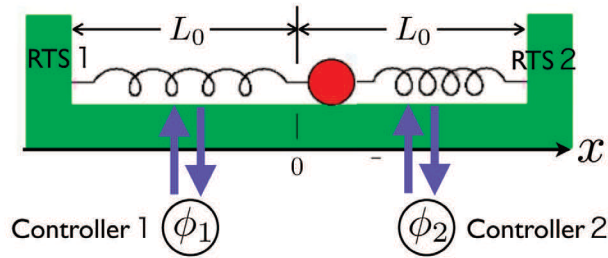

Figure 3.   Setting of the model : Distance between two walls is $2L_0$, the x-axis is set as shown and the origin is taken to be a central point. Mass of the mass point is m, the position of the mass point is $x(t)$ and the resistance force is assumed to be proportional to the velocity.

ously receives a feedback signal derived from the *discrepancy function* which is denoted by I_i hereafter. The interaction between controllers is not taken into account because

we would like to observe only the effect of the feedback. Thus, we have the following equation for driving the phase oscillator.

$$(2.4) \qquad \dot{\phi}_i = \omega - \frac{\partial I_i}{\partial \phi_i} \qquad (i = 1, 2)$$

We have a wide range of choices to determine the form of the *discrepancy function* I_i because it is the quantity that provides the difference between the actual state and the state that the controller desires. It is plausible to use the square of the spring tension as in the model of true slime mold or the absolute value of the spring tension; in addition, the elastic energy stored in the spring can be a candidate. Here, we adopt the last one, i.e., elastic energy (multiplied by positive constant σ) as follows.

$$(2.5) \qquad I_i = \sigma \frac{\kappa}{2} L_i \left(\frac{\ell_i}{L_i} - 1 \right)^2$$

Since $\frac{\partial I_i}{\partial L_i} = \frac{\sigma \kappa}{2} \left[1 - \left(\frac{\ell_i}{L_i} \right)^2 \right]$ holds, the equation of ϕ_i is

$$(2.6) \qquad \dot{\phi}_i = \omega - \frac{1}{2} \sigma \kappa a \bar{L} \left[1 - \left(\frac{\ell_i}{L_i} \right)^2 \right] \cos \phi_i$$

Here we assume $\bar{L} = L_0$ and perform a proper non-dimensionalization, then we get the following model equation system.

$$(2.7) \qquad \begin{aligned} m\ddot{x} + \alpha\dot{x} &= \frac{1 - x}{1 + a \sin \phi_2} - \frac{1 + x}{1 + a \sin \phi_1} \\ \dot{\phi}_1 &= 1 - \sigma \left[1 - \left(\frac{1 + x}{1 + a \sin \phi_1} \right)^2 \right] \cos \phi_1 \\ \dot{\phi}_2 &= 1 - \sigma \left[1 - \left(\frac{1 - x}{1 + a \sin \phi_2} \right)^2 \right] \cos \phi_2 \end{aligned}$$

Note that the equation system (2.7) has a in-phase solution $x(t) \equiv 0$, $\phi_1(t) \equiv \phi_2(t)$ satisfying the equation below.

$$(2.8) \qquad \dot{\phi}_i = 1 - \sigma \left[1 - \left(\frac{1}{1 + a \sin \phi_i} \right)^2 \right] \cos \phi_i$$

The equation (2.6) indicates that the feedback signal shift the phase backward if RTS is pulled and forward if RTS is pushed during the contractile period ($\cos \phi_i < 0$), while the feedback signal works oppositely during the extensional period ($\cos \phi_i > 0$). This can be interpreted that the controlling system compromises to the mechanical system.

§ 2.2.   Overdamping case

Let us consider the case $m = 0$, $\alpha > 0$, meaning that the inertia force is negligible with respect to the resistance force. As shown in Fig.4, the in-phase solution is unstable and the transition to the anti-phase solution is observed, which causes a oscillatory motion of the mass point. Roughly speaking, natural lengths $L_1(t)$ and $L_2(t)$ synchronize in an almost anti-phase manner, and the position $x(t)$ follows to the target position they offer with some delay. This delay produces a periodic *discrepancy* and produce a driving force of the motion of the mass point. The amplitude of the oscillation of the mass point is smaller than the amplitude of the oscillation of the target point, and the observed angular velocity is always smaller than the intrinsic angular velocity of the oscillators.
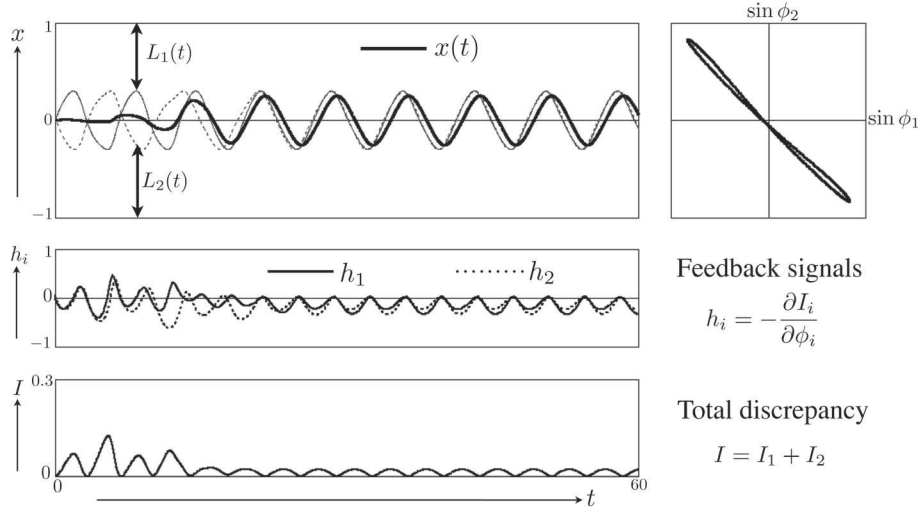

Figure 4.   Transition from in-phase solution to anti-phase solution : $a = 0.3$, $\sigma = 1.2$, $\alpha = 1.5$

The situation under consideration is almost equivalent to the system in which the two cylinders are connected by the narrow tube as shown in Fig.5 (a). Conservation of the fluid amount corresponds to the constraint that the sum of the lengths of two RTSs is kept constant. The fact that the anti-phase oscillation appears as a stable solution can be the simplest explanation of the experimental result that two plasmodium connected by the narrow tube oscillates in the anti-phase manner [6]. Note that the in-phase solution becomes stable and the anti-phase solution becomes unstable if the coefficient σ of the feedback signal is taken to be negative.

§ 2.3.   Inertia dominant case

Let us consider the case $m > 0$ and α is small, meaning that the inertia force is dominant to the resistance force. The transition from the in-phase solution to the
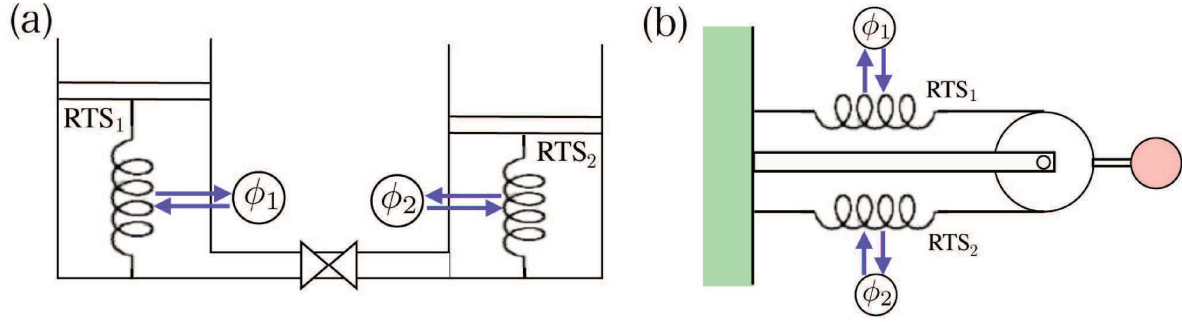
Figure 5. (a) 2 cylinders model : Each cylinder is filled with the incompressible viscous fluid and RTS generate the pressure. (b) Model of antagonistic muscle

anti-phase solution is also observed in Fig.6. The amplitude of the oscillation of the mass point is greater than the amplitude of the oscillation of the target position, which is contrasting to the dissipation dominant case. Observed angular velocity is smaller than the intrinsic angular velocity of the controllers.
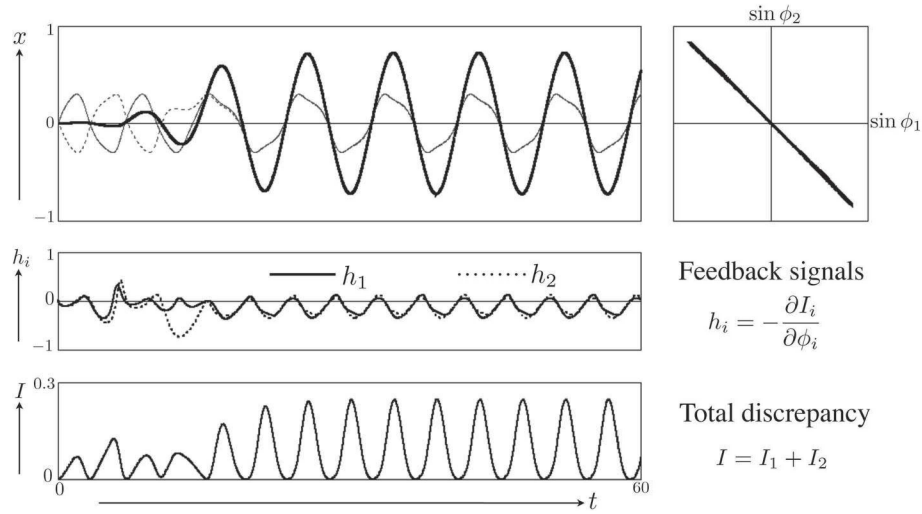

Figure 6. Transition from the in-phase solution to the anti-phase solution : $a = 0.3$, $\sigma = 1.2$, $\alpha = 0.2$, $m = 2.5$

The results when the mass parameter m is gradually changed are presented in Fig.7. As m becomes larger, the amplitude of the steady oscillation becomes larger, and the angular velocity becomes smaller. This can be interpreted that the controller decreases the angular velocity from their intrinsic one to compromise to the angular velocity which the mechanical system prefer.

The model setting shown in Fig.3 can be interpreted as a model of antagonistic muscle driving the joint, if it is rewritten to the setting in Fig.5(b). By changing the
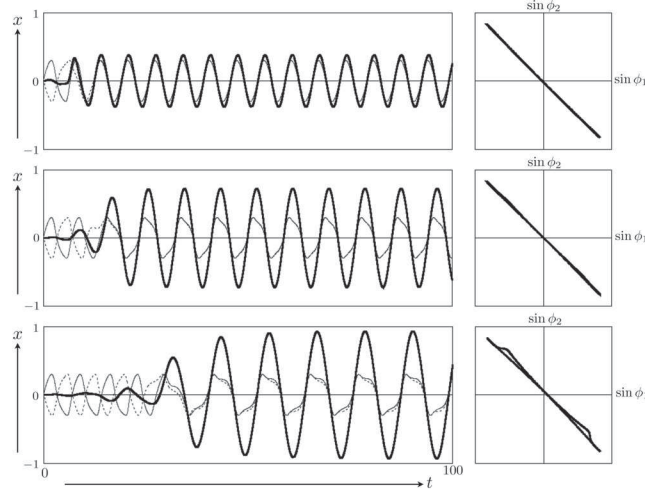
Figure 7. Profiles of oscillation obtained by controlling the parameter m : $m = 0.5, 2.5, 5.0$ from above. $a = 0.3$, $\sigma = 1.2$, $\alpha = 0.2$

central value $\bar{L}$ of the natural length oscillation of RTSs, we can control the stiffness of joints. HAUBOT 2, the robot introduced in the next section, makes use of this stiffness control.

§3. Robots

We extracted a control method from the plasmodium of true slime mold, and named it *discrepancy control*. We examined its effectiveness by constructing mathematical models and by making robots with various types of bodies. In this section, we briefly introduce how *discrepancy control* was implemented to the robots and how it worked in each example.

§3.1. Amoeboid robot : Slimy

We started from the robot with the amoeboid body having a similar nature to the plasmodium of true slime mold, which was named Slimy[5]. The body of this robot is essentially two dimensional which consists of the contractile outer skin and the protoplasmic sol (its substitute) inside it. The outer skin is composed of passive springs ans RTSs as indicated in Fig.8(a). The i-th RTS is controlled by the phase oscillator ϕ_i in the way that the natural length L_i is given by $L_i = \bar{L}_i (1 - a \cos \phi_i)$. By this, the outer skin can produce contractile force periodically. Also, we assumed diffusive interaction between the pair of adjacent oscillators. In the design of Slimy, the *discrepancy function* was given in the form proportional to the sum of the square of
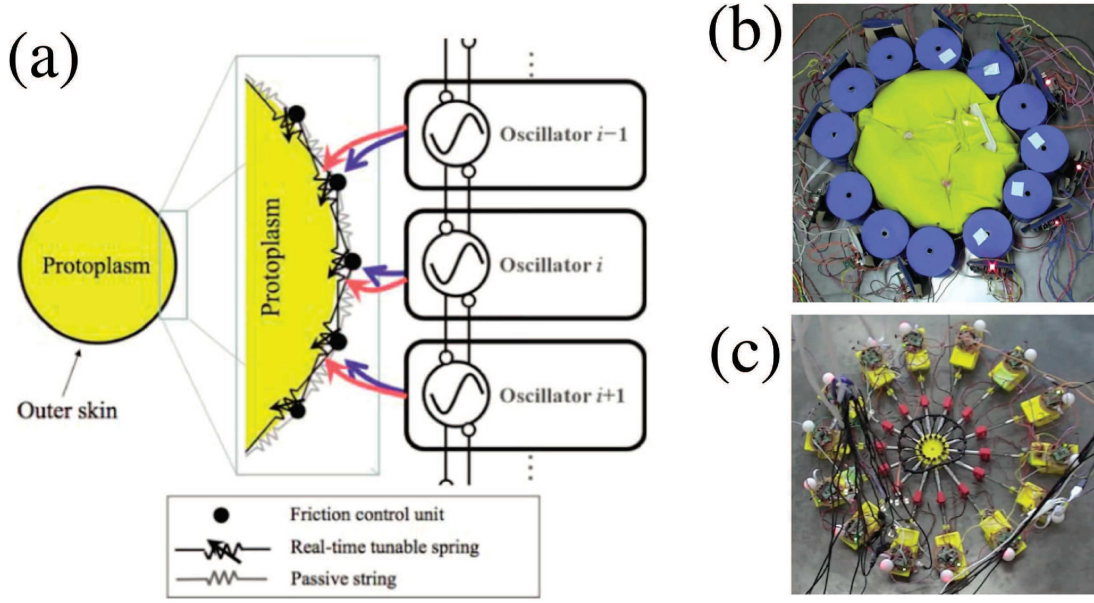
Figure 8.   (a) Sschematic of Slimy   (b) Slimy 1   (c) Slimy 2

tension T_i as follows.

$$I_i = \frac{\sigma}{2} T_i^2 \quad \text{where} \quad T_i = \kappa \left(\frac{\ell_i}{L_i} - 1 \right)$$

Then the feedback signal h_i to the i-th RTS is given by

$$h_i = -\frac{\partial I_i}{\partial \phi_i} = -\sigma T_i \frac{\partial T_i}{\partial \phi_i}$$

It should be emphasized that the feedback signal h_i can be generated only by locally available information.

Slimy is equipped with friction controlling units at the joints of the connected RTSs as shown in Fig.8(a). The phase oscillator controls not only the natural length of RTS but also the switching of the friction control unit locally. In addition, stiffness in the frontal part is lowered in imitation of true slime mold by making the mean natural length $\bar{L}_i$ larger at the near side to the attractant.

We performed simulations under such setting and obtained several results. Fig.9(a) indicates that the phase gradient is generated and the phase wave runs from the frontal part (near side to the attractant) to the rear, and the robot can make locomotion if the anchoring timing is appropriately taken. The simulation that robot successfully pass through the narrow aisle is presented in Fig.9(b). These results indicates that adaptive motility function emerges through spontaneous arrangement of the phase distribution, which is achieved by the complete ADC.
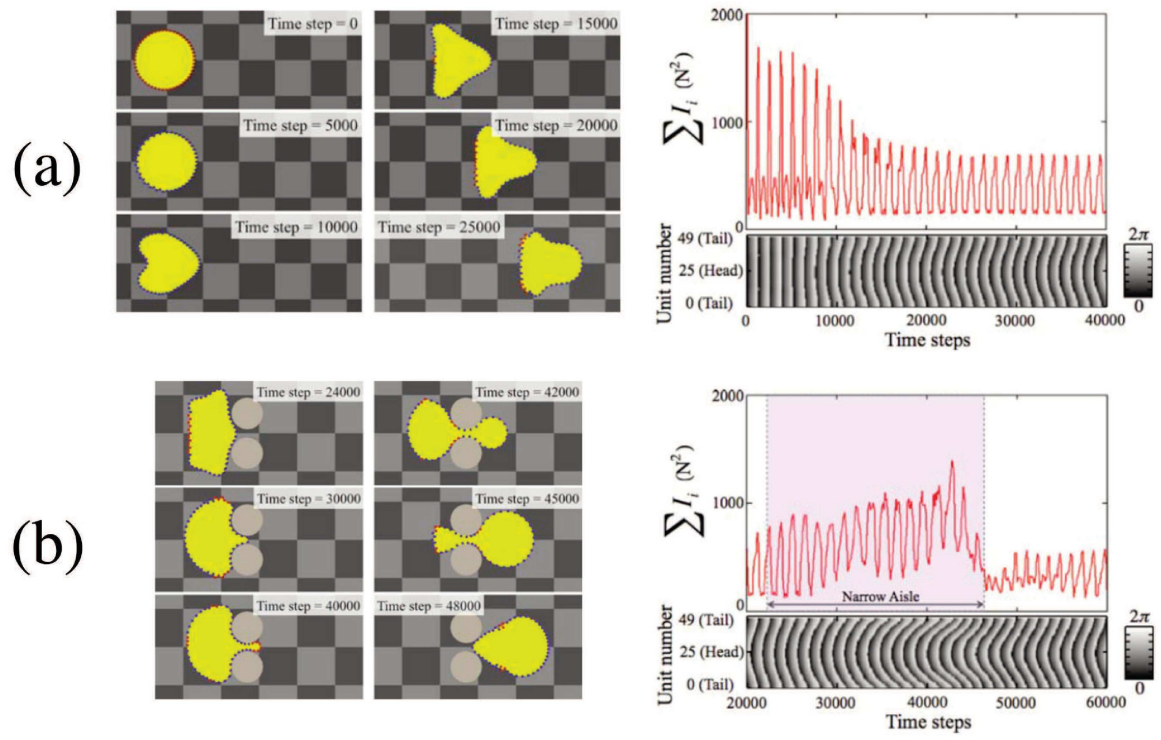
Figure 9.   (a) Generation of the locomotion to the direction of attractant (b) Representative data of the locomotion through the narrow aisle

On the basis of this model we produced real robots Slimy 1 and Slimy 2, shown in Fig.8 (b), (c), both of which control the friction by switching electromagnets. The part of protoplasmic sol is realized approximately by the balloon filled with the air in Slimy 1, while the connected cylinders are equipped in a radial fashion so as to guarantee the strict conservation law in Slimy 2. It was confirmed that both of them could perform locomotion toward the attractant by applying the same control rule with the model.

In our study of Slimy, effective locomotion was attained through the conservation of the protoplasm and the stiffness control in the same way with the plasmodium. Thus, the locomotion of Slimy is a direct imitaion of the locomotion of true slime mold, and the motion of Slimy is rather amoeba-like. However, the robots have no mechanism corresponding to the sol-gel transition, which is indispensable for the locomotion of real amoeba. Thus, they inevitably have characters of a crawler (need a friction control), which is different from true slime mold and amoeba. Therefore, Slimy is regarded as a new type of soft robot inspired by amoeba, rather than as a copy of some animal. Although the simulation could exhibit smooth locomotions, hardness of the devices prevented the real robots from attaining sufficiently soft motion. In order to produce really soft robots, we need soft materials for the hardware, and it is the objective of the next step of our study.

§ 3.2.   Snake-like robot : HAUBOT

HAUBOT series are robots targeting the snake-like locomotion in our project [7, 8]. We present HAUBOT 2 in which the *discrepancy* is used for generating not only a phasic feedback signal but also a tonic one.

HAUBOT 2 has a one-dimensional link mechanism as a backbone, and it generates a motion similar to snakes' lateral undulation by giving torque to each joint. In order to torque the joint, we use either the antagonistic muscles or direct rotation of the motor. In the mathematical model, we adopt the former and express the antagonist by the pair of RTSs, which enables us to provide backdrivability to the actuators and to control the torque and the stiffness simultaneously. The real robot HOUBOT 2 employ the latter, and has elastic elements that can store a *discrepancy* between the target angle given by the motor (exactly speaking, the mean of angles given by the upper and the lower motor) and the actual joint angle. In addition, HAUBOT 2 has a special mechanism to attain tonic control (See Fig.10(b)).

In the simulations of HAUBOT 2, we set actuators (RTS) and controllers aligned along the left line and the right line, in which the controllers are expressed by the phase oscillators ϕ_i^p where $p = 0$ denotes the left line and $p = 1$, the right line. The equation of the controllers given below produces phase waves with a proper velocity running from head to tail in both the left and the right lines, and maintain the anti-phase relation
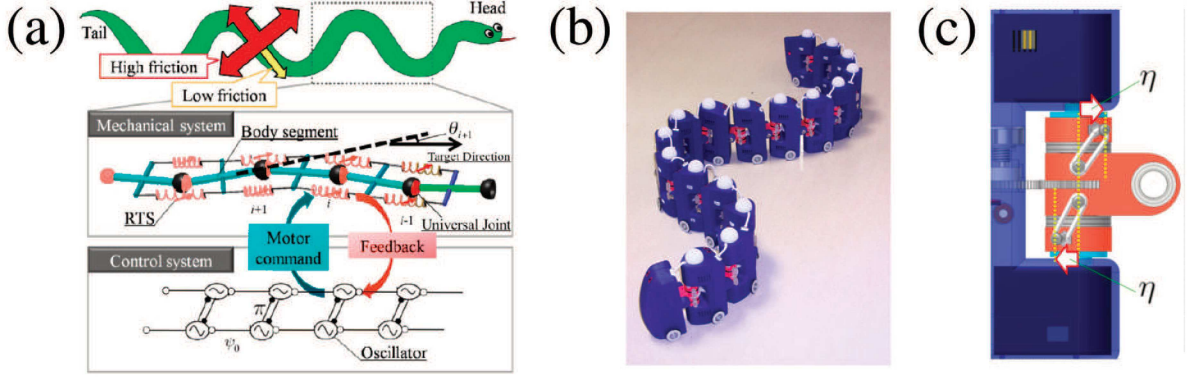
Figure 10.   (a) Schematic of HAUBOT 2   (b) HAUBOT 2 (c) Distortion caused by opposite rotations of the upper and the lower motor can adjust the degree of muscle tonus η.

between the two waves.

$$(3.1) \qquad \dot{\phi}_i^{\,p} = \omega + \epsilon_1 \sin\left(\phi_{i-1}^p - \phi_i^p - \Delta\phi\right) + \epsilon_2 \sin\left(\phi_i^p - \phi_i^{1-p}\right) + h_i^p$$

where h_i^p is a feedback signal to the oscillator ϕ_i^p derived from the *discrepancy function*. Let us define the *discrepancy function* I_i^p by using the tension of RTS $T_i^p = \kappa\left(\frac{\ell_i^p}{L_i^p} - 1\right)$ as follows.

$$(3.2) \qquad\qquad\qquad I_i^p = \sigma |T_i^p|$$

Following the rule of the *discrepancy control*, the feedback signal h_i^p is calculated by

$$(3.3) \qquad\qquad\qquad h_i^p = -\frac{\partial I_i^p}{\partial \phi_i^p}$$

In the design of HAUBOT 2, not only a phasic feedback but also a tonic feedback is taken into account. Tonic feedback is given by the policy "strengthen the stiffness in more stressed actuators", which is achieved by changing the mean natural length $\bar{L}_i^p$ as follows.

$$(3.4) \qquad\qquad \bar{L}_i^p = \bar{L} - \mu \int_{-\infty}^{t} I_i^p(t') e^{-(t-t')/\tau} dt'$$

Fig.11 shows the results of the simulation in which the robot crawls on the high friction surface and the ascending slope. The results of four cases where phasic and tonic feedback are switched on and off, respectively, are compared. These results indicate that the phasic feedback enhances the energy efficiency and the tonic feedback achieves powerful motion, and both of them can collaborate, as shown in Fig.11(iv).
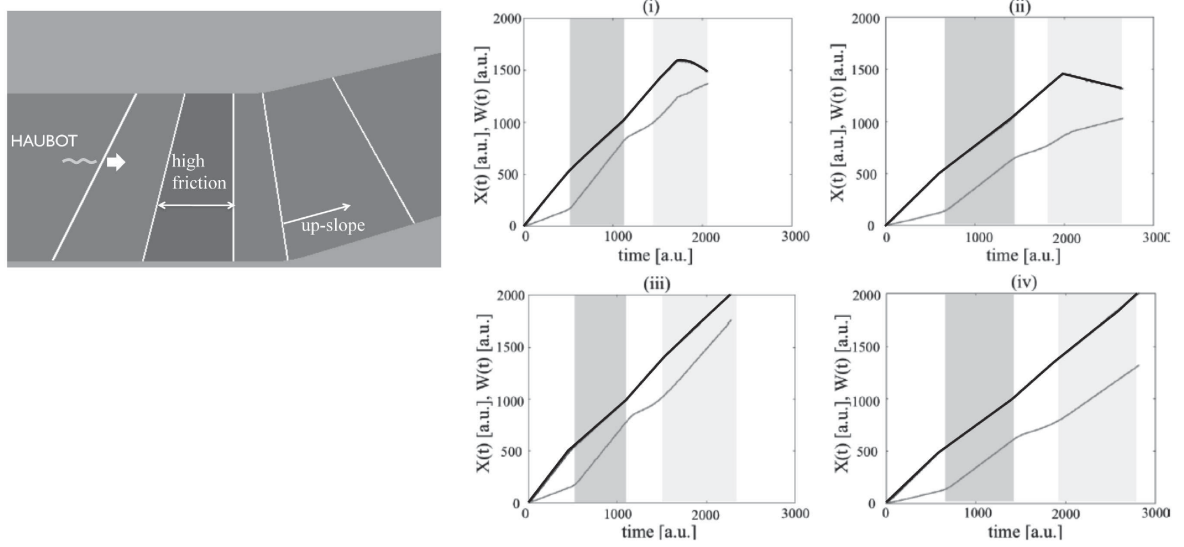
Figure 11.   Simulations of HAUBOT 2 crawling across the high friction surface and the ascending slope. In the panels (i) - (iv), $X(t)$ (black line) indicates the distance which the robot gained, and $W(t)$ (gray line) indicates the consumed energy.   (i) No feedback. Fails to climb a slope. (ii) Only phasic feedback. Energy efficiency is better than (i), but fails to climb a slope. (iii) Only tonic feedback. Succeeds in climbing a slope, but energy efficiency is not so good. (iv) Both of feedback work. Succeeds in climbing a slope, and achieves good energy efficiency.

§ 3.3.   Quadruped Robot – OSCILLEX

We also tried to apply *discrepancy control* to the quadruped robot which is termed as OSCILLEX [9]; it is shown in Fig.12 (a). Each leg of OSCILLEX is controlled by the phase oscillator. More specifically, the target position of the i-th leg's toe is determined by the phase oscillator ϕ_i, as shown in Fig.12 (b), and its orbit is given by the combination of two ellipses. Sensors and elastic elements are provided at the tips of the legs, which enable the robot to obtain the floor reflection force.
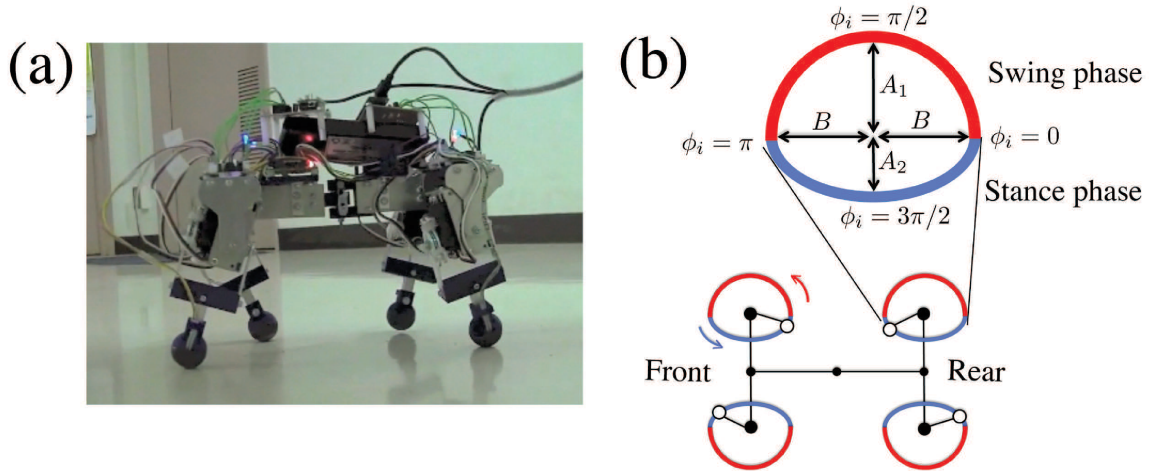

Figure 12.   (a) OSCILLEX   (b) Target position of the toe given by the phase oscillator

In the design of the controller, no direct interaction between the oscillators is assumed and the *discrepancy function* is defined by

$$(3.5) \qquad\qquad\qquad I_i = \sigma N_i \sin \phi_i$$

Thus, the equation of the phase oscillator ϕ_i is

$$(3.6) \qquad\qquad\qquad \dot{\phi}_i = \omega - \sigma N_i \cos \phi_i$$

This *discrepancy function* is not completely the same as the previous two examples in which the *discrepancy function* is a direct measurement of the difference between the real state of actuator and the state of actuator desired by controller. As long as the i-th leg is in a swing phase (*i.e.* $N_i = 0$), no effects exist on the *discrepancy function*. Once the leg becomes a supporting leg (*i.e.* $N_i > 0$), the system resists the increase in $\sin \phi_i$. If the floor reflection force exists, the larger it is, the stronger is the feedback for maintaining the leg as a supporting leg. This seems to be a quite natural feedback. The *discrepancy function* introduced here can be considered to express "some sort of uneasiness of the body", and it is an extended concept of the original meaning in some

sense. Thus, in this robot, each oscillator shift its phase so as to reduce the uneasiness by *discrepancy control.*

In this robot, no direct interactions were assumed between the oscillators because our target here is spontaneous emergence of gait patterns not induced by the elaborated control signals. Of course, there exist implicit interactions between oscillators through the body, and it modifies the phases of oscillators. Actually, if some leg enters a swing phase and the ground reflection vanishes, the ground reflections of the other supporting legs increase, and consequently, they are affected by the feedback signal.

The experiments of the real robot showed good results, i.e., very quick transitions from the initial state to the steady gait. (See Fig.13.) If we use a coupled oscillator system as a controller, it usually takes a long time to attain the phase distribution that assures steady motion from the initial phase distribution, which is in contrast to OSCILLEX. The ability of OSCILLEX for quick adjustment arises from the fact that the character of the controller governed by the equation (3.6) changes from "oscillatory" to "excitable" when σN_i becomes greater than ω. In other words, the equation (3.6) defines *active rotator*, which is an extended concept of the phase oscillator [10]. In this robot, legs with high load are used as supporting legs until the load is weakened; thus, the quick transition to the steady gait is attained. In addition, it is observed that the duty ratio and the diagonality changes adaptively, corresponding to the physical characteristic of the body of robots.
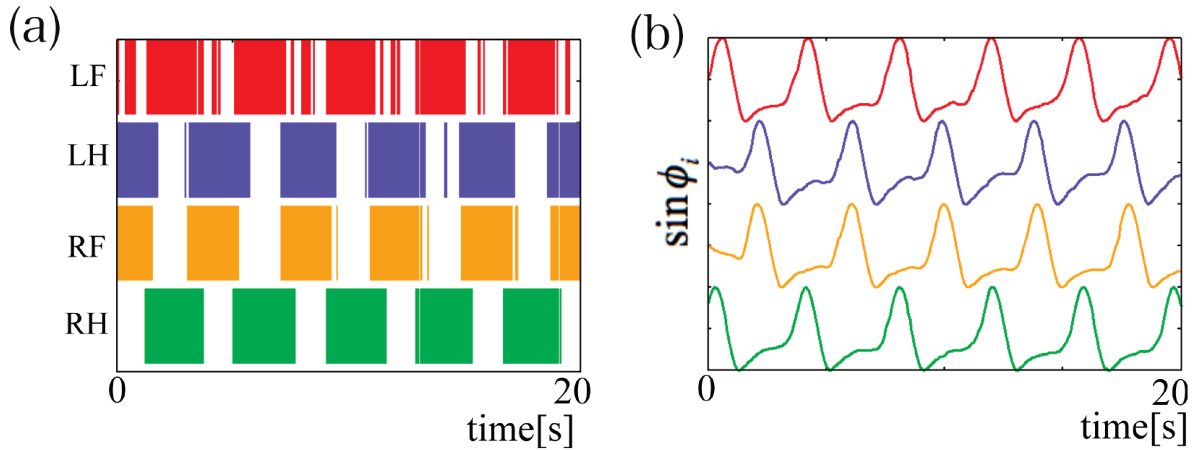

Figure 13.   (a) Gait diagram   (b) Graph of time vs. $\sin \phi_i(t)$

§ 4.   Discussion

In this report, we presented a control method based on the *discrepancy function,* which was learned from the plasmodium of true slime mold. We applied it to robots

with several types of bodies, and examined its potential. We believe that our method is sufficiently effective under the framework of ADC, using coupled oscillators such as CPG.

An important objective of our project was to establish the design principle of ADC. Our current scheme is as follows :

1. Provide backdrivability to the actuators to achieve flexibility of the body and to easily acquire the local sense of force.

2. Design a *discrepancy function* appropriately and generate a feedback signal to the phase of oscillator so as to reduce it.

3. Generate a tonic feedback to the actuator as necessary.

The second item listed above is limited to the case where coupled oscillators or active rotators are used as controllers.

Animals exhibit various types of locomotion; thus, many types of robots mimicking them can be designed. Therefore, one specific control method cannot be a panacea for all types of robots. Our principle is to design a good *discrepancy function* so as to generate good feedback to the controller. It is similar to the approach in mechanics to design the Lagrangian in individual cases, and to then derive the Euler-Lagrange equation. (Particular factors such as the shape of the object or selection of the coordinate system are involved in the design of the Lagrangian.) In our method, particular factors in each case are taken into account in the design of the *discrepancy function*, and the guideline for designing it is to express "some sort of uneasiness of the body" using locally available information. Unfortunately, this design guideline is not as straightforward as that in the case of the Lagrangian, $L = T - U$. We believe that this is unavoidable because the objects under consideration are not simple physical systems, but complex coupled systems composed of physical systems and controllers. At present, we have to determine more concrete design guideline by studying numerous examples.

Although discussions in this report supposed the usage of coupled oscillators (or active rotators), it is not always appropriate. From Nematoda to snakes, many animals have one-dimensional string shapes, and they perform locomotion in almost all the cases by running some wave along their body axis. HAUBOT could mimic the lateral undulation of snakes by assuming a one-dimensional array of coupled oscillators to run a wave from head to tail. It surely indicates the effectiveness of *discrepancy control*; however, it is questionable to adopt coupled oscillators as a controller in such a string-shaped robot. When the one-dimensional array of oscillators is used as a controller, the initial transition of motion is always a problem. Actually, the motion is disordered until the initial phase distribution transforms into coherent distribution, which realizes steady motion. In contrast, animals show a tight and smooth motion from the beginning. In

addition, it seems unnatural to generate a traveling wave along the coupled oscillators because it is equivalent to assuming a very slow wave running through the nervous system. Therefore, we believe that a coupled oscillator is not an appropriate controller for animals with one-dimensional bodies. Instead, a more plausible description is that units consisting of the local nervous system and musculoskeletal system are lined up in a one-dimensional array. We will discuss this issue in a future study.

Finally, we would like to conclude by quoting Prof. Masami Ito, who has been a source of inspiration us.

"Animals get information coming from various sensors located on their body surface. If they integrate all information and examine their all possible combinations searching for the optimum behavior, the decision making process should be too time-consuming. Instead, they must have found a way to obtain good enough and less conflicted solution quickly in their evolution process. In any case, the most important mission of animals is to survive."

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