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A CPG-based Decentralized Control of a Quadruped Robot Inspired by True Slime Mold

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***Abstract*— Despite its appeal, a systematic design of an autonomous decentralized control system is yet to be realized. To bridge this gap, we have so far employed a "back-to-basics" approach inspired by *true slime mold*, a primitive living creature whose behavior is purely controlled by coupled biochemical oscillators similar to central pattern generators (CPGs). Based on this natural phenomenon, we have successfully developed a design scheme for local sensory feedback control leading to system-wide adaptive behavior. This design scheme is based on a "discrepancy function" that extracts the discrepancies among the mechanical system (*i.e.*, body), control system (*i.e.*, brain-nervous system) and the environment. The aim of this study is to intensively investigate the validity of this design scheme by applying it to the control of a quadruped locomotion. Simulation results show that the quadruped robot exhibits remarkably adaptive behavior in response to environmental changes and changes in body properties. Our results shed a new light on design methodologies for CPG-based decentralized control of various types of locomotion.**

I. INTRODUCTION

Animals exhibit astoundingly adaptive, supple and versatile locomotion in real time under unpredictable real world constraints. To endow robots with similar capabilities, their bodies must have significantly many degrees of freedom equivalent to that of living organisms. For successfully coordinating movement with many degrees of freedom based on the various circumstances, *autonomous decentralized control* plays a pivotal role, and has therefore attracted considerable attention. In fact, living organisms nicely orchestrate and maneuver their many degrees of freedom in their bodies by distributed neural networks called *central pattern generators* (CPGs), which are responsible for generating rhythmic movements, particularly locomotion [1]. Based on this knowledge, various studies have been conducted to implement decentralized control schemes in robots so as to generate adaptive locomotion, in particular focusing on legged locomotion [2]-[6]. Thus, autonomous decentralized control method is expected to become an attractive tool for designing highly adaptive robots.

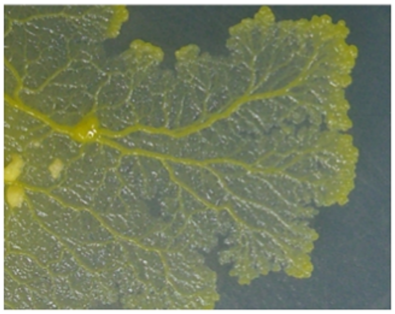

Fig. 1. True slime mold (*Physarum polycephalum*). True slime mold exhibits surprisingly adaptive amoeboid locomotion whose behavior is controlled in a fully decentralized manner based on coupled biochemical oscillators. Due to this, slime mold is a good model organism for understanding how biological decentralized control is achieved.

Despite its appeal, a systematic way of designing such autonomous decentralized controllers is still lacking because a methodology connecting local behavior to global behavior that induces useful functionalities, *e.g.*, adaptability and fault tolerance, has not yet been established. To alleviate this, we must consider the following issues:

(1) Dynamics of the individual components to be implemented, *i.e., intra-modular dynamics*.
(2) Interactions between the components to be implemented, *i.e., inter-modular dynamics*.
(3) Methods of coupling the control and mechanical systems, *i.e., brain-body interaction*.

As the pioneering studies done by Taga *et al.* [4]-[6] indicate, issues (1) and (2) are often modeled as coupled (nonlinear) oscillator systems. In contrast, for issue (3), interactions between control and mechanical systems have been designed on an ad-hoc basis for specific applications. In sum, we face an undeniable lack of consistent methodologies for designing the means of interaction between control and mechanical systems.

In light of these facts, we have previously employed a " back-to-basics " approach by focusing on *true slime mold* (*Physarum polycephalum*; see Fig. 1), which uses purely decentralized control mechanisms based on coupled biochemical oscillators similar to CPGs [7]. The body of true slime mold is soft and malleable. Further, there is an explicit conserved quantity, *i.e.*, the mass of the protoplasm. Therefore, physical interactions are induced inside the body parts of true slime mold, similar to that observed in waterbeds, which guarantees to connect the local behavior to the global behavior effectively. Due to these intrinsic

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properties, slime mold serves as an excellent biological organism that allows us to extract the design methodology of how a biologically decentralized control system can be realized. In our previous study on slime mold, we introduced a systematic design methodology for the interaction between control and mechanical systems based on a *discrepancy function* that extracts the discrepancies among the control system, mechanical system, and the environment [8][9]. A key remaining problem is understanding the extent to which the decentralized control scheme extracted from true slime mold is applicable to the control of different types of locomotion. In other words, is what is true for slime mold also true for different types of living organisms?

To answer this question and better understand locomotion, we implement the abovementioned design scheme to control quadruped locomotion. Simulation results show that remarkable adaptability to both environmental changes and changes in body properties can be successfully achieved by implementing the decentralized control scheme extracted from true slime mold.

In addition to this introductory section, this paper is organized as follows: Section II illustrates our proposed decentralized control method and how we implemented it to control a quadruped robot; Section III presents simulation results particularly in terms of adaptability. Discussions and conclusions with future works are shown in Section IV and V, respectively.

II. QUADRUPED ROBOT MODEL

A. Mechanical System

The mechanical system of the quadruped robot is schematically shown in Fig.2. Each pair of forelegs and hind legs is connected by rigid links (link 5-9-7 and link 6-10-8), respectively. The center of these links is connected by a rigid backbone link (link 9-11-10) such that the foreleg link and hindleg links are perpendicular to the backbone. At the center of the backbone, we embed a universal joint with a passive rotational spring to model the backbone of actual animals which can bend and twist to some extent. In our model, a certain amount of deformation is allowed in each leg by implementing a spring and a damper by which the robot can measure the ground reaction force. We also assume that the ground frictional force is large enough such that the foot at the stance phase does not slip.

A universal joint is implemented in each of the shoulder and hip joints, where the joint angle is controlled according to the proportional-differential (PD) control. To move the legs rhythmically, we also implement an oscillator in each of these joints. As shown in Fig.3, the target position of the tip of the ith leg is actively controlled according to the corresponding oscillator phase ϕ_i defined as follows:

$$\begin{aligned} X_i &= -A\cos\phi_i, & (0 \leq \phi_i < 2\pi), \\ Y_i &= B_1\sin\phi_i & (0 \leq \phi_i < \pi), \\ Y_i &= B_2\sin\phi_i & (\pi \leq \phi_i < 2\pi), \end{aligned} \quad (1)$$

where A, B_1, and B_2 are positive constants with $B_1 > B_2$, and X_i and Y_i represent the sagittal and lateral components of the position vector that points to the target position of the tip of the ith leg with reference to the corresponding shoulder or hip joint. Note that Y_i is positive when the target position is away from the body.

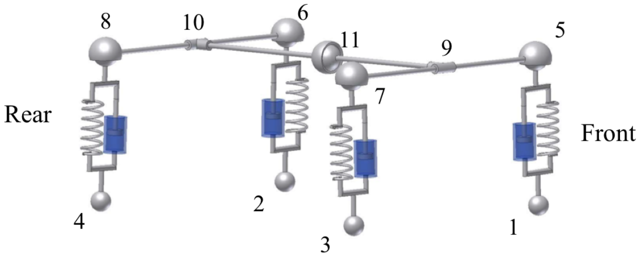

Fig. 2. Schematic illustration of the mechanical system. A universal joint with a passive rotational spring is embedded at the center of the backbone (11). In each leg, a spring and a damper are implemented. A universal joint is implemented into each of the shoulder and hip joints (5,6,7, and 8), where the joint angle is controlled by a PD control.

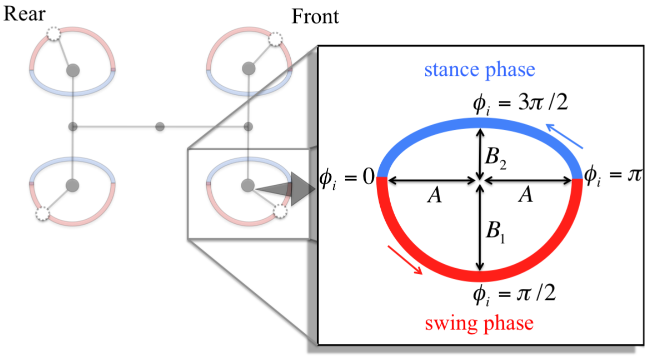

Fig. 3. Target trajectories of the tips of the legs. The legs tend to be in a swing phase for $0 \leq \phi_i < \pi$ (red lines) and a stance phase for $\pi \leq \phi_i < 2\pi$ (blue lines). The magnified view illustrates the target trajectory of the right fore leg.

The proportional gain of the PD control should be set small enough such that the actual position of the tip of the leg can deviate from its target position to some extent. Such a “compliant” mechanical structure yields a situation-dependent discrepancy, which can be used to produce adaptive and supple locomotion, as described below. Further, the ith leg tends to lift off the ground (the swing phase) for $0 \leq \phi_i < \pi$, while it tends to be on the ground to support the body (the stance phase) for $\pi \leq \phi_i < 2\pi$. These leg movements enable the robot to change the position of its center of mass, effectively switching between the stance and swing phases naturally despite its simple mechanical structure.

B. Control System

We describe each individual component that constitutes the CPG as a phase oscillator. To understand the coupling that occurs between the control and mechanical systems, we do not consider the direct interaction between the oscillators but instead focus on the local sensory feedback from the body. The temporal evolution of the oscillator phase ϕ_i is described as follows:

$$\dot{\phi}_i = \omega - \frac{\partial I_i}{\partial \phi_i}, \tag{2}$$

where ω is the intrinsic frequency. The second term expresses the local sensory feedback from the mechanical system. I_i is the discrepancy function, which contains a locally available quantity that characterizes the discrepancies among the control system, the mechanical system, and the environment. Here, we define I_i as

$$I_i = \varepsilon N_i \sin\phi_i, \tag{3}$$

where ε is a positive constant describing the magnitude of the feedback from the mechanical system to the control system, and N_i is the ground reaction force acting on the ith leg.

To understand the physical meaning of (3), we first recall that the ith leg tends to be in the swing phase for $0 \leq \phi_i < \pi$. Thus, if N_i is large when ϕ_i is within the range $0 \leq \phi_i < \pi$, the mechanical system does not follow the command from the control system. Such a discrepancy arises because each leg interacts with the environment and the other legs via the body. Hence, $N_i \sin\phi_i$ contains important information about the discrepancies among the control system, the mechanical system, and the environment. Theses discrepancies are reduced by modifying the oscillator phase, as shown in (2), which leads to "well-balanced" coupling between the control and mechanical systems. Thus, by implementing a "compliant" mechanical structure that yields situation-dependent discrepancy and employing the design scheme to reduce the discrepancy, the robot can move and successfully adapt to changes in the environment. Note that the phase is not modified during the swing phase because I_i becomes zero; however, this does not cause a serious problem, because the discrepancy is reduced to a great extent during the stance phase.

III. SIMULATION RESULTS

We have constructed a simulator and conducted numerical simulations to verify the validity of the proposed design scheme. The effect of the local sensory feedback is investigated through the examination of the adaptability to the changes both in the environment and the body properties. The parameter values employed in the simulations are listed in Table I. Note that these parameters are non-dimensional, which should be properly scaled when we develop a quadruped robot in the real world.

TABLE I
PARAMETER VALUES EMPLOYED IN THE SIMULATIONS.

parameter	value	parameter	value
ω	2.5	A	0.092
B_1	0.060	B_2	0.045
$P-gain$	100	$D-gain$	20
ε	0.02		

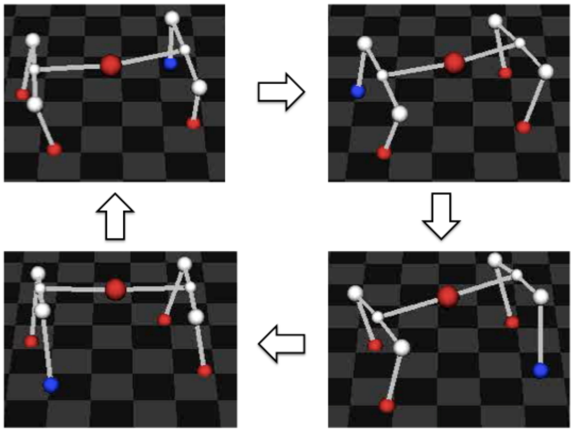

Fig. 4. Snapshots when a walk is generated through local sensory feedback. In each snapshot, the front is to the right. The color of the tip of the leg shows its state: blue when the leg is in the swing phase and red when in the stance phase.

A. Steady Gait

As shown in Fig. 4, a steady gait emerges through local sensory feedback. More specifically, one leg is in the swing phase while the other legs maintain their stance phase; the leg in the swing phase changes regularly, cycling through all four legs. This gait pattern is called a "walk". The gait diagram and the oscillator phases during one cycle of the walk are shown in Fig. 5. The oscillators are synchronized with an equivalent phase difference of approximately $\pi/2$. Each leg enters the swing phase when the phase of the corresponding oscillator is approximately $\pi/2$. These results indicate that the control system and the mechanical systems are well-coordinated through the local sensory feedback.

Note that a stable gait emerges even in the absence of direct interactions between the oscillators. The local sensory feedback plays a crucial role in the interactions between the legs, because N_i of the discrepancy function contains the information about the other legs, as described above. Indeed, the sum of the discrepancies $\sum_{i=1}^{4} I_i$ decreases from its initial conditions because of the local sensory feedback, which leads to the stable gait, as shown in Fig. 6.

To understand how the walk becomes stable, suppose that the left foreleg is in the swing phase while the other legs are in the stance phase, as shown in Fig. 7(a). In this case, the center of mass exists in the support polygon constituting the three legs in the stance phase. Due to the local sensory feedback term in (2), the oscillator phases of the legs in the stance phase are modified so that they remain in the stance phase; however, when the left foreleg contacts the ground, the center of mass moves away from the support polygon. As a result, the left hindleg lifts off the ground and the other three legs form the support polygon, as shown in Fig.7(b). Following this pattern further, the leg in the swing phase cycle through one after another, leading to the stable walk gait.

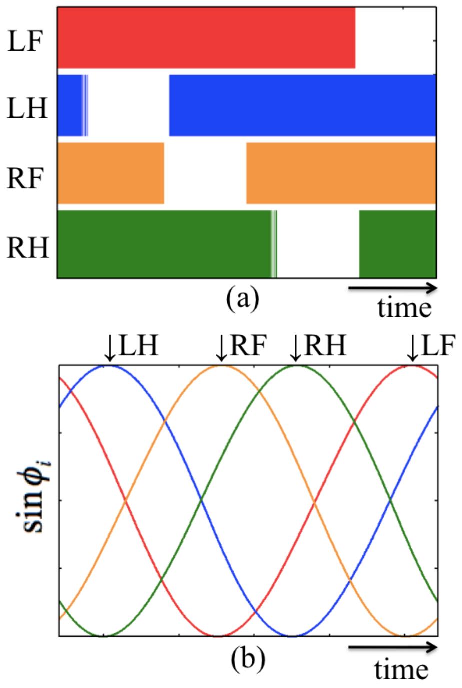

Fig. 5. Simulation results when a walk is generated are shown as (a) a gait diagram and (b) oscillator phases during one cycle of the walk. In (a), legs in the stance phase are shown by the colored bars: the gap between the bars show the legs in the swing phase. *LF*, *LH*, *RF*, *RH* refer to the left fore, left hind, right fore, and right hind legs, respectively.

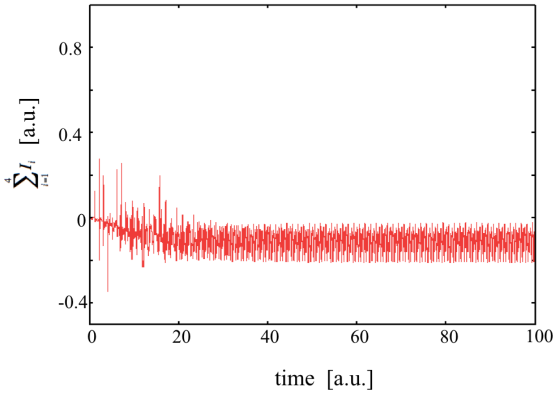

Fig. 6. Temporal evolution of the sum of the discrepancies. Due to local sensory feedback, the discrepancy decreases from that of the initial condition.

B. Adaptability to the Environment

We have examined the adaptability of our model to environmental changes. To do so, we apply an external force to the body. Fig. 8 shows the gait diagram when such an external force is applied to the right shoulder during a walk. Although the body temporarily loses its balance and the switching between the stance and swing phases becomes irregular, the steady gait is restored again after about three cycles. This adaptability is realized by the local sensory feedback. As shown in Fig. 9, the sum of the discrepancies is reduced through approximately three cycles after the external force is applied, although it increases temporarily.

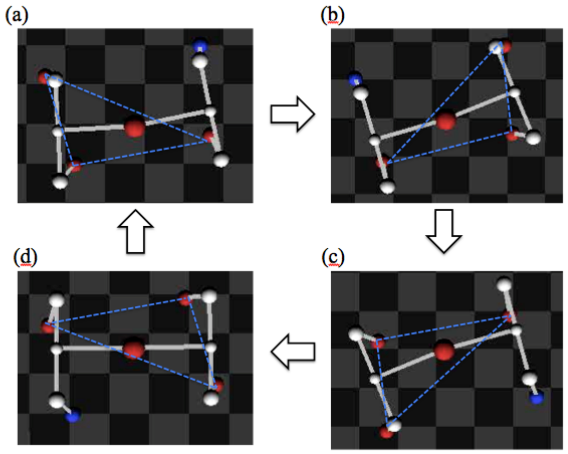

Fig. 7. Movement of the center of mass during a walk. Dashed lines show the support polygon that constitutes the legs in the stance phase. In each snapshot, the front is to the right.

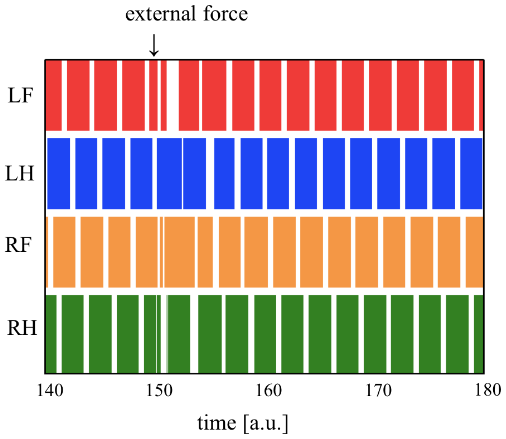

Fig. 8. Gait diagram when an external force is applied to the right shoulder during a walk. Although the switching between the stance and swing phases becomes irregular, the steady gait is restored after about three cycles.

C. Adaptability to Changes of Body Properties

To further investigate adaptability, we studied the impact of changes to body properties. Figs. 10 and 11 illustrate the results when the forelegs are longer than the hindlegs. Although a walk occurs in this case (Fig. 10), the gait diagram differs significantly from the case in which the leg lengths are identical (Fig.5). Indeed, the duty ratio of the forelegs is larger than that of the hind legs. When the hindlegs are longer than the forelegs, the opposite tendency is observed, as shown in Figs.12 and 13.

IV. DISCUSSION

We have applied the CPG-based decentralized control scheme extracted from true slime mold to quadruped locomotion, and have shown that highly adaptive behavior emerges spontaneously without any centralized control mechanism. Although the *phase reset scheme* in which the phase is reset to zero when the foot starts to contact the ground has been used as a useful design methodology for the brain-body interaction of legged locomotion [10], [11], we expect that our design methodology captures the mechanism

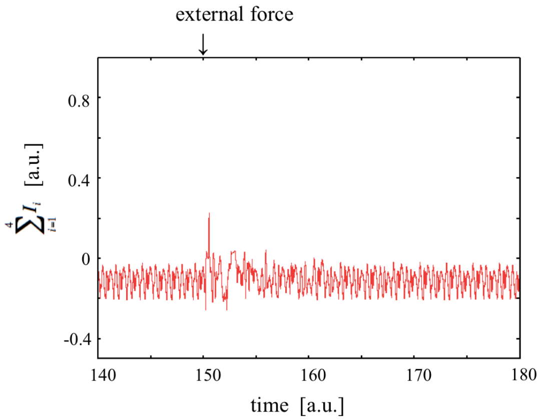

Fig. 9. Sum of discrepancies when an external force is applied to the right shoulder during a walk. Although the discrepancy increases temporarily, it is reduced after about three cycles.

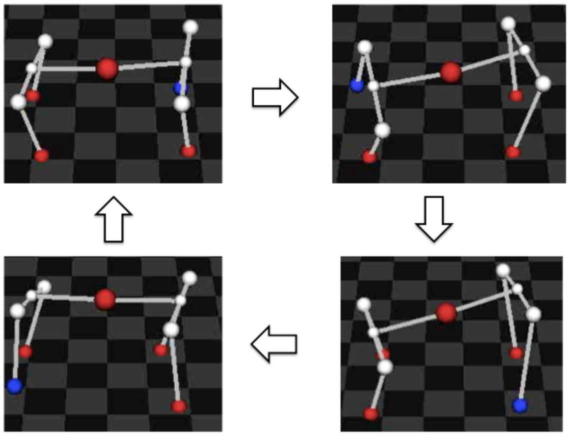

Fig. 10. Snapshots when the forelegs are longer than the hindlegs.

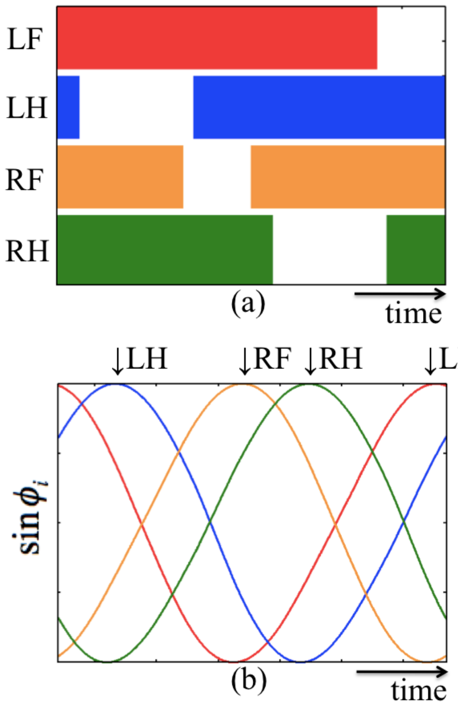

Fig. 11. Simulation result when the forelegs are longer than the hindlegs: (a) gait diagram and (b) oscillator phases during one cycle.

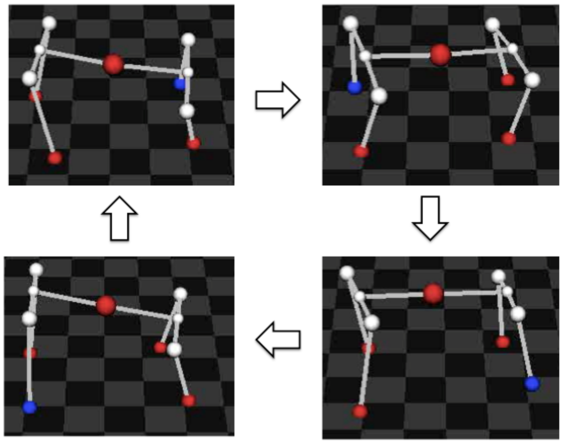

Fig. 12. Snapshots when the hindlegs are longer than the forelegs.

underlying animal's locomotion more accurately because of the following reasons:

First, in the phase reset scheme, the mechanical system reacts to its control system normally only when the foot starts to contact the ground, *i.e.*, the beginning of the stance phase. In contrast, the mechanical system and the control system are interacting continuously during the stance phase in our method. Due to this "continuous" interaction, the system immediately adapts to environmental changes as long as at least one of its legs is in the stance phase. Further, such continuous interaction seems physically more plausible. Second, the phase reset scheme uses only "qualitative" information about the foot's contact (on or off), whereas our design methodology uses "quantitative" information describing how each foot "feels" the ground reaction force. Containing this quantitative information in the sensory feedback term in (2) allows each leg to recognize the positional relationship between the legs, *i.e.*, how the legs support the body at that moment, without an expensive cost of computation. For example, the shift from the stance to the swing phase in the jth leg influences the phase of the ith oscillator ($j \neq i$) through the increase of N_i.

Very interestingly, although we have intensively considered the design scheme using the concept of discrepancy function, the proposed model can also be interpreted from totally different viewpoint. Equations (2) and (3) can be rewritten by the form of an *active rotator model* [12] as

$$\dot{\phi}_i = \omega - a_i \cos\phi_i, \qquad (4)$$

where $a_i = \varepsilon N_i$ is a parameter which determines the dynamics of the phase ϕ_i: $\dot{\phi}_i$ is always positive, *i.e.*, oscillatory regime, for $a_i < \omega$ while ϕ_i is attracted into a steady stable solution *i.e.*, excitatory regime, for $a_i > \omega$ (see Fig. 14). Thus, switching between the oscillatory regime and the excitatory regime is induced by the change of the ground reaction force N_i. We believe that this perspective will also lead to deeper understanding of the mechanisms underlying versatile animal locomotions.

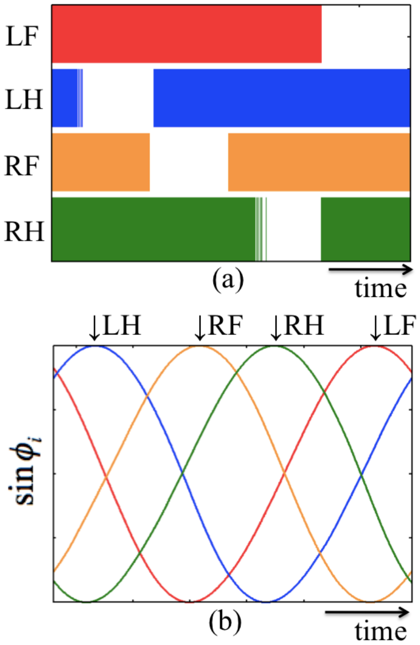

Fig. 13. Simulation result when the hindlegs are longer than the forelegs: (a) gait diagram and (b) oscillator phases during one cycle.

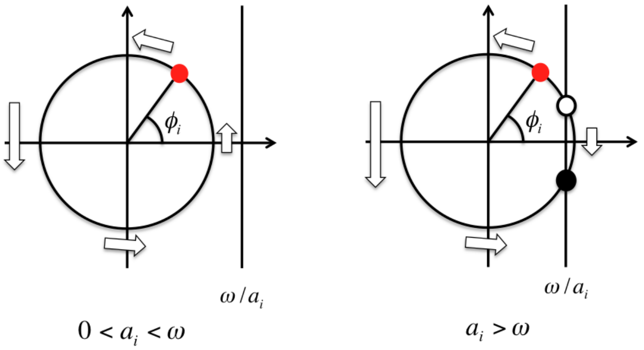

Fig. 14. Dynamics of phase ϕ_i when a_i is varied. Open and filled black circles denote unstable and stable solutions, respectively.

V. CONCLUSION AND FUTURE WORK

In this paper, we developed a CPG-based decentralized control scheme of quadruped locomotion by focusing on the interaction between the control and mechanical systems based on a discrepancy function inspired by the behavior of *true slime mold*. Simulation results show that remarkable adaptability to environmental changes and changes in body properties can be successfully achieved by implementing our design methodology. Highly adaptive behavior emerged spontaneously by employing the local sensory feedback, even in the absence of direct interaction between the oscillators.

In order to verify the validity of the proposed design scheme in the real world, we are now developing a real physical quadruped robot based on the design illustrated in Fig. 15. We will conduct experiments using this robot and investigate the adaptability to environmental changes and changes in body properties in near future. We also endeavor to clarify the mechanism how gait transitions occur. Although we observed walks in the present study, other gait patterns such as a trot, pace, or gallop have not been observed. The development of quadruped robots, in which proper gait patterns emerge spontaneously depending on the situation encountered, is expected.

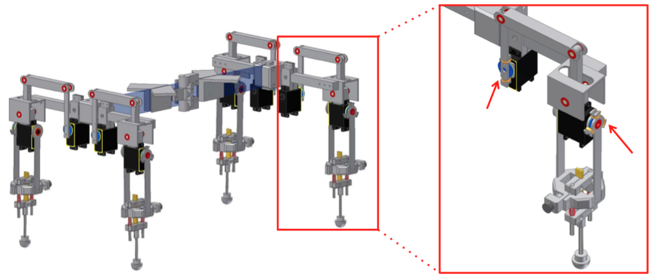

Fig. 15. Design of a real physical quadruped robot. Each leg is driven by a couple of servo motors. Elastic elements are implemented at the leg joints so that actual position of the tip of the leg can deviate from its target position to some extent (arrows). The ground reaction force can be measured by the displacement of the spring embedded on each leg.

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