# Structuring Sensory Information through Body Dynamics

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***Abstract*— As previously demonstrated in dynamic locomotion robots, the use of body dynamics is powerful for generating energy efficient rapid movement. This paper shows that body dynamics is an essential research issue not only for motor abilities but also for sensing; Because body dynamics is always coupled with the environment, the physical properties of the environment can be estimated by observing its own body movement. In particular, we investigate how the body dynamics derived from morphological properties could play a significant role in situated perception. A simulation model of rapid legged locomotion is used to demonstrate that "structured" sensory information can be generated through the intrinsic body dynamics. A set of experiments shows that the advantages of this approach are: (1) the informational structure has a set of discrete entities in continuous sensory space, and (2) multi-modal sensory stimulation can be generated through body dynamics. Based on the experimental results, we discuss how the precision and complexity of informational structure could be augmented.**

## I. INTRODUCTION

The concept of body dynamics has provided a significant impact to our ways of designing robotic systems. Especially one of the most fundamental aspects of the use of body dynamics lies in the fact that behaviors and functions should be viewed as a result from the interplay between the system and the environment. When a system properly exploits the given ecological niche, efficient behavior can be achieved with a very simple mechanism. The studies of passive dynamic walkers and rapid legged locomotion have nicely demonstrated this concept. Even without any actuation and control, the passive dynamic walkers are able to walk down a slope in a very natural way [1], [2], and they require extremely small amount of energy for walking even on the level ground [3], [4]. In addition, by exploiting compliant material properties, a number of legged robots demonstrated energy efficient rapid legged locomotion [5], [6]. The central research interests of this line of research, however, have been the performance of (locomotion) behavior such as energy consumption, maximum forward velocity, and stability.

Another important aspect of the body dynamics is that it can "structure" the sensory information. Recently, it has been shown that the physical properties of the system are significantly related to the perceptual and the learning processes (e.g. [7], [8]). The main argument of this line of research is that, if a system possesses a good morphological properties, the learning and the the perception can be simplified. A similar mechanism has been also shown in the studies of sensory-motor coordination (e.g. [9], [10], [11]). When the behavior is controlled by sensory-motor coordination with respect to a physical object in the environment, the sensory stimulation can be structured such that the object could be more easily discriminated from the background, and as a result, the task of categorization could be simplified. In general, as discussed in [12], the quality of sensory information can be significantly different when the system is designed for the behavior as a result of interplay between the body, control and the environment.

From this perspective, the goal of this paper is to explore the potential abilities of the body dynamics for sensory systems; Because the behavior induced by the intrinsic body dynamics is the result from the system-environment interaction, the proper design of body dynamics should be able to provide a basic setup for the sensory systems. In what follows, we first overview the conceptual mechanisms about what the body dynamics could do for the situated perception. Then, a form of rapid legged locomotion is introduced as a case study of the body dynamics, followed by a set of analyses. Finally, we will speculate implications and further perspectives of the proposed approach.

## II. BODY DYNAMICS AND INFORMATIONAL STRUCTURE

The basic mechanism of sensing ability through the body dynamics is as follows: When the behavior of a system is coupled with the environment, the physical properties of the environment is reflected on the behavior; Namely, the environment could potentially be recognized by observing the behavior. There are two salient properties that we obtain from this approach, which are the main focus of this paper. (1) Sensory information acquired through body dynamics provides a set of discrete entities in a continuous sensory space; And (2) more than trivial sensory information can be extracted through body dynamics, which results in the perception through multi-modal sensory channels.

### *A. Discrete sensory states*

One of the most fundamental issues in the field of machine learning has been how to construct a set of discrete sensory

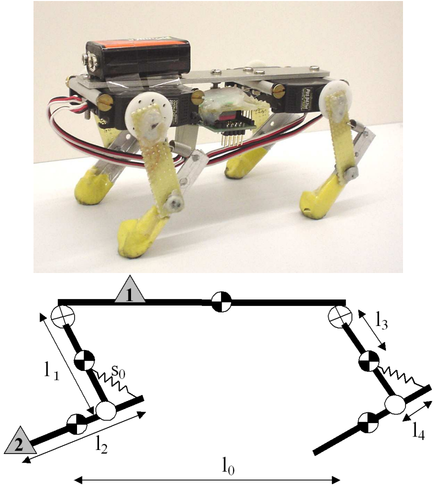

Fig. 1. (a) The quadruped robot, and (b) its simulation model used in the experiments. In the schematic (b), the circles denote passive joints and the circles with a cross inside denote the joints controlled by the servomotors. There are two sensors, labeled 1 and 2, One measures the locomotion speed and the other detects the ground contact, respectively. The specifications of the robot are shown in Table 1.

TABLE I

THE MECHANICAL SPECIFICATION OF THE ROBOT

| Param. | Description | Value |
|---|---|---|
| $l_0$ | length of body | 142 mm |
| $l_1$ | length of upper leg limb | 42 mm |
| $l_2$ | length of lower leg limb | 56 mm |
| $l_3$ | spring attachment | 15 mm |
| $l_4$ | spring attachment | 20 mm |
| $s_0$ | spring constant | 40 g/mm |
| $m$ | mass of the robot | 483 g |

states within the continuous sensory space. Pre-programmed sensory states by a human designer often result in the category error due to the different perspectives of the world between the designer and the system. For example, an object looks very different from the perspective of a robot because the robot has a different sensory system compared to that of the designer. In order to avoid this problem, the system should be situated and construct the state space of the world from its own view.

A trivial way to generate discrete sensory states is to consider sensory morphology; if the sensors are installed properly in the body, the sensory information automatically provides discrete states. The tactile sensors on the feet of a legged system, for example, automatically generate the discrete on-off states while walking or running. In this sense, it is important to have the morphology with the discrete character; the system cannot acquire discrete sensory input from the ground if it has wheels.

Less trivial is the use of body dynamics. For example, an intrinsic resonant behavior derived from the mechanical properties is generally discrete in terms of the frequency parameter. Because the resonant behavior has a discrete nature, it can be also reflected on the sensory space. This idea can be extended to more complicated situation such as legged locomotion. The different gait patterns can be generated by changing the physical conditions such as the ground friction, the heavy load on its back, and the angle of a slope. In other words, these physical conditions can be recognized by observing the gait patterns.

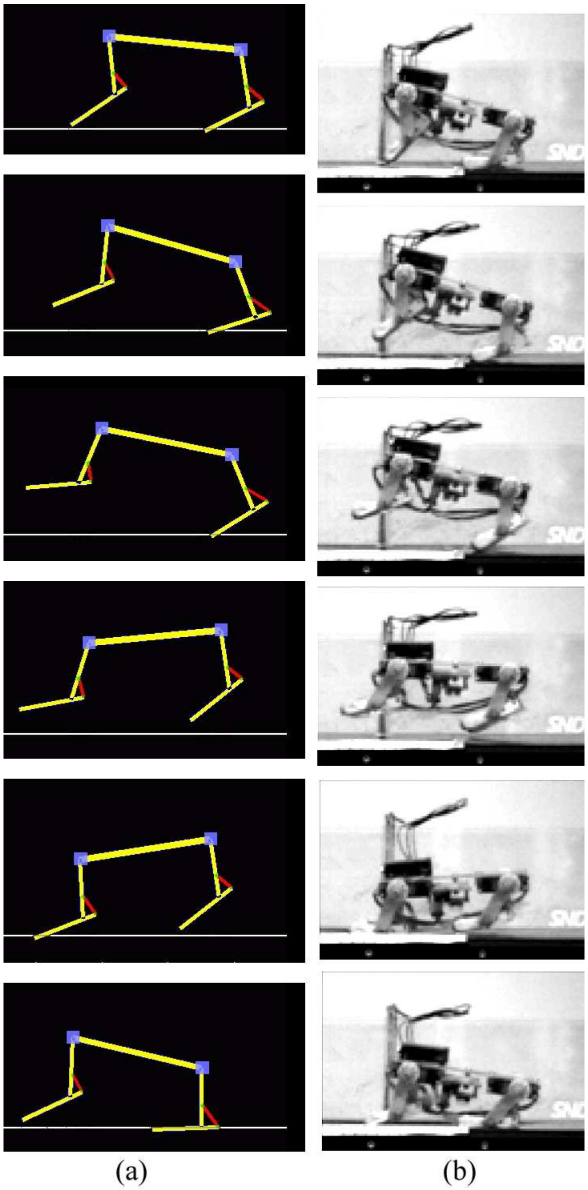

Fig. 2. A time series photographs during the rapid legged locomotion of the simulated robot (a) and the real robot (b). The real robot is running on the treadmill. The time interval between two pictures is approximately 30ms.

### *B. Multi-modal sensory information*

Another salient feature of this approach is that the body dynamics plays a role of "interpreter" of physical properties for the sensory system; In the example of the legged locomotion, the physical properties of the environment are reflected on the whole body dynamics such that many sensory modalities could measure. In other words, as long as a sensory channel can identify the patterns of behavior, it could estimate the physical

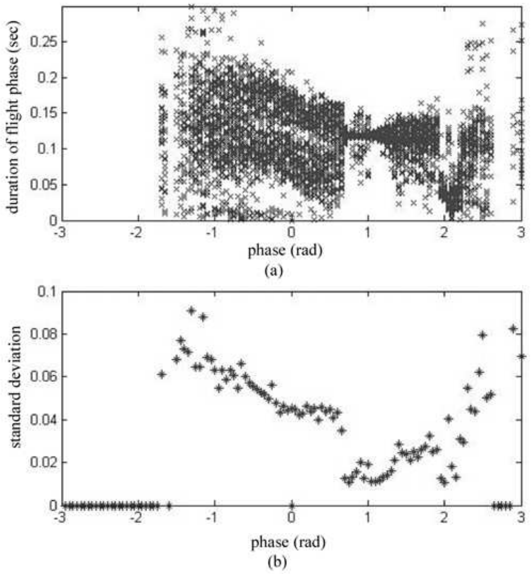

Fig. 3. Body dynamics during the locomotion experiment measured by a contact detector.(a) distribution of the flight phase durations against the phase parameter, and (b) its standard deviation.

properties that induce the gait pattern pattern. As shown later in this paper, by using this mechanism, the body mass and the ground friction can be estimated by using a visual sensor and an on-off contact detector.

## III. EXPERIMENTAL PLATFORM

In the following case study, we explore a form of rapid legged locomotion as a typical example of dynamic system-environment interaction. From the biomechanics and the robotic research, it has been shown that rapid legged locomotion is possible with very little control, whereas the behavior is sensitive to the mechanical design of the robot and the conditions of the environment(e.g. [13], [14], [15], [16]). This section summarizes the basic characteristics of this model.

### A. Design of Morphology and Control

The design of robot is inspired by the spring-mass model studied in biomechanics. As shown in Figure 1, the robot has four identical legs each of which consists of one standard servomotor and a series of two segments connected through a passive elastic joint. The robot is 142mm long, 85mm wide and approximately 75mm high (see Table 1 for more detailed specifications).

A simple sinusoidal oscillation is used to control the motors. The target motor positions are determined as follows:

$$P_f(t) = A_f sin(\omega t) + B_f \qquad (1)$$

$$P_h(t) = A_h sin(\omega t + \phi) + B_h \qquad (2)$$

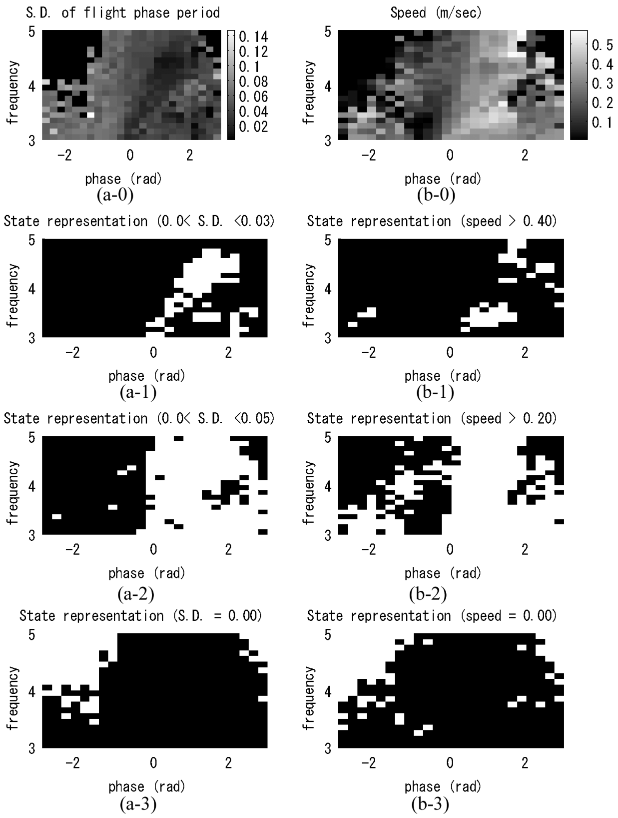

Fig. 4. Behavior landscape obtained by a ground contact detector (a-0), and the visual velocity detector (b-0). This landscape is then segmented by threshold in (a-1-3) and (b-1-3).

where $P_f$ and $P_h$ indicate the target angular positions of the fore (shoulder) and hind (hip) motors, respectively. $A$ and $B$ determine the amplitudes and the set points of the oscillation, and the parameter $\omega$ specifies the frequency and the phase $\phi$ determines the phase delay between these two oscillations of the fore and hind legs. The parameters used in the following experiments are set to: $A_f = A_h = 25$(degree), $B_f = 20$(degree), and $B_h = 10$(degree). The control parameters $\omega$ (frequency) and $\phi$ (phase) will be discussed later. The coordinate of these set points is perpendicular with respect to the spine. Note that this control method does not require any global sensory feedback for the locomotion behavior: The controller does not need to distinguish stance and flight phase, the body attitude or leg angles with respect to the absolute ground plane, but the locomotion behavior is self-organized. Owing to the self-organization mechanism originated in the specific design and control, the running behavior is possible even without feedback, in which all four legs are off the ground during a certain period in a step cycle (Figure 2)[13], [14][1]. .

For the sake of convenience, we have constructed a simulation model of the running quadruped robot, with which all of the results below were obtained. The simulation was conducted in the Mathworks Matlab together with the SimMechanics toolbox. The simplified simulation model of the robot consists of 5 body segments with two spring components in a planar

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[1] Some example behaviors are available in the following webpage. http://www.ifi.unizh.ch/ailab/people/iida/puppy/

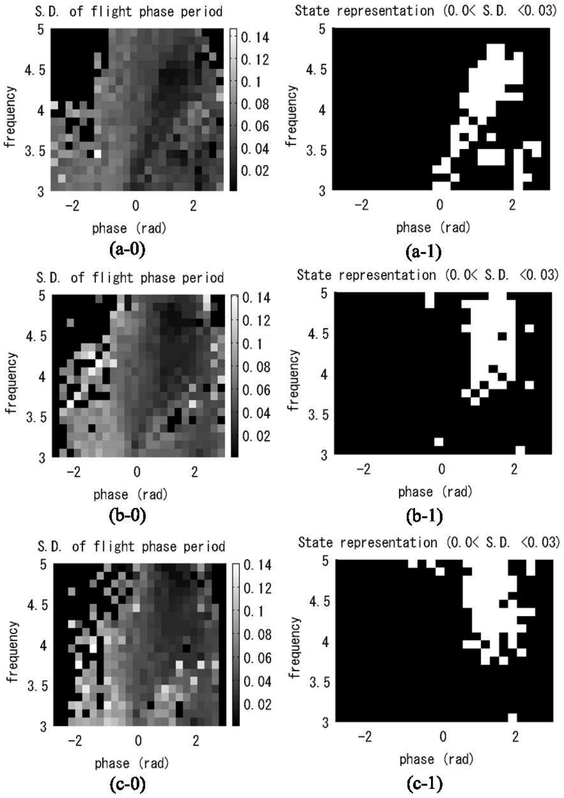


Fig. 5. The different dynamics observed by the contact detector with respect to the different body mass of (a) 0.5, (b) 1.0 and (c)1.5 kg. The landscape is then segmented by threshold in (a,b,c-1).

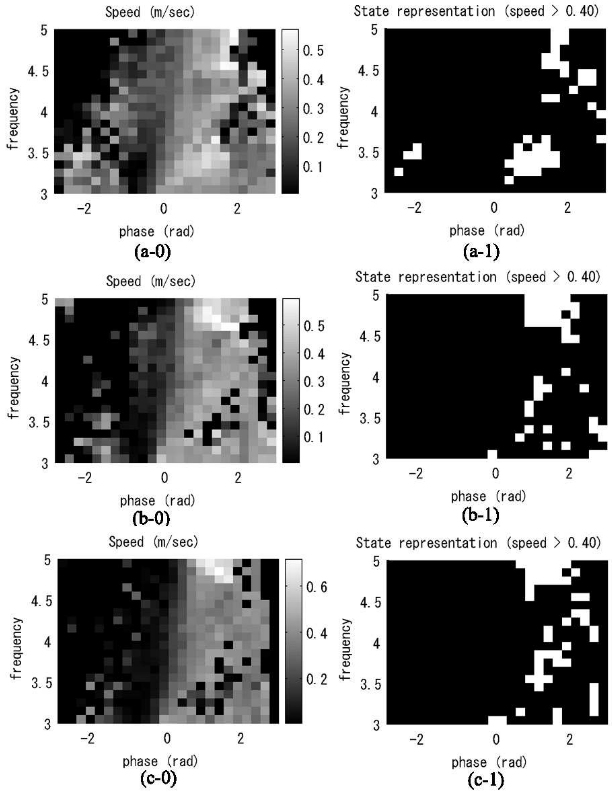


Fig. 6. The different dynamics observed by the speed detector with respect to the different body mass of (a) 0.5, (b) 1.0 and (c)1.5 kg. The landscape is then segmented by threshold in (a,b,c-1).

environment as shown in Figure 1. With a biomechanical ground friction model, the simulated dynamic locomotion is fairly comparable body dynamics of the simulated agent to the real one, as shown in Figure 2. In this simulation model, we implemented two sensors of the ground contact detector in the fore foot and the speed detector at the head for the reason explained later.

### *B. Situated Measurement of Body Dynamics*

In the following experiments, we investigate the influence of frequency $\omega$ and phase $\phi$ to the locomotion behavior. These parameters significantly change the locomotion behavior; it exhibits a stable rapid locomotion; it runs slowly or hops at place; it exhibits chaotic behavior; or it falls over.

This dynamic locomotion behavior can be recognized in a relatively simple manner by analyzing temporal patterns of the sensory signals. First, a ground contact detector (an on-off mechanical switch in the fore foot) is tested. By measuring the duration of a swing phase (i.e. the duration of the leg in the air), the stability of locomotion can be estimated as illustrated in Figure 3. In this figure, the duration of the swing phase during 10 seconds of experiment are plotted with respect to the phase parameter $\phi$. This figure shows that the stability of the locomotion can be identified by measuring the duration. For instance, with the phase parameter around 1.0 radian, the duration is constant at approximately 0.1 second, which indicates that the locomotion behavior is periodic. By contrast, the locomotion with values $\phi$ between -1.5 to 0.5 shows a large variance, which can be interpreted that the locomotion is rather chaotic. The stability of locomotion is more clearly shown by calculating the standard deviation (SD) (Figure 3(b)), in which the lower the value of SD, the more stable locomotion. Note that the plots of $SD = 0.0$ indicate that the robot could not successfully finish 10-second locomotion experiment, but it fell over.

In a similar way, we have conducted the simulation experiments by changing both parameters of frequency and phase. Figure 4(a-0) shows the distribution of SD. In the rest of this paper, we call this two-dimensional diagram "behavior landscape".

Here we introduce another sensory channel which measures the average forward speed of locomotion. (We assume that the robot has a vision sensor which measures the optic flow, for example.) The average forward speed also contains temporal information which indicates the stability and the dynamics. For example, the average forward speed is generally faster when the locomotion behavior is periodic. Figure 4(b-0) shows the behavior landscape in terms of the average forward speed. The average forward speed is obtained in the same 10-second locomotion experiments in which SD was measured.

An interesting aspect is that there is a certain "structure" in these behavior landscapes. To show them clearly, we applied

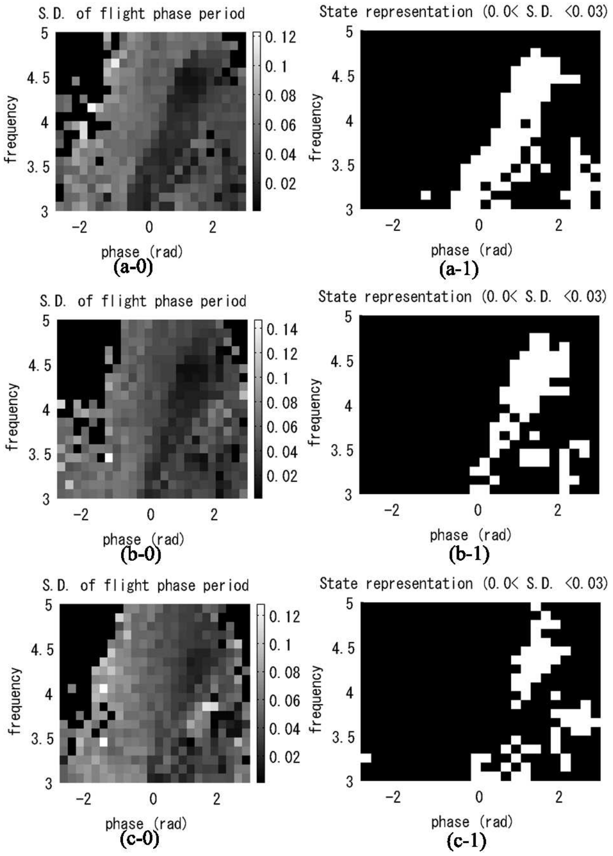


Fig. 7. The different dynamics observed by the contact detector with respect to the different ground friction of (a) 0.5, (b) 0.65 and (c)0.8. The landscape is then segmented by threshold in (a,b,c-1).

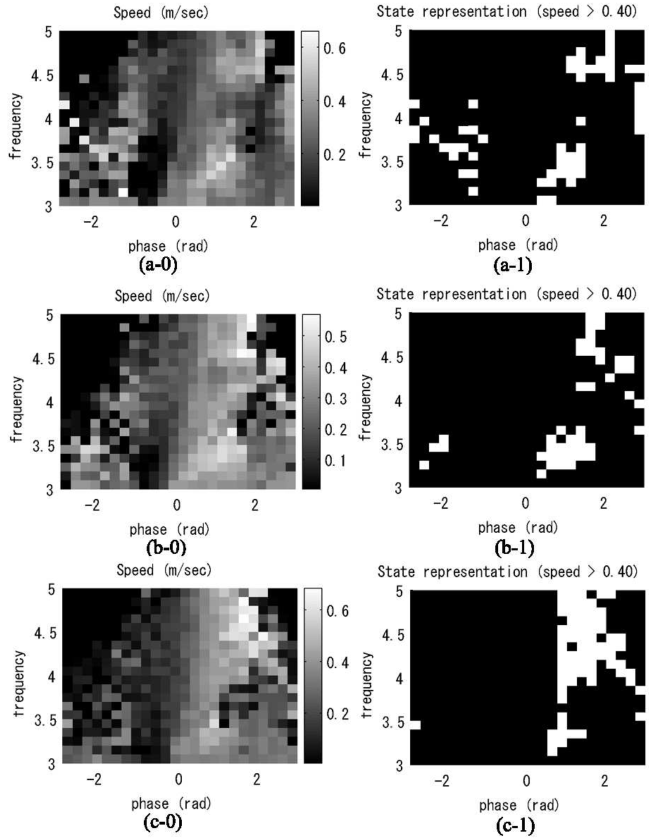


Fig. 8. The different dynamics observed by the speed detector with respect to the different ground friction of (a) 0.5, (b) 0.65 and (c)0.8. The landscape is then segmented by threshold in (a,b,c-1).

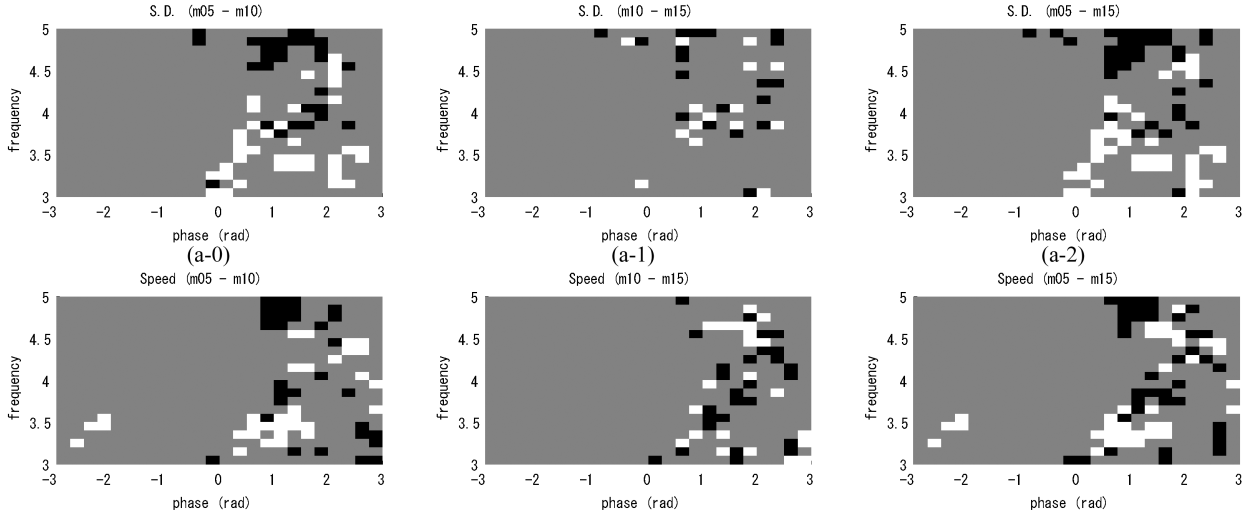
some threshold values. With these thresholds, we re-draw the behavior landscape with the white and black patches, which indicate the values of +1.0 and -1.0, respectively, as shown the Figure 4(a-1-3 and b-1-3). For example, the figure (a-1) has a white region at the right side of the figure, which indicates the "periodic" locomotion; the figure (a-2) shows a large white region in the right half which corresponds to "relatively stable" locomotion; and the figure (a-3) shows the regions of"unstable" locomotion. In a similar way, the figure (b-1) shows the regions of "fast" locomotion; (b-2) "relatively fast". Note that all these physically meaningful terms of stability and velocity (the words with double quotations) are from observer's perspective, and the robot itself does not "know" what these values mean. However, these physically meaningful states can potentially be discretely identifiable owing to the landscape structures originated in the body dynamics.

## IV. SENSING THROUGH BODY DYNAMICS

Here we look into how the measurement of body dynamics can be used for sensing. Two case studies will be introduced by using the above-mentioned simulation, in which two physical parameters were changed. In the first series of experiments, we set the body mass of the robot with three different values, and then analyze how the robot could be discriminate these differences through two sensory channels. In the second experiment, the coefficient of friction is examined also with three different values.

### A. *Effect of Body Mass*

We conducted the three simulation experiments in the same way as described in the previous section, but with three different body mass of 0.5, 1.0 and 1.5 kg by increasing the weight of the spinal segment. And again, the stability of the behavior is analyzed with respect to SD and average forward speed by varying the motor control parameters. The result obtained by the contact detector is shown in Figure 5 and the one by the speed measurement is shown in Figure 6. As shown in Figure 5, the rough structures of the figures (a,b,c-0) look somewhat similar; the area of "unstable" locomotion is in the upper left corners; the area of "periodic" locomotion is at the upper right regions. To show it clearly, we again applied a threshold value as shown in Figure 5(a,b,c-1). (A value of threshold is heuristically determined.) By setting a threshold, we could see that the stable region moves toward higher frequency as the body mass increases. The average forward speed shows an even clearer tendency; with the light body mass, there are two peaks in the landscape, i.e. the regions at the lower middle and at the upper right, whereas the region



(a-0) (a-1) (a-2)

(b-0) (b-1) (b-3)

Fig. 9. The subtracted behavior landscape of the different body mass. (a-0) SD, 0.5kg - SD, 1.0kg, (a-1) SD, 1.0kg - SD, 1.5kg, (a-2) SD, 0.5kg - SD, 1.5kg, (b-0) Speed, 0.5kg - SD, 1.0kg, (b-1) Speed, 1.0kg - SD, 1.5kg, (b-2) Speed, 0.5kg - SD, 1.5kg.

of lower middle disappears as the body mass increases.

An important implication from these experiments is that the difference of the body mass can be identified by using two different sensory channels of the contact detector and the vision sensor. This is because the physical differences are reflected in the dynamic behavior of the body, and the foot contact and the forward speed are physically related to the body mass. As more concrete example, with the light body weight, the periodic running behavior is observed by the sensors at the range of middle motor frequency, whereas the sensors indicate more unstable locomotion as the weight increases.

### B. Effect of Ground Friction

The next case study focuses on the difference in the environment, rather than the body of the robot itself. By following the same procedure as the previous experiments, we now examine the behavior landscape with three different friction coefficients in the ground interaction model, 0.5, 0.65, and 0.8. (The body mass is set to 0.5kg.) The distribution of SD is shown in Figure 7 and the average forward speed in Figure 8.

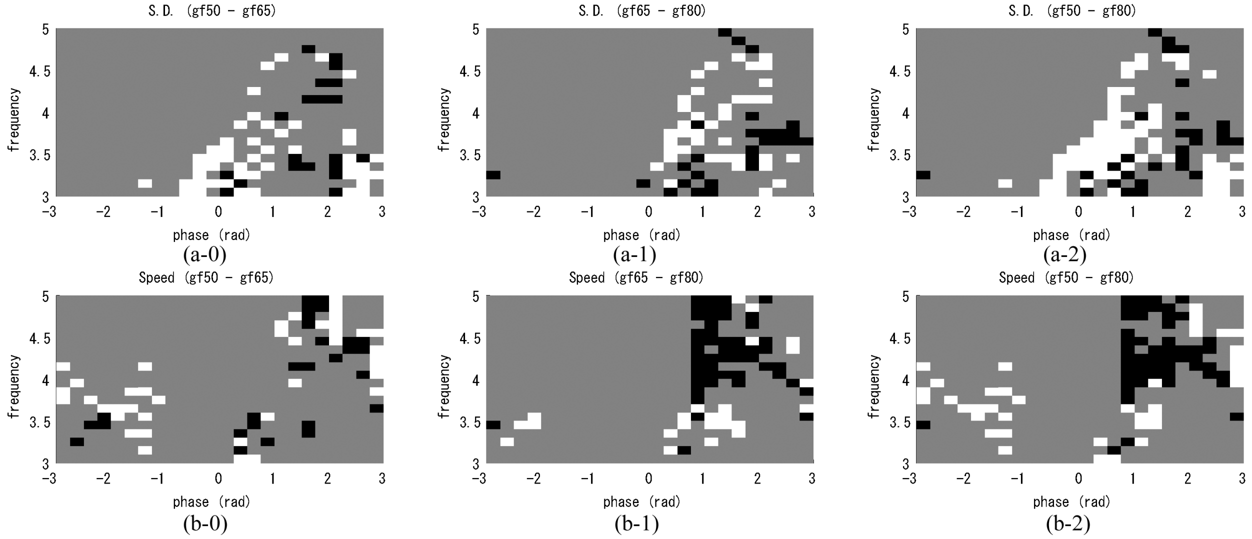
From the distribution of SD shown in Figure 7, the difference in the ground friction can be clearly identified between (a-1) and (c-1); the middle region at low frequency disappears as the friction coefficient increases. For the average forward speed, on the other hand, there is a large white region at the upper right with the high ground friction (Figure 8(c-1)).

This experimental result again shows that both contact detector and visual sensor are able to display the difference in the ground friction. For example, when the ground friction is changed from low to high, the periodic running behavior is no longer possible at the low frequency motor control, which can be detected by a contact detector and a vision sensor.

### C. Exploiting Acquired Experiences

So far, it was explained how the situated experiences can be acquired by observing the behavior. Now we consider how these experiences can be exploited for some practical use. We introduce an additional procedure with which the differences in the body mass and the ground friction can be identified based on the experiences.

In this procedure, in order to compare the different physical properties of its own body and the environment, we subtract one obtained landscape from another within the same sensory channel. For the sake of simplicity, we have applied this procedure for the landscapes which are segmented by the thresholds, thus Figure 5(a-1) is subtracted from (c-1), for example. Because these landscapes have the values of +1.0 and -1.0, the subtracted landscape contains three values of +1.0, 0.0, and -1.0, which correspond to white, gray, and black, respectively in Figure 9 and 10. In some of these figures, there are clear clusters of white and black patches, which indicate that the difference can be reliably distinguishable. According to Figure 9(b-0), for example, the robot should examine the visual sensor at the control parameters of frequency 3.5 Hz and phase 1.0 radian, for the discrimination of the body mass of 0.5 kg and 1.0 kg. To identify the difference between the ground friction coefficient 0.5 and 0.8, the robot should examine the contact detector at the control frequency 3.5 Hz and the phase 0.5 radian, or the visual sensor at 1.5 Hz and 4.25 radians. However, in some of the figures, there is no clear cluster (for example, the difference of body mass between 1.0 and 1.5 kg, Figure 9(a-1) and (b-1))), which means that it is difficult for the robot to identify the difference. We will discuss how to augment the precision of the discrimination in the next section.



(a-0) (a-1) (a-2)

(b-0) (b-1) (b-2)

Fig. 10. The subtracted behavior landscape of the different ground friction coefficient (gfc). (a-0) SD, 0.5(gfc) - SD, 0.65(gfc), (a-1) SD, 0.65(gfc) - SD, 0.8(gfc), (a-2) SD, 0.5(gfc) - SD, 0.8(gfc), (b-0) Speed, 0.5(gfc) - Speed, 0.65(gfc), (b-1) Speed, 0.65(gfc) - Speed, 0.8(gfc), (b-2) Speed, 0.5(gfc) - Speed, 0.8(gfc).

## V. DISCUSSION

Although the dynamic behavior is generally explored only for the physical performance of behaviors such as energy efficiency, speed, and stability, the preliminary experiments presented in this paper suggested that it is also a potentially important topic for our comprehensive understanding of sensory information processes of the situated systems. In particular, by exploiting the body dynamics, it has been shown that the physical properties (e.g. the body mass and the ground friction) can be discriminated through multi-modal sensory channels (e.g. the contact detector and the vision sensor), although many additional case studies are expected in the future in order to generalize the concepts presented in this paper. For further investigation, here we speculate potential research directions based on the experimental results in this paper.

Firstly, the "good" body dynamics is the sole basis to generate a sensory information with rich contents; The problem of the sensing and the learning function can be much simpler, if the robot has a "good" body and dynamics. For example, the morphological properties which determine the body dynamics should be optimized such that the behavior of the physical body can be sensitive to the physical objects of interest. We do not yet have a set of conceptual design principles for this purpose, but we have, at least, a large space of parameter search in the morphological parameters even within the framework of the previous case study, such as material properties (e.g. elasticity of the springs and rigidity of the skeleton), dimensions and shape, body weight distribution and so on. It is interesting to note that it is important to have a complex body dynamics for sophisticated sensing. One kind of behavior pattern can be used for the sensing of one physical property in the proposed scheme. For example, an totally stable wheeled robot cannot measure the ground friction through a visual sensor.

Secondly, the sensory system has to be considered further. The sensory morphology plays a important role, because the contact detector is not useful unless it is on the foot, for example. One of the important (but metaphorical) design principles of this framework is that the sensory system should be designed such that the acquired information characterizes the body dynamics. For example, in the previous case study, we could apply, at least, a set of angle sensors at the passive joints, inertia and force sensors in the motors and springs, which could be measure the stability of the locomotion behavior.

Thirdly, we could also enhance the complexity of motor control, even though we deliberately explored the simplest possible motor control in order to demonstrate the power of morphological properties, more complex motor control and the sensory-motor coordination could potentially provide more interesting structures in the sensory information. It would be particularly interesting to consider to what extent the motor should be coordinated by the sensory information.

And finally, the correlation process of the multi-modal sensory channels will be a highly challenging research issue. Together with motor signal, we will be able to build a system that autonomously extracts the causal relationship between the motor actions and the sensory stimulation. This will lead then to the construction of the so-called body image which has been recently explored extensively in the field of developmental robotics [17]. Along this line of research, we presumably find the way how the internal symbolic representations could be meaningfully grounded in the physical embodied interactions in the real world [18], [19], [20].

## VI. CONCLUSION

This paper presents a few case studies demonstrating the conceptual strategy of exploiting the intrinsic body dynamics for sensing. While it is still in a premature stage of exploration, the experimental results shown in this paper are highly encouraging toward further understanding of the relation between the morphological properties and the cognitive process. In particular, the proposed approach of sensing through intrinsic body dynamics provides, on the one hand, a set of clearly identifiable discrete states in a continuous sensory space, and on the other, sensing through multi-modal sensory channels. Based on the experimental results, we have also speculated the further issues to enhance the precision of the task of categorization. Although we still have to corroborate what we mean by the "good" body dynamics in more concrete terms, this approach will lead to more comprehensive understanding of adaptive behavior and embodied cognitive processes.

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