Cheap Design Approach to Adaptive Behavior: Walking and Sensing through Body Dynamics

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Abstract— **The approach of cheap design has been providing a number of implications by viewing behavior as the result of a system-environment interaction. It states that adaptive behavior cannot be reduced into the problem of control architectures, but the coupling between the system and the environment is essential. Case studies in the past have demonstrated not only the efficient behaviors but also the underlying mechanisms in the perception and the learning processes.**

This paper explores additional insights of the cheap design approach by introducing two recent case studies of the locomotion robots, which involve a few potentially important research directions for our further understanding of adaptive behavior. The first case study investigates the complex leg operation during bipedal walking. A newly developed biped robot will demonstrate the relatively complex human locomotion as a self-organized behavior of the compliant passive legs without the necessity of sensory feedback. In the second case study, we will discuss how the body dynamics influences the cognitive processes; It will be shown that, by exploiting the intrinsic body dynamics, the sensor information can be meaningfully structured for the purpose of situated perception of the environment.

I. Introduction

While the goal of traditional robotics has been reliable behaviors in static environment, more recently there has been a growing interest in the systems which perform dynamic behaviors. One of the reasons seems to lie in the fact that the problem of an adaptive system cannot be decomposed into the body, the control system, and the environment, but a fundamental issue of adaptivity is in the interplay between them. Accordingly the main research focuses have also shifted from precise modeling of the body, the environment and the control architectures to the material properties and the body dynamics in order to investigate the underlying physical system-environment interactions. Previously, several terms have been invented to characterize this approach such as cheap design [1], [2], [3], [4], body dynamics [5], [6], passive dynamics [7], [8], [9], passive control, feedforward/open-loop control. One of the common goals in this line of research is to identify how the physical interactions between the body and the environment contribute the intelligent adaptive behavior.

During the last decades, this approach has shown a number of case studies demonstrating behaviors with impressive naturalness (as shown by the Passive Dynamic Walkers, for example). However, one of the criticisms often addressed in the fields of robotics and artificial intelligence is that, if the behaviors and the functions are dependent on the environment, they would not work when the environment is changed. So what does the cheap design have to do with adaptive behavior?

From the recent development of the field, the importance of the cheap design approach has been becoming clearer. Very briefly, here we point out three principles. Firstly, a somewhat trivial implication is that the cheap design approach generally leads to a cheap operational cost in terms of energy consumption and computation (The principle of cheap operation). When the system exploits the physical constraints derived from the body and its environment, behaviors can be generated with less energy, and control can be very much simplified [7], [8], [10]. Secondly, for the active exploration of the real world, behaviors should be generated with respect to the environment. For example, a particular type of system-environment interaction with sensory-motor coupling has been known to provide a form of “structures” in sensory stimulation which significantly simplify the recognition process of the physical entities in the environment (The principle of sensory-motor coordination, e.g. [11], [12], [13]). Thirdly, the physical mechanical properties considerably influence the learning process of behaviors (The principle of cheap behavior learning). A set of “good” mechanical structures provides a basic setup to reduce the space of exploration [10], [14], [15].

An important implication from these case studies is the fact that most of the aspects related to adaptive behavior are highly dependent on the physical interaction between the body and the environment. In other words, the body of an adaptive system can no longer be arbitrary, but it should be considered as a central issue. This is the reason why we have been investigating various aspects and roles of the morphological properties for adaptive behaviors by using the simplest possible control architectures (e.g. [2], [4], [16]). These attempts have provided the following two major conceptual contributions; Firstly, as a contribution to biology, the synthetic approach provides a number of in-depth insights about the role of body dynamics. More specifically, by building an artificial system, we are able to identify how the morphological properties can contribute to a certain behavior

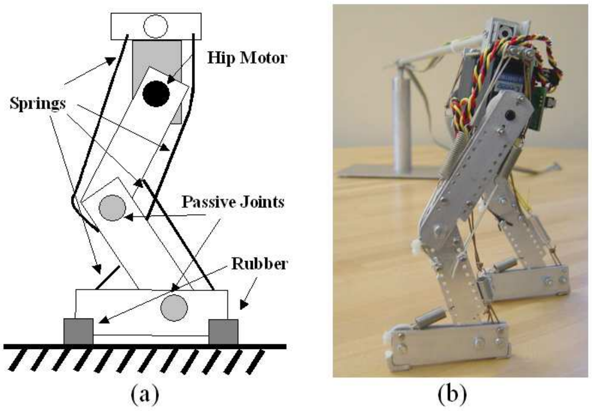


Fig. 1. (a) Schematics of the robot design, (b) photograph of the robot with the supporting rotational bar.

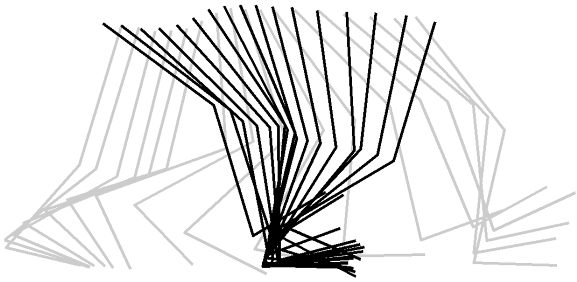


Fig. 2. Leg trajectory of the biped robot during one step. Black and gray lines depict right and left legs, respectively.

or function in the absence of sophisticated control, which is often difficult in the biological studies. This will, in turn, lead to the explanation of what the nervous systems actually do. Secondly, we investigate the influence of body dynamics to the sensory systems. Sensory morphology has been know to be useful for the simple recognition process of the real world. In a similar way, by considering the physical body dynamics as a form of interpreter of the system-environment interaction, we can investigate how dynamic interaction induced by the morphological properties can structure the sensory information to enhance the perceptual capabilities of a situated system.

In this paper, we introduce two case studies which explain these concepts in more concrete terms. Note that this is not a technical paper, but a conceptual one; The goal of this paper is to discuss potential research directions from the interdisciplinary perspective in order to speculate the challenges and the open-problems of the field. Further details of the case studies can be found in the corresponding publications.

II. CASE STUDIES

Locomotion is one of the most fundamental functions for autonomous adaptive systems, on the one hand, and it involves many important research questions, on the other. Here we will introduce two issues; Self-organization of complex leg operation in bipedal walking, and structuring sensory information through body dynamics. In both of the case studies, we deliberately employed simple motor control architectures in order to demonstrate the power of morphological properties in the framework of cheap design.

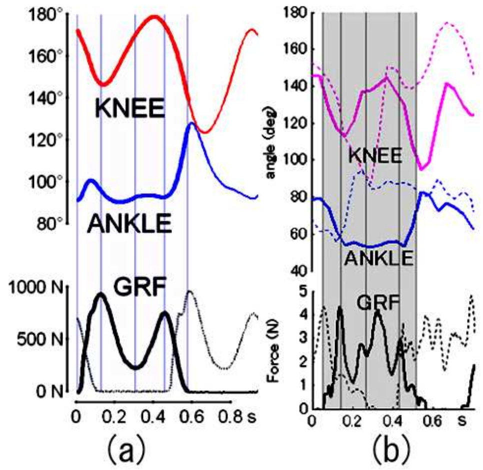


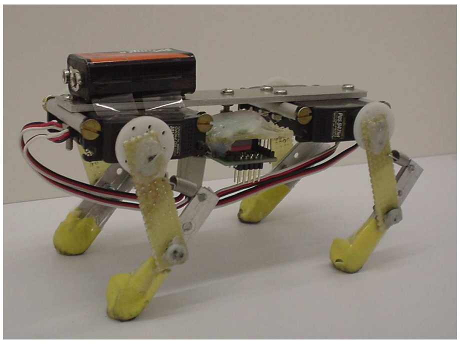
Fig. 3. Angular trajectories of the knee and the ankle joints and the ground reaction force of human locomotion(a), and of the robot(b).

A. *Human-like biped locomotion*

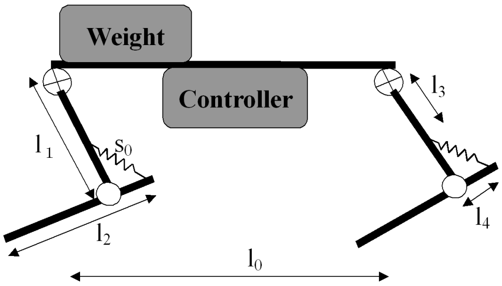
Previously, the Passive Dynamics Walkers (PDWs) have demonstrated a relatively complex behavior of bipedal walking without any actuation [7], [8]. Moreover actuators can be also integrated to the model without a significant loss of the energy efficiency [9], [10]. Despite its natural walking appearance, however, the precise biomechanical analysis revealed that the underlying mechanism of human walking could be different for the following two points; Firstly, while the PDWs comprises of rigid limbs and joints, a theoretical simulation study has shown that the behavior of human bipedal walking is very well characterized by a model of compliant legs [17]. Secondly, the kinematic data of human leg trajectory is more complicated than that of PDWs. Especially, human legs generally shows three different peaks in the angular trajectory of the knee joint, as shown in Figure 3(a); First, at the beginning of stance phase (the left region in the figure), the angle of knee joint goes down (flex) to avoid impact, then it goes up (extend) to support the body. Finally it decreases (flex) again to achieve the ground clearance during the swing phase. Generally the conventional PDWs do not have the first peak.

Toward human-like biped walking, the main focus of our project is whether a pair of elastic passive legs could stabilize themselves into a walking gait cycle without sensory feedback. The newly developed biped robot consists of two legs, each of which has one standard servomotor at the hip and two passive joints at the knee and the ankle (Figure 1(a))[1]. Four springs are implemented as the substitutes for the

[1]For more technical details, refer to [18], and the video clips available at http://www.lauflabor.de.



(a)



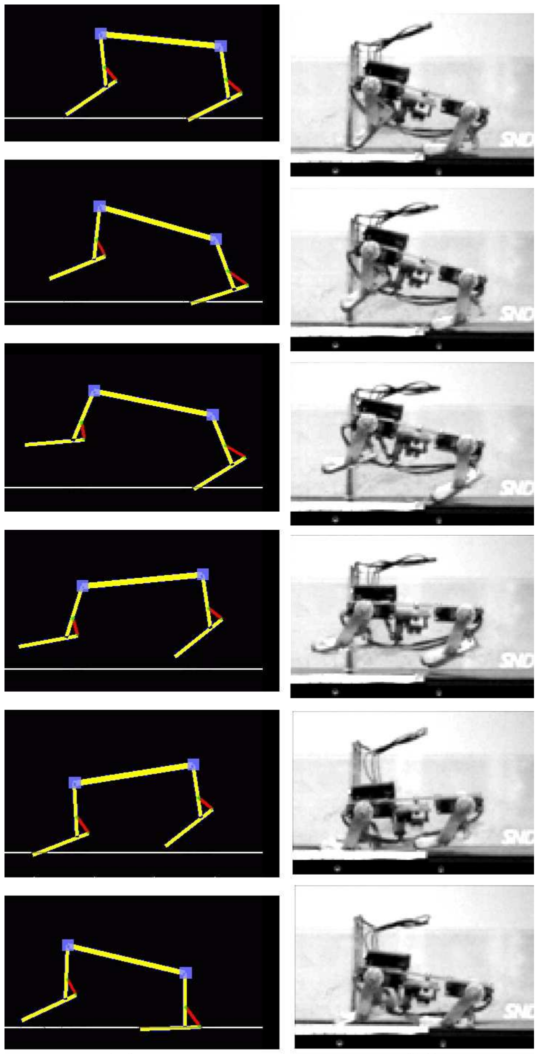
(b)

Fig. 4. (a) A photograph of the quadruped robot. (b)A schematic of the robot. The circles denote passive joints and the circles with a cross inside denote the joints controlled by the servomotors.

muscle-tendon systems, which constrain the passive joints. A unique feature of this robot is that three of the springs are connected over two joints, which are known as the so-called biarticular muscles in the biological systems (i.e. two springs attached between the hip and the shank, another one between the thigh and the heel). For control of the motors, we employed a simple oscillation, in which the angular position of the hip joint is determined by the sinusoidal curve with three fixed parameters of amplitude, frequency and offset. A rotational supporting bar was used to reduce the behavioral complexity (i.e. the roll, yaw and pitch rotation are restricted).

There are two major achievements; Firstly, even though the legs are simply controlled with a fixed oscillation cycle of the motors, the complex movement of passive joints can be self-organized into a periodic gait as shown in Figure 2. In particular, without detecting the states of swing and stance phases, a sequence of each behavior primitives (e.g. bending movement of the knees and the ankles) are generated at the relatively precise point in a cycle. This is possible because the behavior is the result of the interplay between body weight, the ground reaction force and the force generated through the passive joints and the springs. More detailed kinematic analysis shows the unique leg operation of this robot. A pair of biarticular muscles in the thigh induces the movement of the shank as the hip motors rotate, which results in a three-peak angular behavior of the knee joint which is comparable to that of human.

A controversial issue is to what extent this compliant passive mechanism is biological plausible. Although it still needs to be explored further, the biological systems would most probably make use of both mechanisms, i.e. with and without sensory feedback. However, it is important to mention that this relatively complex behavior sequence can be achieved with a very simple control mechanism, which would lead to our comprehensive understanding of the human walking behavior.



(a) (b)

Fig. 5. 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. Structuring sensory information through body dynamics

The second case study shows a set of simulation experiments with a model of the four-legged robot[2]. The model consists of two-segment compliant passive legs and each of them is connected through a servomotor to the body (Figure 4). A simple sinusoidal oscillation is used again to control the

[2]For more technical details, refer to [4], [19], [20] and video clips available at http://ifi.unizh.ch/ailab/people/iida/puppy/

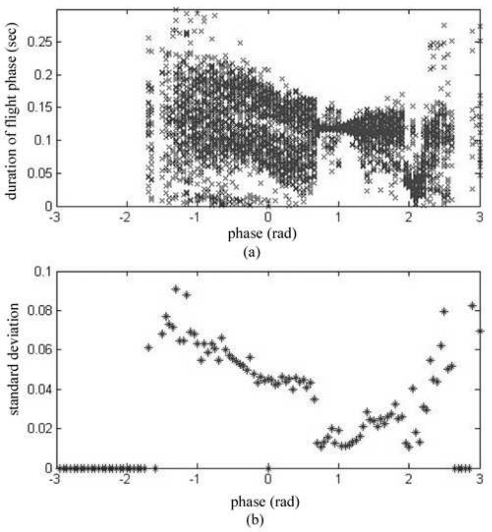


Fig. 6. Body dynamics during the locomotion experiment measured by a contact detector.(a) distribution of the flight phase durations against the phase parameter, and (b) its standard deviation (SD). $SD = 0$ indicates that the running behavior is not possible with the corresponding control parameter.

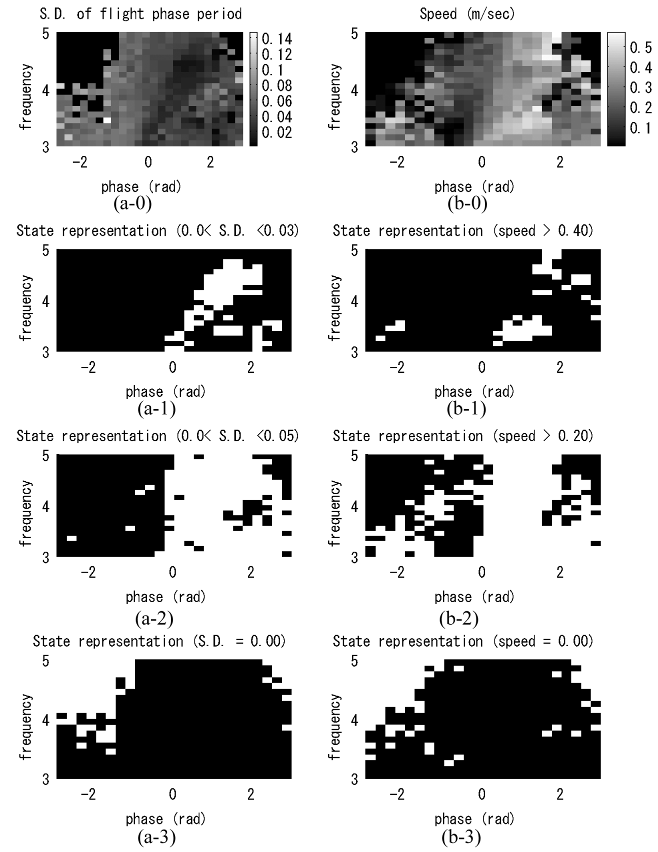


Fig. 7. Behavior landscape obtained by a ground contact detector (a-0), and the visual velocity detector (b-0). This landscape is then segmented by threshold in (a-1-3) and (b-1-3).

legs, in which four legs are synchronized through the control parameters of frequency and phase delay. As in the previous case study, dynamic interaction between the compliant legs and the ground makes the robot possible to perform a kind of running behavior (Figure 5)[4], [19]. This running behavior is, however, sensitive to the environmental conditions due to the physical interaction; For example, when the ground friction is changed, the robot shows a different behavior. The issue discussed in this section is how the robot could exploit the sensitivity to the environmental conditions for the purpose of situated perception.

In this case study, we firstly analyzed the response of an on-off mechanical switch in one of the feet during the 10-second running experiments. Figure 6 shows the duration of an off-state (i.e. swing phase of the leg) with respect to the phase control parameter, which determines the phase delay of the oscillation in the front and the hind legs. Even though the sensor measures only on/off states, the temporal information can be used to estimate the stability of the locomotion process; The locomotion behavior is relatively stable with the phase parameter around 1.0 radian, for example. Therefore, the stability of locomotion can be evaluated by calculating standard deviation (SD) as shown in Figure 6(b).

By following the same manner, the two dimensional landscape of SD can be constructed by varying two motor control parameters of frequency and phase as shown in Figure 7. The similar structures are more clearly shown in the landscape, especially with a set of threshold values (Figure 7(a-1-3 and b-1-3)). It is important to note that these structures in sensory information is physically grounded; 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. Because the running behavior of this robot has a discrete nature in the dynamic behavior, the structures in the continuous sensory space was generated. This structured sensory input plays an important role for the perception of the environment. Figure 8 shows the structures of the landscapes when the ground friction is changed. A large stable region becomes smaller as the ground friction increases, meaning that the ground friction can be estimated by using an on/off touch sensor and the control parameters. For example, when the ground friction is changed from low to high friction, the periodic running behavior with low frequency parameter is no longer possible, and an unstable pattern should be observed in the sensory channel.

One of the most distinctive outcome of this approach is the fact that the recognition of the environment can be easily applied to the multi-modal sensory channels. Because the whole body dynamics is influenced by the environment, many other sensory modalities can be used in the same manner. Figure 7 and 9 show the response of a forward speed detector in the body of the robot model. (We assume that the robot has a vision sensor to measure optic flow, for example.) Because

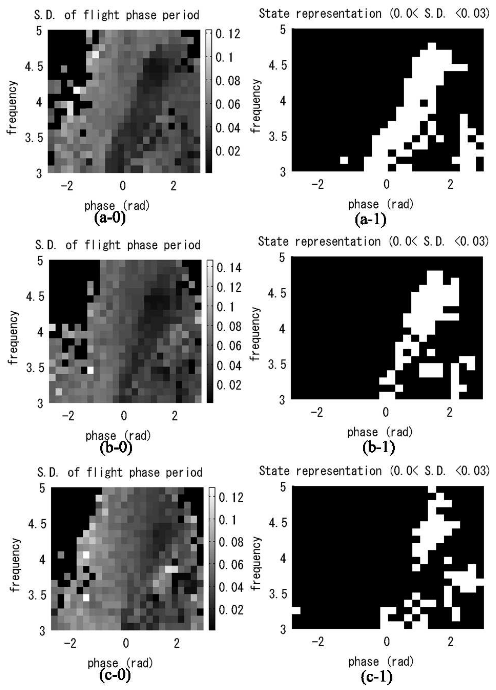


Fig. 8. The different dynamics observed by the contact detector with respect to the different ground friction of (a) 0.5, (b) 0.65 and (c)0.8. The landscape is then segmented by threshold in (a,b,c-1).

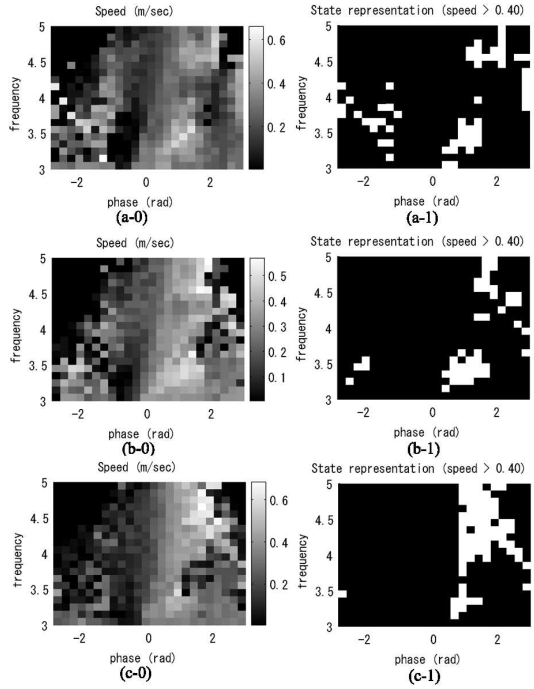


Fig. 9. The different dynamics observed by the speed detector with respect to the different ground friction of (a) 0.5, (b) 0.65 and (c)0.8. The landscape is then segmented by threshold in (a,b,c-1).

the ground friction also influences the forward velocity of the locomotion behavior, the visual sensory stimulation is structured in a similar way to the contact detector. Therefore the ground friction can be eventually estimated by both the vision sensor and the ground contact detector.

III. Discussion and conclusion

Based on the achievement introduced in the previous section, here we speculate two potentially important issues in the future work of the cheap design.

A. Self-organization and behavioral diversity

In the first case study, the biped robot demonstrated a relatively complex sequence of walking behavior by exploiting the physical constraints of the muscle-tendon systems. Particularly, a set of biarticular muscles connected through two joints induced, on the one hand, a periodic walking gait cycle without sensory feedback, and on the other, the sequence of behavior primitives at the precise timing. Behavioral diversity could potentially be enhanced by extending this approach.

There are three potential research directions for this purpose; Firstly, the morphological properties need to be explored further; We have tested only one configuration of musculoskeletal model of the biped robot, but there are a number of different configurations to be examined including the quantity and the locations of the springs, the different elasticity even within the given framework of the case study previously presented. The second question would be the dynamic control of these morphological properties. Especially, considering the fact that biological muscles possess many different functionalities such as force generators, and stiffness and length regulators, the dynamic control of spring constant would be a highly challenging research topic. Thirdly we could integrate the sensory information. It would be particularly interesting to identify to what extent this cheap design approach can be applicable, and at which point we need sensory information and feedback.

B. Situated perception and symbol grounding

The second case study shows that the study of body dynamics is also fundamental for our understanding of cognitive process such as information processing of sensory stimulation. Generally in the field of artificial intelligence, symbols are typically defined in a purely syntactic way by how they relate to other symbols and how they are processed by some interpreter (the symbol grounding problem [21], [22]). The relation of the symbols to the real world is rarely discussed explicitly. One of the fundamental question, therefore, is how the robot is able to acquire the sensory information grounded based on the physical interaction and the meaningful correlation among different sensory channels. The case study demonstrated that the body dynamics plays a significant role in this context; The physical interaction between the body and the environment provides a physically meaningful structures in the multi-modal sensory input for free.

There are two potential research directions toward future; One is what kind of body, control and sensory channels can be used for this approach. In the framework of the second case study, we found that, at least, the inertial and the force sensors in the motors and joints, can be used to estimate the different ground friction, in addition to the contact detector and the forward velocity measurement. Secondly, the correlation process of these sensory and motor information will be a highly challenging research issue. In particular, the causal relationship between the motor and the multi-modal sensory signals will provide an additional insight of the developmental process of the cognitive systems, which has been recently explored extensively in the field of developmental robotics.

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