〈一般研究課題〉　協同現象を活用した二脚受動歩行機械の
引き込み領域の拡大
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Enlarging Attractor Basin of a Passive Dynamic Walker by Exploiting Cooperative Phenomena

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Recently, passive dynamic walkers have been attracting lots of attention in the field of legged robots, in the hope that they allow us to realize surprisingly natural and high energy efficient walking for humanoid bipeds. Despite these interesting properties, current passive dynamic walkers have been faced with serious issues that have to be resolved, particularly in their potential for coping with environmental perturbation: they are significantly sensitive to the change of gradient of slope and initial condition. In light of these facts, this study intensively discusses the enlargement of the attractor basin of a biped passive dynamic walker, exploiting "cooperative phenomena" by carefully increasing its degrees of freedom.

1. Introduction

Since the pioneering work of McGeer in the late 1980s, the concept of *passive dynamic walking* (hereafter PDW) has been attracting lots of attention in the field of legged robots [1] A significant feature of PDW robots is that they have no control system; they merely exploit their intrinsic mechanical dynamics carefully designed, and show surprisingly natural and human-like walking on a gentle slope without any actuation except for gravity. Due to this, PDW robots are expected to largely contribute to the realization of energy- efficient humanoid bipeds, which has been totally difficult with the embodiment of current biped robots.

As observed in many nonlinear dynamical systems, it is widely recognized that there exists *entrainment phenomena* in PDW robots [2] : they continue stable locomotion as long as their state is within the *basin of attraction*. Recently, however, Schwab *et al.* have pointed out that the basin of attraction of PDW robots are significantly small. Furthermore, they have clarified that this basin of attraction becomes smaller as the gradient of slope increases; consequently, this will disappear when the gradient exceeds a critical value [3].

On the other hand, it is well known that mutually-interacting many-body systems often show *cooperative phenomena, i.e.*, temporary and/or spatial ordered patterns emerge as a result of the interaction among the elements. A typical example of the cooperative phenomena can be observed in the *paramagnetic-ferromagnetic phase transition* of an *Ising ferromagnet* . Despite that a small-scaled system --- a system with small degrees of freedom --- does not show a "clear" phase transition due to the *thermal fluctuations* , the transition from one phase to another becomes "sharper" and "clearer" as the system size increases. This is because when several elements --- or degrees of freedom --- deviate from the ordered state, the interaction with the rest of elements will immediately bring them back to the original ordered state. In sum, cooperative phenomena work to stabilize the ordered state over the whole system.

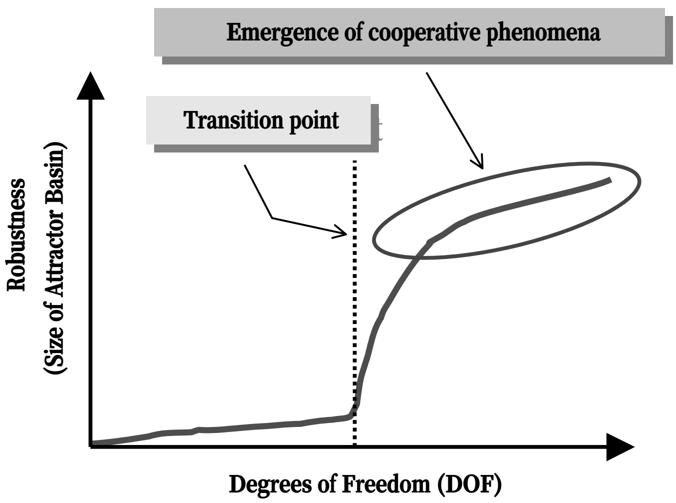


Figure 1: A schematic diagram representing the concept of this study.

Looking back at the PDW robots developed so far from the above viewpoint, one may say that they have been built with relatively small degrees of freedom. This will automatically lead to the following conclusion: the cause for the brittleness against perturbations observed in the current PDW robots might mainly stem from their extremely simple structure --- their degrees of freedom might not be sufficient to elicit cooperative phenomena.

Based on the above considerations, this study is intended to deal with the enlargement of the basin of attraction of a PDW robot by exploiting cooperative phenomena. To this end, the following methods are employed: (1) increasing the degrees of freedom of the embodiment; and (2) implementing passive elements --- *springs and dampers* --- into some of the joints, the latter of which is also expected to efficiently elicit cooperative phenomena. This idea is schematically illustrated in Figure 1.

Simulations have been carried out in a physical simulator developed for this purpose in order to verify the feasibility of our idea. The preliminary results obtained support this idea, and have clarified some interesting phenomena for further investigation.

2. Related Work

In this section, some notable conventional research on PDW robots are introduced. Collins *et al.*

developed a 3D PDW biped robot by exploiting the movement of its arms as yaw compensation[4]. Although they successfully demonstrated that this robot walked in the real world, it is still questionable how much this robot is robust against environmental perturbation as well as the change of initial condition.

Wisse et al. proposed a design for a 3D PDW biped with a pelvic body, which was employed to compensate the undesired roll and yaw motion[5]. They effectively showed that this compensator allowed the robot to move in a similar manner of a 2D PDW biped. They, however, found that this robot is less stable compared to the 2D PDW biped they have developed.

Fujimoto *et al.* implemented a torso and two arms to a PDW robot, and showed that the synchronization between the leg and arm movement contributes to enlarge the range of walkable gradient[6]. However, their robot is not a purely mechanical system; they artificially controlled the posture of torso and the phase relationship between the legs and arms.

As far as the authors have been informed, there are no studies in existence so far which explicitly deal with the enlargement of attractor basin of purely mechanical PDW robots from the viewpoint of "cooperative phenomena".

3. Proposed Method

3.1 The model

Since there still remains much to be understood about which additional degrees of freedom and which additional passive elements implemented will play an essential role to elicit cooperative phenomena, this paper particularly focuses on the following two different embodiments for PDW as a first step of investigation:

Embodiment 1: A kneed biped with an upper body (*i.e.* torso, shoulder, head), and a waist joint rotatable around the yaw and roll axes (see Figure 2). This embodiment is employed for the intensive investigation of the role of upper body.

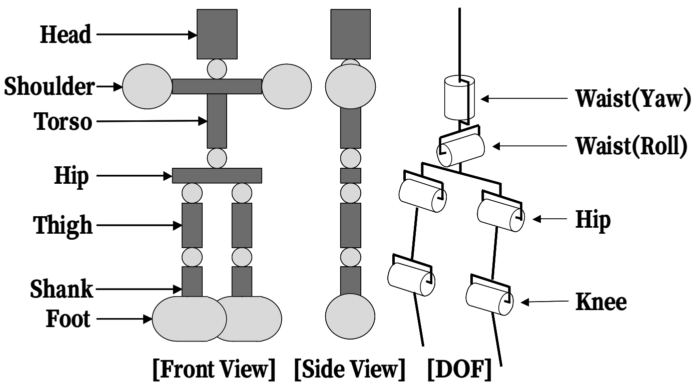


Figure 2: A schematic of embodiment 1 (3D model).

Embodiment 2: A kneed biped with ankle joints which are allowed to rotate depending on the foot contact condition (see Figure 3). This embodiment is dedicated to intensively investigate the role of ankle joints for the emergence of cooperative phenomena.

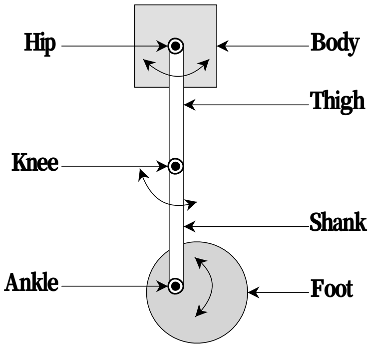


Figure 3: A schematic of embodiment 2 (2D model).

Note that passive elements (*i.e.* springs and dampers) were implemented to the hip and waist joints around the yaw and roll axes in embodiment 1, and the hip, knee and ankle joints in embodiment 2.

3.2 Evolving PDW Robots

As there are no current existing theory about how such PDW can be created, a *synthetic approach* is the method of choice in optimizing the body parameters of these embodiments. Therefore, a genetic algorithm (hereafter, GA) was employed for this purpose. In addition, in order to efficiently create such PDW bipeds, an *incremental evolutionary scheme* is adopted. In the following, it is shown how each stage of the evolution was conducted:

The First Stage of Evolution

The aim of this stage is to create the basic structure of PDW bipeds, which can perform a stable walk on a gentle slope. More specifically, the body parameters --- mass/length of each body part and spring/damper constants of each joint --- and the initial torque applied impulsively to the hip for launching the biped were encoded as a binary-bit string (*i.e.* chromosome) for the evolutionary process. Each individual was tested, and allowed to move for the prespecified evaluation period. The following fitness function was employed for the evaluation:

$$f = D \times S \qquad (1)$$

where D and S are the resultant walking distance traveled, and the number of steps performed during the evaluation period. This fitness function encourages the generation of stable and successful walking by alternatively stepping forward. One hundred individuals were randomly generated as the initial population; they were evolved through 50 generations by applying genetic operators (*i.e.* mutation and crossover). Note that in this stage the gradient of slope is prespecified and remains unchanged during the entire evolutionary process.

The Second or Higher Stage of Evolution

The aim of this stage is to create PDW bipeds that can negotiate environmental perturbation. In other words, this stage is dedicated to enlarge the basin of attraction of the PDW bipeds obtained in the previous stage. To do so, the population obtained at the last generation in the previous stage was used as the initial population of this stage; these individuals were successively evolved through 50 generations under the existence of environmental perturbation. More specifically, each individual was tested on a slope, the gradient of which was randomly changed in every Δt [sec] around the gradient in the first stage within a prespecified range. Note that all individuals in a generation were evaluated under the same pattern of gradient changes, while a different pattern was employed in the next generation. In the following simulations, the gradient of slope θ_i in generation i was dynamically fluctuated, which is given by

$$\theta_i(t) = \sum_{j=1}^{\frac{T}{\Delta t}} a_{i,j} \{u(t-(j-1)\cdot\Delta t) - u(t - j\cdot\Delta t)\} \quad (2)$$

$$u(t) = \begin{cases} 0 & (t < 0) \\ 1 & (t \geq 0) \end{cases} \quad (3)$$

where Δt and T denote the time interval of gradient changes and the evaluation period, respectively. $a_{i,j}$ is a constant determined randomly within a range of [a_{min}, a_{max}].

4. Results

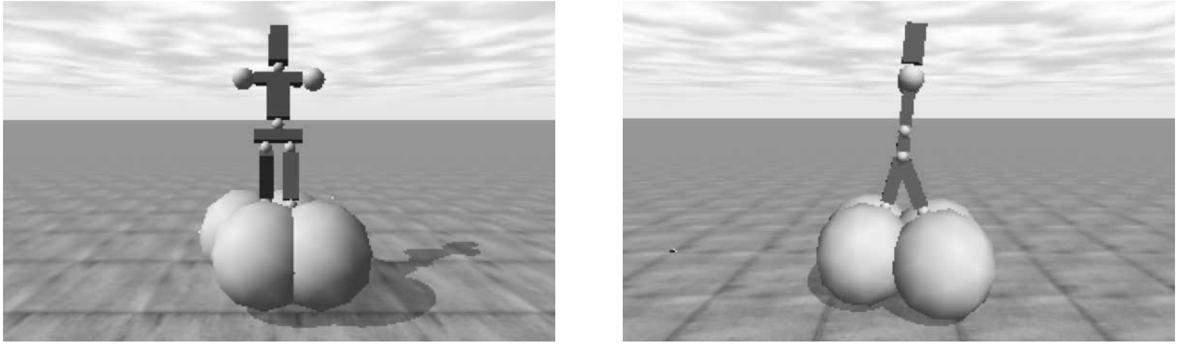
For efficient investigation, a simulator has been developed. The following simulations have been conducted with the use of a physics-based, three-dimensional simulation environment named *Open Dynamics Engine* [7]. This environment simulates both the internal and external forces acting on the agent and objects in its environment, as well as various other physical properties such as contact between the agent and the ground within an acceptable time limit.

4.1 Preliminary Experiments

Experiments under Embodiment 1

Figure 4 explains a view of the simulator developed for embodiment 1. The following simulations were conducted under the condition of the gradient of slope 3 [deg]; and the evaluation period T = 30[sec].

Shown in Figure 5 represents a typical evolutionary run leading to successful PDW. As the figure indicates, the fitness value increases as the evolutionary process proceeds. Figure 6 denotes a representative example of the evolved PDW biped. This snapshot was obtained by recording every 0.2 [sec], and only the right leg is shown for clarity. From the figure, it is recognized that the robot smoothly enters stable and periodical locomotion after a short transition period.



(a) Front view (b) Side view

Figure 4: A view of the simulator developed for embodiment 1.

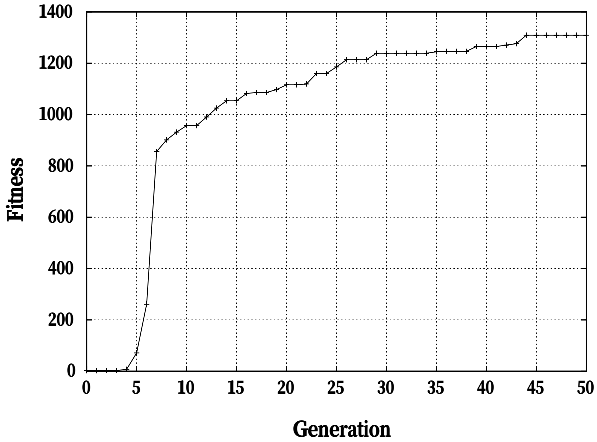


Figure 5: Transition of the fitness in the first stage of embodiment 1.

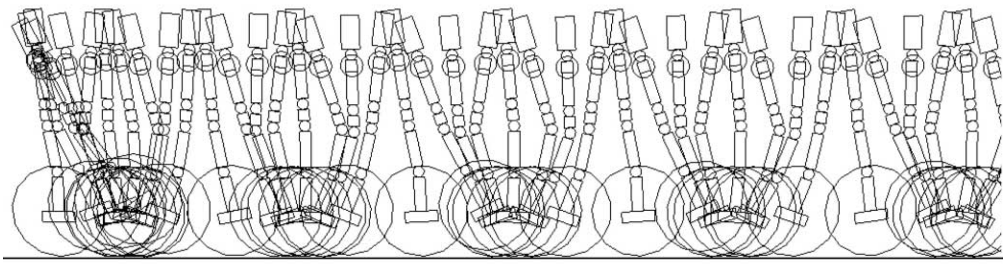


Figure 6: A representative locomotion of the best evolved PDW biped obtained in the first stage of evolution (see from left to right).

Experimentsunder Embodiment 2

Figure 7 illustrates a view of the simulator for embodiment 2. Since this embodiment is dedicated for the intensive investigation of the role of ankle joints in the enlargement of attractor basin, the collision between the left and right legs was not considered for simplicity; they moved independently on the same sagittal plane. The following simulations were conducted under the same condition as that of embodiment 1 except that the gradient of slope was set to 4 [deg]. A typical example of the fitness transition in the first stage under this embodiment is depicted in Figure 8. Figure 9 shows a representative locomotion pattern of the best evolved PDW biped obtained in the first stage. This snapshot was obtained in the same way as shown in Figure 6.

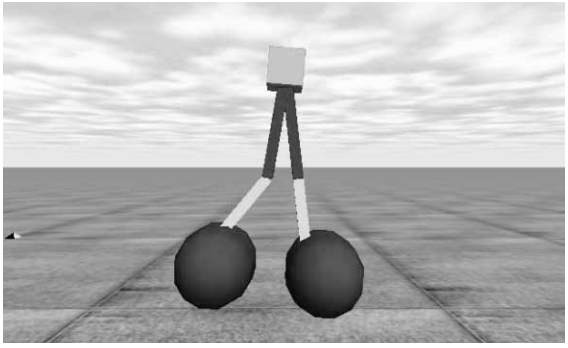


Figure 7: A view of the simulator developed for embodiment 2.

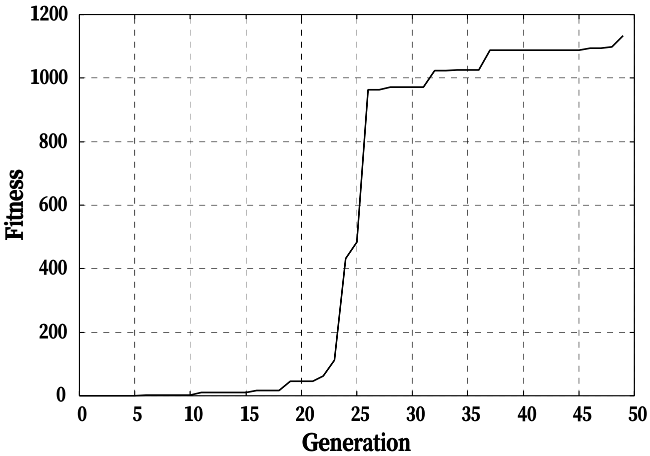


Figure 8: Transition of the fitness in the first stage of embodiment 2.

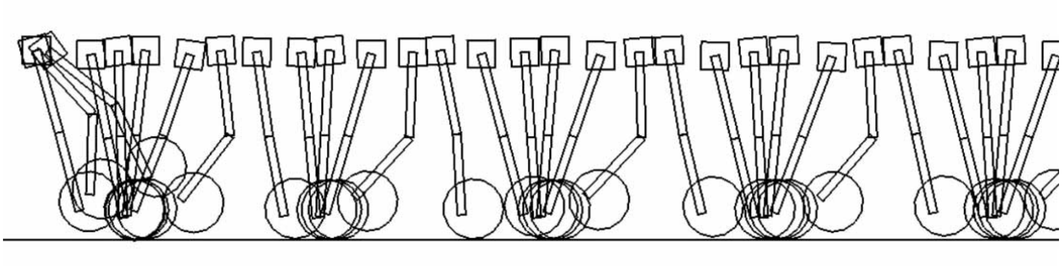


Figure 9: A representative locomotion of the best evolved PDW biped obtained in the first stage of evolution (see from left to right).

4.2 Verification of Robustness

Experiments under Embodiment 1

In order to verify the robustness of the best evolved PDW biped obtained in the first stage, its ability for coping with the gradient changes was investigated. More specifically, the number of steps successfully traveled was recorded under a different gradient of slope never explored in its evolutionary process. Notice that this PDW biped was evolved on the slope, the gradient of which was set to 3 [deg]. The result is shown in Figure 10. As the figure indicates, the number of steps observed fluctuates drastically between 3 and 6 [deg]. In sum, the PDW biped obtained in the first stage does not show a consistent performance in terms of robustness.

Based on the above consideration, the incremental evolutionary scheme described in section 3.2 was conducted in order to enlarge the basin of attraction of this PDW biped. The last population obtained in the first stage was further subjected to the following two-staged evolutionary processes --- the second and third stage of evolution. During these stages, each individual of the population was tested under the existence of environmental perturbations: a_{min} = 0 [deg] and a_{max} = 6 [deg] for the second stage; followed by a_{min} = 0 [deg] and a_{max} = 8 [deg] for the third stage (see section 3.2). Δt was set to 0.2[sec] for both stages.

The verification of robustness of the best evolved PDW biped obtained in the third stage was performed in a similar manner of Figure 10. (see Figure 11). As the figure explains, the range in which the biped can cope with the change of gradient is significantly expanded. Furthermore, in contrast to Figure 10, the fluctuation of its performance is also improved.

For a detailed investigation of the role of degrees of freedom, this embodiment was also evolved in the same manner (*i.e.* from the first to the third stage of evolution) under the condition where its waist joints was forcibly fixed (see Figure 12). As the figure indicates, the PDW biped without these degrees of freedom shows less performance. This strongly suggests that the degrees of freedom in upper body significantly contributes to enlarge the basin of attraction of PDW bipeds.

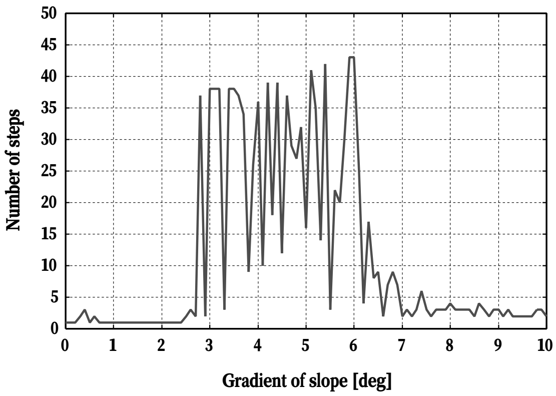


Figure 10: Robustness of the PDW biped obtained in the first stage against gradient changesembodiment 1).

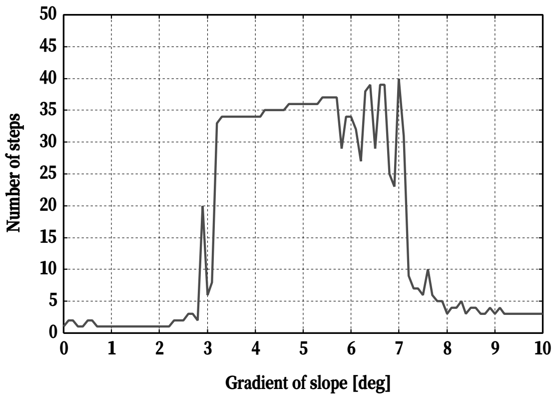


Figure 11: Robustness of the PDW biped obtained in the third stage against gradient changes (embodiment 1).

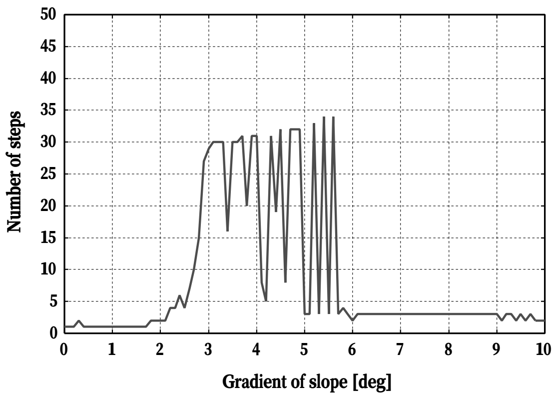


Figure 12: Robustness of the PDW biped obtained in the first stage against gradient changes (embodiment 1).

Experiments under Embodiment 2

The incremental evolutionary scheme was conducted in the same manner as in the case of embodiment 1 except that a_{min}, a_{max} was set to (1, 7) [deg] in the second stage and (0, 9) [deg] in the third stage, respectively. Figure 13 and Figure 14 represent the robustness of the best evolved biped obtained in the first stage and the third stage against the change of the gradient, corresponding to Figure 10 and Figure 11 of embodiment 1, respectively. In order to investigate the role of the degrees of freedom in ankle joints, embodiment 2 with forcibly locked ankle joints was also evolved in the same manner. Shown in Figure 15 indicates the result after the evolution of three stages. As can be recognized from Figure 14 and Figure 15, the biped's walkable range of the gradient is expanded by the degrees of freedom in ankle joints. However, a significant improvement of the robustness cannot be observed in this experiment.

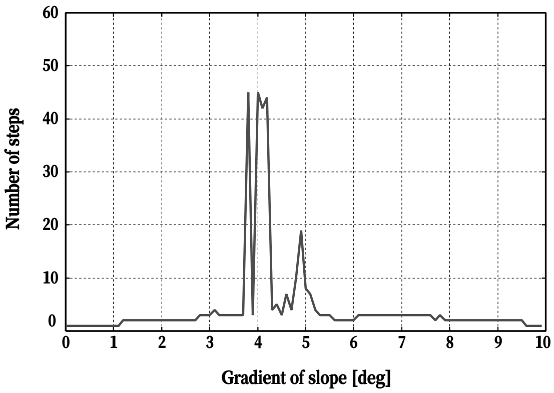


Figure 13: Robustness of the PDW biped obtained in the first stage against gradient changes (embodiment 2).

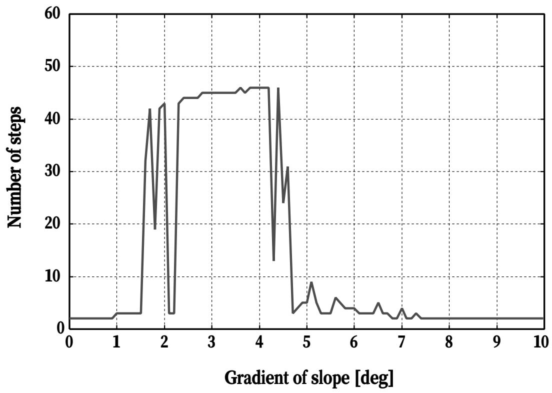


Figure 14: Robustness of the PDW biped obtained in the third stage against gradient changes (embodiment 2).

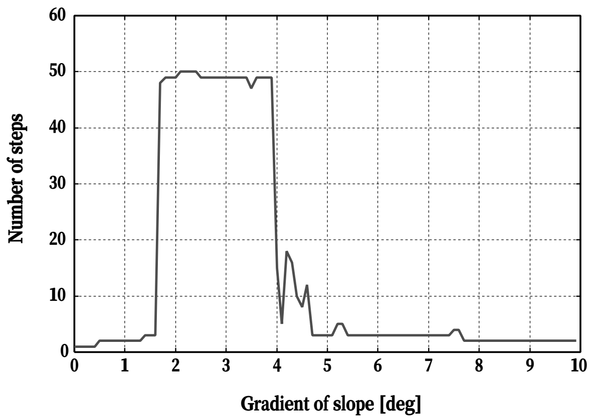


Figure 15: Robustness of the PDW biped obtained in the third stage against gradient changes (embodiment 2 with locked ankle joints).

5. Conclusionand Future Work

This paper has investigated the enlargement of basin of attraction of PDW bipeds. To this end, the concept of cooperative phenomena, widely observed in mutually-interacting many- body systems, has been introduced. The preliminary simulation results have clarified some interesting phenomena for further investigation, which can be summarized as: (1) increasing the degrees of freedom in upper body (*i.e.* embodiment 1) outperforms the one in lower body (*i.e.* embodiment 2); (2) do the current degrees of freedom and the implementation of passive elements successfully lead to the emergence of the cooperative phenomena?; and (3) how the increase of the degrees of freedom in both upper (*e.g.* pelvic body, torso, arms) and lower body (*e.g.* foot, ankle) affects the property of the attractor basin.

References

1) T. McGeer, "Passive Dynamic Walking", The International Journal of Robotics Research, Vol.9, No.~2, pp.62-82, 1990.
2) K. Osuka, and K. Kirihara, "Motion Analysis and Experiment of Passive Walking Robot Quartet II", Journal of the Robotics Society of Japan, Vol.18, No.5, pp.737-742,2000.
3) L. Schwab and M. Wisse, "Basin of Attraction of the Simplest Walking Model", ASME 2001 Design Engineering Technical Conferences, DETC2001/VIB-21363, 2001.
4) S. H. Collins, M. Wisse, and A. Ruina, "A Three-Dimensional Passive-Dynamic Walking Robot with Two Legs and Knees", The International Journal of Robotics Research, Vol.20, No.7, pp.607-615, 2001.
5) M. Wisse, A. L. Schwab, R. Q. vd. Linde, "A 3D Passive Dynamic Biped with Yaw and Roll Compensation", Robotica, Vol.19, pp.275-284, 2001
6) H. Fujimoto, A. Sano, and Y. Ikemata, "Motion Analysis of Passive Biped Walking System with Upper Limb", Proc. of the 19th Annual Conference of the Robotics Society of Japan, pp.41-42, 2001.
7) http://opende.sourceforge.net/