17

Embodiment of Legged Robots Emerged in Evolutionary Design: Pseudo Passive Dynamic Walkers

Kojiro Matsushita and Hiroshi Yokoi
Department of Precision Engineering, University of Tokyo
Japan

1. Introduction

Many legged robots have been developed, and some of them have already achieved dynamically stable bipedal and quadruped locomotion. Common characteristics of these conventional legged robots are that their motions are precisely manipulated by their control (i.e., gait and balance). In the case of ASIMO (Hirose et al., 2001) and HRP2 (Kaneko et al., 2004), their dynamically stable bipedal locomotion is based primarily on the Zero Moment Point (ZMP) concept, which was originally developed by Vukobratovic (Vukobratovic, 1969): the ZMP is a fictitious point on the ground plane, where the torques around the (horizontal) x and y axes (generated by ground reaction forces, inertial forces, and torques) are equal to zero. These robots dynamically stabilize their balance by manipulating the ZMP to remain within the support polygon area defined by their square feet, and their gait control is applied on top of the balance control. As a result, these conventional legged robots require rapid information processing and high-power drives to achieve locomotion. Therefore, they are characterized as having more complex control systems and larger energy consumption than those of biological locomotion.

On the other hand, these design requirements (i.e., fast information processing and high-power drives) are regarded as disadvantageous in biologically inspired robotics. In the field, the specific behaviors and/or structures of biological organisms are imitated (Vogel, 1998) (Alexander, 2002) with robotic technology. As a result, the robot systems have simple design requirements compared to conventional robot systems, and achieve complex tasks. Thus, the design effort tends to focus on control complexity and energy requirements. A representative instance is the Passive Dynamic Walker (PDW), which was originally developed by McGeer (McGeer, 1990). The PDW has no controller (i.e., no sensor and no motor), and the structure is based on the physical characteristics of human walking: passive hip joints, latch knee joints, and curved feet. The PDW walks down a slope, and its structure exploits gravity as the driving force. This design principle has been applied to the Cornell Biped (Collins & Ruina, 2005) and Denise at TU Delft (Wisse, 2003), and the powered passive dynamic walkers achieved passive dynamic walking on a flat plane.

In a summary of these two approaches, conventional robots require expensive design components to achieve dynamically stable locomotion. On the other hand, biologically inspired robots require physical characteristics that exploit their own dynamics to achieve

Source: Frontiers in Evolutionary Robotics, Book edited by: Hitoshi Iba, ISBN 978-3-902613-19-6, pp. 596, April 2008, I-Tech Education and Publishing, Vienna, Austria

dynamically stable locomotion. After all, biologically inspired robots implicitly realize higher adaptability to specific tasks and environments (i.e., more distance traveled, less control complexity, and smaller energy consumption on a flat plane) than conventional robots. It is obvious, then, that physical characteristics greatly contribute to high adaptability.

In the field of embodied cognitive science, such physical characteristics are regarded as □gembodiment□h (Gibson, 1979). Embodiment is defined as special features in a body that result in high adaptability to tasks and environments. There is increasing evidence that embodiment enhances energy efficiency and reduces the complexity of control architecture in robot design (Brooks, 1999) (Pfeifer & Scheier, 1999). However, embodiment has only been demonstrated with heuristically developed robots, and the design process has not been revealed. One current agreement in embodied artificial intelligence hypothesizes that embodiment can emerge in robot design with the following biologically inspired reproductive process: (1) morphologies and controllers of robots are built in the physical world; (2) robots need to interact with physical environments to achieve a specific task; (3) robot settings are evaluated according to their task achievements, and the better ones are reproduced; (4) steps (2) to (3) are repeated (i.e., physical characteristics resulting in better task achievement tend to remain in the process); (5) specific features are hypothesized to form in the body (embodiment). At this point, such a reproduction process has already been implemented in evolutionary robotics, and the evolutionary reproduction process demonstrated a variety of locomotive robots (e.g., mainly crawlers) in the three-dimensional virtual world (Sims, 1994). However, this process has just shown the qualitative characteristics of embodiment, and no physical and numerical evidence of embodiment has been presented.

Therefore, in this paper, the focus is primarily on the physical and numerical illustration of the embodiment of legged locomotion. For this method, an evolutionary design system is implemented to generate various physical characteristics. The physical characteristics that reduce control complexity and energy consumption ? embodiment - are then quantitatively investigated. Further objectives are to present a physical representation of the embodiment of legged locomotion and to demonstrate the use of robots on such a basis.

2. Evolutionary Design of Legged Robots

An evolutionary design system is proposed for emergence of embodiment on legged locomotion. The evolutionary design system consists of two parts. The first part is coupled evolution part, in which a genetic algorithm searches both morphology and controller space to achieve legged locomotion using a virtual robot in a three dimensional physics simulation. The second part involves evaluation of the evolved robots due to specifying their adaptability to tasks. All of the experimental parameters such as the simulation environment, the morphology and controller parameters, and the genetic algorithm are described in this section.

2.1 Three Dimensional Physics World

The design system is implemented using Open Dynamics Engine (ODE) (Smith, 2000), which is an open-source physics engine library for the three dimensional simulation of rigid body dynamics. The ODE is commonly used by program developers to simulate the dynamics of vehicles and robots because it is easier and more robust for implementing

joints, contact with friction and built-in collision detection than solving physical equations using the Euler method.
The environment configuration of the design system is given as sampling time 0.01 [sec], gravity 9.8 [m/s2] as gravity, friction 1.0, ground spring coefficient 5000N/m, ground damper coefficient 3000Ns/m.

2.2 Genetic Algorithm

The coupled evolution part is based on the general GA process, which starts with random genes and conducts 100 to 300 generations using a population size of 100 to 200 for each run. After all generations, the evolutionary process is terminated, and the next evolutionary process starts with new random genes. Such an evolutionary process is called seed. Table 1 lists setting values for the GA.

Parameter	Setting Value	Parameter	Setting Value
Seed	30 to 100	Number of Gene Locus	50 to 100
Generation	150 to 300	Crossover	5 to 10 %
Population	100 to 200	Mutation	5 to 10 %

Table 1. Setting Values in the GA

(i) Selection / Elimination Strategy

The design system uses an elite strategy that preserves constant numbers of higher fitness in the selection/elimination process due to its local convergence. At each generation, each gene acquires a fitness value. At the end of each generation, the genes are sorted from highest to lowest fitness value. The genes in the top half of the fitness order are preserved, while the others are deleted. The preserved genes are duplicated, and the copies are placed in the slots of the deleted genes. The copied genes are crossed at 5-10% and mutated at 5-10%.

(ii) Terminational Condition

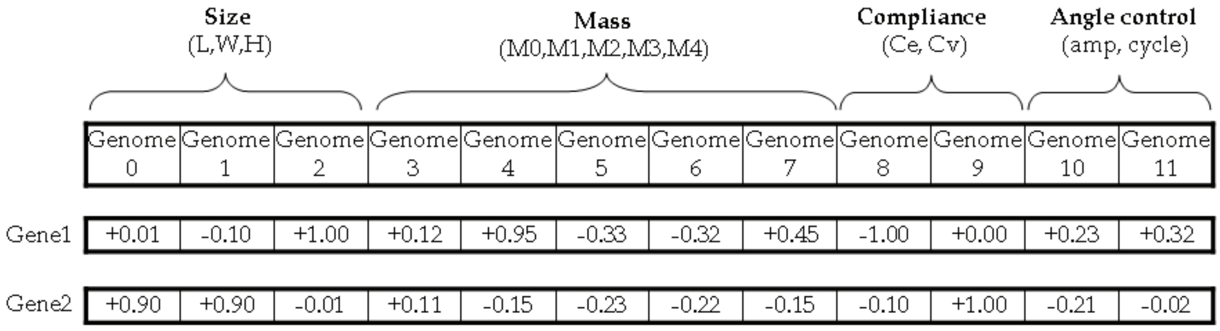
The evolutionary process has two major terminational conditions for emerging legged locomotion: (1) An individual is terminated if the height of the center of gravity drops 90% below the initial height, and the individual acquires -1.0 [m] as its fitness; (2) If the position of the foot does not move more than 0.005 [m], the individual is terminated and acquires -1.0 [m] as its fitness. The former is a necessary condition to prevent falling or crawling solutions. The latter is a necessary condition to achieve cyclic movement (preventing still movement).

(iii) Fitness

Fitness in the evolutionary process is defined as the distance traveled forward for a constant period, which should be sufficient to achieve cyclic movement and short enough to economize the computational power. Normally the period is 6 to 10 [sec].

2.3 Gene Structure

A fixed-length gene is applied to the gene structure in the design system. It is because each gene locus in a fixed-length gene easily inherits specific design parameters during the evolutionary process. Besides, it is easy to save, edit, or analyze those design parameters.
In the gene structure, morphological and control parameters are treated equally (Fig.1) for the evolutionary process so that each locus contains a value ranging from -1.00 to +1.00 at an interval of 0.01. Figure 4-7 shows locus IDs corresponding to the following design parameters: L, W, H, M0, M1, M2, M3, M4, k, c, amp, and cycle, and these parameters are used with conversion equations.



	Genome 0	Genome 1	Genome 2	Genome 3	Genome 4	Genome 5	Genome 6	Genome 7	Genome 8	Genome 9	Genome 10	Genome 11
Gene1	+0.01	-0.10	+1.00	+0.12	+0.95	-0.33	-0.32	+0.45	-1.00	+0.00	+0.23	+0.32
Gene2	+0.90	+0.90	-0.01	+0.11	-0.15	-0.23	-0.22	-0.15	-0.10	+1.00	-0.21	-0.02

Figure 1. Concept figure of gene structure

2.4 Morphological Parameters

Morphology of a legged robot in the design system consists of five kinds of design components in Fig.2 and Table 2: joint type (compliant / actuated), joint axis vector, link size, link angle, and link mass. These physical components are viewed as basic components of a biological system (Vogel, 1999) and, therefore, it is hypothesized that the components satisfy presenting artificial legged locomotion.

		Link 1	Link 2
Size	Length [m]	0.1	0.1
	Width [m]	0.1	0.1
	Height [m]	0.1 to 0.5	0.1 to 0.5
Absolute Angle at Pitch (y) Axis [rad]		-π / 3 to π / 3	-π / 3 to π / 3
Mass [kg] (Total Mass X [kg])		X * 10-90%	X * 10-90%

Table 2. Basic link configuration

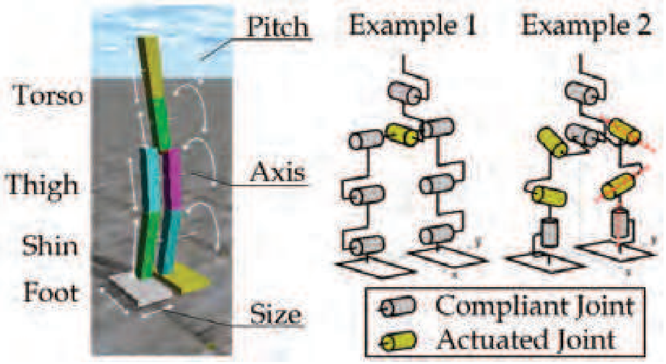


Figure 2. A basic representation of a physical structure

2.5 Control Parameters

It is hypothesized that a simple controller inevitably leads to the formation of special body features for stable legged locomotion in evolutionary processes. Simple rhythmic oscillators are applied in the design system due to identifying special features in a legged robot's body. Fig. 3 shows a basic representation of the joint structure. Contra-lateral set of joints are either rhythmic oscillators or compliance, which are determined in the evolutionary process. The characteristics of the oscillators are mainly determined by two types of parameters: amplitude and frequency (Table 3). In addition, all oscillators have the same wavelength, and contra-lateral oscillators are in anti-phase based on the physiological knowledge of gait control.

			Joint 1	Joint 2
Type	Compliance	Elasticity [N/m]	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}
		Viscosity [Ns/m]	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}
	Angle Control	Amplitude [rad]	0 to $\pi/2$	0 to π / 2
		Cycle [sec]	0.5 to 1.5	
Axis Vector		X	-1.0 to +1.0	-1.0 to +1.0
		Y	-1.0 to +1.0	-1.0 to +1.0
		Z	-1.0 to +1.0	-1.0 to +1.0

Table 3. Basic joint configuration

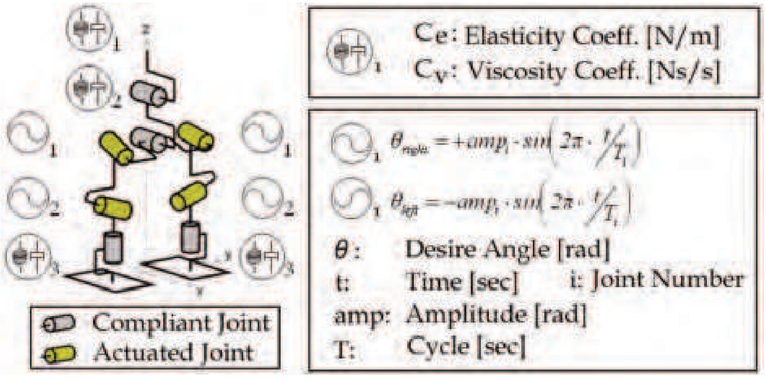


Figure 3. A basic representation of a control architecture

2.6 Evaluation Methods: Energy Consumption and Energy Efficiency

The design system targets legged robots, which achieve stable locomotion with less control complexity and smaller energy consumption than conventional legged robots. Therefore, energy consumption and energy efficiency are applied as the evaluation methods to qualify the evolved legged robots. The calculational procedure is described as follows.

In physics, mechanical work [Nm] represents the amount of energy transferred by a force, and it is calculated by multiplying the force by the distance or by multiplying the power [W] by the time [sec]. In the case of a motor, time and rotational distance are related with its angular speed, and the torque, which causes angular speed to increase, is regarded as mechanical work. Thus, power in rotational actuation is calculated with the following equation 1:

$$\text{Power [W]} = \text{torque [Nm]} * 2\pi * \text{angular velocity [rad/s]} \tag{1}$$

Therefore, energy consumption for a walking cycle is represented with equation 2. Energy efficiency is computed as energy consumption per meter (equation 3). In this equation, total mass is ignored because it is set as a common characteristic.

$$Energy\ Consumption\ for\ a\ walking\ cycle\ [J] = \left(\sum_{i=0}^{N} \int_0^T \left| 2\pi \cdot Tr_i(t) \cdot \dot{\theta}_i \right| dt \right) \cdot T \quad \cdots (2)$$

$$Energy\ Efficiency\ for\ Locomotion\ [\,J/m] = \frac{\left(\sum_{i=0}^{N} \int_0^T \left| 2\pi \cdot Tr_i(t) \cdot \dot{\theta}_i \right| dt \right) \cdot T}{Dis} \quad \cdots (3)$$

N : *The number of actuated joints* dt : *Sampling time[sec]* t : *Time[sec]*
$\dot{\theta}$: *Angular Velocity[rad/s]* Tr : *Torque at each joint* T : *A walking cycle[sec]*
Dis : *Distance traveled for a walking cycle[m]*

3. First Experiment

The evolutionary design of biped robots is conducted to verify emergence of embodiment. In particular, focus on the relations between the physical configurations and the walking characteristics of the acquired biped robots, it is attempted to numerically reveal embodiment of the legged robots.

3.1 Morphological and Control Configuration for Biped Robots

Biped robots are constructed using nine rigid links: an upper torso, a lower torso, a hip, two upper legs, two lower legs, and two feet. These body parts are respectively connected at torso, upper hip, lower hip, knee, and ankle joints, and the robots have eight degrees of freedom.

			Torso	Hip	Knee	Ankle
Type	Compliance	Elasticity Coeff. [N/m]	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}
		Viscosity Coeff. [Ns/m]	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}
	Actuation (Angle control)	Amplitude [rad]	0 to π/2	0 to π/2	0 to π/2	0 to π/2
		Cycle [sec]	0.5 to 1.5	0.5 to 1.5	0.5 to 1.5	0.5 to 1.5
Axis vector		X	1	-1.0 to +1.0	-1.0 to +1.0	-1.0 to +1.0
		Y	0	-1.0 to +1.0	-1.0 to +1.0	-1.0 to +1.0
		Z	0	-1.0 to +1.0	-1.0 to +1.0	-1.0 to +1.0

Table 4. Characteristic of joints (searching parameters colored in blue)

		Upper/ lower Torso	Hip	Thigh	Shin	Foot
Size	Length [m] (X axis)	0.1	-	0.1	0.1	0.1 to 0.5
	Width [m] (Y axis)	0.1	-	0.1	0.1	0.1 to 0.5
	Height [m] (Z axis)	0.1 to 0.5	-	0.1 to 0.5	0.1 to 0.5	0.05
	Radius [m]	-	0.05	-	-	-
Absolute angle at pitch (y) axis [rad]		-π/3 to π/3	-	-π/3 to π/3	-π/3 to π/3	-π/3 to π/3
Parallel displacement on y axis[m]		-	-	-	-	0 to 0.2
Total Mass 20 [kg] (a+2b+2c+2d=100%)		e	a	b	c	d

Table 5. Characteristic of links (searching parameters colored in blue)

Table 4 and table 5 lists control paramters (i.e., amplitude and frequency) and morphological parameters (i.e., size, weight, absolute angle of each link and selection of whether it is oscillatory or compliant, as well as its elasticity coefficient and viscosity coefficient if the joint is compliance or amplitude and frequency if the joint is a oscillator, and axis vector of each joint). In addition to this setting, joint settings are constrained to be contra-laterally symmetric around the xz plane as descriebd in Section 2.5.

3.2 Results

The evolutionry design system performed thirty independent runs. At each time, the genetic algorithm started with a new random set of genomes (i.e., seed). Fig.4 shows fitness transitions of thrty seeds. We focus on the best genome from the nine most successful runs – the biped robots that locomote forward more than seven meters for ten seconds (Fig.5). Then, we analyzed the relationship between the morphologies and locomotion strategies of these robots.

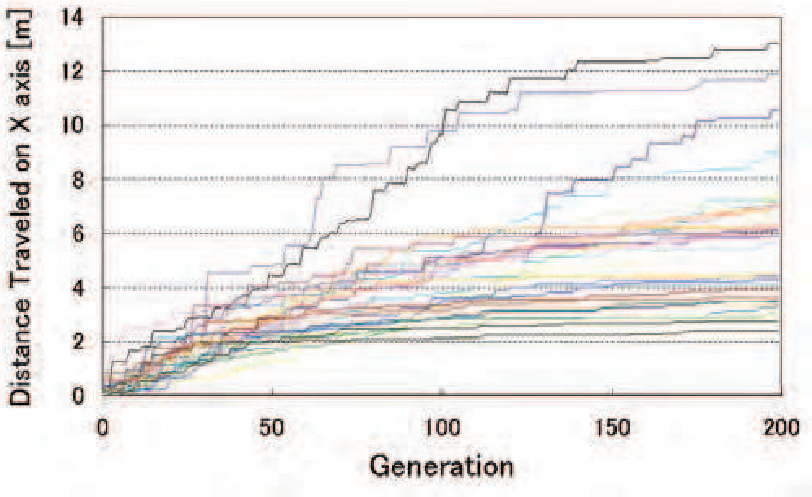


Figure 4. Transition of Best fitness (30seeds, 200generation, 200population)

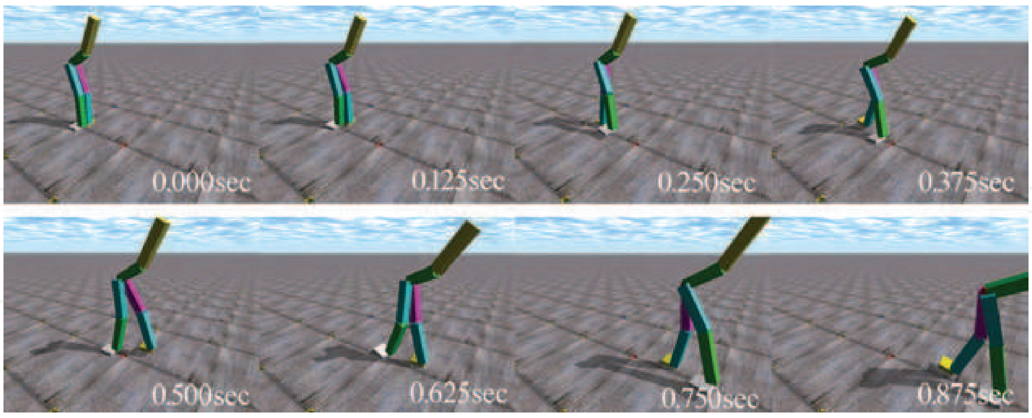


Figure 5. Walking scene of best fitness

Table 6 lists the perfomance of the best nine biped robtos: the second column reports their distance traveled forward for 10 [sec]; the third column, their walking cycle; the fourth column, their angular velocity of oscillators; the fifith column, their energy efficiency; the six column, their numbers of contral-lateral set of actuted joints (i.e., four types - torso hip, knee, ankle joints). The biped robots indicating high energy efficiency tend to have less numbers of actuated joints in their system. It suggest that embodiment, which reduces control complexity and energy consumption, is emerged in the system of the legged robots. Then, further analysis indicates taht hip joints tend to become actuated joints, and knee joints tend to be compliant joints. Especially, focus on the characterisits of the compliant joints, they are categorized into three conditions: free joint, suspension joint, and fixed joint corresponding to the degree of elasticiy and viscocity.

Seed	Distance [m]	Cycle [s]	Angular Velocity [rad/s]	Energy Efficiency [J/m]	Number of Actuated DOFs
09	13.0	1.02	0.50	6.0	2
11	7.3	1.05	0.32	7.0	1
02	7.7	1.17	0.38	7.7	2
00	10.6	1.05	0.55	8.2	3
14	7.0	1.01	0.45	10.0	2
22	11.9	1.06	0.99	13.1	3
08	9.2	1.04	0.81	13.8	3
21	7.1	1.08	0.69	15.2	3
17	7.2	1.04	0.88	19.1	3

Table 6. Performance of best 9 biped robots in ordre of energy efficiency (Energy efficiency is calicuralated with average torque 25.[Nm], and lower values indicate better performance)

	Upper hip joint	Lower hip joint	Knee joint	Ankle joint
Number	4	1	7	2

Table 7. Number of compliant joints among best 9 biped robots

	Condition		Number of Types
Free Joint	0<=Ce<10	0<=Cv<10	3
Suspension Joint	10<Ce<=100	0<=Cv<10	5
Fixed Joint	Ce>100	-	6
	-	Cv>=10	

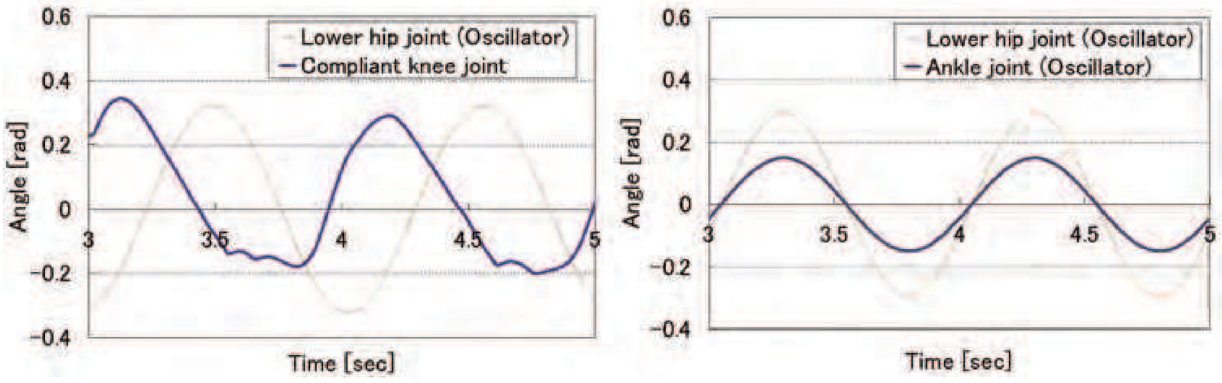
Table 8. Characteristics of compliant joints among best 9 biped robots (Ce: elasticity coefficient [N/m], Cv: viscosity coefficient [Ns/m])

3.3 Active control walker vs Compliant walker

In the previous section, it is confirmed that compliant joints have three conditions, however, it is not revealed that how the conditons contribute to the stable locomotion of the best nine legged robots. So, an additional experiment is conducted to verify roles of the compliant joints. The addtional experiment proceeds as follows: (1) the evolutionary design system of biped robots conductes again under the condtion, which compliance is not involved as design parameters; (2) the best biped robots in the design system – namely, active controlled walkers - are compare analyzed with the best biped robots in the previous design system – namely, compliant walkrs. (The actively controlled walker indicates a biped robot without any compliant joint.)

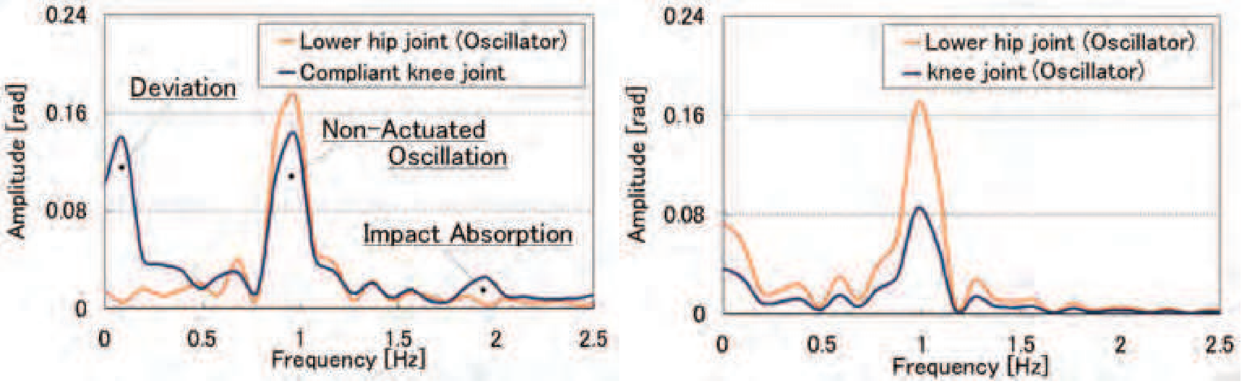
As resutls of the additional experiment, Fig. 6 show joint angle trajectories of the compliant walker and the actively controlled walker, and Fig.7 shows resutls of frequency analysis on the transtions. Here, the compliant walker has remarkable characteristics on hip and knee joint (as desribed in previous section) so taht only those transitions are focused.

Among the varied behavior of the joints, it is observed that the knee oscillation in the compliant walker is induced by oscillators at other joints (self-regulation (Iida & Pfeifer, 2004)). Moreover, amplitude at 2 [Hz] in Fig.7(a) indicates gruond impact absorption (self-stabilization) with compliance. That is, the appropriate state of compliant joints realizes these functions passively and dynamically during locomotion. Therefore, the robots which obtain these characteristics can be called pseudo-passive dynamic walkers. Moreover, these two functions serve as examples of the computational trade-off possible between morphology and controller, because compliant joints can be moved by energy input channels other than controlled motors and filter noise without computational power.



(a) Compliant walker (b) Actively controlled walker

Figure 6. Joint angle trajectories of hip and knee joints



(a) Compliant walker (b) Actively controlled walker

Figure 7. Frequency analysis (i.e., discrete Fourier transform) of joint angle trajectories of hip and knee joints

4. Second Experiment

The second evolutionary design is conducted for clarifying the embodiment: compliance. Basically, the setting parameters in Section 3.1 are applied to the evolutionary design and, for the purpose of narrowing its solution space to specify physical structures exploiting compliance, the condition, that restricts the numbers of actuated joints, is added to the system. Table 9 indicates joint configurations for the second evolutionary design, and a scheme for joint-type selection is as follows: one of four types of joint structures (i.e., either set of torso, hip, knee, and ankle becomes an actuated joint and other sets of the joints are compliant) is selected for a walker. The evolutionary design is conducted using 100 different random seeds, is run for 100 generations, and the population is comprised of 100 individuals.

				Torso	Hip	Knee	Ankle
Type	Compliance	Elasticity Coeff. [N/m]		10^{-2} to 10^{+4}	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}
		Viscosity Coeff. [Ns/m]		10^{-2} to 10^{+4}	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}
	Actuation (Angle control)	Amplitude [rad]		0 to π/2	0 to π/2	0 to π/2	0 to π/2
		Cycle [sec]		0.5 to 1.5	0.5 to 1.5	0.5 to 1.5	0.5 to 1.5
	Selection of Joint Type	0 to 3	0	Act.	Comp.	Comp.	Comp.
			1	Comp.	Act.	Comp.	Comp.
			2	Comp.	Comp.	Act.	Comp.
			3	Comp.	Comp.	Comp.	Act.

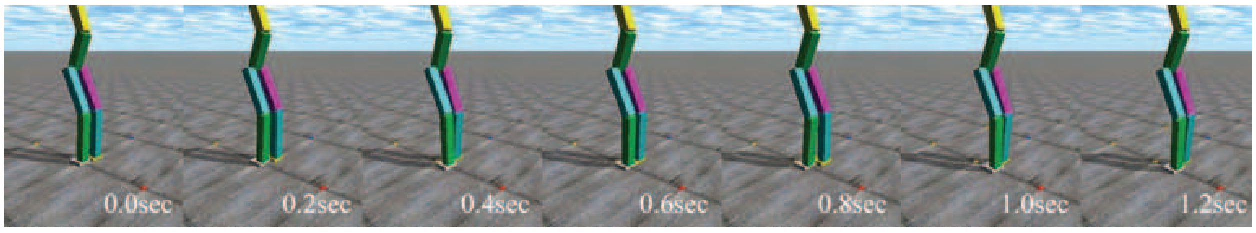
Table 9. Joint Configuration (searching parameters colored in blue)

4.1 Results: Walking Characteristics

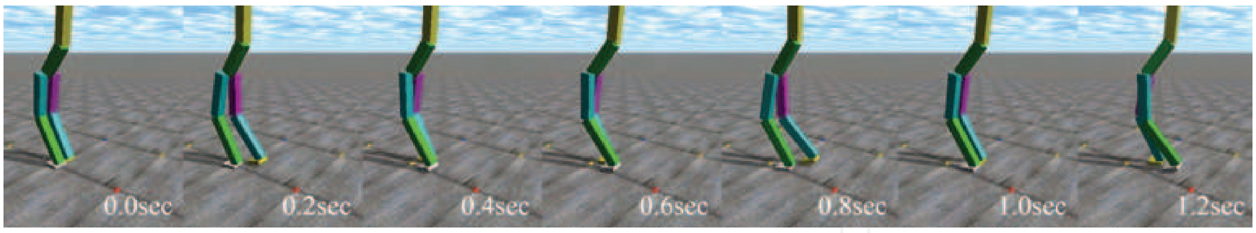
The evolutionary design generated six notable walks. In this section, their walking characteristics are described according to their joint structures.

(i) Hip actuated walkers

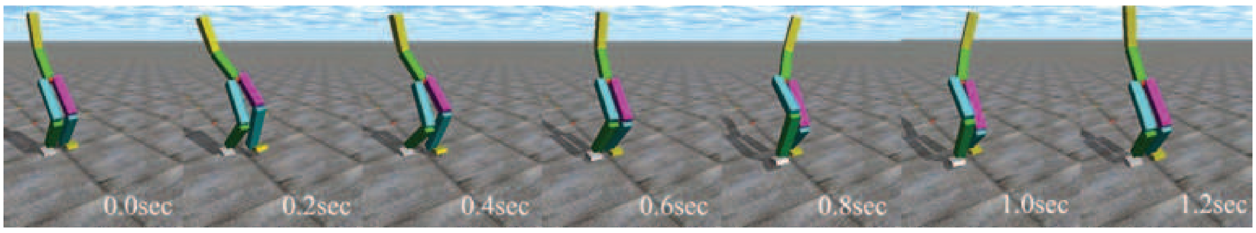
Hip actuated walkers are defined as walkers in which actuation is located at the hip, and the other joints are compliant. This pattern arose often (i.e., 55 out of 100 seeds) in the evolution process. The gaits can be characterized into three notable types: statically stable, dynamically unstable, and dynamically stable walks.



(a) Statically Stable Walk



(b) Dynamically Unstable Walk



(c) Dynamically Stable Walk

Figure 8. Representative hip actuated walkers

The statically stable walk is achieved most often among the hip actuated walkers (Fig.8a): they increase their mechanical stability and keep a narrow amplitude range in their oscillation so that their COG-Xs remain within their supporting polygon while walking. Fig.8 (b) shows a dynamically unstable walk. It walks with a tottering gait because the edges of its feet randomly contact the ground. So, its performance is unstable even on the flat plane. Meanwhile, Fig.8(c) shows a dynamically stable walk. The main feature is the axis vector of its hip joint: the oscillations at the hip axis synchronously move not only the legs in the sagittal plane but also the torso in the lateral plane. It is revealed that hip actuation enhances its stability with this physical feature.

Overall, the hip actuated walkers tend to exploit compliance only a little, and achieve their walks mainly by their actuation.

(ii) Knee actuated walker

Knee actuated walkers are defined as walkers in which actuation is located at the knee and all other joints are compliant, yet the genetic algorithm rarely generated (i.e., 3 out of 100 seeds) such walkers during evolution. The walkers commonly present a unique solution. Fig.9 shows the scene that the walker rotates the knee at the Z axis, and does not fall over for 6 seconds. That is, the walker finds a solution to elude the two termination criteria (i.e., (1) the height of the center of gravity drops 90% below the initial height; (2) the position of the foot does not move more than 0.005 [m]), and therefore remained.

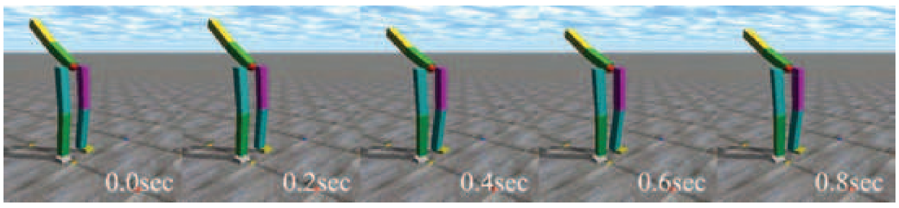


Figure 9. Representative knee actuated walker

(iii) Ankle actuated walker

Ankle actuated walkers are defined as walkers in which actuation is located at the ankle and all other joints are compliant, and also hardly generated solutions (i.e., 12 out of 100 seeds) during evolution. Its walk exploits compliance: the ankle is actuated and, then, the compliance in the walker synchronously moves the hip, knee, and torso joints by the actuation. Fig.10 shows the walking scene. It is observed that the physical structure of the walker is regarded as a laterally oscillating spring while walking. Thus, it indicates that compliance contributes to its stable walk.

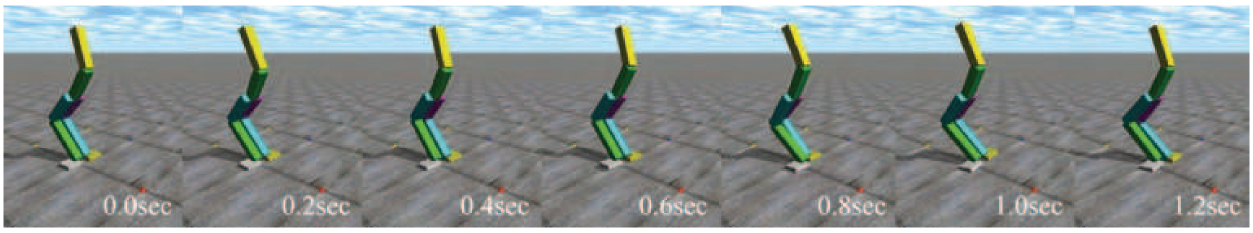


Figure 10. Representative ankle actuated walker

(iv) Torso actuated walkers

Torso actuated walkers are defined as walkers in which actuation is located at the torso and all other joints are compliant, and produced the second most common solutions (i.e., 29 out of 100 seeds) during evolution. Fig.11 shows the representative walking scene. The walker transfers a torso oscillation (actuation) in the lateral plane to hip oscillations (compliance) in the sagittal plane by exploiting its joint structure and material properties, and achieves stable walking.

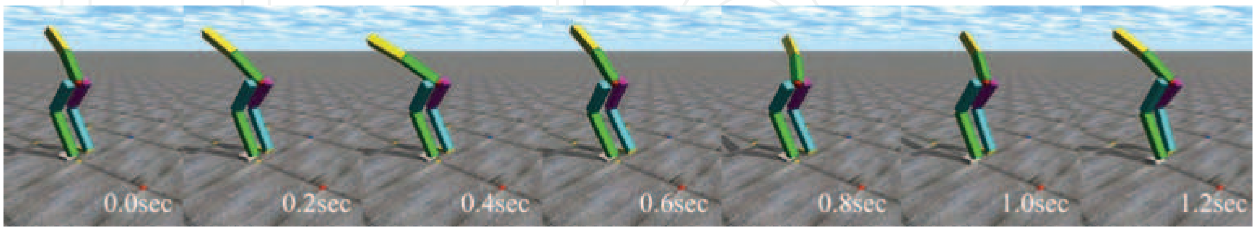


Figure 11. Representative torso actuated walker

4.2 Physical Representation of Embodiment

For illustrating the relations between physical structures, distances traveled, and energy consumption, the best fitness from 100 independent evolutionary runs are plotted on a two-dimensional graph (Fig.12: energy consumption on the vertical axis, distance traveled on the horizontal axis, and markers representing joint structures). It is characterized that each type of walkers is distributed around a certain area on the graph: the hip actuated walkers around the center; the knee actuated walkers around zero; the ankle actuated walkers around the left bottom; the torso actuated walkers around the bottom. Table 10 lists the best performance (i.e., their distances traveled, energy consumption, and energy efficiencies) in each type.

In terms of the rate of solutions generated, the evolutionary design generated the most hip actuated walkers. Meanwhile, the torso and ankle actuated walkers achieved higher energy efficiencies (energy consumption divided by distance traveled) so the rate does not relate to the emergence of embodiment.

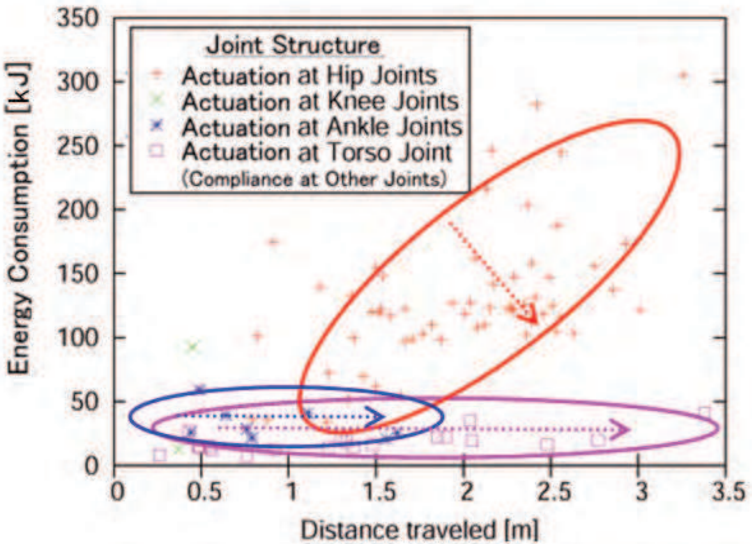


Figure 12. A physical representation of embodiment. It illustrates the relations between joint structure, energy consumption, and distance travelled. Circles indicate distribution of four types of walkers, and arrows indicate the tendency of specific physical characteristics

For physical features, high fitness (i.e., distance traveled) of each walker tends to have specific physical features: (1) the ankle actuated walkers have high compliance at hip for the sagittal rotation, knee and torso for the lateral rotation; (2) the hip actuated walkers have low compliance at knee, ankle, and torso (i.e., only the hip is joints with mobility); (3) the torso actuated walkers have high compliance at hip for the sagittal rotation, low compliance at knee and ankle (i.e., the thigh and shin are regarded as one link). In particular, the walkers with high energy efficiency tend to characterize the specific physical features. Thus, Fig.12 indicates the joint structures and material properties (i.e., special physical features) and distance traveled and energy consumption energy efficiency (i.e., evaluation of embodiment). Then, the walkers with the special physical features have high evaluation on distance traveled and energy efficiency. That is, Fig.12 indicates a physical representation of the embodiment specifying pseudo passive dynamic walkers (the right bottom in the figure is best solutions).

Actuated Joint	Hip	Knee	Ankle	Torso
Number of Best fitness (Total 100 seeds)	56	3	12	29
Max Distance Traveled [m] (For 6 seconds)	3.04	0.48 (fall)	1.62	3.42
Energy Consumption [kJ] (For 6 seconds)	120.	-	25.	45.
Energy Efficiency [kJ/m]	39.4	-	15.4	13.1

Table 10. Best Performance of Four Types of Walkers

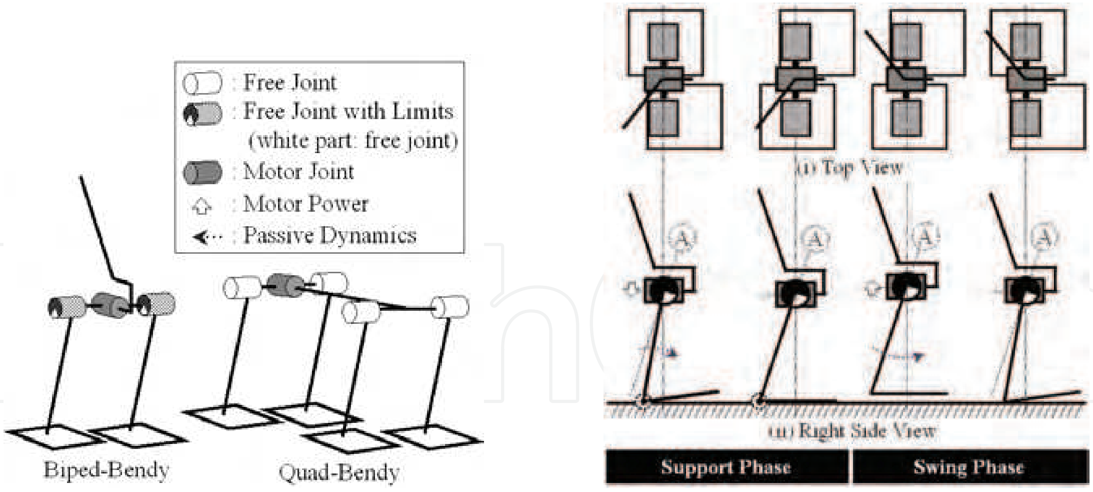
5. Development of Novel Pseudo Passive Dynamic Walkers

In this section, the physical representation of the embodiment (Fig.12) is utilized for development of pseudo passive dynamic walkers (PPDW): specific physical features are extracted from the representation, and simplified for developing novel pseudo passive dynamic walkers.

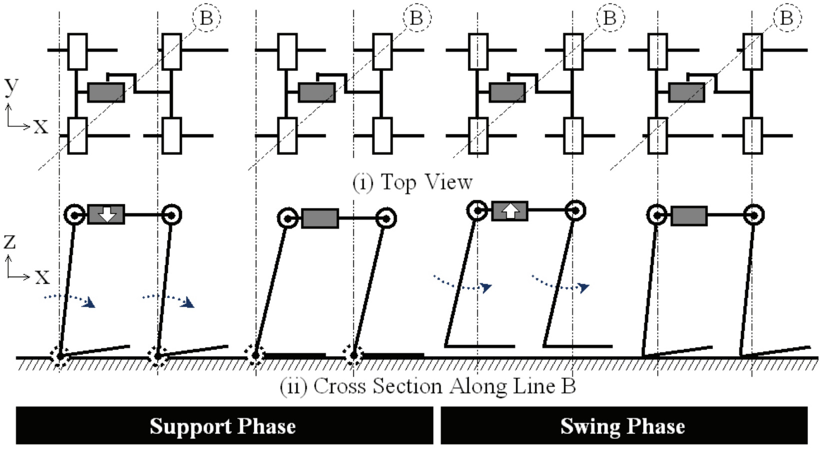
5.1 Novel Pseudo Passive Dynamic Walkers

The best embodiment in the representation (Fig.12) illustrates a structure, which is high compliance at the hip, low compliance at the knee and ankle, and actuation at the torso, and which achieves stable locomotion by transferring actuation power from lateral oscillation at the actuated torso to sagittal oscillations at the compliant hip. Then, such biped robots are simplified, and a novel biped PPDW is design as shown in Fig.13 (a). Fig.13 (b) shows walking mechanism of the Biped PPDW: it exploits its own physical features (i.e., actuation, gravitational, and inertial forces) for taking steps.

Moreover, an evolutionary design of quadruped robots is also conducted as the one of biped robots. Then, the design system also acquire embodiment for quadruped robots as shown in Fig. 13 (right). It basically represents the same design principle as the biped PPDW because the torso actuation transfers to the hip and shoulder joints to move. The conceptual walking mechanism is shown in Fig.13 (c).



(a) DOFs (b) Walk mechanism of Biped-PPDW



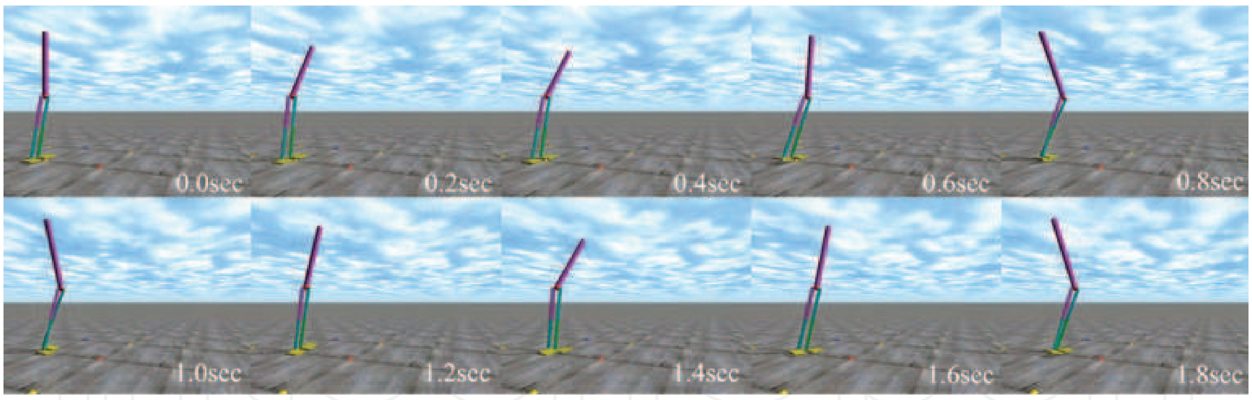
(c) walk mechanism of Quaduped-PPDW

Figure 13. Biped and quadruped pseudo passive dynamic walkers (PPDW)

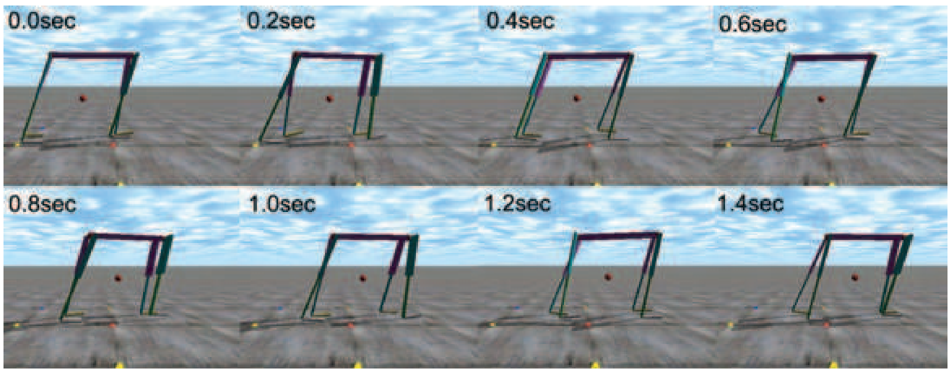
5.2 Demonstration in Real and Virtual World

The biped and quadruped PPDWs are developed for vertification of their embodiments in both virtual and real world. The ODE is used for the implementation of virtual PPDWs. A robotic development kit is applied for the development of real PPDWs. The robotic development kit characterizes using plastic bottles as frames of robot structure, RC servomotors as actuated joints, and hot glues for connecting them (Matsushtia et al, 2007). This unique approach has advantages of shorting machining and building time and enabling easy assembly and modification for begineers. It is not for developing precisely operated robots but the kit is durable enough to realize the desired behavior.

As results, the biped and quadruped PPDWs were developed in both virtual and real world, all the PPDWs achieved desire stable locomotion (Fig.14 and Fig.15). Although the real quadruped PPDW achieved similar performance to the virtual one, the real biped PPDW performed less than the virtual one (i.e., slower). It seems that the biped PPDW requires more dynamical stability than the quadruped PPDW so that it is difficult to tune the parameters of the biped PPDW for better performance. However, it is significant that even the real PPDWs, which are developed with the rough developmental kits, performed desire locomotion. Therefore, the embodiment is highly adaptive to low-cost and stable locomotion on flat plane.

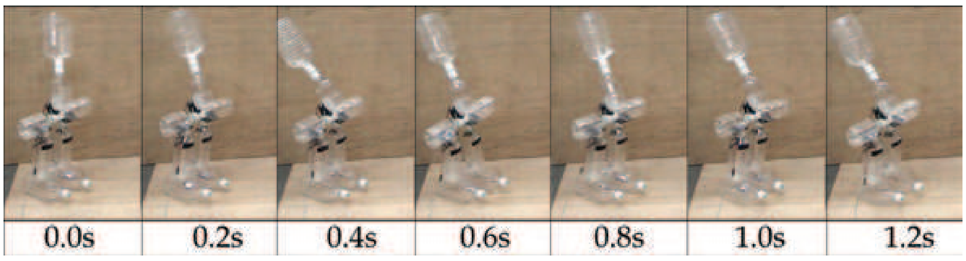


(a) Biped PPDW

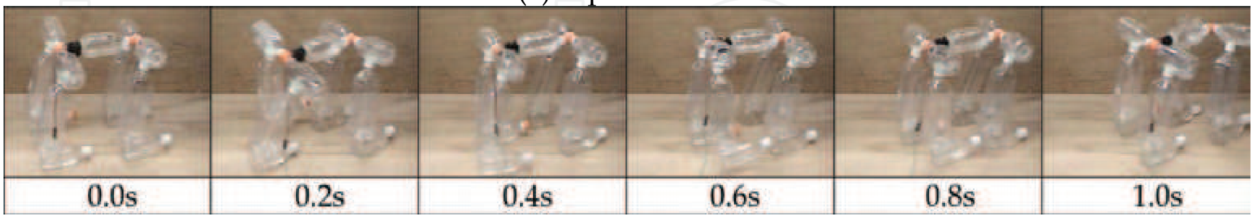


(b) Quadruped PPDW

Figure 14. Walk scenes of the PPDWs in virtual world



(a) Biped PPDW



(b) Quadruped PPDW

Figure 15. Walk scenes of the PPDWs in real world. The robots are developed with a robotic development kit for creative education. <http://www.koj-m.sakura.ne.jp/edutainment/>

6. Conclusion

An objective of this paper is to illustrate a physical representation of the embodiment on legged locomotion. Embodiment is here defined as physical features that reduce control complexity and energy consumption of legged robots. In this method, the embodiment of biped robots is explored by the coupled evolution of morphology and a controller. As a result, (1) the first evolutionary design verified the emergence of embodiment: two functions of compliance contributed to dynamically stable locomotion; (2) the second evolutionary design specified the physical features (i.e., compliance and structures) and the effects: the biped robots resulting in higher energy efficiency tended to have specific physical features (i.e., a physical representation of embodiment). Eventually, the representation led to the development of novel pseudo-passive dynamic walkers, and those robots demonstrated legged locomotion with one motor in both the virtual and real worlds.

7. Acknowledgements

K. Matsushita is financially supported by Research Fellowships of Japan Society for the Promotion of Science for Young Scientists.

8. References

Hirose, M.; Hirukawa, Y.; Takenaka, T. & Hirai, K. (2001). Development of Humanoid Robot ASIMO. *Proceedings of International Conference on Intelligent Robots and System*.

Kaneko, K.; Kanehiro, F.; Kajita, S.; Hirukawa, H.; Kawasaki, T.; Hirata, M.; Akachi, K. & Isozumi, T. (2004). Humanoid robot HRP-2. *Proceedings of 2004 IEEE International Conference on Robotics and Automation*, pp. 1083- 1090

Vukobratovic, M. & Stepanenko, J.Juricie. (1972). On the Stability of Anthropomorphic Systems. *Mathematical Bioscience*. Vol.15, pp.1-37.

Taga, G.; Yamaguchi, Y. & Shimizu, H. (1991) Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment. *Bilogical Cybernetics*, Vol.65, pp.147-159.

Vogel, S. (1998). Cats' Paws and Catapults. W.W.Norton & Company.

Alexander, R. (2002). Principles of Animal Locomotion. Princeton University Press.

McGeer, T. (1990) Passive dynamic walking. *International Journal of Robotics Research*. Vol.9, No.2, pp.62–82.

Collins, S. & Ruina, A. (2005) A bipedal walking robot with efficient and human-like gait. In *Proceedings of 2005 IEEE International Conference on Robotics and Automation*.

Wisse, M. & Frankenhuyzen, I. (2003) Design and construction of MIKE: a 2D autonomous biped based on passive dynamic walking. *Proceedings of International Symposium on Adaptive Motion and Animals and Machines*.

Gibson, J. (1979). The Ecological Approach to Visual Perception. Boston: Houghton-Mifflin.

Brooks, R. (1999). Cambrian intelligence: the early history of the new AI. MIT Press, Cambridge, MA.

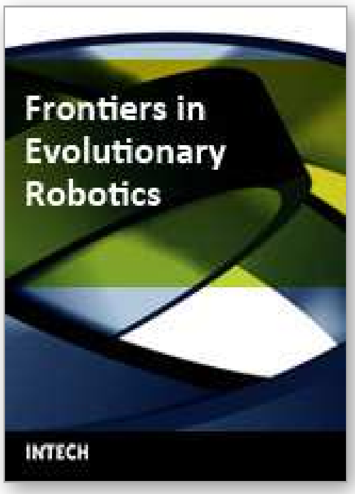
Pfeifer, R. & Scheier, C. (1999). Understanding Intelligence. MIT Press.

Sims, K. (1994) Evolving Virtual Creatures. *Computer Graphics Annual Conference Proceedings*, pp.43-50.

Smith, R. (2000) Open Dynamic Engine. URL: http://www.q12.org/.

Iida, F. & Pfeifer, R. (2004). Self-stabilization and behavioral diversity of embodied adaptive locomotion. *Embodied Artificial Intelligence*, LNCS3139, pp.119-129.

Matsushita, M.; Yokoi, H. & Arai, T. (2007). Plastic-Bottle-Based Robots in Educational Robotics Courses -Understanding Embodied Artificial Intelligence-. *Journal of Robotics and Mechatronics*. Vol.19, No.2, pp. 212-222.



Frontiers in Evolutionary Robotics
Edited by Hitoshi Iba

ISBN 978-3-902613-19-6
Hard cover, 596 pages
Publisher I-Tech Education and Publishing

Published in print edition April, 2008

This book presented techniques and experimental results which have been pursued for the purpose of evolutionary robotics. Evolutionary robotics is a new method for the automatic creation of autonomous robots. When executing tasks by autonomous robots, we can make the robot learn what to do so as to complete the task from interactions with its environment, but not manually pre-program for all situations. Many researchers have been studying the techniques for evolutionary robotics by using Evolutionary Computation (EC), such as Genetic Algorithms (GA) or Genetic Programming (GP). Their goal is to clarify the applicability of the evolutionary approach to the real-robot learning, especially, in view of the adaptive robot behavior as well as the robustness to noisy and dynamic environments. For this purpose, authors in this book explain a variety of real robots in different fields. For instance, in a multi-robot system, several robots simultaneously work to achieve a common goal via interaction; their behaviors can only emerge as a result of evolution and interaction. How to learn such behaviors is a central issue of Distributed Artificial Intelligence (DAI), which has recently attracted much attention. This book addresses the issue in the context of a multi-robot system, in which multiple robots are evolved using EC to solve a cooperative task. Since directly using EC to generate a program of complex behaviors is often very difficult, a number of extensions to basic EC are proposed in this book so as to solve these control problems of the robot.

How to reference

Kojiro Matsushita and Hiroshi Yokoi (2008). Embodiment of Legged Robots Emerged in Evolutionary Design: Pseudo Passive Dynamic Walkers, Frontiers in Evolutionary Robotics, Hitoshi Iba (Ed.), ISBN: 978-3-902613-19-6, InTech, Available from: http://www.intechopen.com/books/frontiers_in_evolutionary_robotics/embodiment_of_legged_robots_emerged_in_evolutionary_design__pseudo_passive_dynamic_walkers

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820

Fax: +385 (51) 686 166
www.intechopen.com

Fax: +86-21-62489821