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Biologically Inspired Adaptive Dynamic Walking in Outdoor Environment Using a Self-contained Quadruped Robot: 'Tekken2'

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Abstract— **We have been trying to induce a quadruped robot to walk with medium walking speed on irregular terrain based on biological concepts. We propose the essential conditions for stable dynamic walking on irregular terrain in general, and we design the mechanical system and the neural system by comparing biological concepts with those essential conditions described in physical terms. PD-controller at joints constructs the virtual spring-damper system as the visco-elasticity model of a muscle. The neural system model consists of a CPG (central pattern generator), reflexes and responses. A CPG generates rhythmic motion for walking. We define a "reflex" as joint torque generation based on sensor information and a "response" as CPG phase modulation through sensory feedback to a CPG. The state of the virtual spring-damper system is switched based on the phase signal of the CPG. CPGs, the motion of the virtual spring-damper system of each leg and the rolling motion of the body are mutually entrained through the rolling motion feedback to CPGs, and can generate adaptive walking. We report our experimental results of dynamic walking on irregular terrain in outdoor environment using a self-contained quadruped robot in order to verify the effectiveness of the designed neuro-mechanical system. MPEG footage of these experiments can be seen at:** *http://www.kimura.is.uec.ac.jp*.

I. Introduction

Many previous studies of legged robots have been performed, including studies on running[1] and dynamic walking [2], [3], [4], [5], [6] on irregular terrain. However, all of those studies assumed that the structure of terrain was known, even though the height of the step or the inclination of the slope was unknown.

On the other hand, studies of autonomous dynamic adaptation allowing a robot to walk over irregular terrain with less knowledge of it have been started only recently and by only a few research groups. One example is the recent achievement of high-speed mobility of a hexapod over irregular terrain, with appropriate mechanical compliance of the legs[7], [8] based on the biomechanical concept[9]. The purpose of this study is to realize high-speed mobility on irregular terrain using a mammal-like quadruped robot, the dynamic walking of which is less stable than that of hexapod robots, by referring to the marvelous abilities of animals to autonomously adapt to their environment.

As many biological studies of motion control progressed, it has become generally accepted that animals' walking is mainly generated at the spinal cord by a combination of a CPG (central pattern generator) and reflexes receiving adjustment signals from a cerebrum, cerebellum and brain stem[10], [11]. A great deal of the previous research on this attempted to generate walking using a neural system model, including studies on dynamic walking in simulation[12], [13], [14], [15], and real robots[16], [17], [18], [19]. But autonomously adaptive dynamic walking on irregular terrain was rarely realized in those earlier studies except for our studies [20], [21]. This paper reports on our progress using a self-contained (power autonomous) quadruped robot called "Tekken2" which was newly developed for adaptive walking on irregular terrain in outdoor environment.

II. Self-contained Quadruped: Tekken2

Each leg of Tekken2 has a hip pitch joint, a hip yaw joint, a knee pitch joint, and an ankle pitch joint (Fig.1). The direction in which Tekken2 walks can be changed by using the hip yaw joints. Two rate gyro sensors and two inclinometers are mounted on the body in order to measure the body pitch and roll angles.

In order to obtain appropriate mutual entrainment between neural system and mechanical system, mechanical system should be well designed to have the good dynamic properties. In addition, performance of dynamic walking such as adaptability on irregular terrain, energy efficiency, maximum speed and so on highly depends on the mechanical design. The design concepts of Tekken2 are:

(1) high power actuators and small inertia moment of legs for quick motion and response,
(2) small gear reduction ratio for high backdrivability to increase passive compliance of joints,
(3) small mass of the lowest link of legs to decrease impact force at collision,
(4) small contacting area at toes to increase adaptability on irregular terrain,

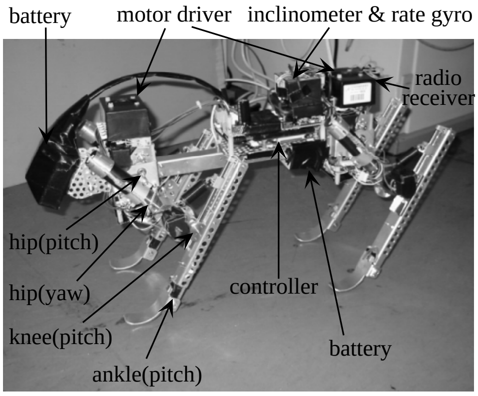


Fig. 1. Self-contained quadruped robot: Tekken2. The length of the body and a leg in standing are 30 [cm] and 20 [cm]. The weight including batteries is 4.3 [kg].

(5) passive ankle joint mechanism to prevent a swinging leg from stumble on an obstacle quickly.

III. Necessary Conditions for Stable Dynamic Walking

We propose the necessary conditions for stable dynamic walking on irregular terrain, which can be itemized in physical terms:

(a) the period of the walking cycle should be shorter enough than the upper bound of it, in which stable dynamic walking can be realized[22],

(b) the swinging legs should be free to move forward during the first period of the swing phase,

(c) the swinging legs should land reliably on the ground during the second period of the swing phase,

(d) the angular velocity of the supporting legs relative to the ground should be kept constant during their pitching motion or rolling motion around the contact points at the moment of landing or leaving,

(e) the phase difference between rolling motion of the body and pitching motion of legs should be maintained regardless of a disturbance from irregular terrain, and

(f) the phase differences between the legs should be maintained regardless of delay in the pitching motion of a leg receiving a disturbance from irregular terrain.

We design the neural system for these necessary conditions to be satisfied in order to realize adaptive walking.

IV. Implementation of Neural System for Adaptive Walking

The basic neural system model of Tekken2 is same with the one of Tekken1. We define a “reflex” as joint torque generation based on sensor information and a “response” as CPG phase modulation through sensory feedback to a CPG. Several reflexes and responses are employed in Tekken2 for adaptive walking in outdoor environment.

A. Rhythmic Motion by CPG

We construct the neural system centering a neural oscillator as a model of a CPG, since the exchange between the swing and stance phases in the short term and the quick adjustment of these phases on irregular terrain are essential in the dynamic walking of a quadruped where the unstable two-legged stance phase appears. Although actual neurons as a CPG in higher animals have not yet become well known, features of a CPG have been actively studied in biology, physiology, and so on. Several mathematical models were also proposed, and it was pointed out that a CPG has the capability to generate and modulate walking patterns and to be mutually entrained with a rhythmic joint motion [10], [11]. As a model of a CPG, we used a neural oscillator proposed by Matsuoka [23], and applied to the biped simulation by Taga[12], [13]. A single neural oscillator consists of two mutually inhibiting neurons (Fig.2-(a)). Each neuron in this model is represented by the following nonlinear differential equations:

$$\begin{aligned} \tau \dot{u}_{\{e,f\}i} &= -u_{\{e,f\}i} + w_{fe} y_{\{f,e\}i} - \beta v_{\{e,f\}i} \\ &\quad + u_0 + Feed_{\{e,f\}i} + \sum_{j=1}^{n} w_{ij} y_{\{e,f\}j} \\ y_{\{e,f\}i} &= \max\left(u_{\{e,f\}i}, 0\right) \\ \tau' \dot{v}_{\{e,f\}i} &= -v_{\{e,f\}i} + y_{\{e,f\}i} \end{aligned} \quad (1)$$

where the suffix e, f, and i mean an extensor neuron, a flexor neuron, and the i-th neural oscillator, respectively. $u_{\{e,f\}i}$ is u_{ei} or u_{fi}, that is, the inner state of an extensor neuron or a flexor neuron of the i-th neural oscillator; $v_{\{e,f\}i}$ is a variable representing the degree of the self-inhibition effect of the neuron; y_{ei} and y_{fi} are the output of extensor and flexor neurons; u_0 is an external input with a constant rate; $Feed_{\{e,f\}i}$ is a feedback signal from the robot, that is, a joint angle, angular velocity and so on; and β is a constant representing the degree of the self-inhibition influence on the inner state. The quantities τ and τ' are time constants of $u_{\{e,f\}i}$ and $v_{\{e,f\}i}$; w_{fe} is a connecting weight between flexor and extensor neurons; w_{ij} is a connecting weight between neurons of the i-th and j-th neural oscillator.

In Fig.2-(a), the output of a CPG is a phase signal: y_i .

$$y_i = -y_{ei} + y_{fi} \quad (2)$$

The positive or negative value of y_i corresponds to activity of a flexor or extensor neuron, respectively.

We use the following hip joint angle feedback as a basic sensory input to a CPG called a “tonic stretch response” in all experiments of this study. This negative feedback makes a CPG be entrained with a rhythmic hip joint motion.

$$Feed_{e\cdot tsr} = k_{tsr}(\theta - \theta_0), \quad Feed_{f\cdot tsr} = -Feed_{e\cdot tsr} \quad (3)$$

$$Feed_{\{e,f\}} = Feed_{\{e,f\}\cdot tsr} \quad (4)$$

where θ is the measured hip joint angle, θ_0 is the origin of the hip joint angle in standing and k_{tsr} is the feedback gain. We eliminate the suffix i when we consider a single neural oscillator.

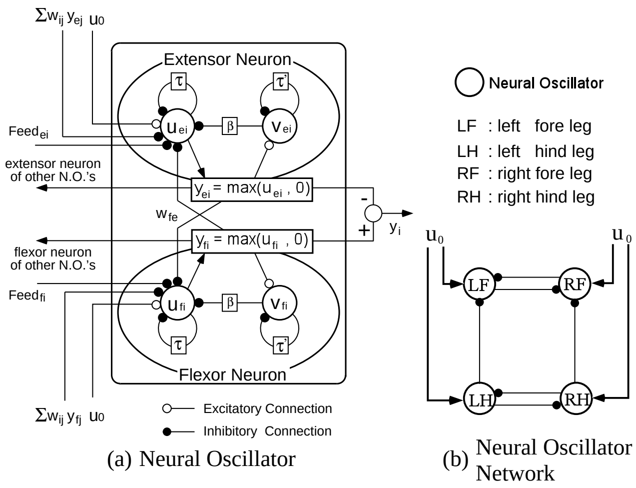


Fig. 2. Neural oscillator as a model of a CPG. The suffix $i, j = 1, 2, 3, 4$ corresponds to LF, LH, RF, RH. L, R, F or H means the left, right, fore or hind leg, respectively.

By connecting the CPG of each leg (Fig.2-(b)), CPGs are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between the CPGs of the legs results in a gait. The gait is a walking pattern, and can be defined by phase differences between the legs during their pitching motion. The typical symmetric gaits are a trot and a pace. Diagonal legs and lateral legs are paired and move together in a trot gait and a pace gait, respectively. A walk gait is the transversal gait between the trot and pace gaits. We used a trot gait and a walk gait. The autonomous gait transition in changing walking speed was discussed in our former study [21].

Although the size and weight of Tekken2 are different from those of Tekken1, the values of the parameters of CPGs used for Tekken2 were same with those used for Tekken1.

B. Virtual Spring-damper System

We employ the model of the muscle stiffness, which is generated by the stretch reflex and variable according to the stance/swing phases, adjusted by the neural system. The muscle stiffness is high in a stance phase for supporting a body against the gravity and low in a swing phase for compliance against the disturbance. All joints of Tekken2 are PD controlled to move to their desired angles in each of three states (A, B, C) in Fig.3 in order to generate each motion such as swinging up (A), swinging forward (B) and pulling down/back of a supporting leg (C). The timing for all joints of a leg to switch to the next state are:

$A \rightarrow B$:
- when the hip joint angle of the leg reaches the desired angle of the state (A)

$B \rightarrow C$:
- when the CPG extensor neuron of the leg becomes active ($y_i \le 0$)

$C \rightarrow A$:
- when the CPG flexor neuron of the leg becomes active ($y_i > 0$)

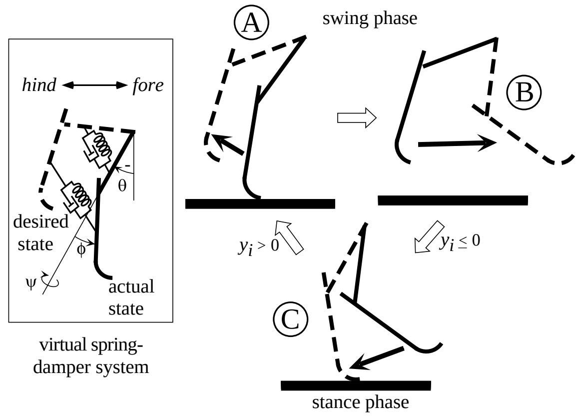


Fig. 3. State transition in the virtual spring-damper system. The desired joint angles in each state are shown by the broken lines.

TABLE I
DESIRED VALUE OF THE JOINT ANGLES AND P-GAINS AT THE JOINTS USED IN THE PD-CONTROLLER FOR THE VIRTUAL SPRING-DAMPER SYSTEM IN EACH STATE SHOWN IN FIG.3.

	P control	
angle in state	desired value[rad]	P-gain[Nm/rad]
θ in A	$1.2\theta_{C\rightarrow A}$	G_1
θ in B	-0.17	$G_2 v + G_3$
θ in C	$\theta_{stance}+$ body pitch angle	$-G_4 v + G_5$
ϕ in A & B	$*$	G_6
ϕ in C	0.61	G_7
ψ in all states	0	G_8

θ, ϕ and ψ are the hip pitch joint angle,the knee pitch joint angle and the hip yaw joint angle, respectively.
$\theta_{C\rightarrow A}$: the hip joint angle measured at the instance when the state changes from (C) to (A).
θ_{stance}: variable to change the walking speed.
body pitch angle: the measured pitching angle of the body used for the vestibulospinal reflex.
$*$ means that the desired angle is calculated on-line for the height from the toe to the hip joint to be constant.
v [m/s]: the measured walking speed of Tekken2.

The desired angles and P-gain of each joint in each state are shown in Table I, where constant values of the desired joint angles and constant P-gains were determined through experiments. Since Tekken2 has high backdrivability with small gear ratio in each joint, PD-controller can construct the virtual spring-damper system with relatively low stiffness coupled with the mechanical system. Such compliant joints of legs can improve the passive adaptability on irregular terrain.

C. CPGs and Pitching Motion of Legs

The diagram of the pitching motion control consisting of CPGs and the virtual spring-damper system is shown in the middle part of Fig.4. Joint torque of all joints is determined by the PD controller, corresponding to a stretch reflex at an α motor neuron in animals. The desired angle and P-gain of each joint is switched based on the phase of the CPG output: y_i in Eq.(2) as described in Section *IV-B*. As a result of the switching of the virtual spring-damper system and the joint angle feedback signal to the CPG in Eq.(4), the CPG and the pitching motion of the leg are mutually entrained.

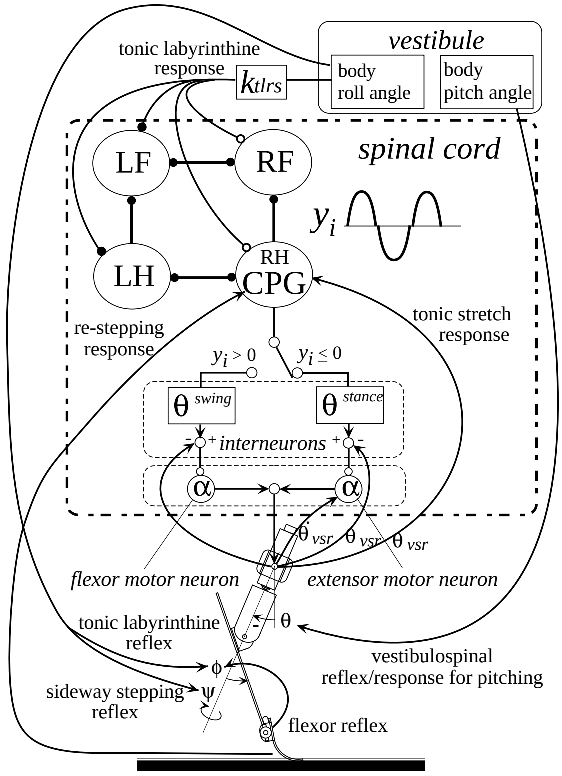


Fig. 4. Control diagram for Tekken2. PD-control at the hip yaw and knee pitch joints are eliminated in this figure.

The necessary condition (f) can be satisfied by the mutual entrainment between CPGs and the pitching motion of legs, and the mutual entrainment among CPGs[20].

D. Reflexes and Responses

Referring to biological knowledge, we employed the several reflexes and responses (Table II, Fig.4) to satisfy the necessary conditions (b)$\sim$(e) described in physical terms in Section **III** in addition to the stretch reflex and response described in Section *IV-B* and *IV-A*. In Table II, the tonic labyrinthine reflex, the sideway stepping reflex and the re-stepping reflex/response were newly employed on Tekken2. Other reflexes and responses had already been employed on Tekken1 [21].

1) Tonic Labyrinthine Reflex: The tonic labyrinthine reflex (TLRF) is employed as the adjustment of P-gain of the knee joint of the supporting legs (G_7 in Table I) according to Eq.(5).

$$\tilde{G}_7 = \delta(leg)\ k_{tlrf} \times \text{(body roll angle)} + G_7 \qquad (5)$$

$$\delta(leg) = \begin{cases} 1, & \text{if } leg \text{ is a right leg;} \\ -1, & \text{otherwise} \end{cases}$$

When an inclination of a body in roll plane (body roll angle) is detected, the knee joint P-gain of the downward-inclined legs is increased to extend those legs. In addition, the knee joint P-gain of the upward-inclined legs is decreased to flex those lges. As a result, the inclination of the body in roll plane is decreased.

2) Sideway Stepping Reflex to Stabilize Rolling Motion: It is known that the adjustment of the sideway touchdown angle of a swinging leg is effective in stabilizing rolling motion against disturbances[24]. We call this a "sideway stepping reflex," which helps to satisfy the condition (d) during rolling motion. The sideway stepping reflex is effective also in walking on a sideway inclined slope.

For examples, when Tekken2 walks on a right-inclined slope (Fig.5), Tekken2 continues to walk while keeping the phase differences between left and right lges with the help of the tonic labyrinthine response. But Tekken2 cannot walk straight and shifts its walking direction to the right due to the difference of the gravity load between left and right legs. In addition, Tekken2 typically falls down to the right for the perturbation from the left in the case of Fig.5-(a), since the wide stability margin: WSM [1]. is small. The sideway stepping reflex helps to stabilize the walking direction and to prevent the robot from falling down while keeping WSM large on such sideway inclined slope (Fig.5-(b)).

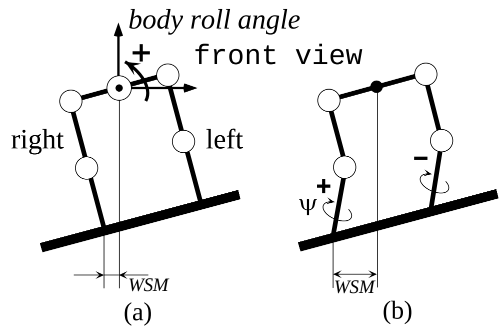


Fig. 5. Walking on a sideway inclined slope. (a):Without a sideway stepping reflex, (b):With.

Since Tekken2 has no joint round the roll axis, the sideway stepping reflex is implemented as changing the desired angle of the hip yaw joint from 0 (Table I) to ψ^* according to Eq.(6).

$$\psi^* = \delta(leg)\ k_{stpr} \times \text{(body roll angle)} \qquad (6)$$

3) Re-stepping Reflex and Response for Walking Down a Step: When loss of ground contact is detected in a swing phase while walking over a ditch, a cat activates re-stepping to extend the swing phase and make the leg land on the forwarder position[25]. We call this "re-stepping reflex/response," which is effective for the necessary condition (c) and (d) to be satisfied also in walking down a large step (Fig.6).

[1]the shortest distance from the projected point of the center of gravity to the edges of the polygon constructed by the projected points of legs independent of their stance or swing phases[21]

TABLE II

REFLEXES AND RESPONSES EMPLOYED ON TEKKEN2

	sensed value or event	activated on	corresponding necessary condition
flexor reflex	collision with obstacle	sw	(b)
stepping reflex	forward speed	sw	(d) for pitching
vestibulospinal reflex/response	body pitch angle	sp	(d) for pitching
tonic labyrinthine reflex	body roll angle	sp	(d) for rolling
tonic labyrinthine response	body roll angle	sp&sw	(c), (d) for rolling, (e)
sideway stepping reflex	body roll angle	sw	(d) for rolling
re-stepping reflex/response	loss of ground contact	sw	(d) for pitching

The sp and sw mean the supporting leg and swinging leg, respectively.

The necessary conditions are described in Section **III**.

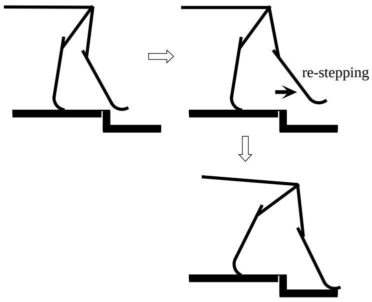


Fig. 6. Re-stepping reflex and response

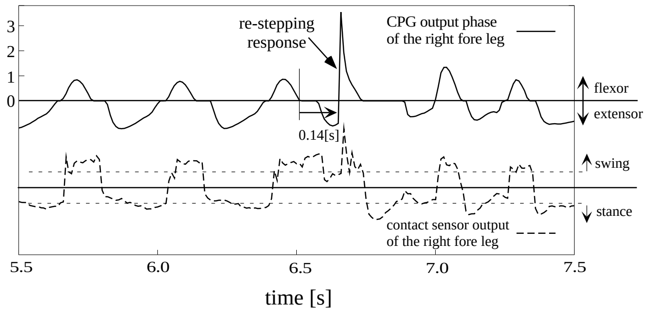


Fig. 7. Walking down a step of 7 [cm] in height. A re-stepping response was activated when the contact of the right fore leg had not been detected for 0.14 [s] after the activity of the flexor neuron became zero.

E. *Reliable Landing Control on the Soft Ground*

While walking on the soft ground, the rolling motion is much disturbed since it takes longer to establish the reliable landing of the swinging legs. In order to obtain the reliable landing of the swinging legs as soon as possible, Tekken2 outputs additional torque at knee joint towards extending direction at the instance when the output phase of a CPG changes from the flexor neuron active phase to the extensor neuron active phase. This control helps the necessary condition (c) be satisfied.

V. EXPERIMENTS

A. *Walking Down a Large Step*

Tekken2 successfully walked down a large step with approx. 0.5 [m/s] speed using the re-stepping reflex/response (Fig.7). Without the re-stepping reflex/response, Tekken2 typically fell down forward because fore legs landed on the backwarder position excessively and could not depress the increased forward speed.

B. *Experiments Under Long-lasting Disturbances*

We made Tekken2 walk on a right-inclined slope of 4 [deg] (0.07 [rad]) in indoor environment with all responses and reflexes described in Section *IV-D* in order to confirm the effectiveness of a tonic labyrinthine reflex and a sideway stepping reflex (Fig.5-(b)) under long-lasting disturbances. As a result of the experiment, the body roll angle and the hip yaw angle ψ of the right hindleg and left hindleg are shown in Fig.8. Tekken2 had walked on the right-inclined slope for 2 [sec], and walked on flat terrain afterwards.

In Fig.8, we can see that the body roll angle was positive (0.05$\sim$0.14 [rad]) while walking on the right-inclined slope. The hip yaw joint of the right hindleg moved to the outside of the body (right) by approx. 0.04 [rad] due to the sideway stepping reflex in the swing phase and moved to the inside of the body by approx. -0.04 [rad] due to the gravity load in the stance phase. On the other hand, the hip yaw joint of the left hindleg moved to the inside of the body (right) by approx. -0.04 [rad] due to the sideway stepping reflex in the swing phase and moved to the inside of the body furthermore by approx. -0.1 [rad] due to the gravity load in the stance phase. Consequently, Tekken2 succeeded in straight walking on the sideway inclined slope.

C. *Outdoor Experiments*

Even on a paved road in outdoor environment, there exist a slope of 3 [deg] at most, bumps of 1 [cm] in height and small pebbles everywhere. With all responses and reflexes described in Section *IV-D*, Tekken2 successfully maintained a stable gait on the paved road for 60 [sec] with approx. 0.5 [m/s] speed while changing its walking speed and direction by receiving the operation commands from the radio controller (Fig.9-(a)).

In addition, the effectiveness of the reliable landing control on the soft ground was confirmed by the successful

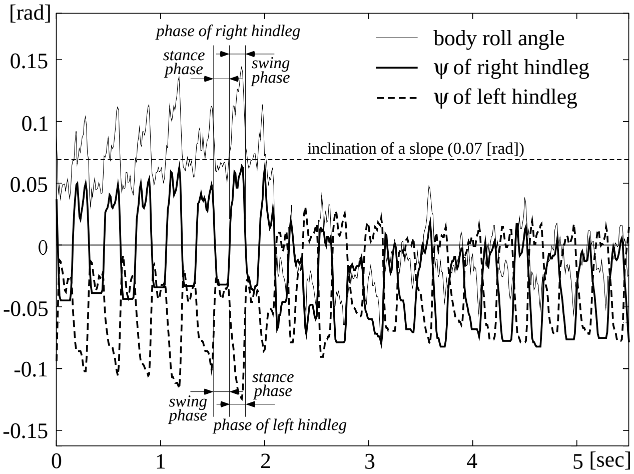
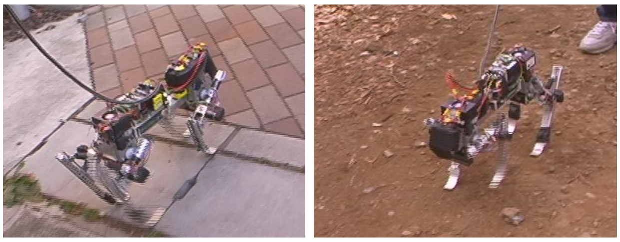


Fig. 8. Walking on a right-inclined slope of 4 [deg]



(a) (b)

Fig. 9. Photos of walking in outdoor environment

experiment of walking on the natural ground with scattered pebbles and grasses (Fig.9-(b)).

VI. Conclusion

In the neural system model proposed in this study, the relationships among CPGs, sensory input, reflexes and the mechanical system are simply defined, and motion generation and adaptation are emergingly induced by the coupled dynamics of a neural system and a mechanical system by interacting with the environment. To generate appropriate adaptation, it is necessary to design both the neural system and the mechanical system carefully. In this study, we designed the neural system consisting of CPGs, responses, and reflexes referring to biological concepts while taking the necessary conditions for adaptive walking into account.

We newly employed a tonic labyrinthine reflex, a sideway stepping reflex, a re-stepping reflex/response, and the reliable landing control of the swinging legs to make the self-contained quadruped robot (Tekken2) walk in outdoor natural environment. In order to increase the degrees of terrain irregularity which Tekken2 can cope with, we should employ additional reflexes and responses, and also navigation ability at the high level using vision.

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