Adaptive Dynamic Walking of a Quadruped Robot 'Tekken' on Irregular Terrain Using a Neural System Model

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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. 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) and reflexes. A CPG receives sensory input and changes the period of its own active phase. The desired angle and P-gain of each joint in 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 terrains of medium degrees of irregularity 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.

1 Introduction

Many previous studies of legged robots have been performed, including studies on running and dynamic walking on irregular terrain. However, autonomous dynamic adaptation in order to cope with an infinite variety of terrain irregularities still remains unsolved.

Many previous studies of legged robots have been performed, including studies on running[1, 2] and dynamic walking[3]∼[6] on irregular terrain. However, autonomous dynamic adaptation in order to cope with an infinite variety of terrain irregularities still remains unsolved.

In contrast, animals show marvelous abilities in autonomous adaptation. It is well known that the movements of animals are controlled by internal neural systems[7]. A great deal of the previous research on this attempted to generate autonomously adaptable dynamic walking using a neural system model in simulation[9, 10], and real robots[11]∼[16]. In our previous studies[12], by the use of a planar quadruped robot called 'Patrush-I,' supported by two poles, we proposed a new method for combining a CPG (Central Pattern Generator) and reflexes based on biological knowledge[7], and showed that reflexes generated via a CPG were much more effective in adaptive dynamic walking on terrains with medium degrees of irregularity.

Since our next goal is dynamic 3D space walking (pitch, roll and yaw planes) free of supporting poles on 2D irregular terrains , we constructed a new quadruped robot called 'Tekken,' which was designed to improve the success ratio of dynamic walking on terrains with a higher degree of irregularity than normal.

In this paper we point out the trade-off problem between the stability and the energy consumption in determining the cyclic period of walking on irregular terrain, and show one example to solve such problem.

2 Adaptive Dynamic Walking based on Biological Concepts

2.1 Rhythmic Motion by CPG

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[7]∼[9, 17]. As a model of a CPG, we used a neural oscillator: N.O. proposed by Matsuoka[18], and applied to the biped simulation by Taga[8, 9]. A single N.O. consists of two mutually inhibiting neurons (Fig.1-(a)). Each neuron in this model is represented by the following nonlinear differential equations:

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

where the suffix e, f, and i mean an extensor neuron, a flexor neuron, and the i-th N.O., 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 N.O.;

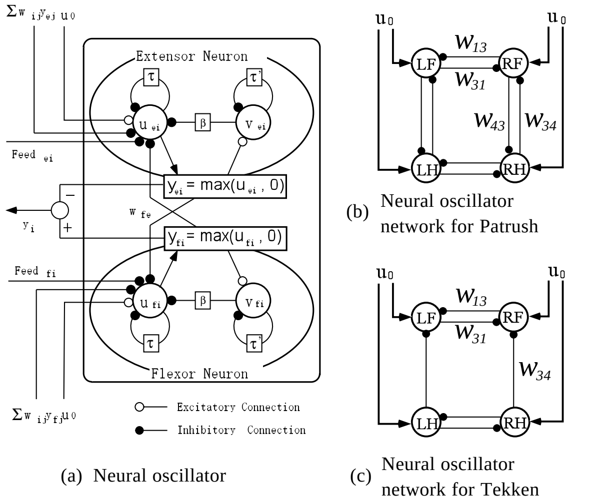

Figure 1: Neural oscillator as a model of a CPG. The suffix $i, j = 1, 2, 3, 4$ corresponds to LF, LH, RF, RH. L, R, F or H means the left, right, fore or hind leg, respectively.

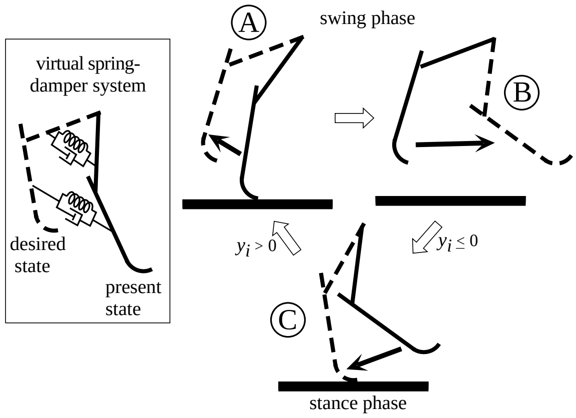

Figure 2: State transition in the virtual spring-damper system. The desired joint angles in each state are shown by the broken lines.

$v_{\{e,f\}i}$ 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 N.O..

In Fig.1-(a), the output of a CPG is a phase signal: y_i .

$$y_i = -y_{ei} + y_{fi} \tag{2}$$

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.

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

$$Feed_{\{e,f\}} = Feed_{\{e,f\} \cdot tsr} \tag{4}$$

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 N.O..

2.2 Virtual Spring-Damper System

Muscles and tendons of animals act as spring-damper system in medium and high speed walking and running, and play an important role for stabilization and energy storage. The whole visco-elasticity of a muscle is the sum of its own visco-elasticity as material and the visco-elasticity as a result of feedback by the stretch reflex and others. It is also known that the muscle stiffness in the stretch reflex is almost proportional to the muscle tension, high in a stance phase for supporting a body against the gravity and low in a swing phase for compliance against the disturbance, during walking of cats[19]. Full et al.[20] pointed out the importance of the mechanical visco-elasticity of muscles and tendons independent of sensory input under the concepts of "SLIP(Spring Loaded Inverted Pendulum)" and the "preflex". Those biological concepts were applied for the development of hexapods with high-speed mobility over irregular terrain[2, 21]. Although we are referring to the concept of SLIP, we employ the model of the muscle stiffness, which is generated by the stretch reflex and variable according to the stance/swing phases, aiming at medium-speed walking on irregular terrain adjusted by the neural system

All joints of Tekken are PD controlled to move to their desired angles in each of three states (A, B, C) in Fig.2 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 ($y_i \leq 0$)

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

Since Tekken has high backdrivability with small gear ratio in each joint, PD-controller can construct the virtual spring-damper system with relatively low

Table 1: Desired value of the joint angles and P-gains at the joints in each state used in the PD-controller for the virtual spring-damper system. θ, ϕ and ψ are the hip pitch joint angle, the knee pitch joint angle and the hip yaw joint angle shown in Fig.3, respectively.

	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_2v+G_3
θ in C	$\theta_{stance}+$ body pitch angle	$-G_4v+G_5$
ϕ in A & B	$*$	G_6
ϕ in C	0.61	G_7
ψ in all states	0	G_8

$\theta_{C\rightarrow A}$: 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 Tekken.

stiffness coupled with the mechanical system. Such compliant joints of legs can improve the passive adaptability on irregular terrain.

2.3 Rolling motion feedback to CPGs

In Tekken, we made the body angle around the roll axis be inputted to the CPGs as a feedback signal expressed by Eq.(5) and Eq.(6).

$$\begin{aligned} Feed_{e\cdot roll} &= \delta(leg)\ k_{roll} \times (\text{body roll angle}) \\ Feed_{f\cdot roll} &= -Feed_{e\cdot roll} \end{aligned} \quad (5)$$

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

$$\begin{aligned} Feed_e &= Feed_{e\cdot tsr\cdot vsr} + Feed_{e\cdot roll} \\ Feed_f &= Feed_{f\cdot tsr\cdot vsr} + Feed_{f\cdot roll} \end{aligned} \quad (6)$$

CPGs, the pitching motions of the legs and the rolling motion of the body, are mutually entrained through the rolling motion feedback to CPGs expressed by Eq.(6). This means that the rolling motion can be the standard oscillation for whole oscillations, in order to compensate for the weak connection between the fore and hind legs in the CPG network. As a result, the phase difference between the fore and hind legs is fixed, and the gait becomes stable.

2.4 Stability evaluation

In this study, we define the "wide stability margin" as 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 (Fig.4). Since the wide stability margin (WSM) is used not for motion planning but for motion evaluation, not ZMP but the projected point of the center of gravity is used eliminating inertia force and so on for simplicity. In such robot like Tekken which can move a swinging leg quickly enough within the short cyclic period of walking (0.2~0.6), a swinging leg can land on floor immediately if needed in Fig.4. Therefore, the WSM can be the substitution of the conventional stability margin or the ZMP margin used in order to avoid excess angular acceleration around the line connecting two supporting points.

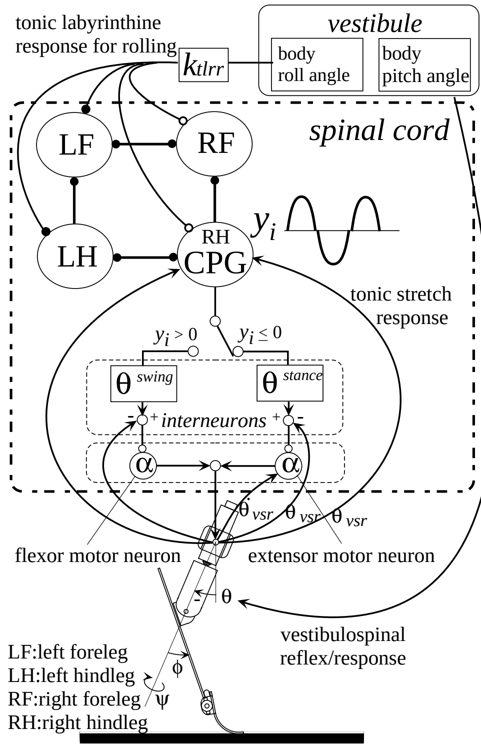

Figure 3: Control diagram for Tekken. PD-control at the yaw hip and knee pitch joints are eliminated in this figure.

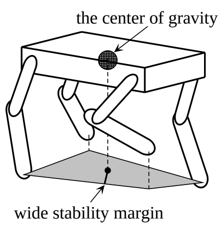

Figure 4: The definition of the wide stability margin

In Fig.5, WSM normalized by the body width of Tekken (w = 120 [mm]) are shown for various

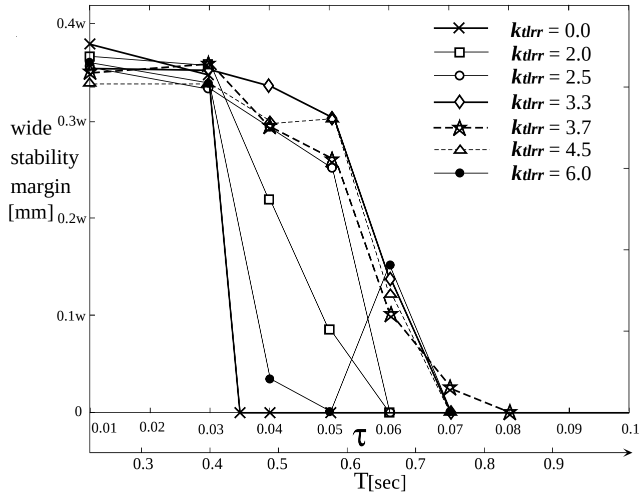

Figure 5: Wide stability margin (WSM) measured in experiments (θ_{stance}=-0.8), which were carried out on flat floor with various time constants of CPGs:τ and various gains of the rolling motion feedback to CPGs:k_{tlrr}. All plotted points mean the average of the minimum WSM in three times experiments. The walking speed and distance were 0.5 [m/s] and 2 [m] in all experiments, respectively. The cyclic period of walking:T corresponding to τ are shown.

τ: the time constant of a CPG in Eq.(1), and various k_{tlrr}: gains of the rolling motion feedback to CPGs. The cyclic periods of walking corresponding to each value of τ is alos shown in Fig.5. In Fig.5, high WSM was obtained without rolling motion feedback to CPG (k_{tlrr} = 0) in walking with the short cyclic period (T < 0.4 [s]). This is because it is not necessary to entrain pitching motion with rolling motion, of which amplitude becomes very small in walking with the short cyclic period. On the other hand, the amplitude of rolling motion in walking with the medium and large cyclic period (T > 0.4 [s]) becomes large, since the angular momentum around the line connecting two supporting points largely changes in the two-legged stance phase. In such cases, k_{tlrr}(=0) makes walking not smooth or unstable due to the lack of entrainment between rolling motion and pitching motion. We use k_{tlrr}(=3.3), which gives $WSM > 0.3w$ for $T < 0.6$ [s], as the optimal value for Tekken in all following experiments.

2.5 Energy consumption evaluation

The energy consumption as Joule thermal loss at DC motors calculated using measured current value are shown in Fig.6 as results of experiments with various values of τ. In Fig.6, we can see that walking with large value of τ, that is, walking with the long cyclic period is superior in the energy consumption while the walking speed is low (0.05 $\sim$ 0.2 [m/s]). On the other hand, walking with small value of τ is

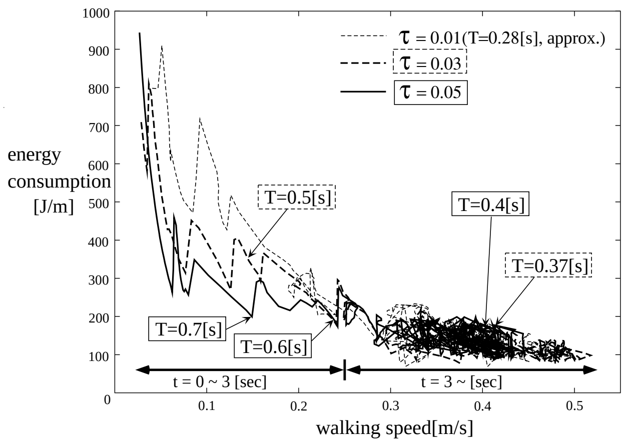

Figure 6: The relation between the walking speed and the energy consumption in walking with three different values of τ. θ_{stance} was changed at 3.5 [s]. The cyclic period of walking: T at several instants are also shown for each value of τ.

superior in the stability as shown in Fig.5. As a result, we have to solve the trade-off problem between the stability and the energy consumption in order to determine the value of τ under the given walk speed.

3 Experiments on terrain of medium degree of irregularity

We made Tekken walk on several irregular terrains with (Eq.(6)) and fixed values of parameters shown in Table 1 and Table 2. We use τ = 0.04 in these experiments. Tekken walked over an obstacle 4 [cm] in height while stumbling (Fig.7-(a)), and walked up and down a slope of 10 [deg] in the forward direction (Fig.7-(b)). Tekken also succeeded in walking over terrains consisting of several boards 1.5 [cm] in height, series of obstacles, Fig.7-(c)) and slopes in a side direction, Fig.7-(d)), with an appropriate adjustment of periods of the stance and swing phases. Without a tonic labyrinthine response for rolling, the gait was greatly disturbed, even if Tekken didn't fall down. Consequently, it was shown that method proposed in this study gives Tekken autonomous adaptation ability, since walking over unknown terrain of medium degree of irregularity was realized with fixed values of parameters.

3.1 How to get good performance on irregular terrain under trade-off of stability and energy consumption

In Section **2.5**, we mentioned the trade-off problem between the stability and the energy consumption in order to determine the value of τ. In this study, we employ the following (Eq.(7)) in order to change τ according to the wide stability margin (WSM). Eq.(7)

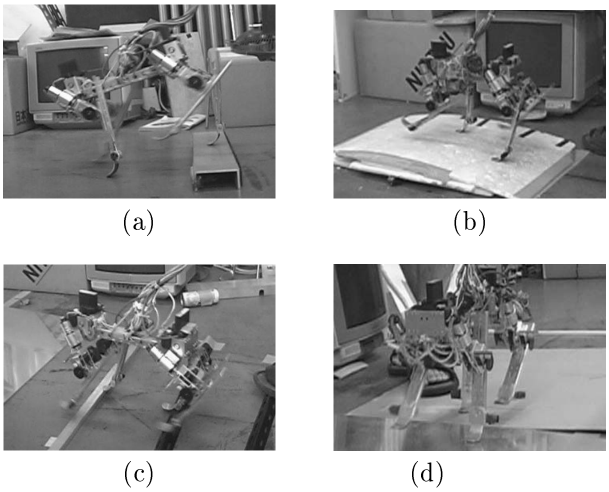

Figure 7: Walking over a step 4 [cm] in height: (a), walking up and down a slope of 10 [deg] in a forward direction: (b), walking over series of obstacles 2 [cm] in height: (c) and walking over slopes of 3 and 5 [deg] in a side direction: (d).

means that we choose the large value of τ while WSM is high in order to decrease the energy consumption, and choose the small value of τ while WSM is low in order to increase WSM.

$$\tau = 0.12(\text{wide stability margin})/\text{w} \tag{7}$$

where WSM is normalized by the body width of Tekken (w = 120 [mm]).

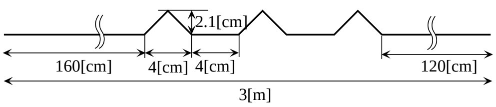

Figure 8: Irregular terrain used for Fig.9 and Fig.10.

The results of experiments, where Tekken walked over terrain shown in Fig.8 with the small constant value of τ(=0.005) and the various value of τ calculated using Eq.(7), are shown in Fig.9 and Fig.10.

In Fig.9, we can see that the minimum WSM for the constant value of τ is approx. 0.25w on the irregular terrain and the stable walking was obtained, since τ is very small. On the other hand, in walking with the various value of τ, WSM became small (0.18w) on the irregular terrain at 9.3 [s]. But the relatively small values of τ(=0.02) calculated by Eq.(7) made the cyclic period of walking be short instantly, increased WSM up to 0.25w and prevented Tekken from falling down. The walking with the large constant value of τ(=0.05) became unstable on the irregular terrain.

In Fig.10, the energy consumption with the small constant value $\tau = 0.005$ is larger than that with the various value of τ (0.02~0.065) at the dominant walking speed (0.3 [m/s]). Since the energy consumption

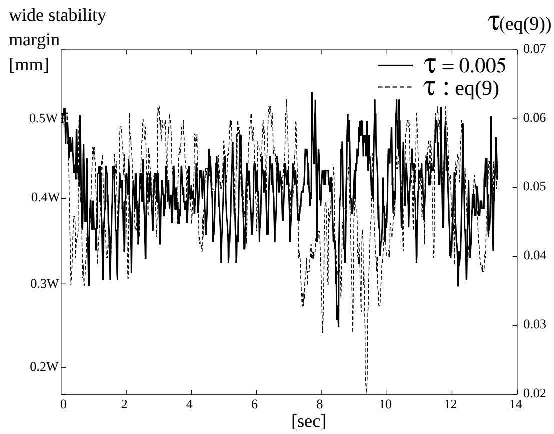

Figure 9: Wide stability margin while walking over terrain shown in Fig.8 (θ_{stance}=-0.7). The cyclic period of walking corresponding to the constant value τ = 0.005 is approx. 0.25 [s]. The cyclic period of walking corresponding to the various value of τ (0.02~0.065) is approx. 0.32~0.7 [s].

in the area B corresponds to the instant energy consumed for adaptation to irregular terrain, the time integration of those energy is not large. As a result, the integration of the energy consumption were 1020 [J] for walking with the constant value of τ(=0.005) and 650 [J] for walking with the various value of τ. Consequently, it was shown that stable walking with the low energy consumption was obtained using Eq.(7).

4 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 emergently 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, the stretch reflex and other reflexes referring to biological concepts. We also designed the passive spring-and-lock mechanism at the ankle joint as mechanical implementation of the flexor/extensor reflexes[11]. The virtual spring-damper system became effective since Tekken had a light-weighted leg and high backdrivability in each joint.

The physical oscillations such as the motion of the virtual spring-damper system of each leg and the rolling motion of the body are mutually entrained with CPGs as the neural oscillations. A CPG receives sensory input and changes the period of its own active phase as responses. The virtual spring-damper system also receives sensory input and outputs torque

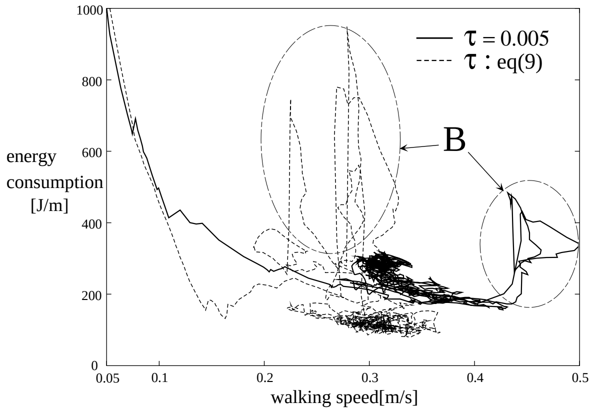

Figure 10: Energy consumption while walking over terrain shown in Fig.8 with the constant value of τ(=0.005) and the various value of τ calculated using Eq.(7). The dominant walking speeds in both walking are almost equal (approx. 0.3 [m/s]).

as reflexes. The states in the virtual spring-damper system are switched based on the phase signal of the CPG. Consequently, the adaptive walking is generated through the interaction with environment.

A Values of the parameters used in experiments

Table 2: Parameters used in experiments

parameters	value	parameters	value
u_0	1.0	θ_0[rad]	-0.87
τ'	0.6	G_1[Nm/rad]	7.0
β	3.0	G_2[Nms/rad]	0.5
w_{fe}	-2.0	G_3[Nm/rad]	0.4
$w_{\{13,31,24,42\}}$	-2.0	G_4[Nms/rad]	1.4
$w_{\{12,34\}}$	0	G_5[Nm/rad]	2.0
$w_{\{21,43\}}$	-0.57	G_6[Nm/rad]	1.0
k_{tsr}[1/rad]	3.0	G_7[Nm/rad]	2.6
k_{tlrr}[1/rad]	3.3	G_8[Nm/rad]	1.0

References

[1] Hodgins, J. K. and Raibert, M. H. 1991. Adjusting step length for rough terrain locomotion. *IEEE trans. on Robotics and Automation.* 7(3):289–298.

[2] Cham, J. G., Karpick, J., Clark J. E., and Cutkosky, M. R. 2001. Stride Period Adaptation for a Biomimetic Running Hexapod. *Proc. of ISRR2001*, pp. 77–87.

[3] Yamaguchi, J., Takanishi, A., and Kato, I. 1994. Development of a biped walking robot adapting to a horizontally uneven surface. *Proc. of IRSO1995*, pp. 1030–1037.

[4] Kajita, S., and Tani, K. 1996. Adaptive gait control of a biped robot based on realtime sensing of the ground. *Proc. of ICRA1996*, pp. 570–577.

[5] Yoneda, K., Iiyama, H., and Hirose, S. 1994. Sky-Hook suspension control of a quadruped walking vehicle. *Proc. of ICRA1994*, pp. 999–1004.

[6] Buehler, M., et al. 1998. Scout: A simple quadruped that walks, climbs and runs. *Proc. of ICRA1998*, pp. 1707–1712.

[7] Grillner, S. 1981. Control of locomotion in bipeds, tetrapods and fish. *Handbook of Physiology II.* American Physiol. Society, Bethesda, MD. 1179–1236.

[8] Taga, G., Yamaguchi, Y., and Shimizu, H. 1991. Self-organized control of bipedal locomotion by neural oscillators. *Biolog. Cybern.* 65:147–159.

[9] Taga, G. 1995. A model of the neuro-musculo-skeletal system for human locomotion II. - real-time adaptability under various constraints. *Biolog. Cybern.* 73:113–121.

[10] Ijspeert, A.J. 2001. A connectionist central pattern generator for the aquatic and terrestrial gaits of a simulated salamander. *Biolog. Cybern.* 84(5):331–348.

[11] Kimura, H., Fukuoka, Y., et al. 2001. 3D adaptive dynamic walking of a quadruped robot by using neural system model. *Proc. of CLAWAR2001*, pp. 97–104.

[12] Kimura, H. and Fukuoka, Y., et al. 2001. Adaptive dynamic walking of a quadruped robot using neural system model. *Advanced Robotics.* 15(8):859–876.

[13] Kimura, H., Akiyama, S., and Sakurama, K. 1999. Realization of dynamic walking and running of the quadruped using neural oscillator. *Autonomous Robots.* 7(3):247–258.

[14] Ilg, W., Albiez, J., Jedele, H., Berns, K., and Dillmann, R. 1999. Adaptive periodic movement control for the four legged walking machine BISAM. *Proc. of ICRA1999*, pp. 2354–2359.

[15] Lewis, M. A., Etienne-Cummings, R., Cohen, A. H., and Hartmann, M. 2000. Toward biomorphic control using a custom aVLSI CPG chips. *Proc. of ICRA2000*, pp. 1289–1295.

[16] Tsujita, K., Tsuchiya, K., et al. 2000. Decentralized autonomous control of a quadruped locomotion robot. *Proc. of Int. Symp. on Adaptive Motion of Animals and Machines (AMAM2000)*, WeA-I-2.

[17] Cohen, A. H., and Boothe, D. L. 1999. Sensorimotor interactions during locomotion: principles derived from biological systems. *Autonomous Robots.* 7(3):239–245.

[18] Matsuoka, K. 1987. Mechanisms of frequency and pattern control in the neural rhythm generators. *Biolog. Cybern.* 56:345-353.

[19] Akazawa, K., Aldridge, J. W., Steeves, J. D., and Stein, R.B. 1982. Modulation of stretch reflexes during locomotion in the mesencephalic cat. *J. of Physiol.* 329:553-567.

[20] Full, R. J. 2000. Biological inspiration: lessons from many-legged locomotors. *Robotics Research 9*, J.M.Hollerbach and D.E.Koditschek Eds, Springer London. pp. 337–341.

[21] Saranli, U., Buehler, M., and Koditschek, D. E. 2001. RHex: a simple and highly mobile hexapod robot. *Int. J. Robotics Research.*