Mechanical Design of a Quadruped "Tekken3&4" and Navigation System Using Laser Range Sensor

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Abstract— **Intending a dog-type service robot in future, we develop a self-contained quadruped robot named "Tekken3&4." We newly equip robots with a laser range sensor and a CCD camera for navigation and demonstration. We try to improve the mechanical reliability of robots for 11 days exhibition at Aichi expo. In this paper, we describe the mechanical design concepts of Tekken3&4, and the navigation system for walking along the wall in the artificial garden at the exhibition.**

I. INTRODUCTION

WE have been developing a quadruped robot as a dog-type partner robot[1], which can serve a human as a guide dog for the deaf and a helper dog, walk outside accompanying a human, and so on. Intending such a dog-type robot in future, we developed self-contained (power autonomous) quadruped robots named "Tekken3" and "Tekken4," while being supported by NEDO for the prototype robot exhibition at Aichi Expo. We newly equipped robots with a laser range sensor and a CCD camera for navigation and demonstration. We improved the mechanical reliability of robots for 11 days exhibition.

In this paper, we describe the mechanical design concepts of Tekken3&4, and the navigation system for walking along the wall in the artificial garden at the exhibition. MPEG footage of experiments can be viewed at: *http://www.kimura.is.uec.ac.jp/*.

II. ADAPTIVE WALKING CONTROL SYSTEM

We have been trying to induce a quadruped robot to walk with medium walking speed on irregular terrain based on biological concepts. We realized autonomous adaptive walking on terrains of medium degrees of irregularity using a tethered quadruped: Tekken1[2] and an untethered quadruped: Tekken2[3].

The basic neural system model of Tekken3&4 is same with the one used in Tekken1&2 (Fig.1). The neural system model consists of a CPG (central pattern generator), reflexes and responses. A CPG generates rhythmic motion for walking. PD-controller at joints constructs the virtual spring-damper system as the visco-elasticity model of a muscle. 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[2]. Several reflexes and responses are employed in Tekken2 for adaptive walking in outdoor environment[3].
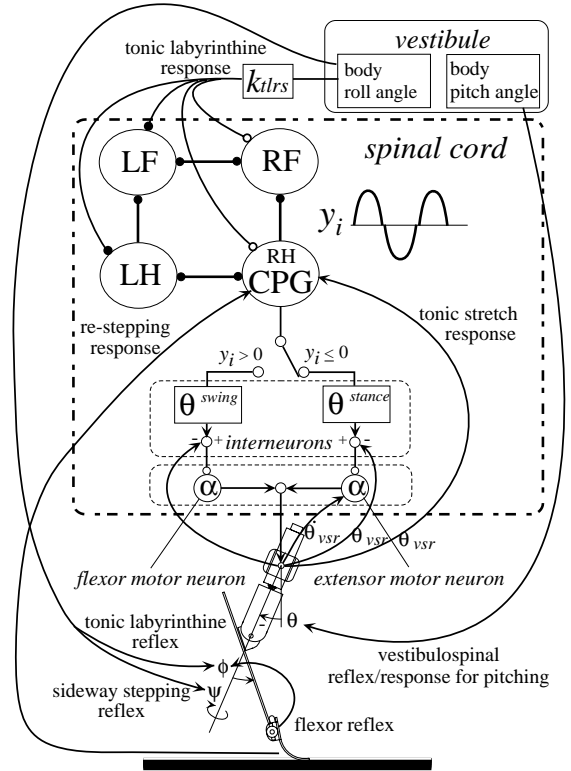

Fig. 1. Control diagram for Tekken3&4. PD-control at the hip yaw and knee pitch joints are eliminated in this figure. LF, LH, RF and RH mean the left fore, left hind, right fore and right hind leg, respectively.

A. 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,

(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 main-

tained 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.

B. 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 [4]. As a model of a CPG, we used a neural oscillator proposed by Matsuoka [5], and applied to the biped simulation by Taga[6]. 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:

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

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 .

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

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.

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

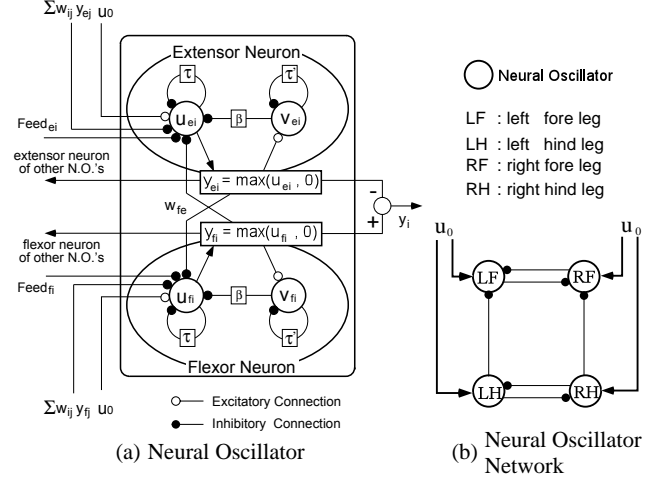
(a) Neural Oscillator   (b) Neural Oscillator Network

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.

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

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 neural oscillator.

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 [2].

Although the size and weight of Tekken3&4 are different from those of Tekken2, the values of the parameters of CPGs used for Tekken3&4 were same with those used for Tekken2.

C. 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 Tekken3&4 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 ($y_i \leq 0$)

$C \rightarrow A$:

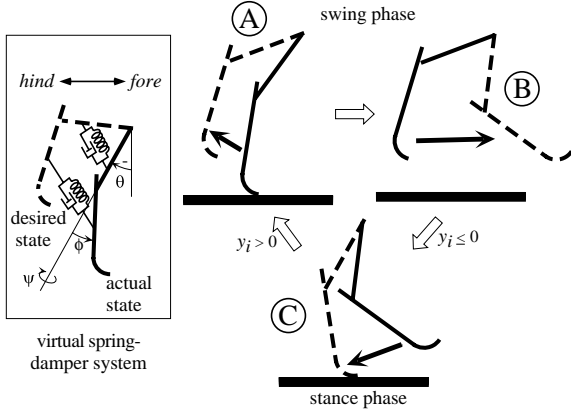- when the CPG flexor neuron of the leg becomes active ($y_i > 0$)

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

The desired angles and P-gain of each joint in each state were determined through experiments. Since Tekken3&4 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.

D. 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.1. 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 *II-C*. 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.

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[7].

E. Reflexes and Responses

Referring to biological knowledge, we employed the several reflexes and responses (Fig.1, Table I) to satisfy the necessary conditions described in Section *II-A* in physical terms in addition to the stretch reflex and response described in Section *II-C* and *II-B*. In Table I, the tonic labyrinthine reflex, the sideway stepping reflex and the re-stepping reflex/response were newly employed on Tekken2[3]. Other reflexes and responses had already been employed on Tekken1 [2].

III. New mechanical design

A. Design concepts of Tekken2 and problems pointed out

Each leg of Tekken2 has a hip pitch joint, a hip yaw joint, a knee pitch joint, and an ankle pitch joint. The direction in which Tekken2 walks can be changed by using the hip yaw joints. Two rate gyro sensors and an accelerometer 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:

- high power actuators and small inertia moment of legs for quick motion and response,
- small gear reduction ratio for high backdrivability to increase passive compliance of joints,
- small mass of the lowest link of legs to decrease impact force at collision,
- small contacting area at toes to increase adaptability on irregular terrain.
- passive ankle joint mechanism to prevent a swinging leg from stumble on an obstacle quickly.

Although Tekken2 successfully walked on natural ground where scattered pebbles and grasses existed, the following problems were pointed out:

- the payload of Tekken2 is not enough to be equipped with vision sensors, PC board for vision, a decoration on the exterior and so on.
- as the result of Joule's thermal loss, the increase of the temperature of DC motors limits operating (continuous walking) time of Tekken2 to 5∼10(min) depending on the temperature of atmosphere.
- passive ankle joint mechanism sometimes causes unnecessary rotation in case of stumbling at the beginning of a swing motion.
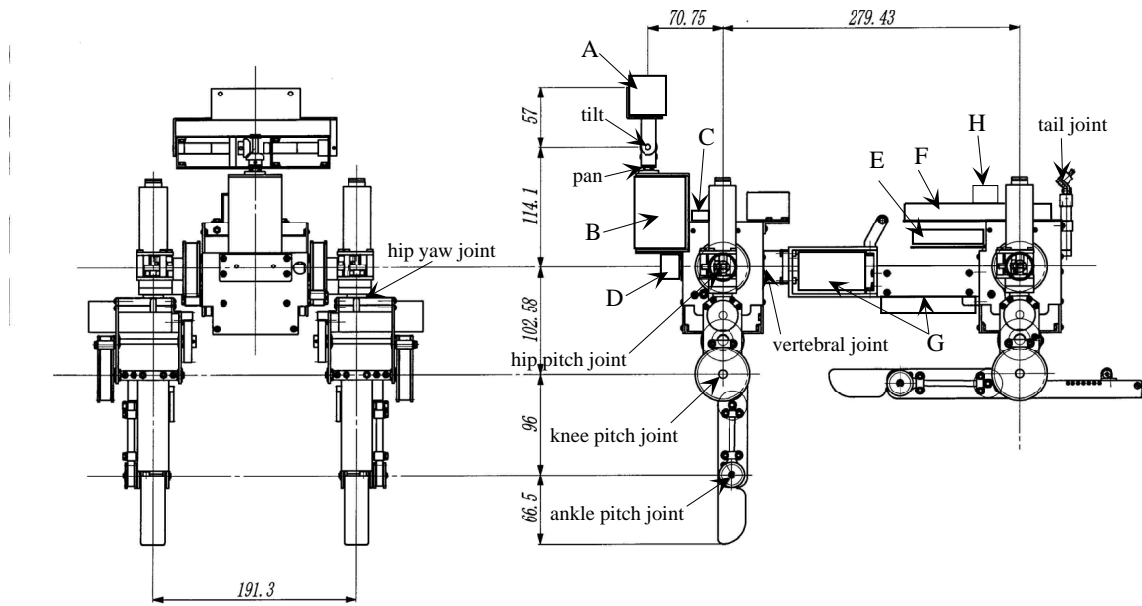
B. Mechanical design of Tekken3

In order to solve the problems described in Section *III-A*, we newly designed Tekken3 (Fig.4). Tekken3 uses 60(W) DC motors at pitch hip and knee joints while Tekken2 uses 23(W) DC motors at those joints. Although such larger powered DC motors increase total weight of the robot, we can expect the larger payload of the robot and less Joule's thermal loss because of relatively less current at DC motor armature. Tekken3 has active ankle joints, where small DC motor rotates ankle joint in the swing phase and lock mechanism prevents ankle joint from rotating in the stance phase. Tekken3 has pan and tilt joints for a CCD camera, and is equipped with a laser range sensor beneath the neck. The total weight of Tekken3, including controller and batteries, and excluding a decoration on the exterior, is approx. 10(Kg).

TABLE I

REFLEXES AND RESPONSES EMPLOYED ON TEKKEN3&4.

	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 *II-A*.

A		CCD camera	DragonFly	Point Grey Research
B		laser range sensor	URG-X002S	Hokuyo, Distance(20~4000mm), Angle(270°)
C		rate gyro sensors around pitch and roll axes	ENC-03M	Murata
D		accelerometer	CXL02LF3	Crossbow, ±2G
E		servo controller	DIMM-PC & I/O (TITech-Wire)	OKK, AMD(Elan SC520)133MHz OS:RT-Linux PWM(40kHz), A/D converter, counter, RC decoder
F		vision PC for CCD camera and laser range sensor	EBC363-1	VIA C3 EBGA CPU1GHz OS:Linux
G		battery	Lithium Polymer Batteries	Sanyo, (11.1V1300mAh × 2 = 24V) for PC, TITech-Wire and sensors, Advanced Energy, (11.1V1320mAh × 4 = 48V) for DC motors
H		transceiver	MEGA TECH T3PDF	Futaba, digital proportional radio control system (3ch, 40MHz)

Fig. 4.   Draft and specifications of Tekken3. The configuration of Tekken4 is same with Tekken3 except for its lighter weight.

C. Experiments in outdoor environment

We made Tekken3 be walking in Univ. campus for 13(min) with approx. 0.7(m/s) walking speed at the day time on Apr. The temperature of DC motors was 40[C.] at highest, and the heating became not a problem in Tekken3. In addition, we never observed unnecessary rotation of ankle joints in case of stumbling at the beginning of a swing motion.

IV. NAVIGATION USING LASER RANGE SENSOR

The navigation in medium or high speed legged locomotion is a newly studied field[8], [9]. We used neither ultrasonic nor tactile sensor but a laser range sensor, since a small one is available these days, and it is reliable and easy to use.

A. Navigation system

The control and navigation system of Tekken3 is shown in Fig.5. In Tekken3, walking speed and direction are sent to the
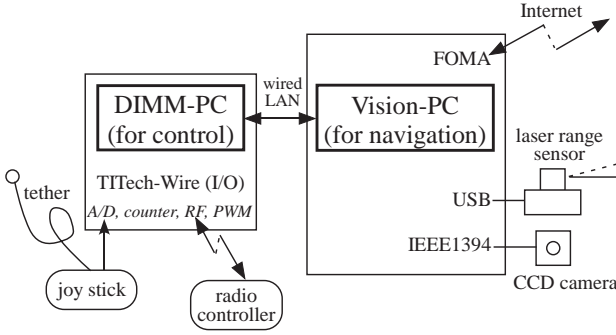
Fig. 5.   Control and navigation system of Tekken3&4
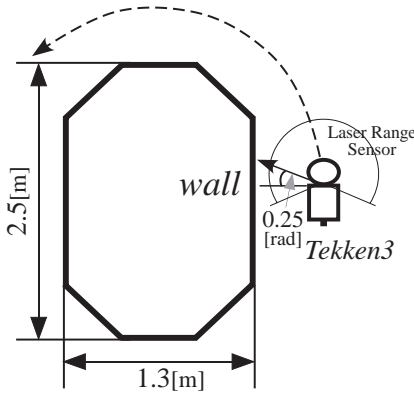

Fig. 6.   Experimental setup of the wall from the top view. The floor is covered by artificial grasses.

controller on DIMM-PC. Tekken3 has three operation modes. Those are:

- manually operated using a radio controller,
- manually operated using a joystick connected to a tether,
- autonomously operated using a laser range sensor.

B. Changing walking direction

Tekken can change the walking direction by changing the angle of yaw joint (Fig.1, Fig.4). In order to realize the left turning of Tekken3 along the wall in Fig.6, we use the following equation to determine the desired angle of yaw joint of each leg: ψ^*_{leg} based on the laser range sensor data.

$$
\begin{aligned}
\psi^*_{\{RF,RH\}} &= (d - 0.38(\mathrm{m})) \times 1000/20 \times \pi/180 \\
\psi^*_{\{LF,LH\}} &= -\psi^*_{\{RF,RH\}}
\end{aligned}
\tag{5}
$$

where $d(\mathrm{m})$ is the distance to the wall measured by the laser range sensor at the left forward orientation of 0.25(rad) (Fig.6), and the angle of yaw joint takes positive value when yaw joint moves to the outside of the body in all legs.

This equation means that the desired angle of yaw joint is set to 5(deg) to the right side when Tekken3 is additionally 0.1(m) away from the wall, for examples. As the result, we can expect the left-side turning rotational velocity of the body of Tekken3 to some extent.

Those values in Eq.(5) were determined manually in experiments.

C. Experiments in the artificial garden

We made Tekken3 walk along the wall in indoor environment (Fig.6). The results are shown in Fig.7, where the laser range sensor output the distance to the wall at every 0.2(s) (5 times per second), the desired angles of yaw joints were calculated by Eq.(5), and the turning rotational velocity of the body of Tekken3 was generated. The forward walking speed is also shown in Fig.7. Although the distance to the wall measured by the laser range sensor was not stable in Fig.7 because of pitching, rolling and yawing motion of the body of Tekken3, Tekken3 walked along the wall successfully.

The walking path of Tekken3 calculated using joint angles and the wall shape calculated using the range sensor data are shown in Fig.8. In order to improve quality of the map calculated using the range sensor data, we need smoothing and other techniques.

D. Exhibition at Aichi expo.

The configuration of Tekken4 is almost same with Tekken3 except for its lighter weight and a decoration on the exterior. The total weight of Tekken4 including all is approx. 9.7(Kg). Tekken4 had shown its high performance and high hardware reliability through the house keeping demonstration in the artificial garden for 11 days at Aichi expo. (Fig.9).

V. CONCLUSION AND FUTURE WORK

For aiming at a dog-type service robot such as a helper dog, we developed a quadruped robot: Tekken3&4 equipped with a laser range sensor for navigation, and exhibited Tekken4 for 11 days at Aichi expo. successfully. As future works, we need improve the locomotion ability, the navigation ability, and increase the useful functions as a service robot.

REFERENCES

[1] Kimura, H., Fukuoka, Y., Yasuda, H., Hirata, S. 2004. Biologically Inspired Motion and Behavior Generation for a Quadruped Robot, *Proc. of Autonomous Distributed System Symposium* (in Japanese), pp.31-34.

[2] Fukuoka, Y., Kimura, H. and Cohen, A.H. 2003. Adaptive Dynamic Walking of a Quadruped Robot on Irregular Terrain based on Biological Concepts. *Int. J. of Robotics Research* 22(3):187-202.

[3] Kimura, H., Fukuoka, Y. 2004. Biologically Inspired Adaptive Dynamic Walking in Outdoor Environment Using a Self-contained Quadruped Robot: 'Tekken2', *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems* pp.986-991.

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

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

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

[7] Kimura, H., Fukuoka, Y., and Konaga, K. 2001. Adaptive dynamic walking of a quadruped robot using neural system model. *Advanced Robotics* 15(8):859–876.
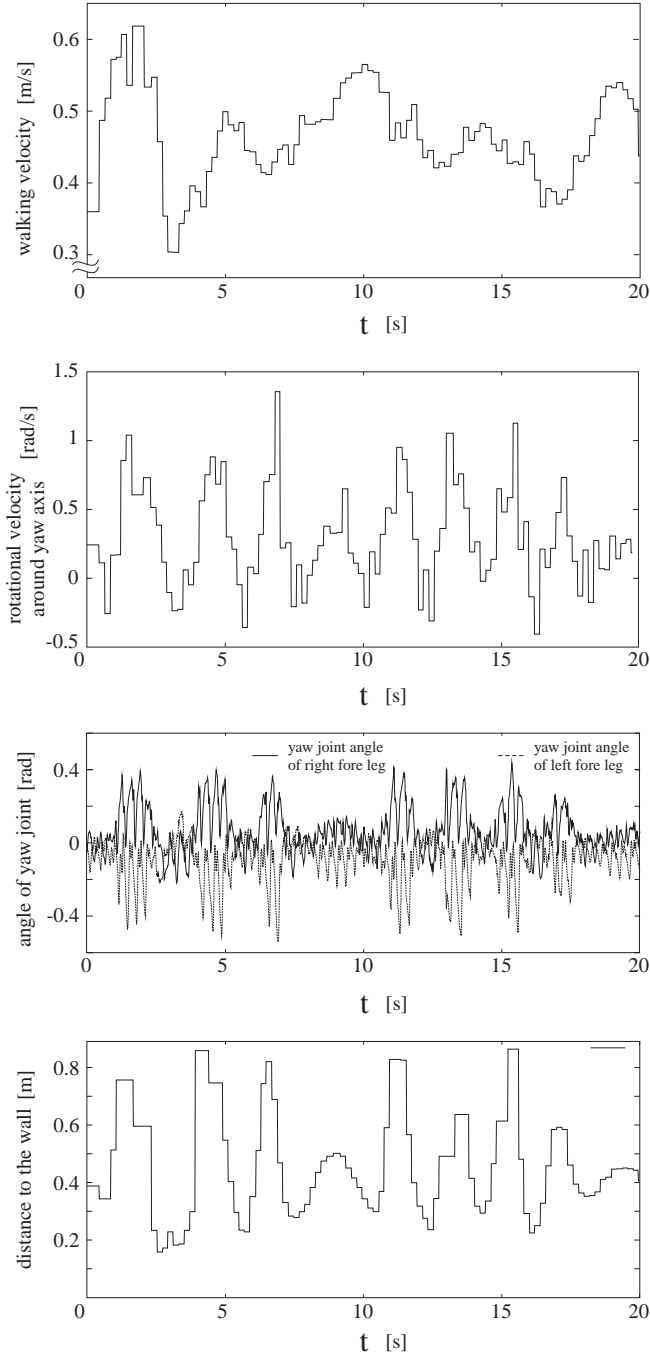
Fig. 8. Walking path of Tekken3 and the map constructed using rage sensor data while walking around the wall.

(a) front view   (b) back view

Fig. 9. Photo of the exhibition of Tekken4 at Aichi expo. Tekken4 was walking along the inside wall in the artificial garden measuring the distance to the wall. The walking speed was approx. 0.5(m/s).

Fig. 7. Experimental data in walking around the wall. The distance to the wall: d was measured using the laser range sensor. The angle of yaw joint was measured using the photo encoder, and the desired angle of yaw joint was determined by Eq.(5). The rotational velocity around the yaw axis was calculated using the yaw joint angle of left and right fore legs. The walking velocity was calculated using hip and knee joint angle of supporting legs.
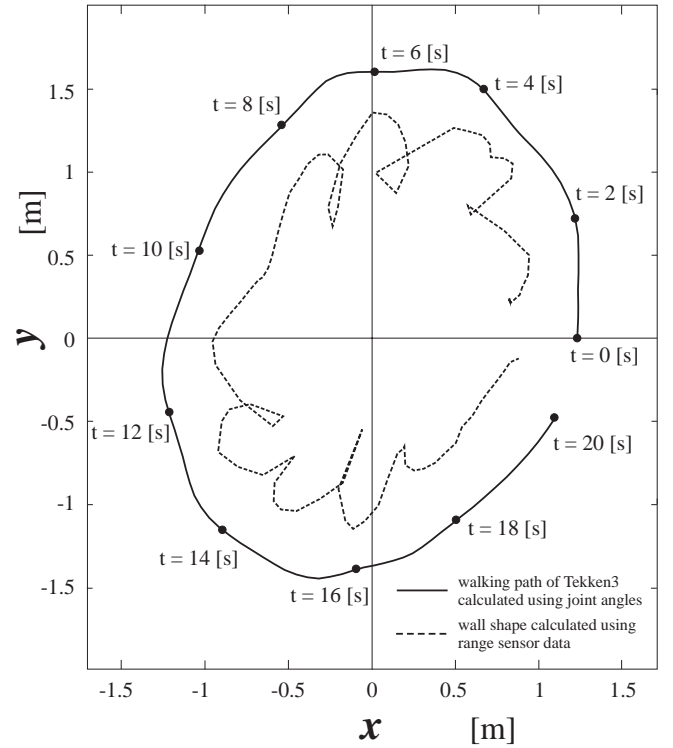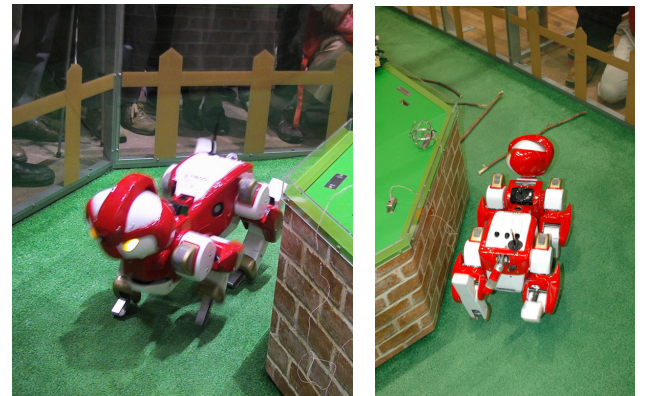
[8] Lewis, M. A. 2002. Detecting surface feature during locomotion using optic flow. *Proc. of IEEE Int. Conf. on Robotics and Automation* pp.305-310.

[9] Cowan, N. J., Ma, E. J, Cutkosky, M., Full, R. J. 2003. A biologically inspired passive antenna for steering control of a running robot. *Prof. of 11th Int. Symp. on Robotics Research*.