Adaptive Walking of a Quadruped Robot in Outdoor Environment based on Biological Concepts

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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. 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.

1 Introduction

Many previous studies of legged robots have been performed, including studies on running and dynamic walking 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. The purpose of this study is to realize high-speed mobility on irregular terrain with less knowledge of it 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[1]. 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[2–5], and real robots[6–8]. But autonomously adaptive dynamic walking on irregular terrain was rarely realized in those earlier studies except for our studies [9,10]. This paper reports on our progress using a self-contained (power autonomous) quadruped robot called "Tekken2" (Fig.1) which was newly developed for adaptive walking on irregular terrain in outdoor environment (Fig.2).

2 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.

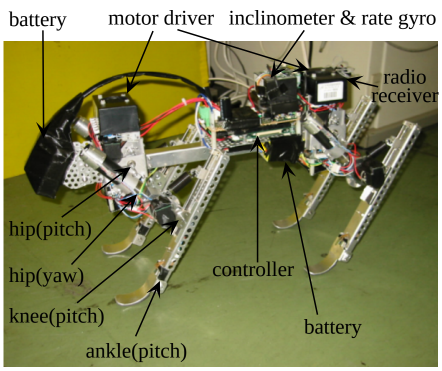


Fig. 1. Tekken2. The length of the body and a leg in standing are 30 [cm] and 20 [cm]. The weight including batteries is 4.3 [kg].

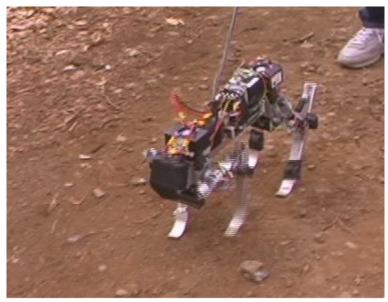


Fig. 2. Photo of walking in outdoor environment.

3 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[11],
(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.

4 Implementation of Neural System for Adaptive Walking

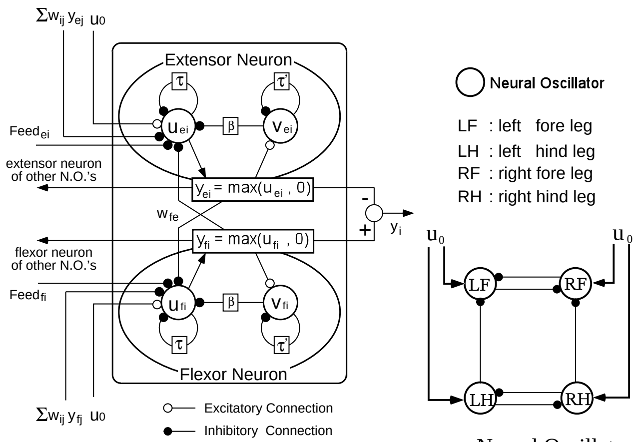
The basic neural system model of Tekken2 is same with the one of Tekken1. We define a “reflex” as joint torque generation based on sensor information and a “response” as CPG phase modulation through sensory feedback to a CPG. Several reflexes and responses are newly employed in Tekken2 for adaptive walking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

4.1 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 [1]. As a model of a CPG, we used a neural oscillator proposed by Matsuoka , and applied to the biped simulation by Taga[2]. A single neural oscillator consists of two mutually inhibiting neurons (Fig.3-(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



(a) Neural Oscillator (b) Neural Oscillator Network

Fig. 3. 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.

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.3-(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 neural oscillator.

By connecting the CPG of each leg (Fig.3-(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 [10].

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.

4.2 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. In order to generate each motion such as swinging up (A), swinging forward (B) and pulling down/back of a supporting leg (C), all joints of Tekken2 are PD controlled to move to their desired angles in each of three states (A, B, C). The timing for all joints of a leg to switch to the next state are:

$A \rightarrow B$: when the hip joint 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 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.

4.3 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 *4.2*. 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[9].

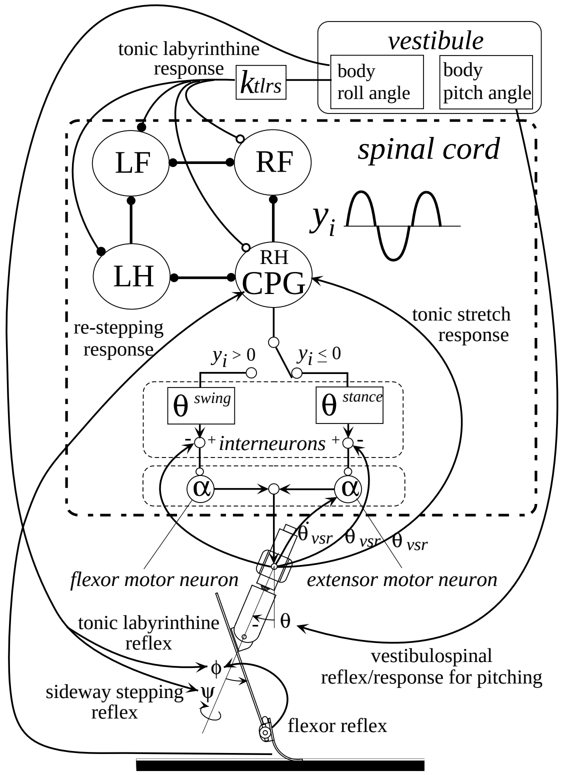


Fig. 4. Control diagram for Tekken2. PD-control at the hip yaw and knee pitch joints are eliminated in this figure.

4.4 Reflexes and Responses

Referring to biological knowledge, we employed the several reflexes and responses (Table 1, Fig.4) to satisfy the necessary conditions (b)∼(e) described in physical terms in Section **3** in addition to the stretch reflex and response described in Section *4.2* and *4.1*. In Table 1, 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 [10].

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[12]. 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

Table 1. Reflexes and Responses employed on Tekken2.

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

The sp and sw mean the supporting leg and swinging leg, respectively.
The corresponding necessary conditions are described in Section **3**.

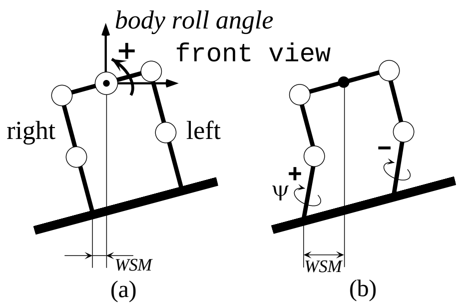


Fig. 5. Walking on a sideway inclined slope. (a):without a sideway stepping reflex, (b):with.

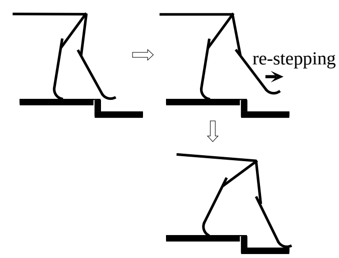


Fig. 6. Re-stepping reflex and response.

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)).

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 to ψ^* according to Eq.(5).

$$\psi^* = \delta(leg)\, k_{stpr} \times \text{(body roll angle)} \tag{5}$$

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

[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[10].

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[13]. 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).

4.5 Active 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. Tekken2 changes the state of the virtual spring-damper system from the swinging to the stance before the actual contact of a leg on the ground, when the output phase of a CPG changes from the flexor neuron active phase to the extensor neuron active phase as described in Section *4.2*. This control contributes to obtain the reliable landing of the swinging legs as soon as possible, and helps the necessary condition (c) be satisfied.

5 Experiments

5.1 Walking on a Sideway Inclined Slope

We made Tekken2 walk on a right-inclined slope of 4 [deg] (0.07 [rad]) in indoor environment in order to confirm the effectiveness of a sideway stepping reflex. As a result of the experiment, the body roll angle and the hip yaw angle ψ of the right foreleg and left foreleg are shown in Fig.7, where Tekken2 walked on the right-inclined slope from 3 to 6.7 [sec]. In Fig.7, we can see that the body roll angle was positive (0.03$\sim$0.18 [rad]) while walking on the right-inclined slope and WSM was kept large (approx. 0.5$\sim$0.7). The hip yaw joint of the right foreleg moved to the outside of the body (right) by approx. 0.13 [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. We can see similar motion of the left foreleg in Fig.7. Consequently, Tekken2 succeeded in straight walking on the sideway inclined slope. Without a sideway stepping reflex, rolling motion of Tekken2 was much disturbed on the sideway inclined slope and Tekken2 sometimes failed in keeping walking.

5.2 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. In Fig.8, 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. 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.

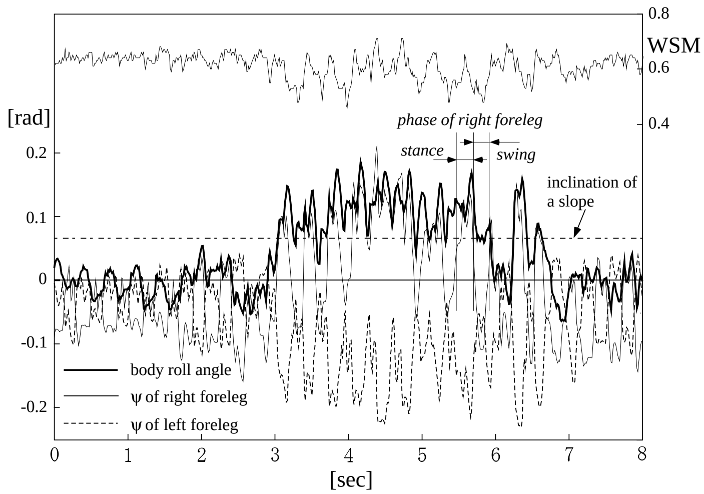


Fig. 7. Walking on a right-inclined slope of 0.07 [rad] (4 [deg]) with a sideway stepping reflex.

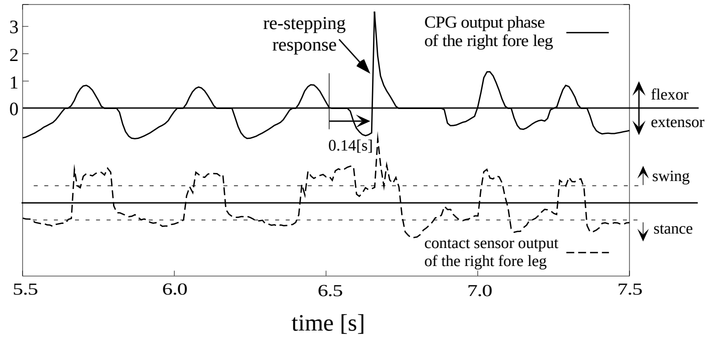


Fig. 8. Walking down a step of 7 [cm] in height with a re-stepping reflex/response.

5.3 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 *4.4*, Tekken2 successfully maintained a stable gait on the paved road for 4 [min] with approx. 0.5 [m/s] speed while changing its walking speed and direction by receiving the operation commands from the radio controller. In addition, the effectiveness of the active landing control on the soft ground was confirmed by the successful experiment of walking on the natural ground with scattered pebbles and grasses (Fig.2). MPEG footage of these experiments can be seen at: *http://www.kimura.is.uec.ac.jp*.

6 Conclusion

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. In this neural system model, the relationships among CPGs, sensory input, reflexes and the mechanical system were simply defined, and motion generation and adaptation were emergingly induced by the coupled dynamics of a neural system and a mechanical system by interacting with the environment.

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

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