Dynamics Based Motion Adaptation for a Quadruped Robot

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Abstract. In this paper, we propose the necessary 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 necessary conditions described in physical terms. PD-controller at joints can construct 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. 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. The motion adaptation can be integrated based on the dynamics of the coupled system constructed by the mechanical system and the neural 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, studies of autonomous dynamic adaptation allowing a robot to cope with an infinite variety of terrain irregularities 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[1,2]. 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[3,4]. 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[5–8], and real robots[9–13]. But autonomously adaptable dynamic

Table 1. Biological concepts of legged locomotion control.

	ZMP based	Limit Cycle based	
		by Neural System (CPG and reflexes)	by Mechanism (spring and damper)
good for control of	posture and low speed walking	medium speed walking	high speed running
main controller	upper neural system acquired by learning	lower neural system (at spinal cord, brain stem, etc.)	musculoskeltal system through self stabilization

walking on irregular terrain was rarely realized in those earlier studies. This paper reports on our progress in the past couple of years using a newly developed quadruped called "Tekken," which contains a mechanism designed for 3D space walking (pitch, roll and yaw planes) on irregular terrain[14].

2 Adaptive Dynamic Walking based on Biological Concepts

Methods for legged locomotion control are classified into ZMP-based control and limit-cycle-based control (Table.1). ZMP (zero moment point) is the extension of the center of gravity considering inertia force and so on. It was shown that ZMP-based control is effective for controlling posture and low-speed walking of a biped and a quadruped. However, ZMP-based control is not good for medium or high-speed walking from the standpoint of energy consumption, since a body with a large mass needs to be accelerated and decelerated by actuators in every step cycle.

In contrast, motion generated by the limit-cycle-based control has superior energy efficiency. But there exists the upper bound of the period of the walking cycle, in which stable dynamic walking can be realized[15]. It should be noted that control by a neural system consisting of CPGs and reflexes is dominant for various kinds of adjustments in medium-speed walking of animals[3]. Full et al.[16] also pointed out that, in high-speed running, kinetic energy is dominant, and self-stabilization by a mechanism with a spring and a damper is more important than adjustments by the neural system. Our study is aimed at medium-speed walking controlled by CPGs and reflexes (Table.1).

2.1 The quadruped "Tekken"

We designed Tekken to solve the mechanical problems which occurred in our past study using a planar quadruped "Patrush"[13]. The length of the body and a leg in standing are 23 and 20 [cm]. The weight of the whole robot is 3.1 [Kg]. Each leg has a hip pitch joint, a hip yaw joint, a knee pitch joint, and an ankle pitch joint. The hip pitch joint, knee pitch joint and hip yaw joint are activated by DC motors of 20, 20 and 5 [W] through gear ratio of 15.6, 18.8 and 84, respectively. The ankle joint can be passively rotated in the direction if the toe contacts with an obstacle in a swing phase, and is locked while the leg is in a stance phase.

Two rate gyro sensors and two inclinometers for pitch and roll axes are mounted on the body in order to measure the body pitch and roll angles. The direction in which Tekken moves while walking can be changed by using the hip yaw joints.

2.2 Virtual Spring-Damper System

Full et al.[16,17] 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[1,2]. 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.1 in order to generate each motion such as swinging up (A), swinging forward (B) and pulling down/back of a supporting leg (C). The constant desired angles and constant P-gain of each joint in each state were determined through experiments.

Since Tekken 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.

2.3 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[3–6].

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[5,6]. In Fig.4, the output of a CPG is a phase signal: y_i. The positive or negative value of y_i corresponds to activity of a flexor or extensor neuron, respectively. We use the hip joint angle feedback as a basic sensory input to a CPG called a "tonic stretch response" in all experiments of this study[14]. This negative feedback makes a CPG be entrained with a rhythmic hip joint motion.

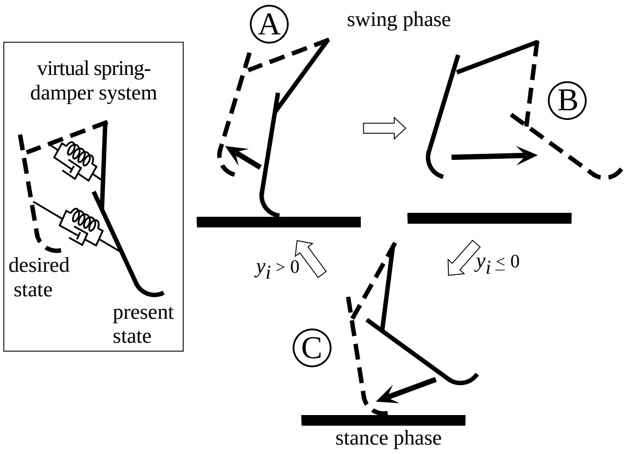


Fig. 1. tate transition in the virtual spring-damper system, where y_i is the output phase signal of a CPG.

By connecting the CPG of each leg (Fig.4), 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. We newly propose an asymmetric CPG network shown in Fig.4 in order to generate an arbitrary gait from a trot to a pace via a walk with a single network configuration of CPGs. In Fig.4, a CPG of a foreleg is inhibited by a CPG of a hindleg with a connecting weight, and a CPG of a hindleg is not inhibited by a CPG of a foreleg.

2.4 Necessary conditions for stable dynamic walking on irregular terrain

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

(a) the swinging legs should be free to move forward during the first period of the swing phase,
(b) the swinging legs should land reliably on the ground during the second period of the swing phase,
(c) the angular velocity of the supporting legs relative to the ground should be kept constant during their pitching motion around the contact points at the moment of landing or leaving,
(d) 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
(e) 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.

2.5 Reflexes and responses

It is well known in physiology that

- some sensory stimuli modify CPG activity and reflexive responses to sensory stimuli are phase dependent under CPG activity[4].

Such interaction between CPG activity and a sensory stimulus is very important for adaptation and corresponds to the necessary conditions described in physical terms in Section **2.4.**. In this paper, 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 flexor and extensor reflexes contribute to satisfy the conditions (a) and (b), respectively. The flexor reflex is implemented as the passive anke joint mechanism in Tekken. The extensor reflex has not yet been implemented in Tekken.

In addition, the following biological concepts are known[19]:

- when the vestibule in a head detects an inclination in pitch or roll plane, a downward-inclined leg is extended while an upward-inclined leg is flexed.

We call the reflex/response for an inclination in the pitch plane a "vestibulospinal reflex/response", the role of which corresponds to the condition (c) and (e). In Tekken, hip joint torque in the stance phase is adjusted by the vestibulospinal reflex, since the body pitch angle is added to pitch hip joint angle. For the vestibulospinal response, the body pitch angle is feedbacked to the CPGs.

On the other hand, we call the response for an inclination in the roll plane a "tonic labyrinthine response for rolling", the role of which corresponds to the condition (b) and (d). The tonic labyrinthine response is employed as rolling motion feedback to CPGs in Section **3.**.

The necessary condition (e) can be satisfied by the mutual entrainments between CPGs and the pitching motion of legs and the mutual entrainments among CPGs[13].

3 Entrainment Between Pitching and Rolling Motions

3.1 Rolling motion feedback to CPGs

Since a dynamic system similar to an inverted pendulum appears in the two-legged stance phase, a rolling motion is naturally generated in most of the gaits as a result. The amplitude of the rolling motion generated in walking on flat terrain is determined mainly by the gait, duty factor, and the period of the pitching motion cycle. As described as the condition (d) in Section **2.4.**,

the change of the phase difference between rolling motion of the body and pitching motion of legs disturbs stable walking.

Therefore, we made the body angle around the roll axis be input to the CPGs as a feedback signal in order to synchronize rolling motion and pitching motion (upper left part of Fig.4)[14]. In Fig.2, CPGs, the pitching motion of the legs and the rolling motion of the body are mutually entrained through the rolling motion feedback to CPGs. 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 (Fig.4). As a result, the phase difference between the fore and hind legs is fixed, and the gait becomes stable.

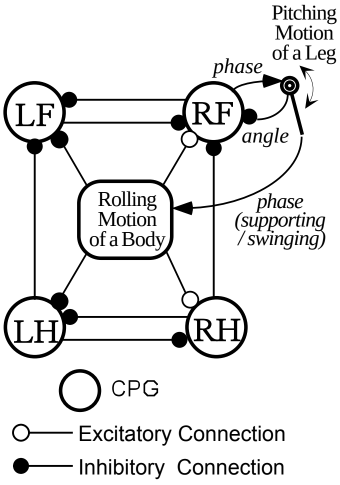
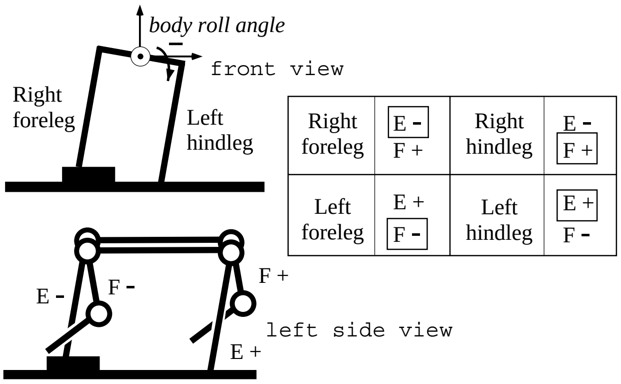


Fig. 2. Relationship among the CPGs, the pitching motion of a leg, and the rolling motion of the body in walking with rolling motion feedback to CPGs.

3.2 Tonic labyrinthine response for rolling

When a leg lands on a bump while walking on irregular terrain, the disturbance of the rolling motion to the pitching motion becomes larger. Therefore, the periods of the current phases of the CPGs in the pitching motion should be adjusted according to the rolling motion, in order to satisfy the condition (b) and (d) described in Section **2.4.**.

The rolling motion feedback to CPGs contributes to an appropriate adjustment of the periods of the stance and swing phases while walking on irregular terrain (Fig.3), as a tonic labyrinthine response for rolling (TLRR) described in Section **2.5.**. In Fig.3, the right foreleg lands on a bump in a trot gait, and the body is inclined in a roll plane. Extending the stance phase of the left hindleg (E+), and shortening the stance phase of the right foreleg (E-) and the swing phase of the left foreleg (F-), prevent the body from the excess inclination in a roll plane and help the condition (d) be satisfied. Extending the swing phase of the right hindleg (F+) enables the reliable landing of the leg on the ground and helps the condition (b) be satisfied..



Right foreleg	$\boxed{\text{E -}}$ F +	Right hindleg	E - $\boxed{\text{F +}}$
Left foreleg	E + $\boxed{\text{F -}}$	Left hindleg	$\boxed{\text{E +}}$ F -

Fig. 3. A tonic labyrinthine response for rolling. E or F means the extensor or flexor neuron of a CPG, respectively. '+' or '-' means the activity of the neuron is increased or decreased by rolling motion feedback to CPGs, respectively.

3.3 Walking on Flat Terrain

The desired angle of the hip joint in the stance phase: θ_{stance}, the time constant of N.O.: τ are variables to change the indexes of walking such as the walking speed and the cyclic period of walking, respectively. For examples, when we shorten the cyclic period of walking by decreasing τ, the stride becomes short since the period of the state (B) in Fig.1 becomes short. As a result, the walking speed is kept almost constant. However, we cannot change the single index independent of other indexes in general, since those variables influence each other and walking is generated through interaction with floor.

Values of all parameters in the neural system including the virtual spring-damper system except for θ_{stance} and τ were determined experimentally. But it should be noted that those values were constant in the following experiments independent of terrain.

4 Adaptive Walking on Irregular Terrain

4.1 Experiments on terrain of medium degree of irregularity

Since the phase difference between rolling motion of the body and pitching motion of legs is largely changed in walking on irregular terrain, a tonic labyrinthine response for rolling (TLRR) is essential.

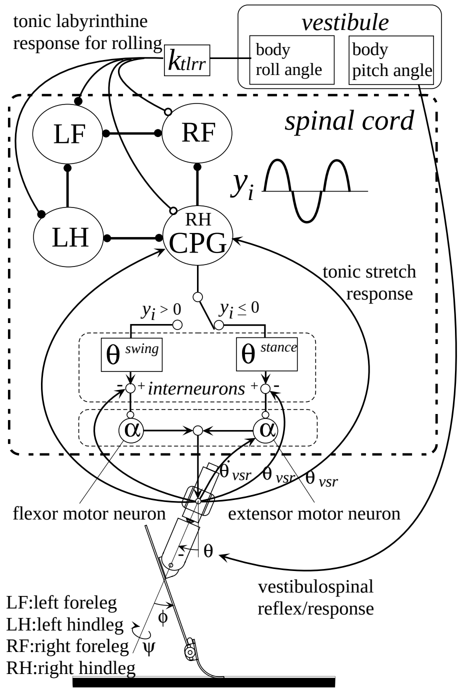


Fig. 4. Control diagram for Tekken.

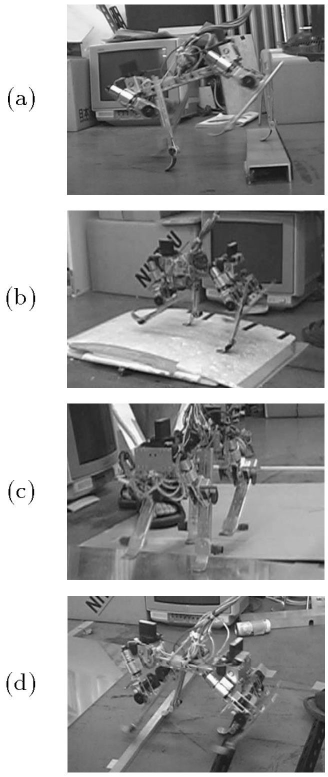


Fig. 5. Walking over irregular terrain.

We made Tekken walk on several irregular terrains with the fixed values of parameters. Tekken walked over an obstacle 4 [cm] in height while stumbling and landing on the obstacle (Fig.5-(a)). Tekken walked up and down a slope of 10 [deg] in the forward direction (Fig.5-(b)), and walked over slopes of 3 and 5 [deg] in a side ways direction (Fig.5-(c)) with an appropriate adjustment of periods of the stance and swing phases. Tekken also walked over terrains consisting of several boards 1.5 [cm] in height, and series of obstacles (Fig.5-(d)) with speed 0.7 [m/s]. Without a TLRR, 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.

4.2 Trade-off of stability and energy consumption

We have to solve the trade-off problem between the stability and the energy consumption[14] in order to determine the value of the time constant of

N.O.: τ. In this study, we employ the following Eq.(1) in order to change τ according to the wide stability margin (WSM)[1] measured using joint angle sensors. Eq.(1) 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.

$$\tau = 0.12(\text{wide stability margin})/\text{w} \tag{1}$$

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

As a result of experiments[14], it was shown that stable walking on irregular terrain with the lower energy consumption was obtained using Eq.(1).

4.3 Visual Adaptation

By detecting the height and the distance to obstacles using vision, the robot can adjust the time constant of N.O.: τ for increasing the stability on terrain of high irregularity while keeping energy consumption low on terrain of low irregularity. In addition, the robot can change the leg length in the swinging phase based on vision in order to prevent the leg from stumbling on obstacles. As a result, Tekken can walk over an obstacle 5.5 [cm] in height (28% of the leg length) with vision.

5 Conclusion

In the neural system model proposed in this study, the relationships among CPGs, sensory input, reflexes and the mechanical system are simply defined. 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 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.

The motion adaptation can be integrated based on the dynamics of the coupled system constructed by the mechanical system and the neural system. The neural system centering the CPGs can afford autonomous adaptation at the several levels from the lower virtual spring-damper system to the higher vision system.

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[1] The WSM is defined 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.

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