Biologically-Inspired Adaptive Dynamic Walking of the Quadruped on Irregular Terrain

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Abstract

In the present study we attempt to induce a quadruped robot to walk dynamically on irregular terrain by using a neural system model. In this paper, in order to realize walking on irregular terrain, we propose the biologically-inspired control method consisting of four levels, those are, "adaptive control using a muscle stiffness model", "adaptive control based on vestibular sensation", "parameters adjustment based on somatic sensation and reflexes coordination based on vestibular sensation", and "motion switching based on visual information". As results of basic experiments of each level, we show that a robot can walk on a single bump and up a slope by using such adaptive control method. We also show that the functions as a lower controller in the Drew's physiological model for leg control mechanism based on visual information are satisfied by a CPG characterized by mutual entrainment with a musculo-skeletal system, automatic interpolation, and self stabilization. These findings suggest a simple method for producing autonomous adaptive dynamic walking on terrain of high degree irregularity.

1 Introduction

Many previous studies of legged robots have been performed. About dynamic walking on irregular terrain, biped[1, 2] and quadruped[3] robots have both been studied. Most of these earlier studies employed precise models of a robot and an environment and involved planning joint trajectories as well as controlling joint motions on the basis of an analysis of the models. However, when a legged robot moves quickly in a variety of places, a method consisting of modeling, planning and control such as these is not effective and not adaptable for the reason identified by Brooks(1991) in his proposal of the behavior-based approach.

On the other hand, it is well known that the motions of animals are controlled by internal nervous systems. Many biological studies of motion control have therefore been done. It is generally accepted that walking of animals is generated by combination of a rhythm pattern generator (Central Pattern Generator:CPG) and reflexes in response to the peripheral stimulus. Much previous research attempted to generate autonomously and emergently adaptable walking using such biologically-inspired control mechanism. Beer[4] was able to achieve static walking in a hexapod robot by incorporating reflexes to several sensor inputs and a few directive signals from the upper level modeled after those of an American cockroach. About two-legged mammal-type dynamic walking, it was shown by simulation that stable and flexible biped walking[5] and three dimensional bipedal stepping[6] could be realized by a global entrainment between a CPG and a musculo-skeletal system. About four-legged mammal-type dynamic walking, it was shown that neural controllers optimized by using a evolutional method like GA[7, 8] or a reinforcement learning method[9] could generate walking of the quadruped. But dynamic walking of a real robot using CPG or neural controllers was rarely realized in these earlier studies.

In our previous studies using a quadruped robot, we realized dynamic walking on flat terrain in trot and pace gaits using a CPG alone, dynamic walking on irregular terrain using a CPG and a reflex mechanism, and running on flat terrain using a CPG and spring mechanism[10]. However, the irregularity of terrain in that study was very low and walking over terrain undulations and up steps where adaptive control based on vestibular and somatic sensation and vision is needed has not yet been realized.

In this paper, in order to realize adaptive dynamic walking on terrain with a high degree of irregularity, we employ four biologically-inspired control mecha-

nisms. It is shown that such control mechanisms are effective in producing dynamic walking on irregular terrain through experiments using a quadruped robot. In comparing results of the experiments in this study to previous experiments using the conventional control method based on dynamics, we discuss our reasons for selecting such a biologically-inspired control mechanism.

2   The Quadruped Robot

The quadruped robot "Patrush" has three joints, namely the hip, knee and ankle joints, that rotate around the pitch axis. A DC motor and a photo encoder are attached to hip and knee joints and ankle joints are passive. When this quadruped robot walks dynamically in trot gait, the body motion of it is constrained on the pitch plane by two poles. For reflex mechanism, micro-switches are attached to the underside of the foot and the toe to detect contact with the floor and with fore obstacles, respectively. In addition, a rate-gyro. as an angular velocity sensor is mounted on a body as vestibule in section **4.3.**.

3   Walking using CPG and reflexes

As a model of CPG, we use a neural oscillator (Fig.1) proposed by Matsuoka[11] and applied to the biped by Taga[5]. Each neuron in this model is represented by the following non-linear differential equations[5]:

$$
\begin{aligned}
\tau \dot{u}_i &= -u_i - \beta v_i + \sum_{j=1}^{n} w_{ij} y_j \\
&\quad + u_0 + Feed_i, \\
\tau' \dot{v}_i &= -v_i + y_i, \\
y_i &= \max(0, u_i),
\end{aligned}
\tag{1}
$$

where u_i is the inner state of the ith neuron; v_i is a variable representing the degree of the self-inhibition effect of the ith neuron; y_i is the output of the ith neuron; u_0 is an external input with a constant rate; $Feed_i$ is a feedback signal from the M.S.S., that is, a joint angle; 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_i and v_i; w_{ij} is a connecting weight between the ith and jth neurons.

A neural oscillator(N.O.) consists of two mutually inhibiting neurons, which alternately induce torque in opposite directions of contraction of the flexor and extensor muscles. By connecting N.O. of each leg, the N.O.'s are mutually entrained and oscillate in a same

period and with a fixed phase difference. This mutual entrainment between the N.O.'s of legs results in a gait. We use a trot gait for walking, where the diagonal legs are paired and move together.

Although we realized dynamic walking on flat terrain in trot and pace gait using a CPG alone, sometimes walking became unstable even on flat terrain because the supporting legs slipped. This meant that it was difficult to realize a stable walking using a CPG alone. Therefore, for dynamic walking on irregular terrain with a low degree of irregularity, we employed a control system involving a CPG and stretch and flexor reflexes[10] (Fig.2). Dynamic walking on flat terrain accomplished via use of a stretch reflex in addition to a CPG became much more stable, compared with use of a CPG alone, because stretch reflex torque assisted in the phase transition from swinging to supporting and in preventing the supporting leg from slipping. In addition, transmission of stretch reflex torque to another supporting leg facilitated synchronization between supporting legs. Stable dynamic walking on terrain furnished with obstructions to swinging legs was made possible by the flexor reflex and the crossed extension reflex.
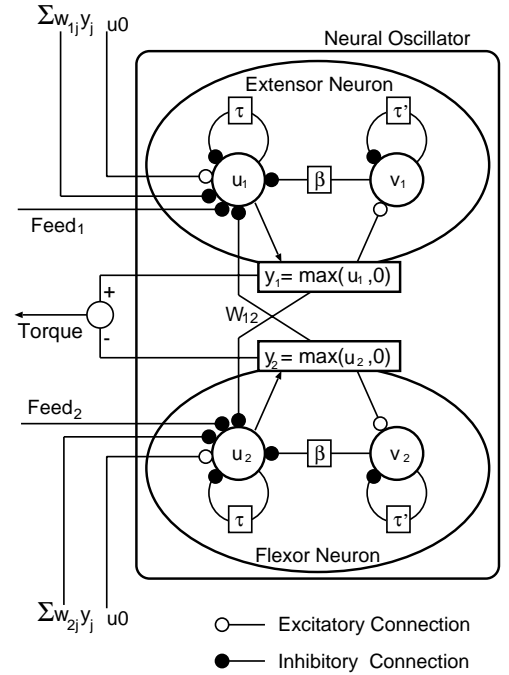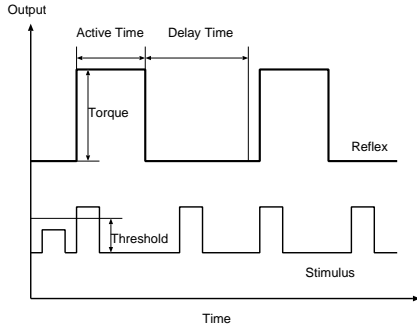

Fig.1 Neural oscillator.

Fig.2 Simplified reflex mechanism.

4 Adaptive Dynamic Walking on Irregular Terrain

4.1 Adaptive Control Mechanism

When we consider walking as an exchange of supporting legs, the stability of walking is nothing but the reliability of the exchange of supporting legs. Therefore, in the case of walking on irregular terrain, it is essential that:

(a) a swinging leg not be prevented from moving forward in the former period of the swinging leg phase and landing reliably on the ground in the latter period of this phase, and

(b) the angular velocity of the supporting legs around the contact points at landing moment be kept constant in spite of changes of height of the ground surface.

For (a) to be satisfied, we have already employed the reflex mechanisms, those are, the flexor reflex for the swinging motion and the stretch reflex for the landing motion[10].

In order to satisfy condition (b) above when a robot goes up and down a step or stairs, a larger torque at the hip joints of the supporting legs is required when going up and a smaller torque is required when going down. In the case that discontinuous change of ground height is recognized by vision, the upper controller can give the directive signal to the lower controller and it is desirable that the external input to a CPG is modified in order to realize such control of angular velocity of the supporting legs as described in section **4.4.**. But, in the case that continuous change of ground height like terrain undulations, bumps on terrain, and a slope exist, it is desirable that walking is adaptively controlled by lower controller without vision in order to satisfy condition (b). Therefore, we

employ the following four biologically-inspired adaptive control mechanisms in order to realize dynamic walking on irregular terrain.

(1) Adaptive control using a muscle stiffness model (Fig.3-A) for walking on terrain with a low degree of irregularity.

(2) Adaptive control based on vestibular sensation (Fig.3-B) for walking on terrain with a middle degree of irregularity.

(3) Adjustment of CPG's parameters by cerebellum based on somatic sensation and coordination of reflexes by cerebellum based on vestibular sensation (Fig.3-C).

(4) Adaptive control based on visual information (Fig.3-D) for walking on terrain of discontinuous irregularity.

These four control mechanisms in animals are made physiologically clear to some extent and control the musculo-skeleton via a CPG and reflex mechanism at the spinal cord (Fig.3).
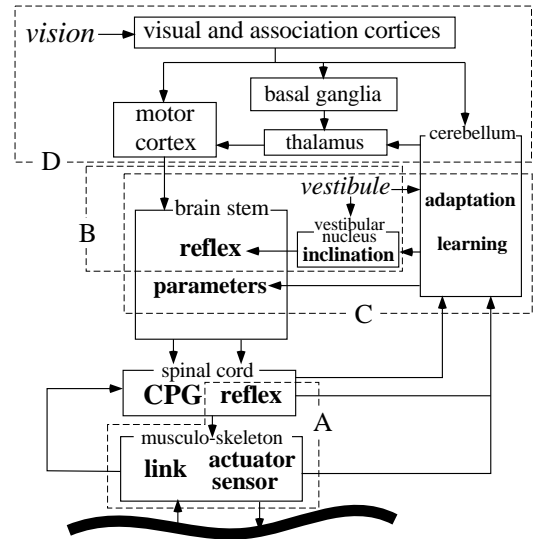

Fig.3 Neural system for adaptive walking

We added the adaptive controls (1), (2), and (3) into the control system consisting of a CPG and reflex mechanism used in our previous study[10] described in **3.** and tried to make a quadruped robot walk on irregular terrain shown in Fig.4.

4.2 Adaptive Control Using Muscle Stiffness Model

When a muscle is stretched, a stretch reflex outputs force contracting the muscle. The stretch reflexes of
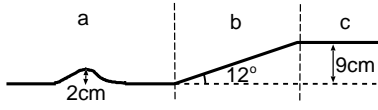
Fig.4 Irregular terrain used in experiments.

extensor muscles of a supporting leg are especially important because they generate torques to support a body. It is pointed out by physiological experiments that when the length of a extensor muscle becomes large, stiffness of a stretch reflex of the muscle becomes small[12]. We call such property of a stretch reflex a "muscle stiffness model". In this study, we assume that stiffness of a stretch reflex has a relation to the length of a muscle shown in Fig.5.

In order to improve adaptability of control performed below a spinal cord, we employ this muscle stiffness model and try to make a quadruped robot walk on a small bump or up a slope by adjusting stretch reflexes of extensor muscles of a supporting leg. When a leg lands on a bump (Fig.6), the knee joint is bended and extensor muscles are more stretched (x_1 in Fig.5) than they are in landing on a flat floor (x^* in Fig.5). Since stiffness of a stretch reflex (S_1 in Fig.5) becomes small according to the muscle stiffness model, the bending of the knee joint is kept and a body is prevented from rising by excess reaction force from the ground.
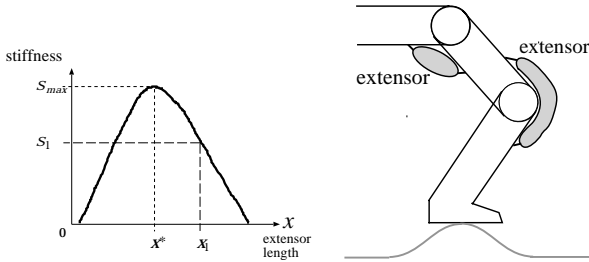

Fig.5 Muscle stiffness model Fig.6 Walking on bumps

As results of experiments, a robot succeeded in walking on a bump 2cm in height and walking up a slope of 7 degrees (Fig.7) smoothly with a low degree of up-and-down motion of a body by using the muscle stiffness model. In Fig.7, we can clearly see that the stiffness of the knee joint in supporting phase becomes small in walking up a slope similar to the case of walking on a bump (Fig.6) because the knee joint was more bended than it was in walking on a flat floor.
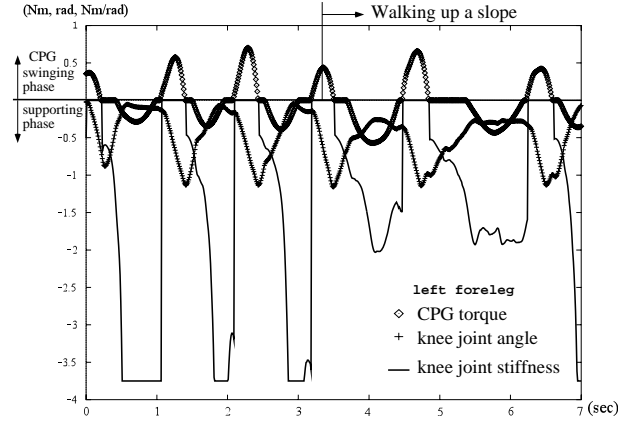

Fig.7 Results of the experiment involving walking up a slope of 7 degrees by using the muscle stiffness model. CPG output torque of the hip joint, the knee joint angle, and the knee joint stiffness of the left foreleg are shown. Positive value and negative value of CPG output torque mean swinging phase and supporting phase of the leg in CPG level, respectively. The knee joint in supporting phase in walking up a slope, for example, from 3.8 to 4.5(sec) was more bended than it was in walking on a flat floor, for example, from 2.7 to 3.2(sec).

4.3 Adaptive Control Based on Vestibular and Somatic Sensation

4.3.1 Walking Up a Slope Using Vestibulospinal Reflex

When a vestibule of a quadruped animal detects a inclination of the head in walking up a slope, it bends knee joints of forelegs and tries to keep posture of the body flat and prevent the center of gravity from being pulled backward. This reflex is called a "vestibulospinal reflex" and generated at a brain stem (Fig.3-B). In addition, when walking up a slope, adjustment of stretch reflexes of extensor muscles of a supporting leg based on the muscle stiffness model described in **4.2.** also assists in keeping body posture flat. As results of experiment, a robot failed in walking up a slope of 12 degrees by using the muscle stiffness model alone, but it succeeded by using both muscle stiffness model and vestibulospinal reflex (Fig.8). In Fig.8, since our robot does not have a head, the inclination of the body is detected by integrating the angular velocity measured by a rate-gyro. sensor attached to the body.
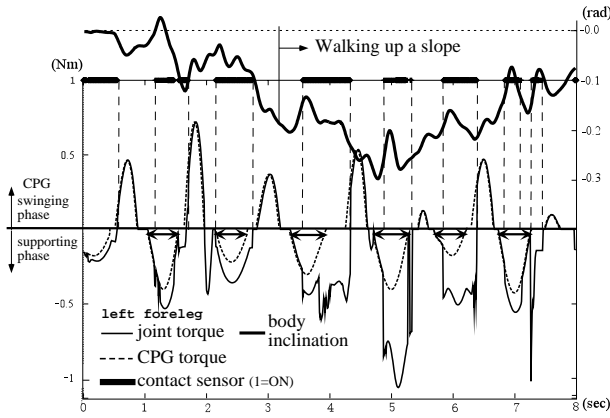
Fig.8 Results of the experiment involving walking up a slope of 12 degrees by using the muscle stiffness model and a vestibulospinal reflex. CPG output torque and the joint torque, which is the sum of output torques of CPG and reflex mechanisms, of the hip joint and contact sensor value of the left foreleg are shown.

4.3.2 Adjustment of CPG's Parameters by Cerebellum

Although walking up a slope of 12 degrees by using the muscle stiffness model and a vestibulospinal reflex was realized in section **4.3.1.**, it was not a smooth walking because of occasional slipping and stamping with no progress. In Fig.8, the periods while the contact sensor value is 1, which are shown by vertical broken lines, mean the actual supporting phase of the left foreleg. On the other hand, the periods shown by thick arrows mean the supporting phase in CPG level. We can clearly see in Fig.8 that the actual supporting phase of the leg in walking up a slope started largely delayed from CPG supporting phase and continued after the end of CPG supporting phase. Therefore, we can say that the reason of slipping and stamping is that the motion of musculo-skeleton was delayed from states of CPG since walking up a slope had required more thrusting force than walking on flat terrain. This showed that a CPG could not cancel a time lag caused by a lack of thrusting force in walking up a slope in spite of its ability of mutual entrainment with a musculo-skeletal system.

In order to adapt a CPG to a delayed motion of musculo-skeleton, we employ a cerebellum model for adjustment of CPG's parameters. When a cerebellum detects a time lag between states of CPG and motion of musculo-skeleton through somatic sensation from peripheral sensors, it changes internal parameters of a

CPG (β in eq.(1)) in order to increase its period. As a result of experiment, walking up a slope became much smooth with less slipping and no stamping because entrainment between a CPG and a musculo-skeletal system had been accomplished (Fig.9). We can clearly see in Fig.9 that the actual supporting phase of the leg in walking up a slope started a little delayed from CPG supporting phase and finished almost at the same time with the end of CPG supporting phase since the period of a CPG had been increased by adjustment of CPG's parameters.
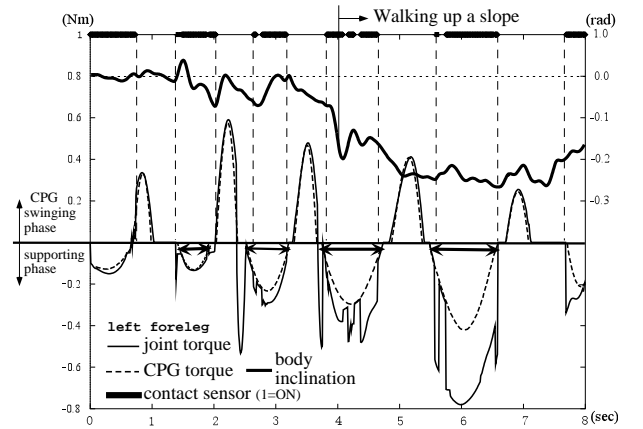

Fig.9 Results of the experiment involving walking up a slope of 12 degrees by using adjustment of CPG's parameters in addition to using the muscle stiffness model and a vestibulospinal reflex.

4.3.3 Coordination of Reflexes by Cerebellum

We implemented adaptive control described in section **4.2.**, **4.3.1.**, and **4.3.2.** on a quadruped robot. As a result of experiment on irregular terrain shown in Fig.4, it was found that vestibulospinal reflex was too sensitive and disturbed smooth walking on flat terrain (Fig.4-a). Therefore, we employ a cerebellum model for coordination of reflexes as non-responsive area of vestibulospinal reflex.

Stretch reflex based on the muscle stiffness model and flexor reflex are always activated. Vestibulospinal reflex is activated when the inclination of a body larger than threshold for a period longer than a constant period is detected, and inactivated when the inclination of a body smaller than threshold is detected (Fig.10). As a result of experiment, by using all adaptive control mechanisms above described (Fig.10), a robot succeeded in walking adaptively and much smoothly (Fig.11) on irregular terrain shown in Fig.4.
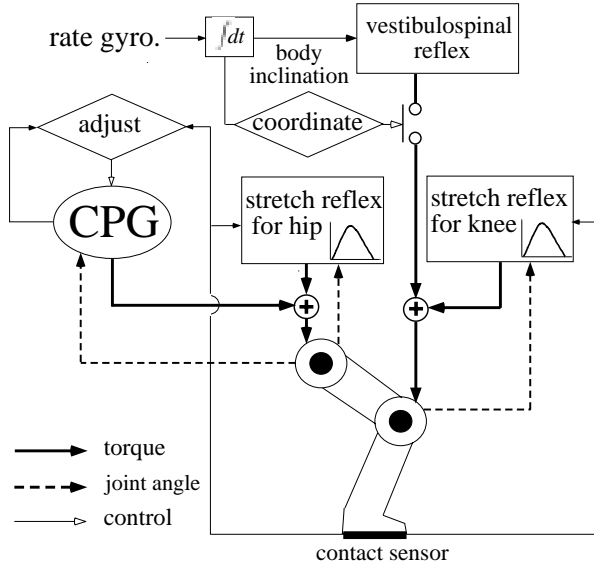
Fig.10 Diagram of actual control of a leg. The flexor reflex in a swinging leg is not included in this figure. The stretch reflexes are activated by contact sensor input. The stretch reflex outputs torque based on the muscle stiffness model. The hip joint torque is the sum of CPG output torque and reflex torque. The parameters of CPG are adjusted by comparing a CPG phase to contact sensor input. The vestibulospinal reflex is activated when the inclination of a body becomes larger than threshold and outputs torque to bend a knee joint of a supporting leg.

The cerebellum models for adjustment of CPG's parameters and coordination of reflexes were introduced based on the physiological knowledge that a cerebellum adjusts parameters of controllers and coordinates motion commands to controllers according to changes of external environment based on several sensations (Fig.3-C).

4.4 Adaptive Control Based on Vision

When the quadruped walks up or down a step, the torque at the hip joints of the supporting legs must be adjusted to keep the angular velocity of the supporting legs around the contact points be constant. This change of motion by torque adjustment of leg joints is made by changing the directive signal to the lower motion controller (u_0 : the external input to a CPG in Fig.1) when the upper controller recognizes a step or an obstacle by vision. Drew et al.[13] proposed a model about the adjustment of the directive signal to a CPG based on visual information (Fig.3-D) by ana-
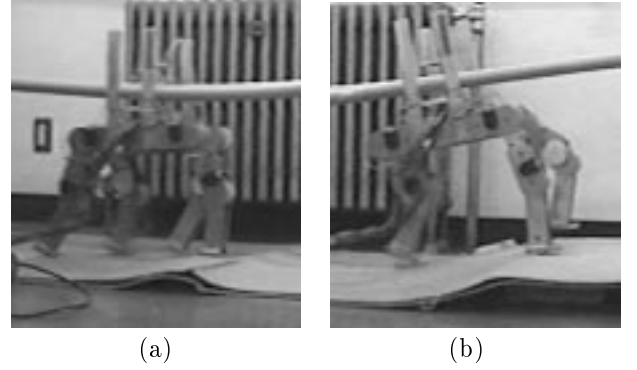

Fig.11 Photos of the quadruped walking on a bump:(a) and up a slope:(b).

lyzing data from physiological experiments.

In order to examine functions of a CPG in this Drew's model, we placed a step 2cm in height in the way of the quadruped and made the quadruped walk up the step by changing u_0. The quadruped succeeded in walking up the step when the changing u_0 was employed (Fig.12) and failed when it was not employed. In Fig.12, the amount of increase of u_0 and the time at which u_0 should be increased were determined heuristically through experiments using simple dynamic models.

This results shows that, once a step has been recognized by the upper controller, knowing when and how much u_0 should be changed is sufficient to generate the signal to the lower motion controller. That is, it is not necessary to direct how the motion of each leg should be changed. This is because a CPG has an ability of automatic interpolation and self stabilization. The fact that a change in only one parameter is enough to achieve a complicated motion such as walking up a step is very interesting and suggests the validity of the Drew's model.

5 Discussion

5.1 Advantages of proposed control

As a result of physiological experiments using decerebrate cats, it is known that walking motion can be initiated both by electrical stimulus to brain stem and by peripheral stimulus from a treadmill. This fact causes a simple question. That is, what kind of role does each stimulus play in initiation and continuation of walking? In the case of static walking, transitions between static states could be initiated and continued by peripheral stimulus alone such as contact
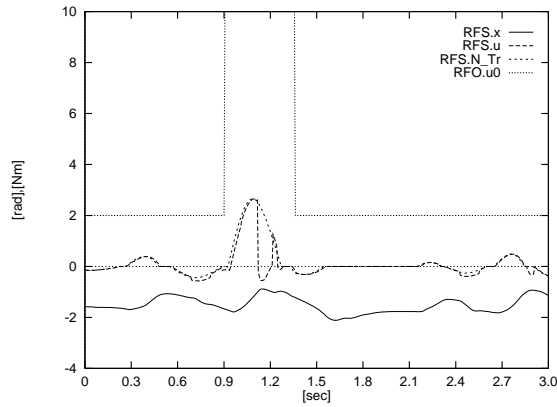
Fig. 12 Results of the experiment involving walking up a step 2cm in height: *RFS.x* and *RFS.N_Tr* are, respectively, the angle and the output torque of the N.O. of the hip joint of the right foreleg. *RFS.u* is the joint torque, which is the sum of *RFS.N_Tr* and the output torque of the reflex mechanism. *RFO.u0* is a driving input to a N.O. network.
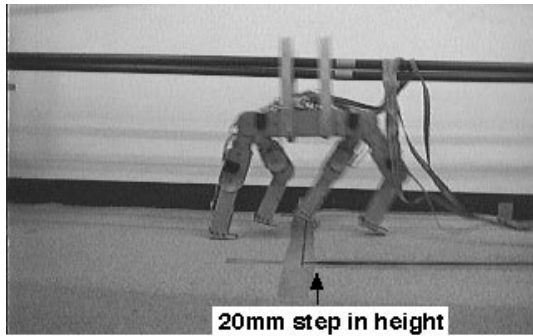

Fig.13 Photo of the quadruped walking up a step.

sensor input. But in the case of dynamic walking, a mechanism in a central nervous system which directly outputs joint driving torque is essential in order to compensate inertia torque needed in quick motion. Feedforward torque calculation using dynamic equation in robotics and CPG in biology correspond with this mechanism. Contact sensor input is considered as a trigger to change a phase of dynamic equation in robotics and to activate a stretch reflex of supporting legs in biology. Therefore, when we compare CPG with feedforward torque calculation, these two mechanisms seem to be much similar.

In order to make the advantages of the biologically-inspired control method clear, let us compare results of the experiments in this study to results from experiments employing the conventional control method based on dynamics[14]. After this comparison, we can remark the following advantages:

(a) All elements of dynamics and algorithm in trajectory generation and control have been condensed into the parameters of a CPG and reflex mechanisms.

(b) A CPG characterized by mutual entrainment with a musculo-skeletal system, automatic interpolation, and self stabilization is very useful as a lower controller.

These advantages suggest the possibility of adaptive walking on terrain with a high degree of irregularity. For example, parameterization of motion generation and control in (a) simplifies adaptation by learning. CPG as a lower controller in (b) has the ability to make motion adaptation by the upper central nervous system based on sensor information relatively simple as described in section **4.3.2.** and **4.4.**.

5.2 Position of this study in the history of legged locomotion studies

The studies on legged locomotion of a robot have various aspects in their intentions. One important goal is to realize a practical walking machine. For this purpose, significant endeavors have been made in mechanical design, static gait control on irregular terrain, and so on. On the other hand, studies aiming to clarify a real nature of legged locomotion have been actively continued. Passive dynamic walking and simplely controlled hopping robot have been analyzed and realized as a non-linear dynamic system. The realization of dynamic walking and running of robots by simplified control showed another real nature of legged locomotion. As a different aspect, several researchers applied their complicated control theory to legged locomotion. In addition, it is clear that adaptability to irregular terrain in legged locomotion is another important aspect. This study aims to clarify a real nature of legged locomotion in view of dynamic adaptation to irregular terrain. For this purpose, we utilize the knowledge in biology and physiology since they have long history about analysis of flexible and robust legged locomotion of living things.

Generally speaking, this study belongs to the category of pattern generation and motion adaptation of dynamic mechanical system involving interaction with environment. There were a lot of previous studies which dealt with autonomous and emergent generations of joint motions and walking patterns by simulation of a CPG. But, this study pointed out for the

first time in robotics that a stretch reflex was important as well as a CPG for the interaction of legs with the ground in dynamic walking of a real robot, even though this fact was well known in biology and physiology. In addition, this study showed that a flexor reflex and a vestibulospinal reflex were also important for walking on irregular terrain. It is worthy of note that adaptive dynamic walking on irregular terrain was realized by using simple adjustments of reflexes and a CPG based on sensor information.

6   Conclusion

In this paper, we proposed the biologically-inspired control method consisting of four levels for adaptive dynamic walking on irregular terrain. As results of experiments, it was shown that

(a) The "adaptive control using a muscle stiffness model" was effective for walking on terrain with a low degree of irregularity,

(b) The "adaptive control based on vestibular sensation" made it possible for a robot to walk up a slope of 12 degrees. But it was not a smooth walking because of occasional slipping and stamping.

(c) The "parameters adjustment based on somatic sensation and reflexes coordination based on vestibular sensation" made it possible for a robot to walk on terrain with a middle degree of irregularity consisting of a bump and a slope much smoothly.

(d) The "motion switching based on visual information" could be easily made possible by using a CPG characterized by mutual entrainment with a musculo-skeletal system, automatic interpolation, and self stabilization as a lower controller.

In this study, several parameters were determined heuristically through experiments by reference to calculations performed using simple dynamic models. Ideally, these parameters should be autonomously determined to fully satisfy the purpose of this research. For this purpose, we are mounting distributed contact sensors under feet and force sensors on supporting legs as somatic sensation in order to evaluate walking in learning or automatic adjustment of parameters. Dynamic walking over terrain undulations and up one or a series of steps by adaptive control based on vestibular sensation, somatic sensation, and vision is the next challenge this study proposes.

Video footage of these experiments can be seen on WWW (*http://www.kimura.is.uec.ac.jp*).

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