Biologically Inspired Dynamic Walking of a Quadruped Robot on Irregular Terrain - Adaptation at Spinal Cord and Brain Stem -

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Abstract

We are trying to induce a quadruped robot to walk dynamically on irregular terrain by using a neural system model. In this paper, we integrate several reflexes such as stretch reflex, vestibulospinal reflex, and extensor and flexor reflex into CPG (Central Pattern Generator). The success in walking on terrain of medium degree of irregularity with fixed parameters of CPG and reflexes shows that the biologically inspired control proposed in this study has an ability for autonomous adaptation to unknown irregular terrain. 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. However, autonomous dynamic adaptation in order to cope with an infinite variety of terrain irregularity still remains unsolved.

On the other hand, animals show marvelous abilities in autonomous adaptation. It is well known that the motions of animals are controlled by internal neural systems. Much previous research attempted to generate autonomously adaptable dynamic walking using a neural system model in simulation[1, 2, 3, 4] and real robots[5, 6, 7]. In our previous studies[7], we realized dynamic walking up and down a slope, and over an obstacle by using a CPG (Central Pattern Generator) and reflexes independent of a CPG. However, the irregularity of terrain in that study was low and walking was not smooth.

In this study we propose a new method for combining CPGs and reflexes based on biological knowledge, and show that reflexes via a CPG is much effective in adaptive dynamic walking on terrain of medium degree of irregularity through experiments. In the proposed method, there does not exist adaptation based on trajectory planning commonly used in the conventional robotics and adaptation to irregular terrain is autonomously generated as a result of interaction of the torque-based system consisting of a rhythm pattern generator and reflexes with environment.

2. Dynamic Walking Using CPGs

2.1. Quadruped robot

In order to apply the control using neural system model, we made a quadruped robot, Patrush. Each leg of the robot has three joints, namely the hip, knee, and ankle joint, that rotate around the pitch axis. An ankle joint is passive. The robot is 36 cm in length, 24 cm in width, 33 cm in height and 5.2 kg in weight. The body motion of the robot is constrained on the pitch plane by two poles since the robot has no joint around the roll axis. For a reflex mechanism, 6 axes force/torque sensor is attached on a lower link beneath the knee joint. A rate-gyro as an angular velocity sensor is mounted on a body as vestibule. All control programs below are written in C language and executed on RT-Linux.

In this study, we define the virtual extensor and flexor muscles on a quadruped robot, and origin and direction of joint angle and torque as shown in Fig.1. In addition, we use such notation as L(left), R(right), F(fore), H(hind), S(hip), x(joint angle), f_x and f_z(force sensor value in x and z direction). For example, LFS means the hip joint of the left foreleg, and LFS.x and LF.fx mean the angle at this joint and force sensor value at this leg.

2.2. Walking on flat terrain using CPGs

By investigation of the motion generation mechanism of a spinal cat, it was found that CPGs are located in the spinal cord, and that walking mo-

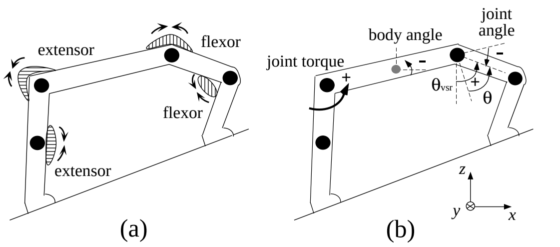


Figure 1: (a) Virtual extensor and flexor muscle on a quadruped robot. (b) Origin and direction of angles and direction of torque.

tions are autonomously generated by the neural systems below the brain stem[8, 9]. Several mathematical models of a CPG were also proposed, and it was pointed out that a CPG has the capability to generate and modulate walking patterns[10], to be mutually entrained with rhythmic joint motion, and to adapt walking motion to the terrain[1, 2].

As a model of a CPG, we used a neural oscillator (NO) proposed by Matsuoka[11] and applied to the biped by Taga[1, 2]. The stability and parameters tuning of a NO was analyzed using describing function method[12]. Single NO consists of two mutually inhibiting neurons (Fig.2-(a)). Each neuron in this model is represented by the nonlinear differential equations:

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

where suffix e, f, and i mean extensor muscle, flexor muscle, and the ith neuron, respectively. u_i is the inner state of 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 robot, that is, a joint angle, angular velocity and so on. u_{0i} is constant except for experiments of vision based adaptation described in Section 4.. As a result, a CPG outputs torque proportional to the inner state u_e, u_f to a DC motor of a joint:

$$N\_Tr = -p_e u_e + p_f u_f \qquad (2)$$

The positive or negative value of N_Tr corresponds to activity of flexor or extensor muscle, respectively.

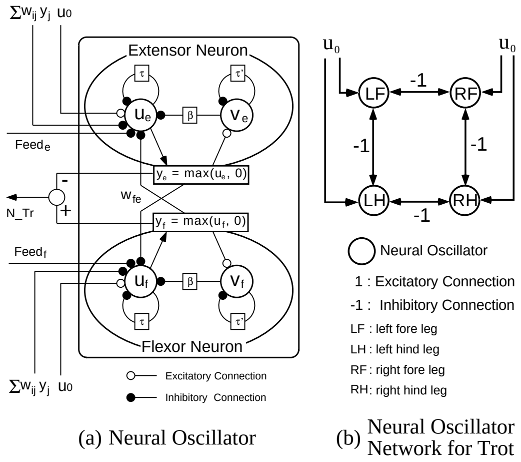


Figure 2: Neural oscillator as a model of a CPG.

A stretch reflex in animals acts as feedback loop[13]. The neutral point of this feedback in upright position of a robot is $\theta = 0$, where $\theta =$ (joint angle) $+ \pi/2$ in Fig.1-(b). It is known in biology that there are two different types of stretch reflexes. One is a short term reflex called a "phasic stretch reflex" and another is a long term reflex called a "tonic stretch reflex." When we assume that a tonic stretch reflex occurs on the loop between CPG and muscles, the joint angle feedback to CPG used in Taga's simulation[1, 2] based on biological knowledge[14] corresponds to a tonic stretch reflex. We use such joint angle feedback to a CPG:Eq.(3) in all experiments of this study.

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

We also assume that a phasic stretch reflex occurs on the loop between α motor neurons and muscles locally, and use this reflex in Section 2.3..

By connecting NO of a hip joint of each leg, the NOs are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between the NOs of legs results in a gait. We used a trot gait, where the diagonal legs are paired and move together, and two legs supporting phase are repeated.

In all experiments of this study, only hip joints are controlled by a CPG and knee joints are PD-feedback controlled for simplicity. The desired angle of a knee joint in a supporting phase is 4 degrees and that in a swinging phase is calculated based on Eq.(4) by using output torque of a CPG:N_Tr at a hip joint of the same leg.

$$\text{desired angle} = 1.7 N\_Tr + 0.26 \qquad (4)$$

By the experiment using only CPGs and tonic stretch reflexes, where $Feed_e = Feed_{e \cdot tsr}$, $Feed_f = Feed_{f \cdot tsr}$, we confirmed that Patrush can walk stably on flat terrain. This control was almost same as the one proposed and used in simulation of biped walking by Taga[1, 2]. Patrush walked dynamically with approximately 25 cm stride, 0.8 sec. period and 0.6 m/sec. speed in this experiment.

2.3. Walking on irregular terrain using CPGs and Reflexes

It is well known in biology that adjustment of CPG and reflexes based on somatic sensation such as contact with floor and tension of muscle of supporting legs, and vestibular sensation are very important in adaptive walking[9, 13, 15]. Although it is also well known that activity of CPG is modified by sensory feedback[15], the exact mechanism of such modification in animals is not clear since the neural system of animals is too complicated. Therefore, we consider the following three types of models for adaptation based on sensory information, discuss about which model is better through results of experiments, and propose physical mechanism of relation between CPG and reflexes in view of robotics.

(a) a CPG only involving a tonic stretch reflex
(b) a CPG and reflexes independent of a CPG
(c) a CPG and reflexes via a CPG

By using model (a) (Fig.3-(a)), we realized dynamic walking on flat terrain as described in Section 2.2.. But Patrush failed in walking over an obstacle 3 cm in height and walking up a slope of more than 7 degrees by using this control model[5, 7].

In model (b), we consider reflexes independent of a CPG, and sum of CPG torque and reflexes torque is output to a motor (Fig.3-(b)). By using a phasic stretch reflex, a vestibulospinal reflex and a flexor reflex independent of a CPG, we realized walking up and down a slope of 12 degrees, and walking over an obstacle of 3 cm in height[5, 7]. But following problems were pointed out:

(1) The delay of joint motion from the phase of a CPG in walking up a slope resulted in slipping and stamping with no progress[7].
(2) Since CPGs could not extend the supporting phase corresponding to the extended swinging phase caused by a flexor reflex, it happened for both legs to be in the swinging phase at the same time and Patrush often fell down forward.
(3) Sensor based adjustments to solve such problems increased number of parameters and made control system complicated[7].

In model (c), reflexes torque is output as part of CPG torque by feedback of all sensory information to a CPG (Fig.3-(c)).

3. Reflexes via a CPG

In this section, we consider reflexes via a CPG in response to vestibular sensation, tendon force and contact with floor. Since these reflexes may be confused with such usual reflexes as a vestibulospinal reflex and so on, we call reflexes via a CPG as a vestibulospinal “response” and so on.

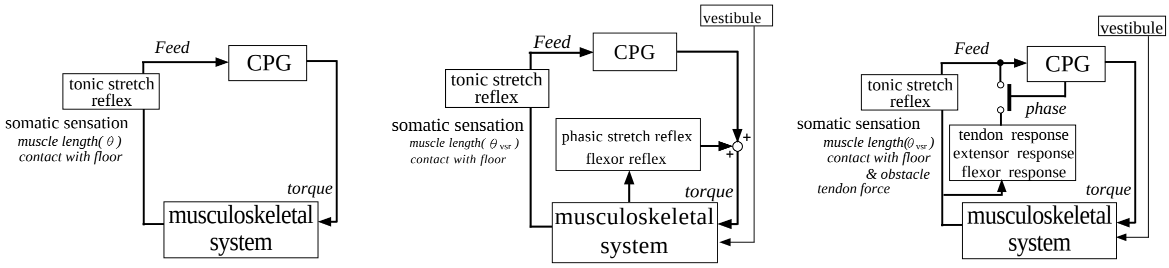
3.1. Vestibulospinal response

Since a tonic stretch reflex continues while a muscle is extended, it is appropriate to adjust activity of antigravity muscles for posture control by a tonic stretch reflex utilizing the body angle detected by vestibule. Therefore, the vestibulospinal response for posture control based on vestibular sensation is via a CPG and expressed by:

$$\begin{aligned} \theta_{vsr} &= (\text{joint angle}) + \pi/2 - (\text{body angle}) \\ Feed_{\{e,f\} \cdot tsr \cdot vsr} &= \pm k_{tsr} \theta_{vsr}. \end{aligned} \tag{5}$$

Since excitatory feedback signal to the extensor neuron of a CPG in walking up a slope makes the active period of the extensor neuron of a CPG become longer, difference between phases of a CPG and joint motion becomes small. In Fig.4, we can see that the vestibulospinal response via a CPG in walking up a slope made the active period of the extensor neuron of a CPG and the supporting phase of a leg be longer in comparison with those in walking on flat terrain. This means that autonomous adaptability of a CPG solved the problem (1) mentioned in Section 2.3..

As a result, Patrush succeeded in walking up and down a slope of 12 degrees by using a vestibulospinal response much more stably and smoothly without increasing number of parameters.



(a) involving tonic stretch reflex (b) reflexes independent of CPG (c) reflexes via CPG

Figure 3: Relation between CPG and reflexes in Taga's model:(a) and models proposed in this study:(b),(c)

3.2. Tendon response

Pearson[16] pointed out that extensor neuron of a CPG gets excitatory signal when the tendon organ detects the load to the ankle joint muscle in a supporting phase. We call this as a tendon response, which acts to complement thrusting force against reaction force from floor in a supporting phase.

We use amount of decrease of $\dot{\theta}$ of a hip joint of a supporting leg for the tendon response instead of the load to the ankle joint muscle. The tendon response via a CPG on a supporting leg is generated by the excitatory feedback signal:$Feed_{e \cdot tr}$ to the extensor neuron of a CPG.

$$Feed_{e \cdot tr} = \begin{cases} k_{tr}(\dot{\theta}+1) & (\dot{\theta} \geq -1) \\ 0 & (\dot{\theta} < -1) \end{cases} \tag{6}$$

$$\begin{aligned} Feed_e &= Feed_{e \cdot tsr \cdot vsr} + Feed_{e \cdot tr} \\ Feed_f &= Feed_{f \cdot tsr \cdot vsr} \end{aligned} \tag{7}$$

By using sensory feedback to a CPG expressed by Eq.(7), Patrush succeeded in walking up and down a slope of 12 degrees (Fig.4). In Fig.4, output torque of the tendon response via a CPG appears as bumps on N_Tr while the extensor neuron of a CPG is active ($N\_Tr < 0$) at 1.9 and 2.3 sec., for example. Although Patrush took 4 sec. to walk up a slope in the experiment without the tendon response in Section 3.1., it took only 2.2 sec. in Fig.4. This means that faster walking up a slope was realized by using the tendon response.

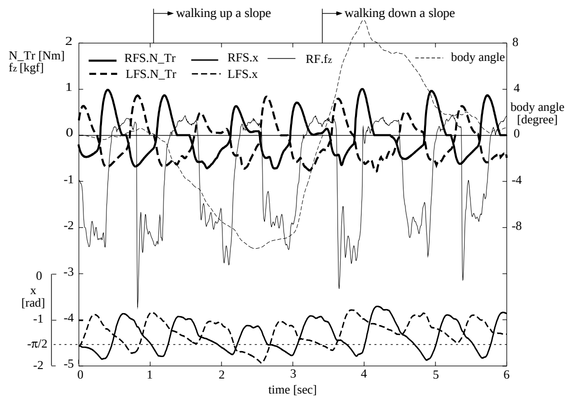


Figure 4: Walking up and down a slope of 12 degrees using feedback:Eq.(7). $N\_Tr < 0$ means the active period of the extensor neuron of a CPG. $f_z < 0$ means the supporting phase of a leg.

3.3. Extensor and Flexor responses

It is known in biology that the response to stimulus on the paw dorsum in walking of a cat depends on which of extensor or flexor muscles are active:

[a] When extensor muscles are active, a leg is strongly extended in order to avoid falling down.

[b] When flexor muscles are active, a leg is flexed in order to escape from the stimulus.

We call [a] and [b] as an extensor response and a flexor response respectively, and assume that phase signal from a CPG switches such responses[15].

For the extensor response, we employ the following excitatory feedback signal:$Feed_{e \cdot er}$ to the extensor neuron of a CPG, when reaction force larger than threshold ($f_x > 1.5$[Kgf]) is detected by force sensor while the extensor neuron is active ($N\_Tr < 0$).

$$Feed_{e \cdot er} = \begin{cases} k_{er}\theta_{vsr} & (\theta_{vsr} \geq 0) \\ 0 & (\theta_{vsr} < 0) \end{cases} \tag{8}$$

For the flexor response, we employ the following instant excitatory feedback signal:$Feed_{f \cdot fr}$ to the flexor neuron of a CPG, when reaction force larger than threshold ($f_x > 1.5$[Kgf]) is detected by force sensor while the flexor neuron is active ($N\_Tr > 0$).

$$Feed_{f \cdot fr} = (k_{fr}/0.12)(0.12 - t) \tag{9}$$

where $t = 0$ sec. means the instance when a leg stumbles, and $Feed_{f \cdot fr}$ is active for t=0∼0.2 sec.

Finally, feedback signal to a CPG to avoid falling down after stumbling is expressed by:

$$
\begin{aligned}
Feed_e &= Feed_{e \cdot tsr \cdot vsr} + Feed_{e \cdot tr} + Feed_{e \cdot er} \\
Feed_f &= Feed_{f \cdot tsr \cdot vsr} + Feed_{f \cdot fr}
\end{aligned}
\qquad (10)
$$

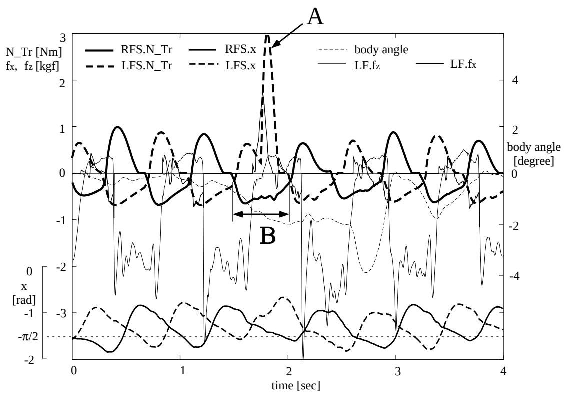


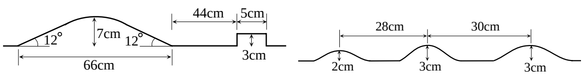
Figure 5: Avoidance of falling down after stumble on an obstacle by using a flexor response.

In Fig.5, the left foreleg stumbled on an obstacle at 1.7 sec., and neuron torque of the left foreleg (LFS.N_Tr) was instantly increased by the flexor response (Fig.5-A). This flexor response made the period of the swinging phase of the left foreleg much longer (1.4∼2.0 sec.). Autonomous adaptability of a CPG made the period of the supporting phase of the right foreleg be longer correspondingly (Fig.5-B) in order to prevent Patrush from falling down by solving the problem (2) mentioned in Section 2.3..

3.4. Adaptation to terrain of medium degree of irregularity

We tried to realize dynamic walking on terrain of medium degree of irregularity, where a slope, an obstacle and undulations continue in series (Fig.6). By realization of such adaptive walking using control method expressed by Eq.(1) and (10) (Fig.7) with fixed values of all parameters, we was able to show that the control method proposed in this section (Fig.7) has ability for adaptation to unknown irregular terrain. The photos of walking on such irregular terrain are shown in Fig.8 and Fig.9.

The experimental results of walking on irregular terrain (Fig.6-(a)) is shown in Fig.10. In Fig.10,



(a) (b)

Figure 6: Terrain of medium degree of irregularity

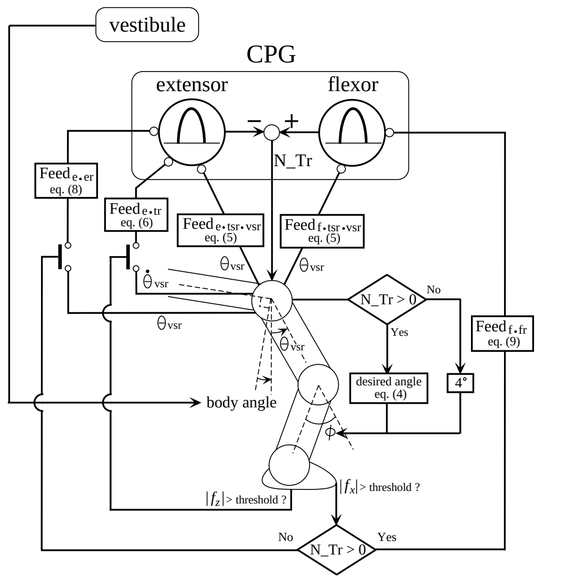
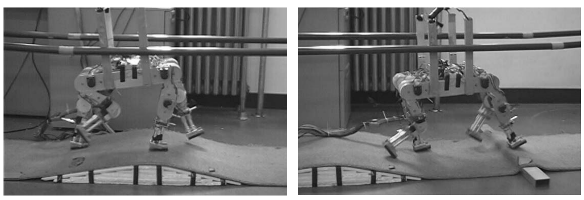


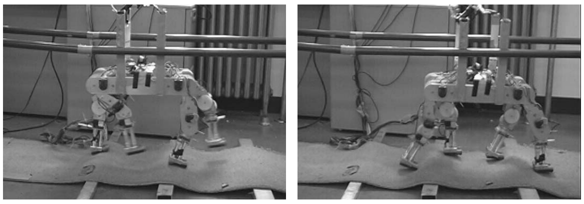
Figure 7: Diagram of actual control of a leg consisting of a CPG and reflexes via a CPG.

Patrush walked up a slope for 1∼3.7[sec] with the tendon response. For 2.8∼3.2[sec], the right hindleg had stumbled on the slope 3 times in a swinghing phase, and CPGs much extended their swinging or supporting phases autonomously influenced by a flexor response. In addition, Patrush walked down a slope (3.7∼4.9) and walked over an obstacle by another flexor response at 5.5[sec]. We can see that RHS.N_Tr in the next supporting phase after those flexor responses was also increased autonomously by CPG and reflexes in order to complement necessary torque after the flexor response.



(a) (b)

Figure 8: Photos of walking up and down a slope:(a) and walking over an obstacle:(b).



(a) (b)

Figure 9: Photos of walking on terrain undulations.

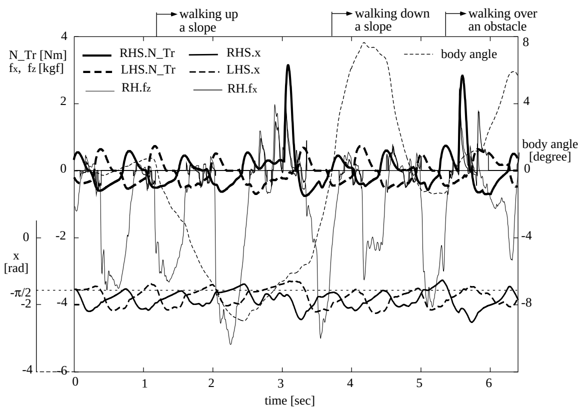


Figure 10: Walking up and down a slope of 12 degrees and over an obstacle 3 cm in height using feedback:Eq.(10).

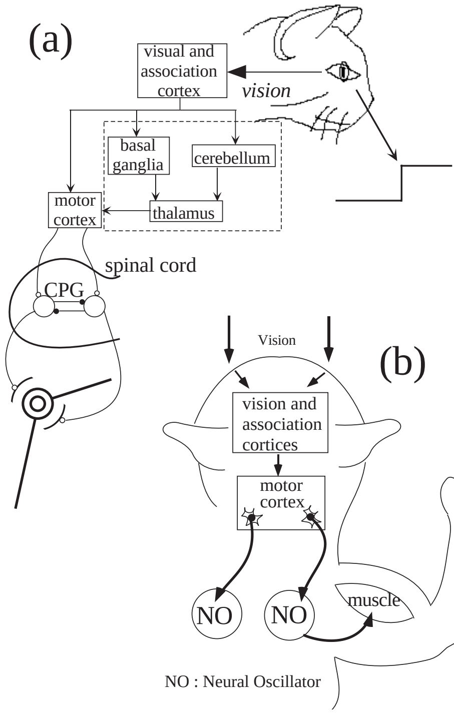


Figure 11: The leg control mechanism of an animal for adaptive walking. (a):a model proposed by Drew[17] and (b):a simplified model used in experiments.

4. Adaptive control based on vision

Drew[17] proposed a model about the adjustment of the directive signal to a CPG based on vision(Fig.11-(a)). When we use neural oscillators as a model of a CPG, the directive signal to a CPG corresponds with external input to neural oscillators: u_0 (Fig.2-(a),(b)). We use a simplified model (Fig.11-(b)) where u_0 for each neural oscillator is determined based on vision and there is neither automatic learning nor adaptation about motion generation at the basal ganglia and cerebellum level. In experiments in this section, we don't use other reflex mechanisms described in Section 3. in order to examine the ability of CPG alone.

The robot succeeded in walking up a step 3 cm in height (Fig.12-(a)) by increasing u_0 based on the height of and distance to the step measured by using stereo vision before start walking.

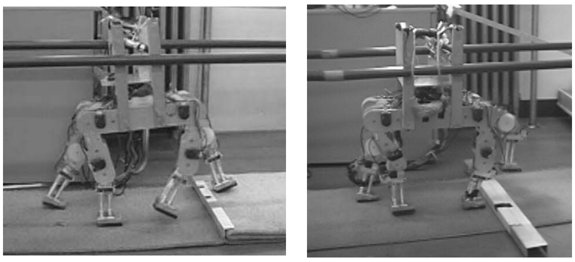
When a robot had found a marked obstacle on the way, a robot tracked the obstacle while walking forward and succeeded in walking over the obstacle without collision by increasing u_0 of each neural oscillator of a hip joint one by one ((Fig.12-(b)), Fig.13). In Fig.13, we can see that u_0 of each CPG was 5 times increased in swinging phase and 2 times increased in supporting phase in the order of LF, RF, RH and LH, and that CPG torque of a hip joint of each leg became large in the same order.

About adjustment based on vision in walking generated by CPG, Taga[18] and Lewis[19] employed reflex independent of CPG. Since we confirmed that adjustment via CPG is much better than adjustment independent of CPG in Section 3., we employed modification of the directive signal to a CPG referring to Drew's model. But it is still open question that which adjustment is better in visual adaptation of a walking robot. In addition, learning[19] is a key issue in visuomotor adaptation. But we have not yet employed it.

5. Discussion

5.1. What is walking using a CPG?

In order to make the role of CPG be clear, let us consider passive dynamic walking: PDW where a walking machine with no actuator can walk down



(a) (b)

Figure 12: Photos of the quadruped robot walking up a step:(a) and over an obstacle:(b) by using vision.

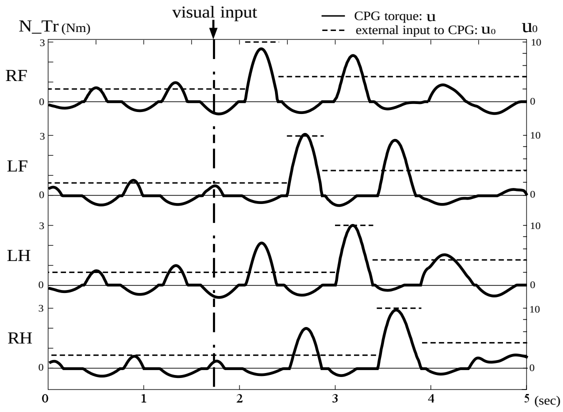


Figure 13: Result of the experiment involving walking over an obstacle 3 cm in height by using adjustment of external input to CPG based on vision.

a slope dynamically[20]. There is similarity between PDW and walking using a CPG in the sense that dynamic walking is autonomously generated on a link mechanism by external force (gravity) or internal torque (CPG torque) as a result of interaction with environment. The result of comparison of additional gravity torque in calculation of PDW with output torque of a CPG in experiment of walking on flat terrain is shown in Fig.14.

In Fig.14, gravity torque on a leg in PDW is reversed at switching of supporting/swinging phases. This shows that walking is exactly passive. On the other hand, switching of torque of extensor/flexor muscles occurs approx. 60 degrees in phase before switching of supporting/swinging phases in walking using a CPG. This switching of torque of extensor/flexor muscles in the latter period of supporting/swinging phases is actually observed in animals' walking[21]. Through this comparison, we can say that active walking using internal torque is nothing but to switch supporting/swinging phases actively by switching of extensor/flexor torque.

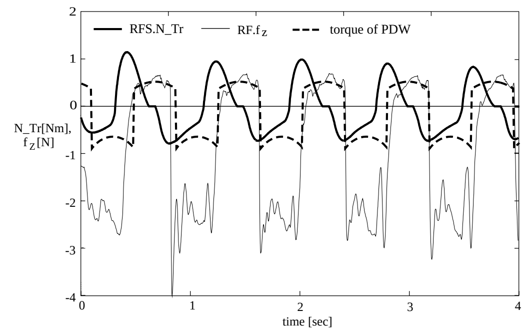


Figure 14: Comparison of CPG torque and additional gravity torque in passive dynamic walking.

This is the reason why active walking using a CPG is much more stable than PDW under errors of initial conditions and disturbances.

Moreover, in dynamic walking on irregular terrain, we can say that the adjustment of phases of CPGs and active switching of supporting/swinging phases of legs are important corresponding to delay of motion caused on a slope and bumps, and extension of phases caused by reflexes CPGs are surely superior in this function because of abilities of mutual entrainment and autonomous adaptation. This is the reason why autonomous adaptive dynamic walking on irregular terrain was realized so simply in this study. As a result, CPGs are much more useful as a lower controller than combination of feedforward torque calculation and feedback control in the conventional robotics method[22].

5.2. CPG and Reflexes

Reflexes independent of CPG had several problems as described in Section 2.3. In the case of reflexes via CPG, it was shown by experiments in Section 3. that the period of phases of CPGs can be appropriately adjusted autonomously by ability of CPG for entrainment while reflexes via CPG output necessary torque for instant adaptation based on sensory information. In addition, the following results obtained in experiments using control system expressed by Eq.(1), (10):

- several reflexes via CPG coincide with each other without improper conflicts,
- adaptive walking on terrain of medium degree of irregularity was realized with fixed value of all parameters,

- strengthening sensory feedback to CPG promotes the autonomous adaptability of walking,

showed that the simple control method using neural system model (Fig.3-(c), Fig.7) has ability for adaptation to unknown irregular terrain.

6. Conclusion

By referring to the neural system of animals, we integrated several reflexes, such as a stretch reflex, a vestibulospinal reflex, and extensor/flexor reflexes, into a CPG. In the case of reflexes via a CPG, it was shown by experiments that the active periods of flexor and extensor neurons of CPGs could be appropriately adjusted autonomously by ability of CPGs for entrainment, while reflexes via a CPG output necessary torque for instant adaptation based on sensory information. The success in walking on terrain of medium degree of irregularity with fixed parameters of CPG and reflexes showed that the biologically inspired control method proposed in this study has an ability for autonomous adaptation to unknown irregular terrain. It was also shown that principles of dynamic walking as a physical phenomenon are identical in animals and robots in spite of difference of actuators and sensors. 3D dynamic walking on 3D irregular terrain is one of the next challenges this study aims for.

Acknowledgments

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