Dynamic Walking and Running of the Quadruped Using Neural Oscillator

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Abstract

In the present study we attempt to induce a quadruped robot to walk dynamically on irregular terrain and run on flat terrain by using a nervous system model. For dynamic walking on irregular terrain, we employ a control system involving a neural oscillator network, a stretch reflex and a flexor reflex. Stable dynamic walking when obstructions to swinging legs are present is made possible by the flexor reflex and the crossed extension reflex. A modification of the single driving input to the neural oscillator network makes it possible for the robot to walk up a step. For running on flat terrain, we combine a spring mechanism and the neural oscillator network. It became clear in this study that the matching of two oscillations by the spring-mass system and the neural oscillator network is important in enabling the robot to hopping. The present study also shows that entrainment between neural oscillators causes the running gait to change from hopping to bouncing. This finding renders running fairly easy to attain in a bounce gait. It must be noticed that the flexible and robust dynamic walking on irregular terrain and the transition of the running gait are realized by the modification of a few parameters in the neural oscillator network.

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. About running of quadruped robots, Raibert[4] and Furusho[5] were able to realize a bounce gait, etc., using a spring mechanism. 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[6] in his proposal of the behavior-based approach.

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. As those studies[7, 8] progressed, it became clear that a rhythm generator called a neural oscillator controlled periodic motions in animals such as breathing, the heartbeat, locomotion, and others. A neural oscillator had the capability to become synchronized with external oscillations and to change its own oscillation. The study of the nervous systems of insects became particularly advanced because of the simplicity of these systems. Beer[9] 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. In the realm of vertebrate motion control, Shik[10] investigated the motion generation mechanism of a cat. He found that a neural oscillator generating locomotion rhythm was located in the spinal cord, and that walking motions were autonomously generated by the nervous systems below the mid-brain.

In this study, we consider both walking and running as stable oscillations of a robot-environment system, and we use a neural oscillator as a control mechanism to keep this oscillation steady. While much previous research attempted to generate autonomously and emergently adaptable walking using a neural oscillator[11, 12, 13, 14], dynamic walking of a real robot was not realized in these earlier studies. As far as we know, our work producing dynamic walking of a quadruped in trot and pace gaits[15] is the only success. Neither dynamic walking on irregular terrain nor running have yet been realized using a neural oscillator.

Moreover, walking in the mammal is controlled not only by a neural oscillator network but also by other nervous systems. It is well known that adjustment of activity of a neural oscillator and muscles by the reflex at the spinal cord and the control signals from the upper central nervous systems based on sensor signals are important in order to adapt walking to the environment.

In this study, we try to achieve flexible and robust dynamic walking and running using a quadruped robot. Our research shows that a nervous system consisting of a neural oscillator network and a reflex mechanism is effective in producing dynamic walking on irregular terrain. It also shows that a neural oscillator network and spring mechanisms, because of their stability and adaptability, are effective in helping to realize running on flat terrain.

2 Neural Oscillator

2.1 Neural Oscillator Model

In an earlier study, Matsuoka[16] analyzed the mutually inhibiting neurons and found the conditions under which the neurons generated oscillation. In another study, Taga[13] similarly proposed the mutually inhibiting neurons as the model for a neural oscillator. He showed by simulation that stable and flexible biped walking could be realized as a global limit cycle generated by a global entrainment between the rhythmic activities of the neural oscillator (N.O.) and the rhythmic movements of a musculo-skeletal system (M.S.S.).

We use the same model of a N.O. in this study. Each neuron in this model is represented by the following non-linear differential equations[13]:

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

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.

Each N.O. consists of two mutually inhibiting neurons. These two neurons alternately induce torque proportional to the inner state u_i in opposite directions, namely the directions of contraction of the flexor and extensor muscles (Fig.1). The N.O. and M.S.S. are mutually entrained and oscillate with the same period and phase.

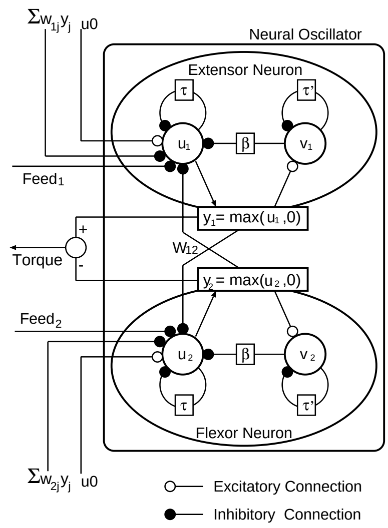

Figure 1: Neural oscillator.

2.2 Neural Oscillator Network

For the quadruped, we constructed a N.O. network by connecting four N.O.'s, each of which drives the hip joint of one of the legs. The N.O.'s are mutually entrained and oscillate in a same period and with a fixed phase difference. This synchronization is called mutual entrainment.

This mutual entrainment between the N.O.'s of legs results in a gait. A gait is a walking pattern which is defined by phase differences between the legs. Representative gaits of the quadruped are named. In a trot gait, the diagonal legs are paired and move together. In a hopping gait, all legs move together. In a bounce gait, the forelegs are paired, so are the hindlegs, and the paired legs move together. There is a 180 degree phase difference between the pairs of legs in a trot gait and a bounce gait. We use a trot gait for walking and a hopping gait and a bounce gait for running. The N.O. networks for these gaits are shown in Fig.2. The parameters in each N.O. network are determined by simulation.

It must be noticed that while being connected to each other N.O.'s can also generate a gait by mutual entrainment in addition to controlling legs by receiving joint angles as feedback signals and inducing joint torques. In the following experiments, the hip joints are controlled by N.O.'s, but, for simplicity, the knee joints are controlled by PD controller so that the angle of each knee joint has a constant relationship to that of a hip joint on the same leg.

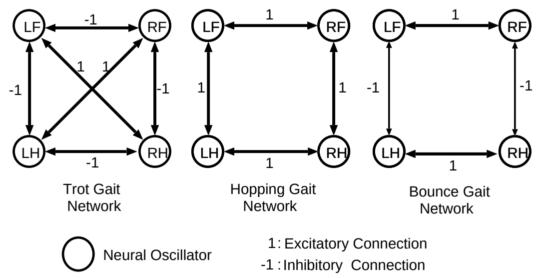

Figure 2: Neural oscillator networks for walking (a trot gait) and running (hopping and bounce gaits). An excitatory connection makes the phase difference between legs zero. An inhibitory connection makes the phase difference 180 degrees. LF, LH, RF and RH stand for left foreleg, left hindleg, right foreleg and right hindleg, respectively.

3 Dynamic Walking on Irregular Terrain Using a Neural Oscillator and Reflex Mechanism

We consider the HC (Horizontally Composed) terrain introduced by Yoneda[17] as irregular terrain. It is constructed from several horizontal planes situated at different heights. Even though there are steps in HC terrain, the contact points are considered to be on the planes. 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 HC 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 plane in the latter period of this phase, and

(b) the angular velocity of the supporting legs around the contact points be kept constant in spite of changes of plane height.

For (a) to be satisfied, we employ the reflex mechanisms, those are, the flexor reflex for the swinging motion and the stretch reflex for the landing motion described in sections **3.5.** and **3.3.**, respectively.

In order to satisfy condition (b) above, a larger torque at the hip joints of the supporting legs is required when going up a step and a smaller torque is required when going down. To meet these requirements, we change u_0, the external input to the N.O.'s, when a step is found, as described in section **3.4.**.

3.1 The Quadruped Robot for Walking

The quadruped robot Patrush has two joints, namely the hip and knee joints, that rotate around the pitch axis. A DC motor and a photo encoder are attached to each joint. For walking on irregular terrain, micro-switches are attached to the underside of the foot and the toe to detect contact with the floor and with fore obstacles, respectively. The body motion of the quadruped is constrained on the pitch plane by two poles.

3.2 Reflex Mechanism and Network

The reflex mechanism in animals is initiated by a stimulus from the environment. A reflex occurs when instant and rapid motion is needed. The features of the reflex are rapid output, weariness, a reflex threshold and non-responsive time (Fig.3). A reflex is induced in response to a stimulus larger than its threshold. The reflex produces a constant torque for a constant period, known as the active time. The next response is delayed for a period known as the delay time. The non-responsive time is the sum of the active time and the delay time. We consider these features when we introduce reflexes into the neural system of the quadruped as mechanisms which output a large torque for a short period of time in response to input from sensors.

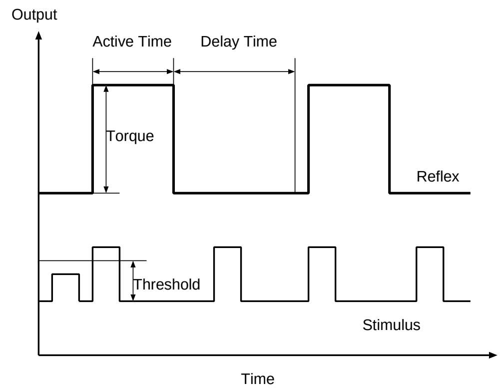

Figure 3: Reflex mechanism.

In animals, the torque produced by reflex affects one muscle or several muscles of a leg. In our nervous system, the sum of the reflex torque and the N.O.'s output torque is output to a joint. In some cases, the reflex torque is transmitted to other legs. The crossed extension reflex in animals is a well-known example of such transmission. In the present study, we introduce reflex networks based on the N.O. network (Fig.4), so that the reflex torque of one leg is transmitted to other legs through reflex network connections as described below in sections **3.3.** and **3.5.**.

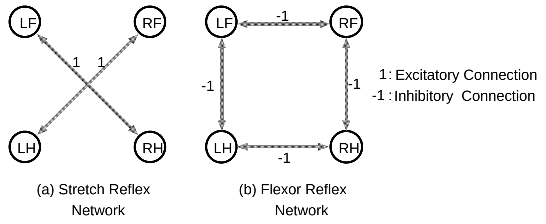

Figure 4: Reflex networks. Raw torque is transmitted through an excitatory connection. Negated torque is transmitted through an inhibitory connection.

3.3 Walking on Flat Terrain Using the Stretch Reflex

The stretch reflex produces torque that supports a body in the supporting leg phase when it responds to a contact sensor on the underside of the foot. This torque is directly transmitted to the synchronized diagonal leg in a trot gait (Fig.4-(a)). The stretch reflex compensates for the change of load at the moment of transition when a leg passes from a swinging phase to a supporting phase, and transmission of the reflex helps maintain synchronization between supporting legs.

The successful results of our experiment intended to verify the effectness of using a N.O. network and stretch reflex for walking on flat terrain are shown in Fig.5, where the joint angle, output torque, etc., of the hip joint of a right foreleg are shown. We see that the output torque $RFS.N\_Tr$, which is proportional to the inner state of a N.O., is entrained by the rhythmic movements of a leg. This entrainment causes the stable oscillation, that is, walking. We can clearly see that torque produced by the stretch reflex in response to an input from a contacting sensor on the right foreleg is added to the N.O.'s torque output, for example, at 0.6 and 1.3(sec). We can also see that torque produced by the stretch reflex of a left hindleg is transmitted to a right foreleg through a stretch reflex network connection (Fig.4-(a)), for example, at 1.8 and 2.5(sec). The torque caused by the stretch reflex appears at the beginning of the supporting leg phase and disappears after about 0.2(sec). This means that the added torque helps to support the body and move it forward only in the initial part of the supporting leg phase, when a large torque is required.

3.4 Walking up a Step by Changing an External Input

It is possible for the quadruped to walk stably on flat terrain by using a N.O. network and stretch reflex together. But when the quadruped walks up or down a step, the torque at the hip joints of the supporting legs

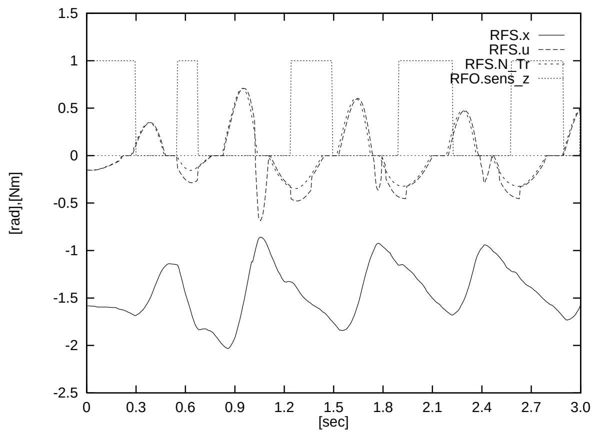

Figure 5: Results of the experiment involving walking on flat terrain using the stretch reflex: $RFS.x$ and $RFS.N\_Tr$ are, respectively, the angle and the output torque of the N.O. of the hip joint of the right foreleg. $RFO.sens\_z$ is the vertical contact sensor output of the right foreleg. $RFS.u$ is the joint torque, which is the sum of $RFS.N\_Tr$ and the output torque of the reflex mechanism.

must be adjusted to keep the angular velocity of the supporting legs around the contact points be constant. This adjustment is made by changing u_0, an external input to the N.O.'s(Fig.1), when a step is found.

We placed a step 20mm in height in the way of the quadruped. The quadruped succeeded in walking up the step when the changing u_0 was employed and failed when it was not employed. Results and photos from this experiment are shown in Fig.6 and Fig.7. We can see that the amplitude of the output torque of the N.O. and of the joint torque become large when u_0 is increased from 0.9 to 1.4(sec).

The amount of increase of u_0 and the time at which u_0 should be increased are determined heuristically through experiments using simple dynamic models. This is possible because we take the directive signal from the upper controller, which may be determined by information from a visual sensor, to be u_0. This means 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. 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. This finding suggests a simple method for producing autonomous dynamic walking on irregular terrain.

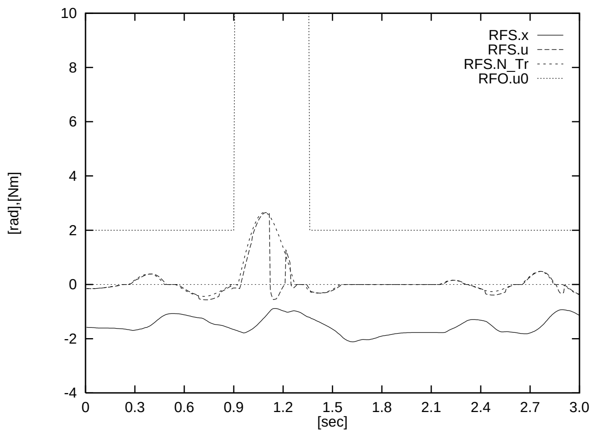

Figure 6: Results of the experiment involving walking up a step: *RFS.x* and *RFS.N_Tr* are, respectively, the angle and the output torque of the N.O. of the hip joint of the right foreleg. *RFS.u* is the joint torque, which is the sum of *RFS.N_Tr* and the output torque of the reflex mechanism. *RFO.u0* is a driving input to a N.O. network.

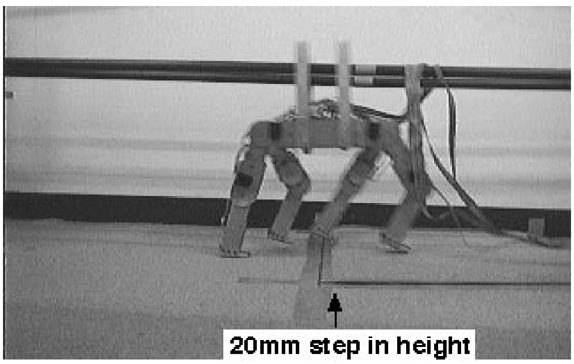

Figure 7: Photo of the quadruped walking up a step.

3.5 Walking with a Swinging Leg Obstructed Using the Flexor Reflex

In response to an input from a contact sensor on the toe, the flexor reflex produces torque to lift a swinging leg over an obstacle. This torque is negated and transmitted as stretch reflex torque to the supporting legs through a flexor reflex network connection (Fig.4-(b)). This transmission is known as the crossed extension reflex. It extends the supporting period by stretching the supporting legs in response to the extension of the swinging period caused by the flexor reflex in the swinging leg.

We placed a box 30mm in height in the way of the right legs of the quadruped. The quadruped succeeded

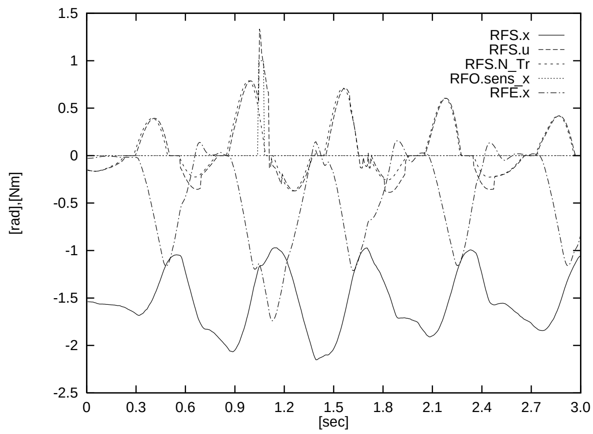

Figure 8: Results of the experiment involving walking with a swinging leg obstructed using the flexor reflex: *RFS.x* and *RFS.N_Tr* are, respectively, the angle and the output torque of the N.O. of the hip joint of the right foreleg. *RFO.sens_x* is the horizontal contact sensor output of the right foreleg. *RFS.u* is the joint torque, which is the sum of *RFS.N_Tr* and the output torque of the reflex mechanism. *RFE.x* is the angle of the knee joint.

in walking over the box when it used the flexor reflex but failed without using the reflex. The parameters in Fig.3 were determined heuristically through experiments.

The results and photos from this experiment are shown in Fig.8 and Fig.9. The collision between the right foreleg and the box occurs at 1.0(sec). The flexor reflex caused by this stimulus makes the period of collision very short, about 0.06(sec). The influence of the flexor reflex is restricted to one period of walking, and the N.O. and M.S.S. subsequently restart the stable oscillation by mutual entrainment. This experiment shows that it is possible to avoid obstructions in the path of a swinging leg using the flexor reflex mechanism and to maintain stable walking by entrainment between the N.O. and M.S.S..

4 Running on Flat Terrain Using a Neural Oscillator and a Spring Mechanism

In running in animals, the tendon acts as a shock absorber for landing and as an actuator for jumping. In the present study we use a spring mechanism[4, 5] in place of a tendon. The entrainment between the oscillations of the N.O. network and the spring-mass and environment system (S.M.E.S.) causes the

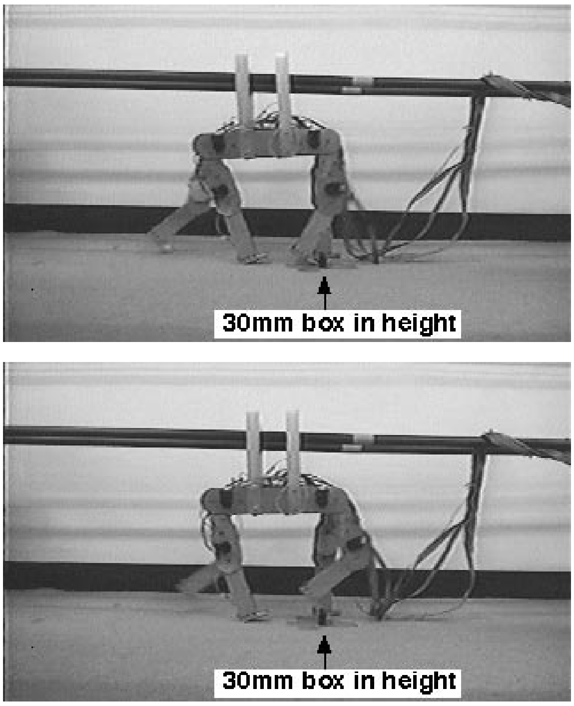

Figure 9: Photos of the quadruped walking with a swinging leg obstructed using the flexor reflex. The contact of the right foreleg with a box is sensed in the upper photo. The flexor reflex torque lifts the right foreleg over a box in the lower photo.

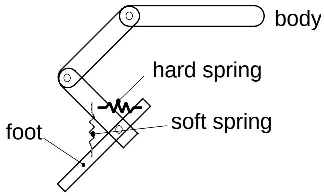

Figure 10: Spring mechanism at an ankle joint.

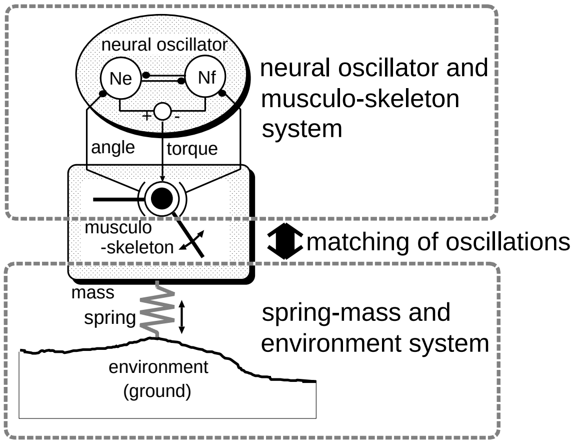

Figure 11: Matching of oscillations of two systems. One pair of oscillations includes the oscillation of the neural oscillator and that of the musculo-skeletal system. Another pair includes that of the spring-mass.

quadruped to run.

A bounce gait appears when quadruped animals run fast. It is difficult to transfer the robot's state from stationary standing to running in a bounce gait, since the movement of the body is large in a bounce gait, and the motions of the fore and hind legs are much different from each other. We realized a bounce gait by transition from a hopping gait.

4.1 The Quadruped Robot for Running

For running, a passive ankle joint with neither sensor nor actuator was added to each leg. Micro-switches were not attached to the feet. Two springs were attached between the lower limb and the foot (Fig.10). Of these, one was a hard spring for absorbing shock and reusing kinetic energy. The other was a soft spring to keep the angle of the ankle joint constant in the air.

4.2 Hopping Period

Stable jumping is essential in order to realize running. Because of this, we tested the jumping of the quadruped in a hopping gait using the N.O. network. In a quadruped with spring mechanisms, hopping is generated by the entrainment between the oscillation of the N.O.'s and M.S.S. and that of the S.M.E.S. (Fig.11). Each of these two oscillating systems has an eigen-period. In order to examine the relationship between these two eigen-periods and the hopping period, we tested hopping with a constant spring factor and in various periods of the N.O.'s. The results for the most stable hopping are shown in Table.1. The hopping period of 0.41(sec) is the sum of two periods. These are the landing period and the flying period, whose durations are respectively determined by spring-mass factors and by the hopping height. The landing period equals half of the eigen-period of the spring-mass system, 0.17(sec). The flying period is 0.24(sec).

In Table.1, we can see that the period of the N.O.'s becomes slightly longer (0.33(sec)) than the eigen-period 0.30(sec) through entrainment by M.S.S.. The period of the N.O.'s finally comes into correspondence with the hopping period (0.41(sec)) by mutual entrainment between N.O.'s-M.S.S. and S.M.E.S.. This means that we should determine the period of the N.O.'s-M.S.S. system so that the N.O.'s-M.S.S. system can be entrained to the period of the S.M.E.S. in order to produce stable hopping.

Since the hopping height, which is controlled by u_0, an external input to the N.O.'s, determines the flying period, we see that the oscillation of the S.M.E.S. is also entrained by the oscillation of the N.O.'s-M.S.S. system. This means that the hopping height and period can be controlled by a single external input, u_0, to N.O.'s.

Table 1: Periods of Oscillation Systems. N.O.'s, M.S.S. and S.M.E.S. stand for neural oscillator, musculo-skeletal system, and spring-mass and environment system, respectively.

oscillation system	period [sec]
N.O.'s	0.30 (from calculation)
N.O.'s-M.S.S.	0.33 (from experiment with the robot hanged in the air)
spring-mass	0.34 (from calculation)
N.O.'s-M.S.S. and S.M.E.S.	0.41 (from experiment of hopping)

4.3 The Gait Transition from Hopping to Bouncing

There is a 180 degree phase difference between the fore and hind legs in a bounce gait. While standing, the phase difference is zero. In order to shift from standing to a bounce gait, the N.O.'s and motions of the quadruped should change from stationary states to steady states by virtue of many entrainments, such as the mutual entrainment between N.O.'s and that among the N.O.'s, M.S.S., and S.M.E.S.. Therefore, it is difficult to realize a bounce gait from a standing position, but it is easy to realize a hopping gait from a standing position, since the phase differences in a hopping gait, as in a standing position, are zero. In addition, since the mutual entrainments among the N.O.'s, M.S.S. and S.M.E.S. are already established in a hopping gait, it becomes easy for the quadruped to shift from a hopping gait to a bounce gait by using the mutual entrainment between N.O.'s. For this reason, we achieve bouncing by a gait transition from hopping.

In order to realize the gait transition, the parameters of the N.O. network are set as follows:

(a) The initial values of the inner states of neurons are set equal so that the phase differences between legs become zero. These values correspond to the initial state in a hopping gait.

(b) The N.O. network of a bounce gait (Fig.2) is used, where the connecting weights between the fore and hind N.O.'s are small in comparison with those between the N.O.'s of paired legs. It takes a relatively long time to generate the phase difference between the fore and hind N.O.'s on this N.O. network.

The successful results and photos from this experiment are shown in Fig.12 and Fig.13. Because the initial state was that of a hopping gait, we see that a hopping gait, where the phase differences are zero, appears for $0 \sim 1$(sec). As the influence of inhibitory connections between the fore and hind N.O.'s becomes dominant, the gait transition from hopping to bouncing appears for $1 \sim 2.5$(sec). The steady bounce gait is finally realized at and after 2.5(sec).

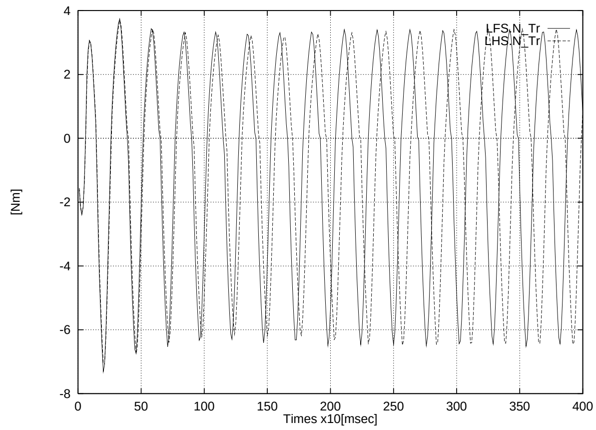

Figure 12: Results of the experiment involving the gait transition from standing to bouncing via hopping: *LFS.N_Tr* and *LHS.N_Tr* are, respectively, the joint torques of the hip joints of the left foreleg and left hindleg.

5 Conclusion

We realized dynamic walking on irregular terrain in a quadruped robot by using a nervous system consisting of a neural oscillator network and reflex mechanisms. We also induced the quadruped to run on flat terrain by using a neural oscillator network and spring mechanisms. It must be noticed that the flexible and robust dynamic walking on irregular terrain and the transition of the running gait were realized by modifying only a few parameters of the neural oscillator network. This finding shows the potential of a neural oscillator network for adaptation in dynamic walking and running.

In this study, several parameters were determined heuristically through experiments by reference to cal-

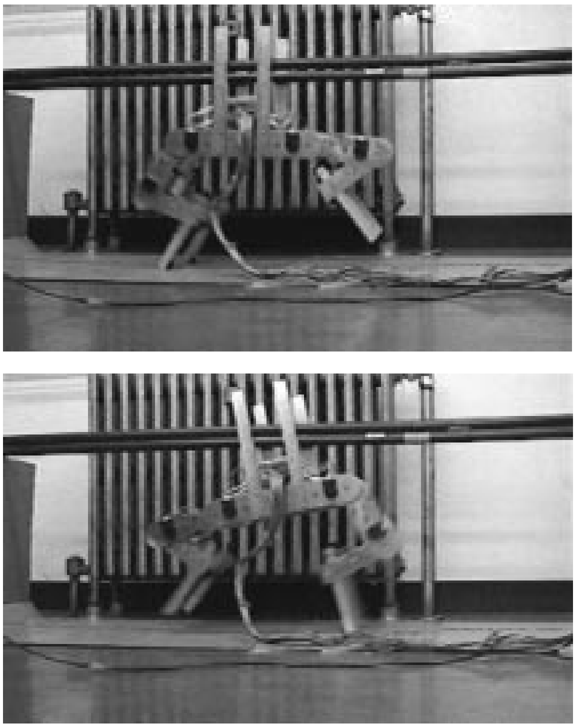

Figure 13: Photos of the quadruped running in a bounce gait.

culations performed using simple dynamic models. Ideally, these parameters should be autonomously determined to fully satisfy the purpose of this research. In addition, the realization of running on irregular terrain and faster running in a gallop gait will be subjects of future study.

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

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