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Realization of 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 order to keep jumping in a pronk gait. The present study also shows that entrainment between neural oscillators causes the running gait to change from pronk to bound. This finding renders running fairly easy to attain in a bound 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.

Keywords: Quadruped Robot, Neural Oscillator, Reflex Mechanism, Walking on Irregular Terrain, Gait Transition in Running

1. Introduction

Many previous studies of legged robots have been performed. About dynamic walking of a quadruped robot, the author realized trot and pace gaits on a flat plane and analyzed criteria in order to make the quadruped walk in a better manner[1]. About dynamic walking on irregular terrain, biped[2, 3] and quadruped[4] robots have both been studied. About running of quadruped robots, Raibert[5] and Furusho[6] were able to realize a bound gait, etc., using a spring mechanism. Buehler[7] also realized dynamic walking up a step and running of a quadruped robot. 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 based on an analysis of the models. If we know all about one particular irregular terrain previously, we can prepare control program for it. But, in order to cope with infinite variety of terrain irregularity, we need autonomous adaptation. As far as we know, such conventional method consisting of modeling, planning and control has not yet shown good methodology for autonomous adaptation in dynamic walking on irregular terrain.

On the other hand, animals show marvelous ability about autonomous adaptation. 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[8, 9, 10] 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. The study of the nervous systems of insects became particularly advanced because of the simplicity of these systems. Beer[11] 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[12] 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. Much previous research attempted to generate autonomously and emergently adaptable walking using a neural oscillator by simulation[13, 14, 15, 16, 17, 18]. It was pointed out in these previous studies that a neural oscillator had the capability to become synchronized with external oscillations and to adapt its own oscillation to environment. About a biped robot, it was shown by simulation that stable and flexible biped walking[17, 18] and three dimensional bipedal stepping[19] could be realized. About four-legged walking, it was shown that neural controllers optimized by using a evolutional method like GA[20, 21] or a reinforcement learning method[22] could generate walking. However, dynamic walking of a real robot was not realized in these previous studies. Although several studies[23, 24, 5] succeeded in realization of dynamic walking and running by constructing stable limit cycle on the phase plane utilizing exchange of supporting legs, they did not use a neural oscillator but used explicit dynamics model of a robot. As far as we know, our work producing dynamic walking of a quadruped in trot and pace gaits[25] was the first successful study using a neural oscillator and not using explicit dynamics model for control. Neither dynamic walking on irregular terrain nor running have yet been realized using a neural oscillator.

Moreover, walking in animals is controlled not only by a neural oscillator network but also by other nervous systems. It is well known that adjustment of activities of a neural oscillator and muscles by reflexes at the spinal cord in response to the peripheral stimulus are important in order to adapt walking to the environment[9, 26] as well as the control signals from the upper central nervous systems.

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 reflex mechanisms is effective in producing dynamic walking on simple irregular terrain. It also shows that a neural oscillator network and spring mechanisms are effective in realizing running on flat terrain. This finding, obtained through experiments using the quadruped called "Patrush" (Figure 1), shows the potential ability of a neural oscillator network to facilitate adaptation in dynamic walking and running.

2. Control Mechanism of Legged Locomotion

The primitive control mechanism of legged locomotion in animals is shown in Figure 2. The musculoskeletal system is mainly controlled by a neural oscillator and reflex at the spinal cord. The neural oscillator is driven by the signal from the upper level, that is, midbrain located at the brain stem. There exists a motion switching mechanism at the cerebrum. It starts legged locomotion and changes the motion pattern based on the sensory information from vision and so on. There exists a motion adaptation mechanism at the cerebellum. It adapts the motion signals and parameters based on signals from peripheral sensors and other mechanisms. Of course, the real control mechanism in animals is more complicated. For example, motion planning at the cerebrum and motion pattern generation at the cerebellum are not considered in this figure. The dotted box shows the control mechanism used in this study.

2.1. *Neural Oscillator*

2.1.1. Neural Oscillator Model In an earlier study, Matsuoka[27] analyzed the mutually inhibiting neurons and found the conditions under which the neurons generated oscillation. In another study, Taga[17] 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 musculoskeletal system (M.S.S.).

We use the same model of a N.O. in the study by Taga. Each neuron in this model is represented by the following non-linear differential equations[17]:

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

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 (Figure 3). The N.O. and M.S.S. are mutually entrained and oscillate with the same period and phase.

2.1.2. Neural Oscillator Network For a quadruped robot, we constructed a N.O. network by connecting four N.O.'s, each of which drives a hip joint of a leg. 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 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 pronk gait, all legs move together. In a bound gait, the forelegs are paired, so are the hindlegs, and paired legs move together. There is a 180 degree phase difference between pairs of legs in a trot gait and a bound gait. We use a trot gait for walking, and pronk and bound gaits for running. The N.O. networks for these gaits are shown in Figure 4.

The parameters in each N.O. and its network were determined by simulation referring to the conditions found by Matsuoka[27]. If we know the appropriate period in dynamic walking of the quadruped robot[1], it's not difficult to determine the parameters in N.O. and its network applicable to the quadruped robot. In the case of our quadruped robot which is 330mm in height, the appropriate period is approximately 0.6(sec). Too small period makes dynamic walking inefficient and limits walking speed. Too large period makes dynamic walking unstable[1]. Once the parameters in eq.(1) are determined by simulation, u_0 and $Feed_i$ are easily tuned by experiments since slight modification of these parameters does not affect quality of walking.

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.

We realized dynamic walking on flat terrain in trot and pace gaits using N.O. networks alone[25]. However, sometimes walking became unstable even on flat terrain because supporting legs slipped. This meant that it was difficult to realize a stable dynamic walking using a N.O. network alone since N.O. is nothing but a rhythm generator and N.O. itslef cannot deal with interaction between legs and floor directly. Therefore, we propose a new walking control system by combining a N.O. network and reflex mechanisms.

2.2. 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 (Figure 5). 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 nervous system of the quadruped as mechanisms which output a large torque for a short period of time in response to input from sensors.

In animals, the torque produced by reflex affects one muscle or several muscles of a leg. 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 (Figure 6), so that the reflex torque of one leg is transmitted to other legs through reflex network connections as described below in sections **3.2.** and **3.3.**.

2.3. Control Mechanism

Actual control diagram in our quadruped robot for dynamic walking and running is shown in Figure 7, where reflex mechanisms are not used in running.

In this control system, a hip joint is controlled by a N.O. and reflexes, where the sum of N.O. output torque and reflex torque is output to a DC servo motor. However, knee joints are simply controlled by PD controller and reflexes in order to reduce the number of tuned parameters of N.O.'s in the system. For examples, in the case of walking, knee joints are controlled so that the angles of knee joints become 3 degree in a supporting phase and 60 degree in a swinging phase. In the case of running, knee joints are controlled so that the angles of knee joints become 90 degree in both phases. The phase information comes from a N.O. to PD controller (Figure 7).

Parameters of a N.O. and its network for each gait are determined by simulation and experiments as described in **2.1.2.**. Parameters in Figure 5 for stretch reflex and flexor reflex were determined heuristically through experiments by reference to calculations performed using very simple dynamics models. Major parameters used in experiments are shown in Appendix.

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

We consider the HC (Horizontally Composed) terrain introduced by Yoneda[28] 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 phase and landing reliably on the plane in the latter period of this phase, and
(b) the angular velocity of supporting legs around the contact points at landing instant 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 **3.3.** and **3.2.**, respectively.

Condition (b) was commonly used in control of dynamic walking and running on flat terrain[23, 5, 1] in oder to construct stable limit cycle on the phase plane as an inverted pendulum involving exchange of supporting legs. In order to satisfy condition (b) above, a larger torque at the hip joints of 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.**. That is to say, we do not generate joint trajectories based on the environment model as in previous studies, but use adaptability caused by neural oscillators and reflex mechanism for walking on irregular terrain.

3.1. The Quadruped Robot for Walking

The quadruped robot Patrush (Figure 1) 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. 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 robot is 360mm in length, 240mm in width, 330mm in height and 4.8kg in weight. The body motion of the quadruped is constrained on the pitch plane by two poles since the quadruped has no joint around the roll axis.

3.2. Walking on Flat Terrain Using the Stretch Reflex

The stretch reflex produces torque that supports a body in a supporting 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 (Figure 6-(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 Figure 8, 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 N.O.'s output torque, 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 (Figure 6-(a)), for example, at 1.8 and 2.5(sec). The torque caused by the stretch reflex appears at the beginning of a supporting 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 a supporting phase, when a large torque is required.

As a result, by using N.O. and stretch reflex, walking became much more stable in comparison with walking using a N.O. network alone[25] because supporting legs were prevented from slipping.

3.3. 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 supporting legs through a flexor reflex network connection (Figure 6-(b)). This transmission is known as the crossed extension reflex. It extends the period of the supporting phase by stretching supporting legs in response to the extension of the period of the swinging phase 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 in walking over the box when it used the flexor reflex, but fell down forward without using the reflex.

The results and photos from this experiment are shown in Figure 9 and Figure 10. 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..

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, torque at the hip joints of supporting legs must be adjusted to keep the angular velocity of supporting legs around the contact points at the next landing instant be constant. This adjustment is made by changing u_0, an external input to N.O.'s (Figure 3), 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 changing u_0 was employed, and fell down backward when it was not employed. Results and photos from this experiment are shown in Figure 11 and Figure 12. 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 (Figure 2), 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 and the validity of the Drew's model[29] based on physiological experiments.

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[5, 6] in place of a tendon. The mutual entrainment between oscillation of a N.O. network and oscillation of the spring-mass and environment system (S.M.E.S.) causes the quadruped to run.

A bound gait appears when quadruped animals run fas. We use a bound gait for running because running in a bound gait does not need actuators around the roll axis and is suitable for the quadruped which has large powered actuators around the pitch axis at hip joints of hindlegs. It is difficult to transfer the robot's state from stationary standing to running in a bound gait, since the movement of the body is large in a bound gait, and the motions of the fore and hindlegs are much different from each other. We realized a bound gait by transition from a pronk gait.

4.1. The Quadruped Robot for Running

For running, two springs were attached between the lower limb and the long foot (Figure 1, 13). Of these, one was a hard extensible 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. Micro-switches were not attached to the feet because reflex mechanisms were not used in running in this study.

4.2. Period in a Pronk Gait

Stable jumping is essential in order to realize running. Because of this, we tested the jumping of the quadruped in a pronk gait using the N.O. network. In a quadruped with spring mechanisms, jumping in a pronk gait is generated by entrainment between oscillation of N.O.'s-M.S.S. and oscillation of S.M.E.S. (Figure 14). Each of these two oscillating systems has an eigen-period. In order to examine the relationship between these two eigen-periods and the period in a pronk gait, we tested jumping in a pronk gait with a constant spring factor and in various periods of N.O.'s. The results for the most stable jumping are shown in Table.1. The period in jumping, 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 jumping 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 N.O.'s becomes slightly longer (0.33(sec)) than the eigen-period 0.30(sec) through entrainment with M.S.S.. The period of N.O.'s finally comes into correspondence with the period in jumping, 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 N.O.'s-M.S.S. so that N.O.'s-M.S.S. can be entrained with S.M.E.S. in order to produce stable jumping in a pronk gait.

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

4.3. The Gait Transition from Pronk to Bound

There is a 180 degree phase difference between forelegs and hindlegs in a bound gait. While standing, the phase difference is zero. In order to shift from standing to a bound gait, the N.O.'s and motions of the quadruped should change from stationary states to steadily oscillating states by virtue of entrainment between N.O.'s and entrainments among N.O.'s, M.S.S., and S.M.E.S.. Therefore, it is difficult to realize a bound gait from a standing position. But it is easy to realize a pronk gait from a standing position, since the phase differences in a pronk gait are zero as well as in a standing position. In addition, since mutual entrainments among N.O.'s, M.S.S. and S.M.E.S. are already established in a pronk gait, it becomes easy for the quadruped to shift from a pronk gait to a bound gait by using the mutual entrainment between N.O.'s. For this reason, we achieve bound by a gait transition from pronk.

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 in a N.O. network are set equal so that the phase differences between legs become zero. These values correspond to the initial state in a pronk gait.

(b) The N.O. network of a bound gait (Figure 4) is used, where connecting weights between fore and hind N.O.'s are small in comparison with those between N.O.'s of paired legs (Appendix : w_{no} in a bound gait). 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 Figure 15 and Figure 16. Because the initial state was that of a pronk gait, we see that a pronk gait, where the phase differences are zero, appears for 0∼1(sec). As the influence of inhibitory connections between the fore and hind N.O.'s becomes dominant, the gait transition from pronk to bound appears for 1∼2.5(sec). The steady bound gait is finally realized at and after 2.5(sec).

5. Conclusion

We realized dynamic walking of a quadruped robot on terrain of low degree irregularity by using a nervous system consisting of a neural oscillator network and reflex mechanisms. We also realized running of a quadruped robot 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 in reflex mechanisms and how to change an external input to a neural oscillator network 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. Dynamic walking over terrain undulations and a slope by adaptive control based on vestibular sensation and somatic sensation, and dynamic walking up one or a series of steps by adaptive control based on vision are being studied as the next challenges[30].

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

Appendix

A.1. Parameters Used in Experiments

Parameters of N.O.'s, reflex mechanisms, and physical values of a quadruped robot used in experiments are shown in Table.2-4.

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