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Towards 3D Adaptive Dynamic Walking of a Quadruped Robot on Irregular Terrain by Using Neural System Model

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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 our previous study, we integrated several reflexes into a CPG (Central Pattern Generator) and realized adaptive 2D walking on terrain of medium degree of irregularity. In this paper, in order to make the role of a CPG be clear, we investigate the relation between parameters of a CPG and the mechanical system by simulations and experiments. In addition, we show a newly developed quadruped robot, of which mechanism is designed to make adaptive 3D walking on irregular terrain be realized more simply. At this moment, 3D walking on flat terrain is realized by using a neural system model consisting of CPG and reflexes. MPEG footage of those simulations and experiments can be seen at: http://www.kimura.is.uec.ac.jp.

1 Introduction

Many previous studies of legged robots have been performed including studies on running and dynamic walking on irregular terrain. However, 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 and real robots. In our previous studies[1] by the use of a 2D quadruped robot:'Patrush-I', we proposed a new method for combining CPGs and reflexes based on biological knowledge, and showed that reflexes via a CPG was much effective in adaptive dynamic walking on terrain of medium degree of irregularity through experiments. However, parameters of a neural system in experiments were determined after repeated try and error and meaning of parameters of CPGs regarding to the mechanical system was not clear. In this paper, we show results of simulations and experiments in order to investigate such relation between parameters of CPGs and the mechanical system by the use of a new quadruped robot:'Patrush-II', which has same configuration with Patrush-I and can change length of its legs.

Since another issue unsolved in our previous studies was 3D dynamic walking using a neural system model, we constructed a new 3D quadruped robot:'Tekken', which was designed to improve the success ratio of dynamic walking on terrain of higher degree of irregularity. In this paper, we show the basic concept of the design and results of experiments of 3D dynamic walking on flat terrain.

2 Analysis of 2D Dynamic Walking Using CPG

2.1 Quadruped robot 'Patrush-II'

For simulations and experiments of walking using neural system model, we made a quadruped robot: Patrush-II. Each leg of the robot has three joints, namely the hip, knee, and ankle joint, that rotate around the pitch axis. The ankle joint is passive. The gear ratio at hip and knee joints is relatively small: 40 to keep passive mechanical compliance high for adaptive walking and to make viscosity at hip and knee joints small for easy modeling for simulation. The robot is 28~41 cm in length, 22 cm in width and 3.0 kg in weight. The leg is 20~30 cm in length. The body motion of these robots is constrained on the pitch plane by two poles since robots have no joint around the roll axis.

2.2 Neural oscillator as a model of CPG

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 motions are autonomously generated by the neural systems below the brain stem. As a model of a CPG, we used a neural oscillator: N.O. proposed by Matsuoka and applied to the biped by Taga. Single N.O. consists of two mutually inhibiting neurons. Each neuron in this model is represented by the nonlinear differential equations:

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

where suffix e, f, and i mean an extensor neuron, a flexor neuron, and the ith N.O., respectively. $u_{\{e,f\}i}$ is u_{ei} or u_{fi}, that is, the inner state of an extensor neuron or a flexor neuron of the ith N.O.; $v_{\{e,f\}i}$ is a variable representing the degree of the self-inhibition effect of the neuron; $y_{\{e,f\}i}$ is the output of the neuron; u_0 is an external input with a constant rate; $Feed_{\{e,f\}i}$ is a feedback signal from the robot, that is, a joint angle, angular velocity and so on; 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 $u_{\{e,f\}i}$ and $v_{\{e,f\}i}$; w_{fe} is a connecting weight between flexor and extensor neurons; w_{ij} is a connecting weight between neurons of the ith and jth N.O.. When we consider a N.O., we eliminate the suffix i. As a result, a N.O. 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.

A stretch reflex in animals acts as feedback loop. We use the following joint angle feedback to a CPG: eq.(3) as a stretch reflex in all experiments of this study.

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

By connecting a CPG of a hip joint of each leg, CPGs are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between CPGs 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.

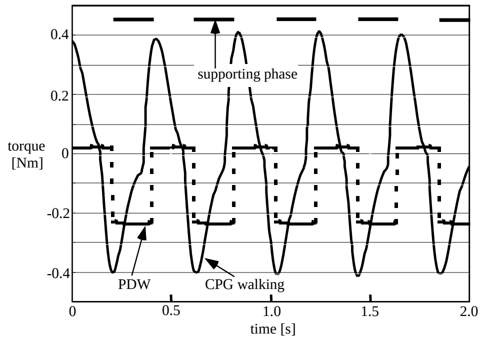

Fig.1 Comparison of CPG torque and additional gravity torque in PDW. Walking speed is 0.5 m/s in both PDW and CPG walking.

2.3 Entrainment between CPG and Mechanical System

By the experiment using only CPGs and a stretch reflex, where $Feed_e = Feed_{e \cdot tsr}$, $Feed_f = Feed_{f \cdot tsr}$, we confirmed that Patrush-I can walk stably on flat terrain with approximately 25 cm in stride, 0.8 s in walking period and 0.6 m/s in speed. . In that experiment, dynamic stable walking was realized by constructing a stable limit cycle through mutual entrainment between CPGs and the mechanical system. On the other hand, conventional control methods of dynamic walking of a biped and a quadruped can be classified into a “ZMP-based method” and an “limit-cycle based method.” In limit-cycle based control, constructing a stable limit cycle on the phase plane utilizing exchange of supporting legs means stabilization of walking and hopping. Therefore, limit-cycle based control has much similarity with the generation and control of walking by CPGs. The typical limit-cycle based walking is the passive dynamic walking: PDW where a walking machine with no actuator can walk down a slope dynamically.

The result of comparison of additional gravity torque[2] in PDW simulation with output torque in CPG walking simulation by using the physical values of Patrush-II is shown in Fig.1. In Fig.1, we can see that CPG output torque in a supporting phase is comparable with additional gravity torque in PDW and CPG output torque in a swinging phase is much larger than additional gravity torque in PDW since a swinging leg is accelerated and decelerated for phase switching in CPG walking as described in Section **2.5.**.

In order to make the role of a CPG be clear, we investigate the relation between parameters of a CPG and the mechanical system by simulations and experiments using Patrush-II in the following subsections.

2.4 Coupling of dynamics of CPG and mechanical system

The one of reasons why such simple CPG described in Section **2.2.** can generate dynamic stable walking is that dynamics of the mechanical system is encoded into parameters of a CPG. Therefore, understanding of relation between parameters of a CPG and the mechanical system is important in order to understand roles of a CPG, reduce the time for parameter tuning and help the design of a new walking machine. As previous studies on features of a CPG, Williamson analyzed the stability of CPG-plant system by using describing function and Miyakoshi proposed a method for automatic tuning of frequency and amplitude parameters for entrainment with external input. We focus on investigating relation between parameters of a CPG and the walking mechanism.

2.4.1 Important parameters of CPG

Properties of a CPG can be expressed by amplitude, period and phase. In eq.(1)~(3), important parameters of a CPG in relation with the mechanical system are τ, u_0, p_e, p_f and k_{tsr}. The amplitude of CPG output is approximately proportional to u_0 and CPG output is translated into torque at a hip joint by p_e and p_f in eq.(2). We can determine the approx. value of u_0, p_e and p_f by comparing CPG output torque with additional gravity torque in PDW in a supporting phase shown in Fig.1. Therefore, once proper values of u_0, p_e and p_f is found in simulation or experiment, those values will be used as constant values in other simulations or experiments. The period of a CPG is mainly determined by τ and τ'. It was pointed out that proper value of τ/τ' for stable oscillation is 0.1~0.5. In this section, we change the value of τ with constant value of τ/τ' and investigate how the walking period is changed. The phase difference between CPGs is kept constant through entrainment on CPG network. We discuss on the phase difference between a CPG and the mechanical system in Section **2.5.**. We make duty factor of walking be 0.5 for simplicity. This means that the duration of a supporting phase is equal to that of a swinging phase and the amplitude of supporting motion is equal to that of swinging motion.

2.4.2 CPG period and stability

The walking period is a very important factor since it much influences stability, maximum speed and energy consumption of dynamic walking. The walking mechanism has its own natural walking period determined mainly by the length of its leg. In this section, we consider the relation between the natural walking period of the mechanism, the free oscillating period of a CPG: T^o_{cpg} determined by τ and the walking period obtained as a result of entrainment between a CPG and the mechanical system.

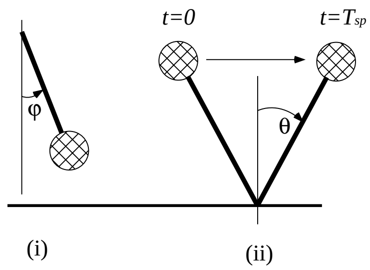

Fig.2 Simple one link models for a swinging phase:(i) and a supporting phase:(ii).

Walking motion is constructed by swinging phase and supporting phase. We use a single pendulum as a model in swinging phase and a single inverted pendulum as a model in supporting phase shown in Fig.2 in order to analyze the coupling of dynamics of a CPG and the mechanical system. It is well known that the free motion period (natural period) of the pendulum: T^o_{sw} is proportional to the square root of its length. We determine τ as T^o_{cpg} is equal to T^o_{sw}. When we connect a CPG with the pendulum, output torque of the CPG drives the pendulum and the CPG receives the angle of the pendulum as feedback signal expressed by eq.(3). As a result, the CPG and the pendulum are mutually entrained and oscillate with the same period, which becomes smaller than the original period (Fig.3). This is because the feedback signal $Feed_{\{e,f\}\cdot tsr}$ gives the CPG an inhibitory effect and makes the period of the CPG be smaller consequently.

In the case of walking, CPGs are entrained with reciprocating motion where a swinging phase and a supporting phase alternate. The period of a CPG entrained with walking is the CPG walking period: T^w_{cpg}, half of which is equal to durations of a swinging phase and a supporting phase. Half of T^w_{cpg} obtained through the simulation of walking on flat terrain are shown in Fig.3, where T^o_{cpg} for each length of a leg is chosen to be equal to T^o_{sw}. For comparison, half of T^o_{sw}, the

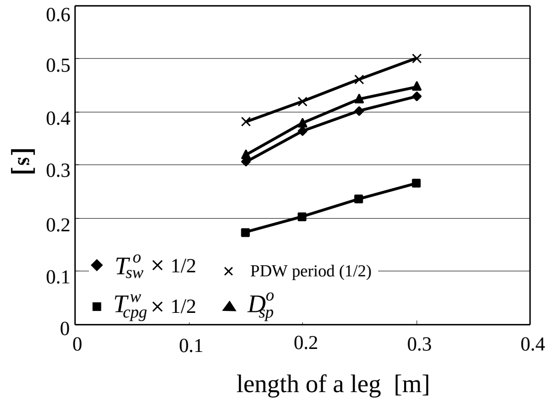

Fig.3 Half of the period of CPG walking: $T^w_{cpg} \times 1/2$, half of the natural period of a swinging leg: $T^o_{sw} \times 1/2$, the duration of the free motion of a supporting leg: D^o_{sp} and half of the period of PDW for various length of a leg. k_{tsr} is 8 rad^{-1}.

duration of free motion of the inverted pendulum as a model of a supporting leg: D^o_{sp}, and half of the period of PDW are shown in Fig.3. Since D^o_{sp} depends on not only the length of a leg but also the amplitude of the motion, we used the amplitude of supporting motion in CPG walking for each length of a leg in order to determine D^o_{sp}.

In Fig.3, we can see that T^w_{cpg} is much smaller that the original period as a result of entrainment with walking motion even though T^o_{cpg} is equal to T^o_{sw} in both cases. When the walking period is small, influence of disturbance in a single supporting phase becomes small and stabilization utilizing phase exchange becomes effective. Therefore, if we choose the same T^o_{cpg} with T^o_{sw}, the CPG is entrained with both swinging and supporting motions and stable walking with the smaller period than the original period can be realized as shown in Fig.3. This is one example of coupling of dynamics of a CPG and the mechanical system.

On the other hand, half of T^w_{cpg} for various T^o_{cpg} and the fixed length of a leg are shown in Fig.4. In Fig.4, the stable walking was realized while T^o_{cpg} is close to T^o_{sw}. But the walking became unstable when the half of T^o_{cpg} is smaller than 0.19 s or larger than 0.52 s, since entrainment between a CPG and the mechanical system was lost. This is an example where the coupling of dynamics was not established.

2.4.3 CPG period and energy consumption

As the second criterion, we consider the energy consumption. In general, when swinging motion or supporting motion is closer to free motion of the pendulum or the inverted pendulum in each phase, the motion is more effective. On the other hand, when swinging or supporting motion is far from free motion, additional acceleration and deceleration make the motion be less effective. As the energy consumption, we use the Joule thermal loss at armatures of DC motors.

In Fig.4 where the energy consumption in walking for various T^o_{cpg} is shown, we can see that T^o_{cpg} close to T^o_{sw} gives the minimum energy consumption. In order to analyze the reason why such minimum energy consumption exists, let us consider the relation of a CPG with free motions in swinging phase and supporting phase. Half of T^o_{sw} (the duration of free motion of a swinging leg) and D^o_{sp} (the duration of free motion of a supporting leg) are also shown in Fig.4. The energy consumption becomes large as the sum of T^o_{sw} and D^o_{sp} becomes different from T^o_{cpg}, since unnecessary acceleration and deceleration is required due to the less entrainment of a CPG with swinging motion and supporting motion.

We realized stable walking in Patrush-II with two different sizes: 0.2 m and 0.3 m in its leg length, by using the same parameters in simulation and confirmed the validity of the above results. The results of experiment using Patrush-II of which leg length is 0.2 m are shown in Fig.4.

2.5 Phases of CPG and mechanical system

There is similarity between PDW and CPG walking 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.

In Fig.1, additional gravity torque on a leg in PDW is reversed at switching of supporting and swinging phases. This shows that walking is exactly passive. On the other hand, switching of torque of extensor/flexor muscles occurs before switching of supporting and swinging phases in CPG walking. This switching of torque of extensor/flexor muscles in the latter period of supporting and swinging phases is actually observed in animals' walking. Through this comparison, we can say that active walking using a CPG is nothing but to switch supporting and swinging phases actively by switching of extensor/flexor torque. This is the reason why active walking using a CPG is much

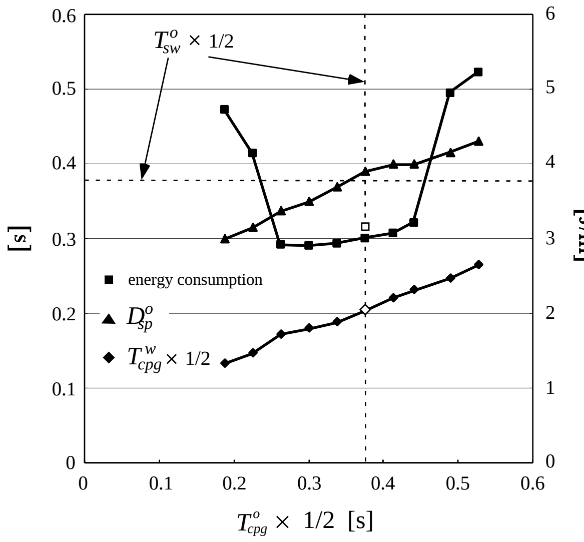

Fig.4 Half of the period of CPG walking: $T^w_{cpg} \times 1/2$, half of the natural period of a swinging leg: $T^o_{sw} \times 1/2$, the duration of the free motion of a supporting leg: D^o_{sp} and energy consumption in CPG walking for half of various free oscillating period of a CPG: $T^o_{cpg} \times 1/2$. The leg length is 0.2 m and k_{tsr} is 8 rad^{-1}. Solid marks and blank marks mean results of simulations and experiments, respectively.

more stable than PDW under errors of initial conditions and disturbances.

2.6 Sensory adaptation of CPG

The CPG receives inhibitory input from joint angle as a sensory feedback signal, shortens its own period through entrainment with the mechanical system and generates stable walking suitable for the mechanical system adaptively. The CPG receives excitatory input from reflexes as a sensory feedback signal, enables the mechanical system to adapt to irregular terrain, extends its own period in response to delay of motion of the mechanical system and adjusts phase difference between CPGs[1]. The coupling of dynamics of reflexes via CPG and mechanical system has not yet been analyzed. Such analysis is very important in order to make what the neural system model control is be clear.

2.7 Summary

In this section, we considered relation between a CPG and the mechanical system. Matching T^o_{cpg} with T^o_{sw} can generate the following superior walking through entrainment between CPGs and swinging/supporting motions.

(1) stable walking with smaller period than the original period,

(2) efficient walking in energy consumption with less additional acceleration and deceleration.

3 Realization of 3D Dynamic Walking Using CPG

3.1 Problems pointed out in 'Patrush-I'

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 leg not be prevented from moving forward in the former period of the swinging phase,

(B) a leg be landed reliably on the ground in the latter period of the swinging leg phase, and

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

In our previous study using Patrush-I, we focused on the control by a neural system model rather than mechanism in order to realize dynamic walking on irregular terrain. For (A), (B) and (C) to be satisfied, we have already employed a flexor reflex, an extensor reflex, and vestibulospinal and tendon reflexes, respectively.

But following problems in mechanism were getting clear while we increased the level of irregularity on terrain in experiments using Patrush-I. Regarding to (A), since inertia moment of the lower limb of Patrush-I was relatively large, the robot sometimes fell down due to delay of swinging up motion caused by a flexor reflex in stumbling on a large obstacle. Regarding to (B), since a knee joint of Patrush-I is straightened at the landing moment, large torque at a hip joint at the beginning of a supporting phase induces slipping if the leg is not landed forward enough.

3.2 Quadruped robot 'Tekken'

Draft of a newly developed quadruped robot is shown in Fig.5. The weights of the robot, a leg and a lower limb are 3.1 Kg, 0.5 Kg and 0.06 Kg, respectively. The length and height of the robot are changeable as shown in Fig.5. Each leg has four joints, those are, a hip pitch joint, a hip yaw joint, a knee joint, and an ankle joint. Only the ankle joint is passive.

In order to solve problems described in Section **3.1.**, we designed Tekken according to the following concepts:

(1) a light weight lower limb,

(2) a passive ankle joint with lock and spring mechanisms,

(3) a bent knee joint at the standing position,

(4) a small gear ratio (15.6:hip pitch joint, 18.8:knee joint) for backdrivability and passive compliance at a joint.

The light weight of lower limb makes inertia moments around the hip yaw axis and the knee pitch axis be small and a leg be swung quickly if needed. The ankle joint is locked while the leg is in a supporting phase and can be passively rotated in the direction shown in Fig.5 if the toe contacts with an obstacle in a swinging phase. This passive mechanism quickly prevents a swinging leg from stumbling on a small obstacle before a flexor reflex being activated.

3.3 Experiments

Tekken successfully walked on flat terrain without additional supporting poles with the period: 0.33 s and the speed: 0.7 m/s (Fig.6) and walked on simple irregular terrain by using rolling motion feedback to CPG[3]. We are trying to make Tekken dynamically walk on irregular terrain by using the similar neural system model as used in Patrush-I[1] with rate-gyro sensors and force sensors.

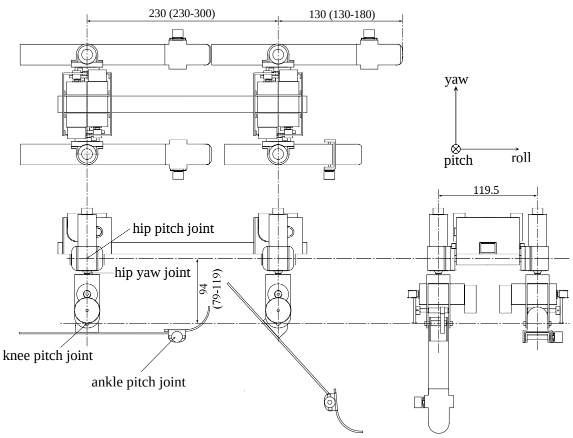

Fig.5 Draft of Tekken

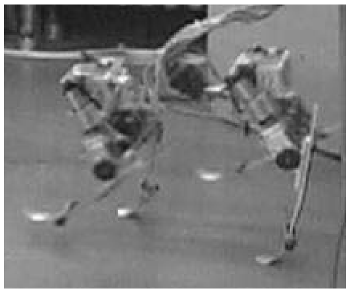

Fig.6 Photo of dynamic walking of 'Tekken'

4 Conclusion

In the neural system model method, only relations among CPGs, reflexes and the mechanical system are simply defined, and motion generation and adaptation is emergently induced by dynamics in neuro-mechanical system and environment. Therefore, the appropriate coupling of dynamics of the neural system model and the mechanical system should be established for emergence of desirable motion. The analysis of relation between parameters of a CPG and the mechanical system in this study is the first step for establishing such coupling of dynamics.

For autonomous dynamic walking on terrain of higher irregularity, not only adaptive control but also adaptive mechanism are important in order to cope with the delay of sensor input and in order to increase the robustness and reduce the complexity of control. Concurrent design of mechanical system and control system is essential for more adaptive dynamic walking.

References

[1] H. Kimura and Y. Fukuoka, Adaptive dynamic walking of the quadruped on irregular terrain - autonomous adaptation using neural system model -, *Proc. of ICRA2000*, pp.436-443, 2000.

[2] H. Kimura, Y. Fukuoka and K. Konaga, Adaptive Dynamic Walking of a Quadruped Robot by Using Neural System Model, *Advanced Robotics* (accepted), 2001.

[3] H. Kimura, Y. Fukuoka, Y. Hada and K. Takase, 3D Adaptive Dynamic Walking of a Quadruped Robot by Using Neural System Model, *Proc. of CLAWAR2001*, (accepted), 2001