Decentralized Autonomous Control of a Quadruped Locomotion Robot

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Abstract

This paper deals with the design method of a control system for a quadruped locomotion robot. The proposed control system has a hierarchical architecture. It is composed of a leg controller and a gait pattern controller. The leg controller drives the actuators of the legs by using local feedback control. The gait pattern controller involves non linear oscillators. Various gait patterns emerge through the mutual entrainment of these oscillators. The performance of the proposed control system is verified by numerical simulations and hardware experiments.

As a result, the system locomotes stably in a wider velocity range by changing its gait patterns and the amount of power required for locomotion is decreased.

1. Introduction

Locomotion is one of the basic functions of a mobile robot. Using legs is one of the strategies for accomplishing locomotion. Using legs for locomotion allows the robot to move on rough terrain. Therefore, a considerable amount of research has been done on motion control of legged locomotion robots. This paper deals with the motion control of a quadruped locomotion robot.

The motion control of a walking robot has generally been achieved using a model-based approach[1][2] in which the inverse kinematics and the inverse dynamics of the robot are preprogrammed and when the desired motion is given, the motion of each link is controlled on the basis of the inverse models.

In the future, a walking robot which can carry out tasks in the real world, where the geometric and kinematic conditions of the environment are not specially structured, will be required. However, it is difficult for the model-based control system to carry out various tasks or to adapt to variations of the environment.

It is necessary to overcome the following difficulties in order to develop a walking robot which can carry out tasks in the real world: One is motion control of a large number of elements with nonlinear interactions. The other is evolution of a task specific motion pattern for many elements.

A considerable amount of study has been done on the motion of animals from the viewpoint of the dynamical systems theory [3] $\sim$ [6]. These studies reveal that the body of an animal is composed of a lot of joints and muscles, but during motion many of such elements are organized into a collective unit to be controlled as if it had fewer degrees of freedom and yet retain the necessary flexibility for changing internal and external contexts.

Recently, mechanisms of motion of animals have been studied in the field of ethology. Cruse et al.[7] have studied the locomotion mechanisms of insects from the viewpoint of ethology. According to their research, each leg autonomously repeats a forward and backward motion periodically when the leg has no mechanical interaction with the ground. Each leg has a touch sensor at its tip and motions of the legs interact with each other through the input signals from the touch sensors. As a result, a gait pattern that can satisfy the requirements of the locomotion velocity of the properties of the environment emerges. Kelso et al.[8] have investigated motions of animals from the viewpoint of synergetics. Motion of animals result from the processes of self-organization and a task-specific motion appears when a certain control parameter is scaled to be larger than some critical threshold. Knowledge of motion patterns of animals teaches us some solutions to the problem of controlling a lot of elements and the problem of forming a task specific gait, walking pattern.

Based on the latest achievements of neurobiology and ethology, a new approach to robotics has been developed. Brooks [9], [10] has proposed the subsumption architecture as a principle of design of an autonomous mobile robot which can carry out tasks in the real world. The control system is composed of behavior-generating units. Each unit responds to the changes in the environment and generates a stereotyped action. Responses from all units compete with each other and one of them determines the action of the robot. Using the subsumption architecture, Brooks developed a six-legged robot, Genghis to walk over a rough terrain. Although the trajectory of the body was not specified, the robot successfully navigated on a rough terrain.

This paper deals with the design method of the control system of a quadruped locomotion robot based on decentralized autonomous control. In this method, a non-linear oscillator is assigned to each leg. The nominal trajectory of the leg is determined as a function of phase of its oscillator. We design the local feedback controller for each joint of the legs using the nominal trajectories as the reference. Touch sensors at the tips of the legs are used as triggers on which the dynamic interactions of the legs are based. The mutual entrainment of the oscillators with each other generate a certain combination of phase differences, which leads to the gait pattern. As a result, a gait pattern that can satisfy the requirements of the state of the system or the properties of the terrain emerges and the robot establishes a stable locomotion.

The performance of the proposed control system is verified by numerical simulations and hardware experiments.

2. Equations of Motion

Consider the quadruped locomotion robot shown in figure 1, which has four legs and a main body. Each leg is composed of two links which are connected to each other through a one degree of freedom (DOF) rotational joint. Each leg is connected to the main body through a one DOF rotational joint. The inertial and main body fixed coordinate systems are defined as $[\boldsymbol{a}^{(-1)}] = [\boldsymbol{a}_1^{(-1)},\ \boldsymbol{a}_2^{(-1)},\ \boldsymbol{a}_3^{(-1)}]$ and $[\boldsymbol{a}^{(0)}] = [\boldsymbol{a}_1^{(0)},\ \boldsymbol{a}_2^{(0)},\ \boldsymbol{a}_3^{(0)}]$, respectively. $\boldsymbol{a}_1^{(-1)}$ and $\boldsymbol{a}_3^{(-1)}$ coincide with the nominal direction of locomotion and vertically upward direction, respectively. Legs are enumerated from leg 1 to 4, as shown in figure 1. The joints of each leg are numbered as joint 1 and 2 from the main body toward the tip of the leg. The position vector from the origin of $[\boldsymbol{a}^{(-1)}]$ to the origin of $[\boldsymbol{a}^{(0)}]$ is denoted by $\boldsymbol{r}^{(0)} = [\boldsymbol{a}^{(-1)}]r^{(0)}$. The angular velocity vector of $[\boldsymbol{a}^{(0)}]$ to $[\boldsymbol{a}^{(-1)}]$ is denoted by $\boldsymbol{\omega}^{(0)} = [\boldsymbol{a}^{(0)}]\omega^{(0)}$. We define $\theta_i^{(0)}$ $(i = 1,\ 2,\ 3)$ as the components of Euler angle from $[\boldsymbol{a}^{(-1)}]$ to $[\boldsymbol{a}^{(0)}]$. We also define $\theta_j^{(i)}$ as the joint angle of link j of leg i. The rotational axis of joint j of leg i is parallel to the $\boldsymbol{a}_2^{(0)}$ axis.

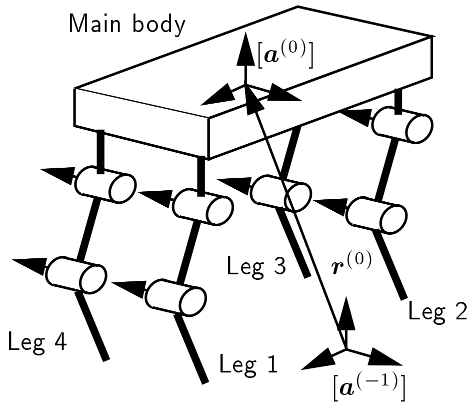


Figure 1: Schematic model of a quadruped locomotion robot

The state variable is defined as follows;

$$q^T = \left[\begin{array}{ccc} \dot{r}_k^{(0)} & \omega_k^{(0)} & \dot{\theta}_j^{(i)} \end{array}\right] \quad (1)$$

$$(i = 1, \cdots, 4, \quad j = 1, 2, \quad k = 1, 2, 3)$$

Equations of motion for state variable q are derived using Lagrangian formulation as follows;

$$M\ddot{q} + H(q,\ \dot{q}) = G + \sum(\tau_j^{(i)}) + \Lambda \quad (2)$$

where M is the generalized mass matrix and the term $M\ddot{q}$ expresses the inertia. $H(q,\ \dot{q})$ is the nonlinear term which includes Coriolis forces and centrifugal forces. G is the gravity term. $\sum(\tau_j^{(i)})$ is the input torque of the actuator at joint j of leg i. Λ is the reaction force from the ground at the point where the tip of the leg makes contact. We assume that there is no slip between the tips of the legs and the ground.

3. Gait pattern control

The architecture of the proposed control system is shown in figure 2. The control system is composed of leg controllers and a pattern controller. The leg controllers drive all the joint actuators of the legs so as to realize the desired motions that are generated by the pattern controller. The pattern controller involves non linear oscillators corresponding to each leg. The pattern controller receives the commanded signal of the nominal gait pattern as the reference. It also receives the feedback signals from the touch sensors at the tips of the legs. The generated gait pattern is determined by the phase differences between the non linear oscillators. A modified gait pattern is generated from the nominal gait pattern through the mutual entrainment of the oscillators with the feedback signals of the touch sensors. The generated gait pattern is given to the leg controller as the commanded signal of the locomotion pattern of the legs.

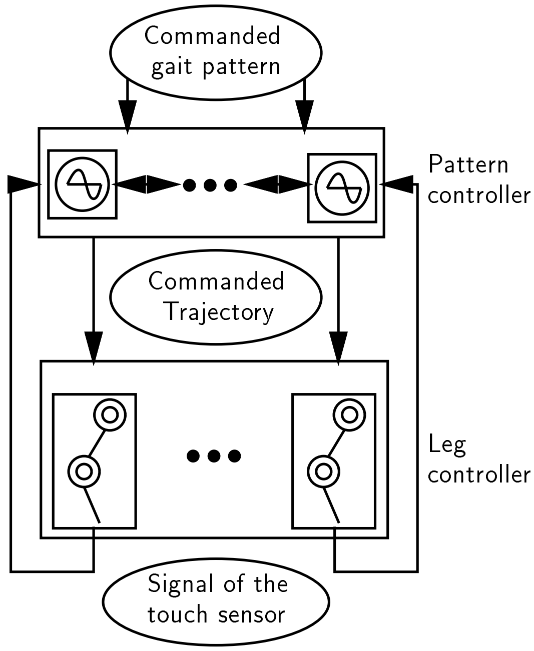


Figure 2: Architecture of the proposed controller

3.1. Design of the gait

3.1.1. Design of the trajectories of the legs

The position of the tip of the leg where the transition from the swinging stage to the supporting stage occurs is called the anterior extreme position (AEP). Similarly, the position where the transition from the supporting stage to the swinging stage occurs is called the posterior extreme position (PEP). We determine the nominal trajectories which are expressed in the coordinate system $[\boldsymbol{a}^{(0)}]$ in the following way: First, we define the nominal PEP $\hat{r}_{eP}^{(i)}$ and the nominal AEP $\hat{r}_{eA}^{(i)}$. The index $\hat{*}$ indicates the nominal value.

The trajectory for the swinging stage is a closed curve given as the nominal trajectory $\hat{r}_{eF}^{(i)}$. This curve involves the points $\hat{r}_{eA}^{(i)}$ and $\hat{r}_{eP}^{(i)}$. On the other hand, the trajectory for the supporting stage is a linear trajectory given as $\hat{r}_{eS}^{(i)}$. This linear trajectory also involves the points $\hat{r}_{eA}^{(i)}$ and $\hat{r}_{eP}^{(i)}$. The position of each leg on these trajectories is given as functions of the phase of the corresponding oscillator. The state of the oscillator for leg i is expressed as follows;

$$z^{(i)} = \exp(j \ \phi^{(i)}) \tag{3}$$

where $z^{(i)}$ is a complex number representing the state of the oscillator, $\phi^{(i)}$ is the phase of the oscillator and j is the imaginary unit.

The nominal phase dynamics of the oscillator is defined as follows;

$$\dot{\hat{\phi}}^{(i)} = \omega \tag{4}$$

The nominal trajectories $\hat{r}_{eF}^{(i)}$ and $\hat{r}_{eS}^{(i)}$ are given as functions of the phase $\hat{\phi}^{(i)}$ of the oscillator.

$$\hat{r}_{eF}^{(i)} = \hat{r}_{eF}^{(i)}(\hat{\phi}^{(i)}) \tag{5}$$
$$\hat{r}_{eS}^{(i)} = \hat{r}_{eS}^{(i)}(\hat{\phi}^{(i)}) \tag{6}$$

The nominal phases at AEP and PEP are determined as follows;

$$\hat{\phi}^{(i)} = \hat{\phi}_A^{(i)} \quad \text{at AEP}, \qquad \hat{\phi}^{(i)} = \hat{0} \quad \text{at PEP} \tag{7}$$

We use one of these two trajectories alternatively at every step of AEP and PEP to generate the desired trajectory of the tip of the leg $\hat{r}_e^{(i)}(\hat{\phi}^{(i)})$.

$$\hat{r}_e^{(i)}(\hat{\phi}^{(i)}) = \begin{cases} \hat{r}_{eF}^{(i)}(\hat{\phi}^{(i)}) & 0 \le \hat{\phi}^{(i)} < \hat{\phi}_A^{(i)} \\ \hat{r}_{eS}^{(i)}(\hat{\phi}^{(i)}) & \hat{\phi}_A^{(i)} \le \hat{\phi}^{(i)} < 2\pi \end{cases} \tag{8}$$

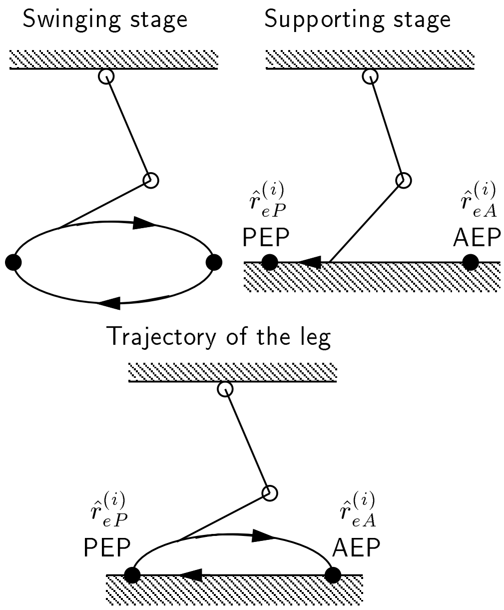


Figure 3: Trajectory of the leg

The nominal duty ratio $\hat{\beta}^{(i)}$ for leg i is defined to represent the ratio between the nominal time for the supporting stage and the period of one cycle of the nominal locomotion.

$$\hat{\beta}^{(i)} = 1 - \frac{\hat{\phi}_A^{(i)}}{2\pi} \tag{9}$$

The nominal stride$\hat{S}^{(i)}$ of leg i and the nominal locomotion velocity $\hat{v}$ are given as follows;

$$\hat{S}^{(i)} = \hat{r}_{eA}^{(i)} - \hat{r}_{eP}^{(i)}\ , \qquad \hat{v} = \frac{\hat{S}^{(i)}}{\hat{\beta}^{(i)}\hat{T}} \tag{10}$$

where, $\hat{T}$ is the nominal time period for a locomotion cycle.

3.1.2. *Design of the gait pattern*

The gait patterns, which are the relationships between motions of the legs, are designed. There are three gait patterns in which two legs support the main body at any instant during locomotion: In the trot pattern legs 1 and 3 form one pair and legs 2 and 4 form the other pair, in the pace pattern legs 1 and 2 form one pair and legs 3 and 4 form the other pair, finally in the bounce pattern legs 1 and 4 form one pair and legs 2 and 3 form the other pair. In such patterns, phases of the pairs of oscillators are coupled and the phase difference between them are zero.

A shift of the phase differences between the coupled oscillators by $\frac{\pi}{2}$ causes the gait pattern to change from those explained above to the walk pattern (Figure 4: The thick solid lines represent supporting stages). In walk pattern, tree legs support the main body at any instant during locomotion. Walk pattern has two types; One is transverse walk in which the legs 1,3,2 and 4 touch on the ground in this order. The other is rotary walk in which legs 1,2,3 and 4 touch on the ground in this order.

Each pattern is represented by a matrix of phase differences $\Gamma_{ij}^{(m)}$ as follows;

$$\phi^{(j)} = \phi^{(i)} + \Gamma_{ij}^{(m)} \tag{11}$$

where, $m = 1, 2$ represent transverse walk pattern and rotary walk pattern, respectively. $m = 3, 4, 5$ represent trot pattern, pace pattern and bounce pattern, respectively.

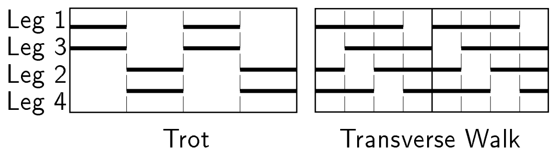


Figure 4: The trot and the transverse walk patterns

3.2. Locomotion control

3.2.1. *Trajectory controller of legs*

The angle of joint j of leg i is derived from the geometrical relationship between the trajectory $\hat{r}_e^{(i)}(\hat{\phi}^{(i)})$ and the joint angle. $\hat{\theta}_j^{(i)}$ is written as a function of phase $\hat{\phi}^{(i)}$ as follows;

$$\hat{\theta}_j^{(i)} = \hat{\theta}_j^{(i)}(\hat{\phi}^{(i)}) \tag{12}$$

The commanded torque at each joint of the leg is obtained by using local PD feedback control as follows;

$$\tau_j^{(i)} = K_{Pj}(\hat{\theta}_j^{(i)} - \theta_j^{(i)}) + K_{Dj}(\dot{\hat{\theta}}_j^{(i)} - \dot{\theta}_j^{(i)}) \tag{13}$$
$$(i = 1, \cdots, 4, j = 1, 2)$$

where $\tau_j^{(i)}$ is the actuator torque at joint j of leg i, and K_{Pj}, K_{Dj} are the feedback gains, the values of which are common to all joints in all legs.

3.2.2. Gait pattern controller

We design the phase dynamics of the oscillators corresponding to each leg as follows;

$$\dot{\phi}^{(i)} = \omega + g_1^{(i)} + g_2^{(2)} \qquad (i = 1, \cdots, 4) \quad (14)$$

where $g_1^{(i)}$ is the term which is derived from the nominal gait pattern and $g_2^{(i)}$ is the term caused by the feedback signal of the touch sensors of the legs.

Function $g_1^{(i)}$ is designed in the following way: We first define the following potential function.

$$V(\phi^{(i)}, \Gamma^{(m)}) = \frac{1}{2} K \sum_i \left(\phi^{(i)} - \phi^{(j)} - \Gamma_{ij}^{(m)} \right)^2 \quad (15)$$

where matrix of phase differences $\Gamma_{ij}^{(m)}$ represents the commanded gait pattern defined in Eq.(11).

Function $g_1^{(i)}$ is then derived from the potential function V as follows;

$$g_1^{(i)} = -K \left(\phi^{(i)} - \phi^{(j)} - \Gamma_{ij}^{(m)} \right) \quad (16)$$

Function $g_2^{(i)}$ is designed in the following way: Suppose that $\phi_A^{(i)}$ is the phase of leg i at the instant when leg i touches on the ground. Similarly, $r_{eA}^{(i)}$ is the position of leg i at that instance. When leg i touches the ground, the following procedure is undertaken.

1. Change the phase of the oscillator for leg i from $\phi_A^{(i)}$ to $\hat{\phi}_A^{(i)}$.
2. Alter the nominal trajectory of the tip of leg i from the swinging trajectory $\hat{r}_{eF}^{(i)}$ to the supporting trajectory $\hat{r}_{eS}^{(i)}$.
3. Replace parameter $\hat{r}_{eA}^{(i)}$, that is one of the parameters of the nominal trajectory $\hat{r}_{eS}^{(i)}$, with $r_{eA}^{(i)}$.

Function $g_2^{(i)}$ is given as follows:

$$g_2^{(i)} = \hat{\phi}_A^{(i)} - \phi_A^{(i)} \quad \text{at the instant leg } i \text{ touches the ground} \quad (17)$$

The pair of oscillators form a dynamic system that affect each other through two types of interactions. One is continuous interactions derived from the potential function V which depends on the nominal gait pattern. The other is the pulse-like interactions caused by the feedback signals from the touch sensor. Through these interactions, the oscillators generate gait patterns that satisfy the requirements of the environment.

4. Stability analysis of motion

The steady locomotion of the quadruped locomotion robot is strictly periodic and is characterized by a limit cycle in the state space.

The stability of the limit cycle is examined in the following way: First, four variables are selected as state variables.

$$X \in R^4, \quad X = \left[\begin{array}{cccc} \theta_1^{(0)} & \theta_2^{(0)} & \dot{\theta}_1^{(0)} & \dot{\theta}_2^{(0)} \end{array} \right] \quad (18)$$

When the robot starts the locomotion under a certain initial condition, the variable set X moves on a certain trajectory in the four-dimensional state space. If we choose a Poincaré section using the timing when the tip of a leg touches the ground, the first intersection of the trajectory of X with the Poincare section is mapped as X_0, and for every intersection, the corresponding values of X lead to a sequence of iterates in the state space.

$$X_1 \quad X_2 \quad \cdots \quad X_n \quad \cdots$$

The Poincaré map from X_n to X_{n+1} is expressed as follows;

$$X_{n+1} = F(X_n) \quad (19)$$

The fixed point $\bar{X}$ is defined such that $\bar{X}$ satisfies the following equation on the Poincaré section.

$$\bar{X} = F(\bar{X}) \quad (20)$$

This Poincaré map is approximated by use of linearization around the fixed point.

$$X_{n+1} - \bar{X} = M(X_n - \bar{X}) \quad (21)$$

Stability of the sequence of points $\{X_n\}$ is examined by checking the eigen values λ_k $(k = 1, \cdots, 4)$ of matrix M.

5. Numerical simulation

Table 1 shows the physical parameters of the robot which are used in numerical simulations.

Table 1

Main body		
Width	0.182	[m]
Length	0.338	[m]
Height	0.05	[m]
Total Mass	9.67	[kg]
Legs		
Length of link 1	0.188	[m]
Length of link 2	0.193	[m]
Mass of link 1	0.918	[kg]
Mass of link 2	0.595	[kg]

Numerical simulations are implemented under the condition that the nominal stride $\hat{S}$ and the nominal gait pattern $\Gamma^{(m)}$ are fixed. The nominal duty ratio $\hat{\beta}$ is selected as a parameter.

The nominal time period of the swinging stage is chosen as 0.20 [sec]. The frequency band width of joints 1, 2 are given as 5.5 [Hz] and 9.5 [Hz] for feedback gains of the joints, respectively.

We investigated the performance of the model-based control system through numerical simulation as a comparison with the performance of our system. The model-based control system is designed in the following way: The trajectories of the legs are given as functions of time. The actuators of the joints are controlled by using feedback control with the desired joint angles as the reference signals.

First, we investigated stability of the proposed control system, selecting duty ratio $\hat{\beta}$ as a parameter. The result is shown in figure 5. CASE 1 represents the model-based control system, and CASE 2 represents the proposed control system. From these figures, we can find that the proposed control system established stable locomotion of the robot with a wide parameter variance for duty ratio $\hat{\beta}$.

Variance of energy consumption of actuators E_c is investigated, selecting duty ratio $\hat{\beta}$ as a parameter. The results are shown in figure 6. Energy consumption of actuators E_c is defined as follows;

$$E_c = \frac{< \sum_{i,j} \tau_j^{(i)} \theta_j^{(i)} >}{< v >} \tag{22}$$

where, $< * >$ expresses the time averaged value of $*$.

From figure 6, we can see that the values of E_c of the proposed control system and also their variance with respect to the variance of the duty ratio is smaller than those of the model-based control system.

In order to clarify the adaptability of the proposed control system, we investigated variance of the gait patterns, selecting duty ratio $\hat{\beta}$ as a parameter. We investigated the variance of the gait pattern according to duty ratio in the following way: The states of leg i are represented by introducing the variable $\zeta^{(i)}$ as follows;

$$\zeta^{(i)} = \begin{cases} \dfrac{1}{1-\beta} & \text{Swinging stage} \\ -\dfrac{1}{\beta} & \text{Supporting stage} \end{cases} \tag{23}$$

Correlation between the swinging or supporting states of leg i and those of leg j is defined as follows;

$$W_{ij} = < \zeta^{(i)} \zeta^{(j)} > \tag{24}$$

Each gait pattern is characterized by correlation matrix W_{ij}. $\hat{W}^{(m)}$ and W are the correlation matrices according to the nominal gait pattern and the actually obtained gait pattern, respectively. The similarity between these two gait patterns is defined as follows;

$$D^{(m)} = \frac{1}{4} trace(\hat{W}^{(m)T} W) \tag{25}$$

Figures 7 and 8 show the similarity of gait patterns $D^{(m)}$ with respect to duty ratio $\hat{\beta}$ when we used the proposed control system and a model-based control system, respectively. From figure 7, we can find that although trot pattern is given as the nominal gait pattern, similarity between the obtained gait pattern and transverse walk pattern increases as duty ratio $\hat{\beta}$ increases. To the contrary, from figure 8, we can see that the gait pattern does not change from the given gait pattern when we use a model-based control system.

Gait pattern diagrams for $\hat{\beta} = 0.5$ and $\hat{\beta} = 0.75$ are shown in figures 9 and 10.

From these results, it is clear that the robot using the proposed control system adapts to variance of duty ratio $\hat{\beta}$ by changing the gait patterns, it keeps the stability of locomotion in a wide parameter area, and suppresses the energy consumption.

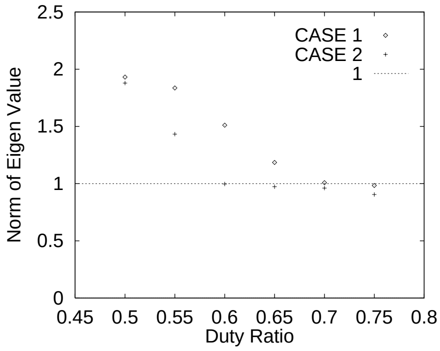


Figure 5: Stability
Commanded pattern: transverse walk

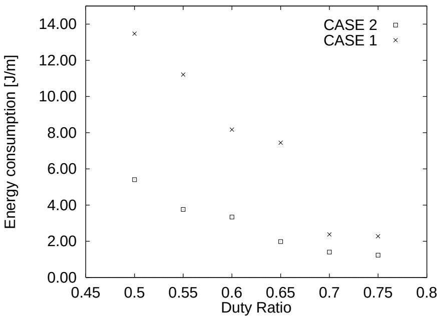


Figure 6: Energy consumption
Commanded pattern: transverse walk

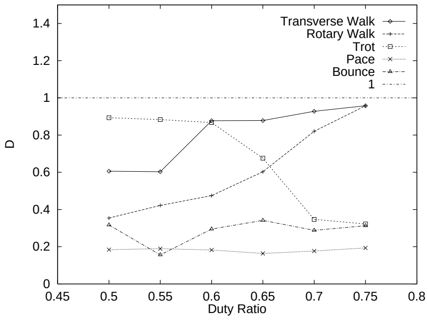


Figure 7: Similarity of gait pattern $D^{(m)}$
Commanded pattern: Trot
(proposed controller)

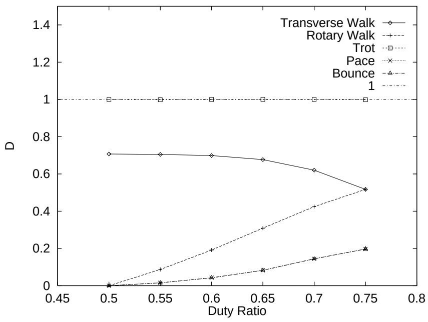
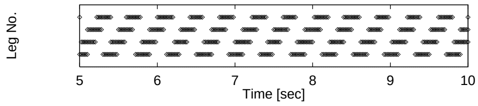
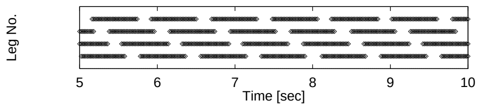


Figure 8: Similarity of gait pattern $D^{(m)}$
Commanded pattern: Trot
(model-based controller)

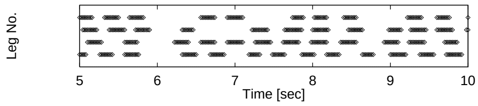


(a) $\hat{\beta} = 0.50$

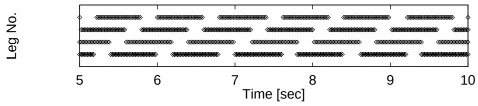


(b) $\hat{\beta} = 0.75$

Figure 9: Gait pattern diagram
Commanded pattern: Transverse walk
(proposed controller)



(a) $\hat{\beta} = 0.50$



(b) $\hat{\beta} = 0.75$

Figure 10: Gait pattern diagram
Commanded pattern: Transverse walk
(model-based controller)

6. Hardware Experiments

The hardware equipment is shown in figure 11. The architecture of the hardware equipment is shown in figure 12.

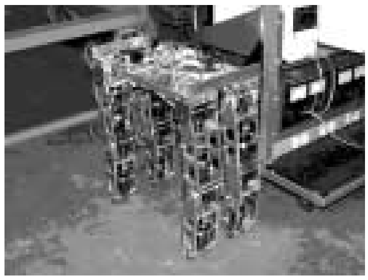


Figure 11: The hardware model

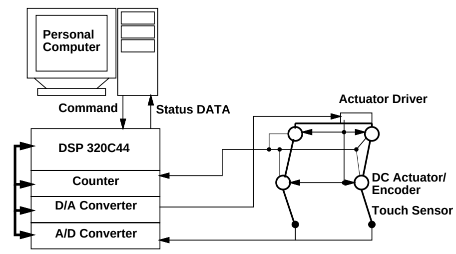
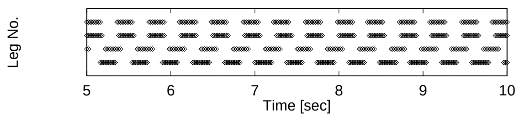
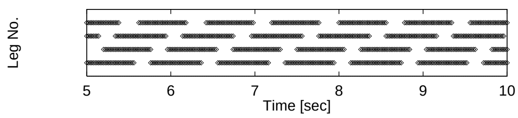


Figure 12: The architecture of the hardware equipment

The performance of the proposed control system was verified by hardware experiments. Figures 13.a and 13.b show the effects of duty ratio $\hat{\beta}$ when the trot walk pattern is commanded. From these figures, we can see that the proposed control system works well on the hardware equipment and realizes stable locomotion adaptively generating the appropriate gait patterns according to the variance of duty ratio $\hat{\beta}$.



(a) $\hat{\beta} = 0.50$



(b) $\hat{\beta} = 0.75$

Figure 13: Gait pattern diagram
Commanded pattern: Trot

7. Conclusions

We proposed a control system for a walking robot with a hierarchical architecture which is composed of leg controllers and a gait pattern controller. The leg controller drives the actuators at the joints of the legs by use of high-gain local feedback based on the commanded signal from the gait pattern controller. Whereas the gait pattern controller alternates the motion primitives by synchronizing with the signals from the touch sensors at the tips of the legs, and stabilizes the phase differences among the motions of the legs adaptively. In this paper, the nominal gait pattern is given as the command. In the future, we are planning to design the control system in which the nominal gait pattern is selected or generated according to the state of the robot. Using such a control system, it is expected that adaptability of the robot to variations of the environment will be highly improved.

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