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Katsuyoshi Tsujita · Kazuo Tsuchiya · Ahmet Onat

# Decentralized autonomous control of a quadrupedal locomotion robot using oscillators

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**Abstract** This article deals with the design of a control system for a quadrupedal locomotion robot. The proposed control system is composed of a leg motion controller and a gait pattern controller within a hierarchical architecture. The leg controller drives actuators at the joints of the legs using a high-gain local feedback control. It receives the command signal from the gait pattern controller. The gait pattern controller, on the other hand, involves nonlinear oscillators. These oscillators interact with each other through signals from the touch sensors located at the tips of the legs. Various gait patterns emerge through the mutual entrainment of these oscillators. As a result, the system walks stably in a wide velocity range by changing its gait patterns and limiting the increase in energy consumption of the actuators. The performance of the proposed control system is verified by numerical simulations.

**Key words** Quadrupedal locomotion robot · Oscillators · Decentralized autonomous control

## 1 Introduction

Locomotion is one of the basic functions of a mobile robot. Using legs is one possible strategy for accomplishing locomotion. Although simpler forms of locomotion, such as wheels, can be easier to design and control, using legs for locomotion allows the robot to move on rough terrain, and therefore improves its access to many locations. Therefore, a considerable amount of research has been carried out into motion control of locomotion robots with legs. This article deals with the motion control of a quadrupedal locomotion robot.

Several gait patterns can be considered for quadrupedal locomotion robots. The gait pattern in which any combination of three legs of the robot support the main body at any instant during locomotion is called a walk pattern. For low velocities in which the inertia effect is small enough, the walk pattern is statically stable in terms of the dynamics of the robot mechanism. However, if the velocity of locomotion increases, the locomotion of the robot becomes unstable. The gait pattern in which two legs of the robot support the main body at any instant during locomotion are called trot or pace patterns. These patterns are statically unstable, and it is difficult for a robot to sustain stable locomotion at low velocities. However, at higher velocities, the robot can sustain stable locomotion with the trot pattern by using its inertia effectively. Designing a control system to realize stable locomotion by changing the gait pattern to adapt to the desired velocity, or to the properties of the environment, is an important subject of research into the motion control of a quadrupedal locomotion robot.

There are two ways to design the control system of a robot: the top-down approach and the bottom-up approach. The top-down approach is based on control theory. The designs of the trajectories of the legs and the gait patterns are implemented through optimization based on the inverse model of the robot. By eliminating nonlinear dynamics such as Coriolis forces by a computed torque method, or the nonlinear feedback method, etc.,[1,2] the motion controllers are designed based on a linearized model. A control system designed by the top-down approach is a model-based control system, and is not always robust against changes in the dynamic states of the system or the physical properties of the environment. On the other hand, the bottom-up approach to designing a control system is based on animal behavior science.[3–6,9] Animal behavior science teaches us that animals make their legs repeat a forward and backward motion periodically if the legs have no mechanical interac-

K. Tsujita (✉) · K. Tsuchiya · A. Onat
Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan
Tel. +81-774-38-3961; Fax +81-774-38-3962
e-mail: tsujita@kuaero.kyoto-u.ac.jp

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tion with the ground, that animals have touch sensors at the tips of their legs, and that the motions of the legs interact with each other through the input signals from the touch sensors. These interactions modify the phase relations of the periodic motions of the legs in an appropriate manner. As a result, a gait pattern emerges that can satisfy the requirements of locomotion velocity, or the properties of the environment. The bottom-up approach design is performed in the following way. First, we introduce nonlinear oscillators in the leg motion controllers, and then determine the periodic motions of the legs as functions of the phase of the oscillators. Next, we design the local feedback controllers of the legs that use the nominal motions of the legs as reference signals. Alternatively, we determine the dynamic interactions among the nonlinear oscillators so that they interact with each other through the input signals from the touch sensors at the tips of the legs. The phase differences among the nonlinear oscillators emerge through the mutual entrainments of the oscillators. As a result, the proposed control system is expected to generate adequate and stable gait patterns which correspond to the dynamic state of the system or to the physical properties of the environment.

Control systems based on the bottom-up approach design have already been applied to the locomotion of hexapod robots in some research. In such work, it has been shown that the control system can adaptively generate adequate gait patterns corresponding to the system state or to variations in the environment. The efficiency of the control system was also verified by hardware experiments.[7] However, there is only a small amount of research based on the bottom-up approach that deals with the control system of a quadrupedal locomotion robot.[8]

This article deals with the design method for the control system of a quadrupedal locomotion robot based on the bottom-up approach.[11,12] The proposed control system has a hierarchical architecture. It is composed of a leg motion 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 nonlinear oscillators. Various gait patterns emerge through the mutual entrainment of these oscillators. The performance of the proposed control system is verified by numerical simulations.

## 2 Equations of motion

Consider the quadrupedal locomotion robot shown in Fig. 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 also 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 the vertically upward direction, respectively. The legs numbered 1 to 4, as shown in Fig. 1. The leg joints next to the body and

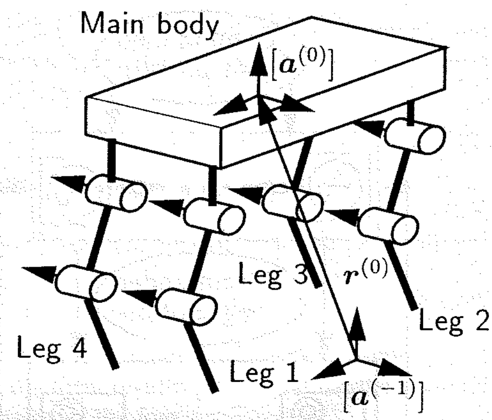


**Fig. 1.** Schematic model of a quadrupedal locomotion robot

at the tip are numbered 1 and 2, respectively. 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 $\omega^{(0)} = [\boldsymbol{a}^{(0)}]\omega^{(0)}$. We define $\theta_i^{(0)}$ ($i$ = 1, 2, 3) as components 1, 2, 3, respectively, of the 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.

The state variable is defined as

$$q^{\mathrm{T}} = \left[r_k^{(0)}\ \theta_k^{(0)}\ \theta_j^{(i)}\right] \qquad (1)$$
$$\left(i = 1, \ldots, 4, \quad j = 1,2, \quad k = 1,2,3\right)$$

The equations of motion for state variable $q$ are derived using the Lagrangian formulation as

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

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

## 3 Locomotion control

The architecture of the proposed control system is shown in Fig. 2. The control system is composed of the leg motion controllers and the gait pattern controller. The leg motion controllers drive all the joint actuators of the legs in order to realize the desired motions generated by the gait pattern controller. The gait pattern controller involves nonlinear oscillators corresponding to each leg. The gait pattern controller receives the command signal of the nominal gait pattern as a reference. It also receives feedback signals from the touch sensors at the tips of the legs.

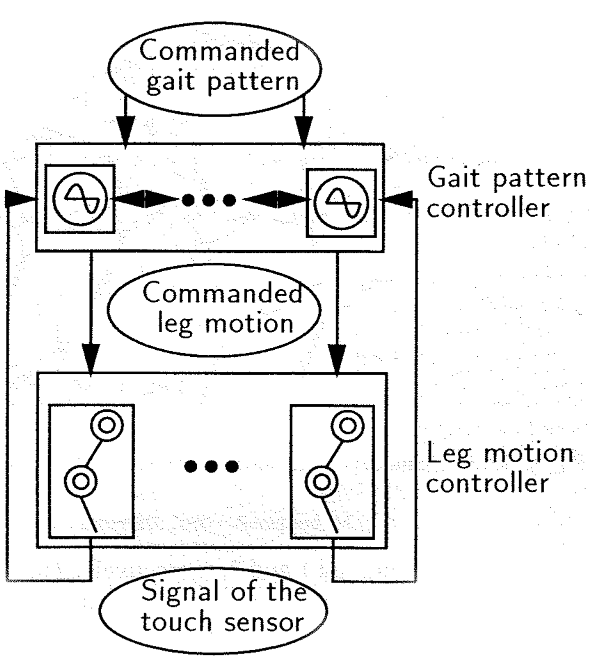


**Fig. 2.** Architecture of the proposed controller

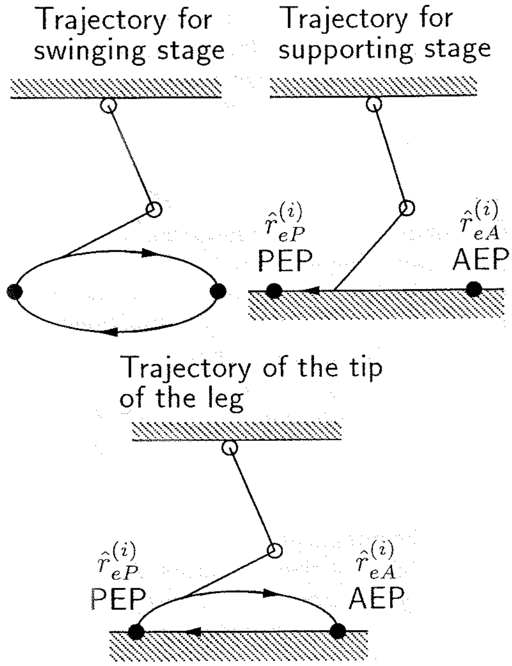


**Fig. 3.** Nominal trajectory of the tip of the leg

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 gait pattern generated is given to the leg motion controller as a command signal.

## 3.1 Gait design

Oscillator $i$ is assigned to leg $i$. The state of oscillator $i$ is expressed as

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

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.

### *3.1.1 Design of the leg motions*

We designed the nominal trajectories of the tips of the legs. First, we defined the position of the tip of the leg, where the position of the transition from the swinging stage to the supporting stage, and the position of the transition from the supporting stage to the swinging stage, are called the anterior extreme position (AEP) and the posterior extreme position (PEP), respectively. We then set the nominal PEP, $\hat{r}^{(i)}_{eP}$, and the nominal AEP, $\hat{r}^{(i)}_{eA}$, in the coordinate system $[\boldsymbol{a}^{(0)}]$, where the index "$\hat{r}$" indicates the nominal value. The nominal trajectory for the swinging stage, $\hat{r}^{(i)}_{eF}$, is a closed curve which involves the points $\hat{r}^{(i)}_{eA}$ and $\hat{r}^{(i)}_{eP}$. On the other hand, the nominal trajectory for the supporting stage, $\hat{r}^{(i)}_{eS}$, is a straight line which also involves the points $\hat{r}^{(i)}_{eA}$ and $\hat{r}^{(i)}_{eP}$. These trajectories are given as functions of the phase of the corresponding oscillator. The nominal phase dynamics of the oscillator is defined as

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

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

$$\hat{\phi}^{(i)} = \hat{\phi}^{(i)}_A \quad \text{at AEP;} \qquad \hat{\phi}^{(i)} = \hat{0} \quad \text{at PEP} \tag{5}$$

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

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

$$\hat{r}^{(i)}_{eS} = \hat{r}^{(i)}_{eS}\left(\hat{\phi}^{(i)}\right) \tag{7}$$

We use one of these two trajectories alternately at every step of AEP and PEP to generate the nominal trajectory of the tip of the leg $\hat{r}^{(i)}_e(\hat{\phi}^{(i)})$ as follows (Fig. 3):

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

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

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

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

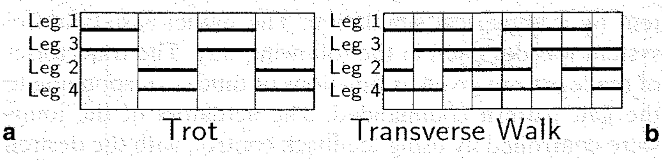


**Fig. 4.** Gait pattern diagrams. **a** Trot. **b** Transverse walk

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

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

### 3.1.2 *Design of the gait pattern*

We then designed the gait patterns, which are the relationships between the motions of the legs. 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, the phase difference of the oscillators in a pair is zero, and the phase difference between the pairs is $\pi$.

There are two gait patterns in which three legs support the main body at any instant during locomotion: one is the transverse walk, in which legs 1, 3, 2, and 4 touch the ground in this order, and the other is the rotary walk, in which legs 1, 2, 3, and 4 touch the ground in this order. Figure 4 shows diagrams of gait patterns trot and transverse walk, where the thick solid lines represent the supporting stages.

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 $m$ values of 1 and 2 represent the transverse walk pattern and the rotary walk pattern, respectively, and $m$ values of 3, 4, and 5 represent the trot pattern, the pace pattern, and the bounce pattern, respectively.

## 3.2 Gait control

### 3.2.1 *Leg motion controller*

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

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

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

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

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

### 3.2.2 *Gait pattern controller*

We designed the phase dynamics of oscillators $i$ as follows:

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

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

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

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

where the matrix of phase differences $\Gamma_{ij}^{(m)}$ represents the command gait pattern defined in Eq. 11. The function $g_1^{(i)}$ is derived from the potential function $V$ as follows:

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

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 the ground. Similarly, $r_{eA}^{(i)}$ is the position of leg $i$ at the instant. 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 $\hat{r}_{eA}^{(i)}$, i.e., one of the parameters of the nominal trajectory $\hat{r}_{eS}^{(i)}$, with $r_{eA}^{(i)}$.

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

$$g_2^{(i)} = \hat{\phi}_A^{(i)} - \phi_A^{(i)} \tag{17}$$

at the instant that leg $i$ touches the ground

The oscillators form a dynamic system, and affect each other through two types of interaction. One is a continuous interaction derived from the potential function $V$, which depends on the nominal gait pattern. The other is the pulse-like interaction 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 of locomotion

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

The stability of the limit cycle is now examined. First, four variables are selected as state variables.

$$X \in R^4, \qquad X = \left[\theta_1^{(0)}\ \theta_2^{(0)}\ \dot{\theta}_1^{(0)}\ \dot{\theta}_2^{(0)}\right] \tag{18}$$

The variables $\theta_1^{(0)}$ and $\theta_2^{(0)}$ are the roll and pitch angles of the main body. When the robot starts its locomotion under a set initial condition, the variable set $X$ moves on a set trajectory in four-dimensional state space. If we choose a Poincaré section using the time when the tip of one leg touches the ground, the first intersection of the trajectory of $X$ with the Poincaré 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.

$$X_1\, X_2 \ldots X_n \ldots$$

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

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

The fixed point $\overline{X}$ is defined so that $\overline{X}$ satisfies the following equation on the Poincaré section and expresses a limit cycle.

$$\overline{X} = F(\overline{X}) \tag{20}$$

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

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

The stability of the sequence of points $\{X_n\}$ is examined by checking the Eigen values $\lambda_k$ ($k = 1, \ldots, 4$) of matrix $M$.

## 5 Numerical analysis

Table 1 shows the physical parameters of the robot which are used in numerical analysis. Numerical simulations were carried out under the conditions that the nominal stride $\hat{S}$ was set at 0.10m, and the command gait patterns $\Gamma^{(m)}$ were fixed at $\Gamma^{(1)}$ for the transverse walk and $\Gamma^{(3)}$ for the trot. The nominal time period of the swinging stage was chosen as 0.20s, and the nominal duty ratio $\hat{\beta}$ was selected as a parameter.

The frequency band width of joints 1 and 2 are given as 5.5Hz and 9.5Hz, respectively, for the feedback gains of the joints.

We investigated the performance of the model-based control system compared with the performance of our system by a numerical simulation. The model-based control system was designed in the following way. The trajectories of the legs were given as functions of time corresponding to the gait pattern commanded. The actuators of the joints were controlled by using feedback control, with the desired joint angles as the reference signals.

First, we investigated the stability of the proposed control system, selecting the duty ratio $\hat{\beta}$ as a parameter. Figure 5 shows the stability of the period-one gait, i.e., the largest eigenvalue modulus of matrix $M$ (Eq. 21) associated with the fixed point of the Poincaré map (Eq. 20). Cases 1 and 2 indicate the model-based control system and the proposed control system, respectively. In the figure, the region labeled "period-one gait" is the region where the walking solution with a period-one gait exists. The region labeled "other gaits" is the region where the robot walks with other

**Table 1.** The physical parameters of the robot

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

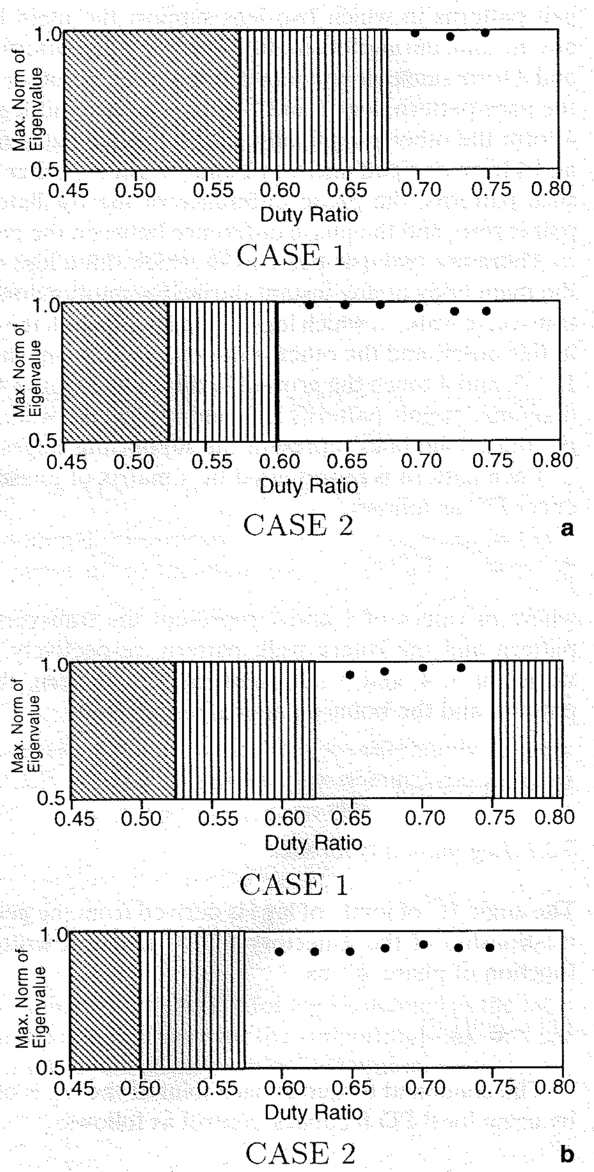


**Fig. 5.** Stability of locomotion. **a** Command pattern: transverse walk. **b** command pattern: trot. *Open block*, period 1 gait; *vertical hatching*, other gaits; *diagonal hatching*, tumble

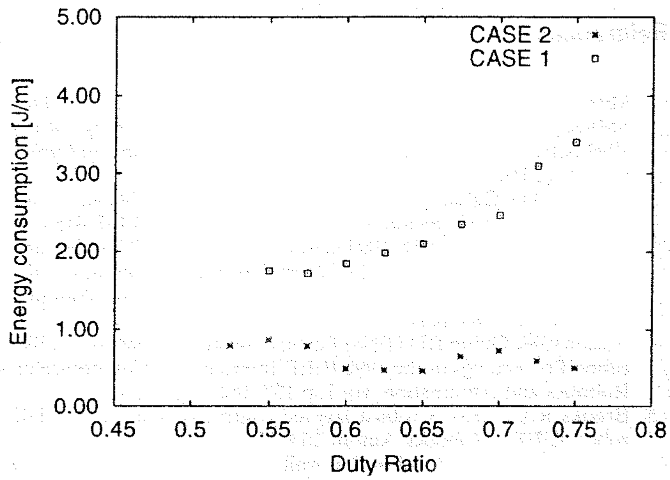


**Fig. 6.** Energy consumption $E_c$. Command pattern: trot

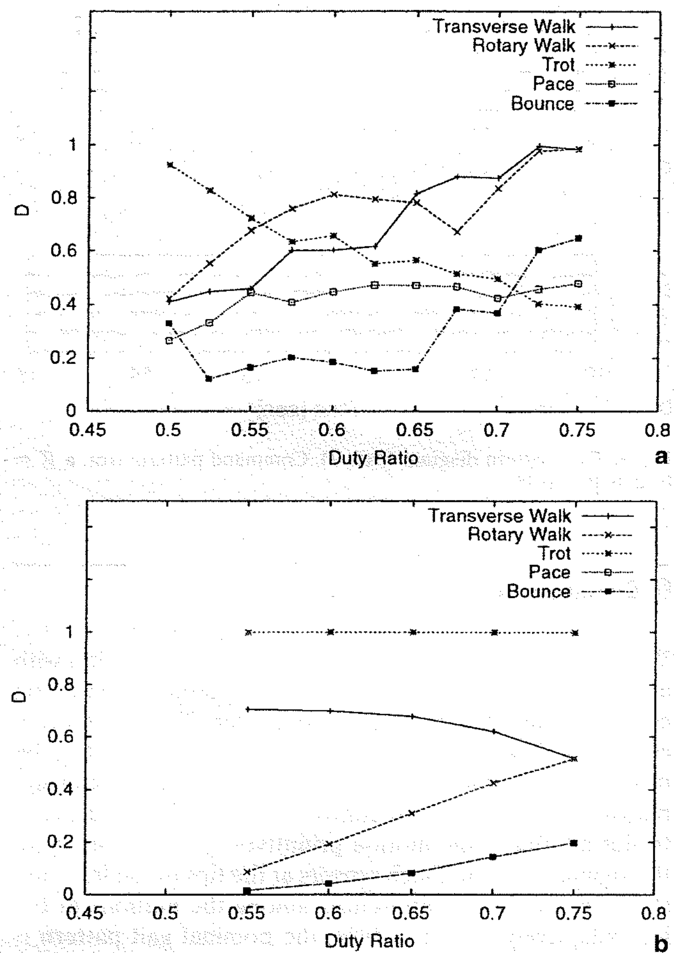


**Fig. 7.** Similarity of gait pattern $D^{(m)}$. Command pattern: trot. **a** Case 2. **b** Case 1

periodic or nonperiodic gaits, and the region labeled "tumble" is the region where the robot cannot walk and falls down. From these figures, we find that the proposed control system established stable locomotion in the robot with a wide parameter variance for duty ratio $\hat{\beta}$.

The variance of the energy consumption of actuators $E_c$ was investigated selecting the duty ratio $\hat{\beta}$ as a parameter. The energy consumption of actuators $E_c$ is defined as

$$E_c = \frac{\left\langle \sum_{i,j} \tau_j^{(i)} \theta_j^{(i)} \right\rangle}{\langle \upsilon \rangle} \tag{22}$$

where $\langle * \rangle$ indicates the time-averaged value of *. The results are shown in Fig. 6. From Fig. 6, we can see that the values of $E_c$ with the proposed control system are smaller than those with the model-based control system. The increase in $E_c$ relates to the variance of the duty ratio $\beta$.

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

$$\zeta^i = \begin{cases} \dfrac{1}{1-\beta} & \text{swinging stage} \\ -\dfrac{1}{\beta} & \text{supporting stage} \end{cases} \tag{23}$$

The correlation between the swinging or supporting states of leg $i$ and those of leg $j$ is defined as

$$W_{ij} = \left\langle \zeta^{(i)} \zeta^{(j)} \right\rangle \tag{24}$$

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

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

Figure 7 shows the simularity of the gait patterns, $D^{(m)}$, with respect to the duty ratio $\hat{\beta}$. From Fig. 7a, we can see that although the trot pattern is given as the nominal gait pattern, the similarity between the gait pattern obtained and the transverse walk pattern $D^{(1)}$ increases as the duty ratio $\hat{\beta}$ increases. Conversely, from Fig. 7b, 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 Fig. 8. From these results, it is clear that the robot using the proposed control system adapts to the variance in the duty ratio $\hat{\beta}$ by changing the gait patterns, maintaining the stability of locomotion in a wide parameter area, and limiting the increase in energy consumption of the actuator.

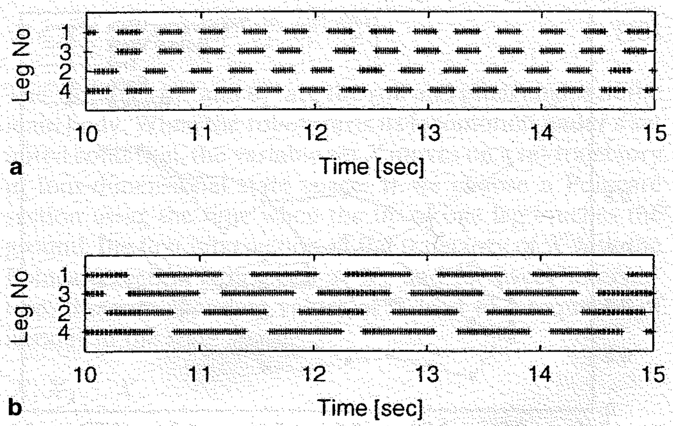


**Fig. 8.** Gait pattern diagram (case 2). Command pattern: trot. **a** $\hat{\beta} = 0.50$. **b** $\hat{\beta} = 0.75$

## 6 Conclusions

We have proposed a control system for a walking robot with a hierarchical architecture which is composed of leg motion controller and a gait pattern controller. The leg motion controller drives the actuators at the joints of the legs by using high-gain local feedback based on the command signal from the gait pattern controller. The gait pattern controller alternates the motion primitives 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 article, the nominal gait pattern is given as the command. In the future, we are planning to design a 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 the adaptability of the robot to variations in the environment will be greatly improved.

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