AN EMERGENT CONTROL OF GAIT PATTERNS OF LEGGED LOCOMOTION ROBOTS

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Abstract: This paper deals with control system of legged locomotion robots based on the Central Pattern Generator (C.P.G.) principle. The controller is composed of a leg motion controllers and a gait pattern controller. The leg motion controller drive all the joint actuators of the legs so as to realize the desired motion generated by the gait pattern controller. The gait pattern controller is composed of the oscillators assigned to each leg. The controller tunes the phases of the oscillators by the feedback signals from the touch sensors at the tips of the legs, and is able to adapt to a changing environment emerges. On the other hand, the controller does not depend on the detailed model of the robot, and so can be widely applied to various types of legged locomotion robot. By applying the proposed controller to two types of legged locomotion robot,quadruped locomotion robot and ten-legged locomotion robot, the merits of the controller are demonstrated numerically.

Keywords: Legged locomotion robot, Locomotion control, Gait patterns, Central pattern generator

1. INTRODUCTION

A legged locomotion robot is a robot with legs. Using the legs, the legged locomotion robot can move on a rough terrain and approach many locations. Now, research on a legged locomotion robot is proceeding actively[1]. In the future, a legged locomotion robot is to carry out a task in the real world, where the geometric and kinematic conditions of the environment are not structured. At that time, a legged locomotion robot is required to realize the real-time adaptability to a changing environment.

The legged locomotion robots are classified according to the number of the legs, biped robot, quadruped locomotion robot, many legged locomotion robot, etc. Now, the controllers are designed for each type of legged locomotion robot based on each model of robot. In the future, the legged locomotion robot may change its configuration according to a task. At that time, a principle of design of controller is to be common to the various types of legged locomotion robot.

The walking motion of an animal seems to offer a solution to the problem[2]. It is widely believed that animal locomotion is generated and controlled, in part, by a common principle, central pattern generator (CPG)[3] principle. The CPG is a neuronal ensemble capable of producing rhythmic output in the absence of sensory feedback or brain input. The CPG, while not requiring external control for their basic operation, is highly sensitive to sensory feedback and external control from the brain. Sensory and descending systems are crucially involved in making the animal locomotion adaptive and stable.

A considerable amount of research has been done on design of a control system for legged locomotion robot which enables to adapt to variances of the environment based on the CPG principle[4~7]. M.A.Lewis et al developed a VLSI CPG Chip and using the chip, they implemented experiments of control of an underactuated running robotic leg; Periodic motion of the hip is driven by an oscillator, and then by controlling phase of oscillator using sensor signal, they established a stable running motion of the leg[4]. K.Akimoto et al designed a locomotion controller for hexapod robot by using CPG[5]. Oscillators, which are assigned for each leg, drive the periodic motion of each leg. The phase of oscillator is controlled by evaluating energy consumption of motors at joints of the legs. By using this control system, they realized a hexapod robot which can change the gait pattern adaptively to the walking velocity. In this paper, a control system for a legged locomotion robot based on CPG principle is proposed. Oscillators are assigned at each leg and they drive the periodic motion of legs. The phase of oscillator is controlled by the signal of touch sensor at the tip of the leg. As a result, the robot with the proposed controller can adapt to changing environments. On the other hand, the proposed controller does not depend on the detailed dynamic model of the robot. As a result, the proposed controller can be widely applied to various types of legged locomotion robot. By applying the proposed controller to two types of legged locomotion robot, quadruped locomotion robot and ten-legged locomotion robot, the merits of the controller are demonstrated numerically.

2. EQUATIONS OF MOTION

Consider the legged locomotion robot shown in Fig. 1, which has N body modules and each body has two legs. Each leg is composed of two links which are connected to each other through a one degree of freedom (DOF) rotational joint and connected to the body module through a one DOF rotational joint. The body modules are connected to each other through a two DOF rotational joint. The coordinate systems which are fixed at an inertial space and the first body module 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. Axes $\boldsymbol{a}_1^{(-1)}$ and $\boldsymbol{a}_3^{(-1)}$ coincide with the direction of locomotion and vertically upward direction, respectively. And axes $[\boldsymbol{a}_1^{(0)}]$ and $[\boldsymbol{a}_3^{(0)}]$ coincide with axes $[\boldsymbol{a}_1^{(-1)}]$ and $[\boldsymbol{a}_3^{(-1)}]$ at a nominal state, respectively. Body modules are numbered from 1 to N and legs of each module are labeled as leg 1 for the left one and leg 2 for the right one, as shown in Fig. 1. The joints of each leg are numbered as joint 1 and 2 from the body module 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 1-2-3 Euler angle from $[\boldsymbol{a}^{(-1)}]$ to $[\boldsymbol{a}^{(0)}]$ and $\theta_j^{(i)} (i = 1, 2)$ as the components of 1-2 Euler angle from $[\boldsymbol{a}^{(j-1)}]$ to $[\boldsymbol{a}^{(j)}]$. We also define $\psi_k^{(i,j)}$ as the joint angle of link k of leg j of module i.

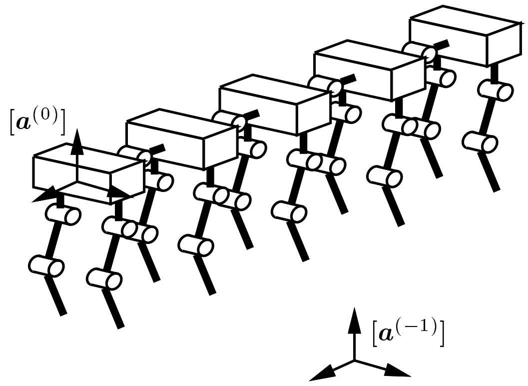


Fig. 1: Schematic model of a legged locomotion robot

The state variable is defined as follows;

$$q^T = \left[\ r_m^{(0)}\quad \theta_m^{(0)}\quad \theta_l^{(j)}\quad \psi_l^{(i,k)}\ \right] \tag{1}$$
$$i = 1, \cdots, N, \quad j = 2, \cdots, N,$$
$$k, l = 1, 2, \quad m = 1, 2, 3$$

Equations of motion for state variable q are derived using Lagrange equations as follows;

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

where M is the generalized mass matrix and $H(q,\ \dot{q})$ is the nonlinear term which includes Coriolis forces and centrifugal forces. G is the gravity term and $\sum(\tau_k^{(i,j)})$ is the input torque of the actuator at joint k of leg j of module 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. LOCOMOTION CONTROL

The architecture of the proposed control system is shown in Fig. 2. The control system is composed of leg motion controllers and a gait pattern controller. The leg motion controllers drive all the joint actuators of the legs so as to realize the desired motions that are generated by the gait pattern controller. The gait pattern controller involves non linear oscillators assigned to each leg. The gait pattern controller receives the feedback signals from the touch sensors at the tips of the legs. A gait pattern emerges through modulation of the phases of the oscillators with mutual interactions and the feedback signals from the touch sensors. The generated gait pattern is given to the leg motion controller as the commanded signal.

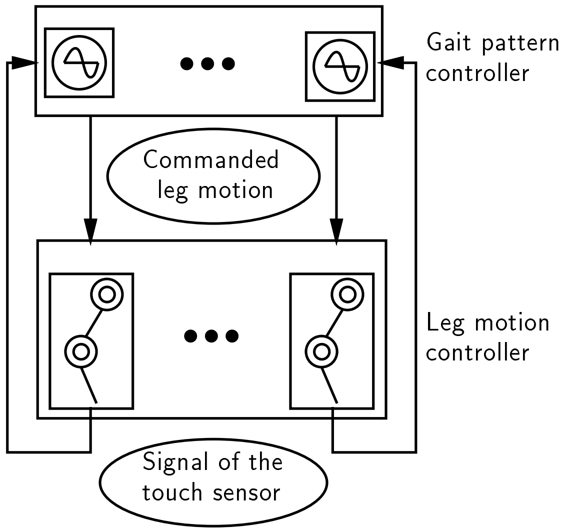


Fig. 2: Architecture of the proposed controller

3.1 Design of gait

Oscillator (i, k) is assigned on leg k of module i. The state of the oscillator (i, k) is expressed as follows;

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

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

We design the nominal trajectories of the tips of the legs as follows; We define the position of the tip of the leg where the transition from the swinging stage to the supporting stage as the anterior extreme position (AEP) and the position where the transition from the supporting stage to the swinging stage as the posterior extreme position (PEP) and then define the nominal PEP, $\hat{r}_{eP}^{(i,j)}$ and the nominal AEP, $\hat{r}_{eA}^{(i,j)}$ in the coordinate system $[\boldsymbol{a}^{(i)}]$ where the index $\hat{*}$ indicates the nominal value. We set the nominal trajectory for the swinging stage, $\hat{r}_{eF}^{(i,j)}$ as a closed curve which involves the points $\hat{r}_{eA}^{(i,j)}$ and $\hat{r}_{eP}^{(i,j)}$, and the nominal trajectory for the supporting stage, $\hat{r}_{eS}^{(i,j)}$ as a straight line which also involves the points $\hat{r}_{eA}^{(i,j)}$ and $\hat{r}_{eP}^{(i,j)}$. On the other hand, the nominal phase dynamics of the oscillator is defined as follows;

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

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

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

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

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

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

Using these two trajectories alternatively we design the nominal trajectory of the tip of the leg $\hat{r}_e^{(i,j)}(\hat{\phi}^{(i,j)})$ as follows(Fig. 3);

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

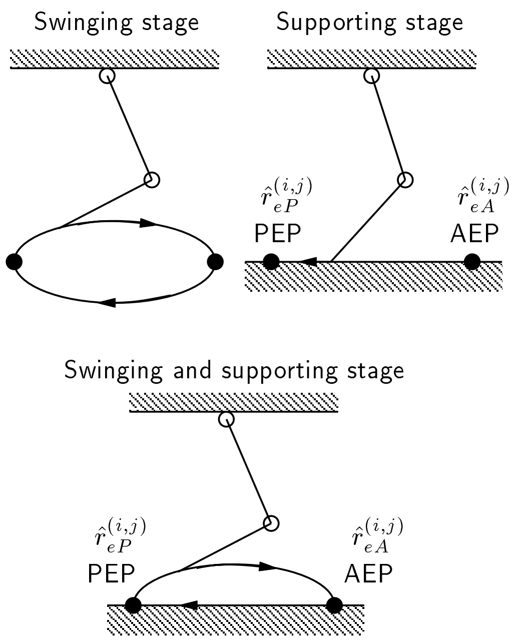


Fig. 3: Nominal trajectory of the tip of the leg

The nominal duty ratio $\hat{\beta}^{(i,j)}$ for leg j of module 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.

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

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

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

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

The gait patterns are defined as the relationships between motions of the legs. There are many gait patterns of the legged locomotion robot. A gait pattern is represented by a corresponding matrix of phase differences $\Gamma_{(ii'),(jj')}$ as follows;

$$\phi^{(i',j')} = \phi^{(i,j)} + \Gamma_{(ii'),(jj')} \tag{11}$$

where $\Gamma_{(ii'),(jj')}$ is a phase difference of oscillator (i, j) and oscillator (i', j').

3.2 Control of gait

(i) Leg motion controller

The angle $\hat{\theta}_k^{(i,j)}$ of joint k of leg j of module i is derived from the trajectory $\hat{r}_e^{(i,j)}(\hat{\phi}^{(i,j)})$ and is written as a function of phase $\hat{\phi}^{(i,j)}$ as follows;

$$\hat{\theta}_k^{(i,j)} = \hat{\theta}_k^{(i,j)}(\hat{\phi}^{(i,j)}) \quad (12)$$

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

$$\begin{aligned}\tau_k^{(i,j)} &= K_{Pk}^{(i,j)}(\hat{\theta}_k^{(i,j)} - \theta_k^{(i,j)}) \\ &\quad + K_{Dk}^{(i,j)}(\dot{\hat{\theta}}_k^{(i,j)} - \dot{\theta}_k^{(i,j)}) \quad (13) \\ &\quad (i = 1, \cdots, N, j, k = 1, 2)\end{aligned}$$

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

(ii) Gait pattern controller

We design the phase dynamics of oscillator i as follows;

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

Term $g_1^{(i,j)}$ is given by

$$g_1^{(i,j)} = -K \sum_{i'j'} \left(\phi^{(ij)} - \phi^{(i'j')} - \Gamma_{(ii'),(jj')}^{(m)} \right) \quad (15)$$

Term $g_1^{(i,j)}$ acts so as to realize a nominal phase difference $\Gamma_{(ii'),(jj')}^{(m)}$ of oscillator (i, j) and oscillator (i', j').

Term $g_2^{(i,j)}$ is the term caused by the feedback signal of the touch sensors of the legs which is designed in the following way: Suppose that $\phi_A^{(i,j)}$ is the phase of leg i at the instant when leg i touches the ground. Similarly, $r_{eA}^{(i,j)}$ is the position of leg j of module i at that instance. When leg i touches the ground, the following procedure is undertaken.

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

Then, term $g^{(i,j)}$ is given with a mathematics as follows:

$$g^{(i,j)} = \hat{\phi}_A^{(i,j)} - \phi_A^{(i,j)} \quad (16)$$

at the instant that leg j of module i touches the ground

As a result, the oscillators form a dynamic system that affect each other through the pulse-like interactions caused by the feedback signals from the touch sensor. Through the interaction, the oscillators generate gait patterns adapted to the changing environment.

4. NUMERICAL ANALYSIS

Dynamic properties of the designed legged robot is investigated by numerical simulation. One of the purpose of the simulation is to demonstrate the applicability of the proposed controller to various types of legged locomotion robot. As the examples, we adopt a quadruped locomotion robot and a ten-legged locomotion robot. Physical parameters of each robot are shown in Table 1.

The other one is to verify the adaptability of the proposed controller to the changing environments, that is, the proposed controller can form a gait pattern adapted to the variance of the environment. Duty ratio β is selected as a parameter which expresses the change of the environment, the speed of locomotion.

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]

(Quadruped locomotion robot)

Body module		
Width	0.13	[m]
Length	0.14	[m]
Height	0.08	[m]
Total Mass	8.0	[kg]
Legs		
Length of link 1	0.075	[m]
Length of link 2	0.075	[m]
Mass of link 1	0.20	[kg]
Mass of link 2	0.10	[kg]

(Ten-legged locomotion robot)

4.1 Quadruped locomotion robot

First, the proposed controller is applied to a quadruped locomotion robot. The angle $\theta_m^{(1)}$ $(m = 1, 2)$ of gimbal between module 1 and 2 is fixed to zero. In terms of angular velocity of oscillators, time period of swinging stage is fixed to 0.2 [sec].

Stride is also fixed to 7.0[cm]. The nominal phase difference is designed as follows;

$$\Gamma^{(m)}_{(12),(12)} = \Gamma^{(m)}_{(12),(21)} = \pi \tag{17}$$

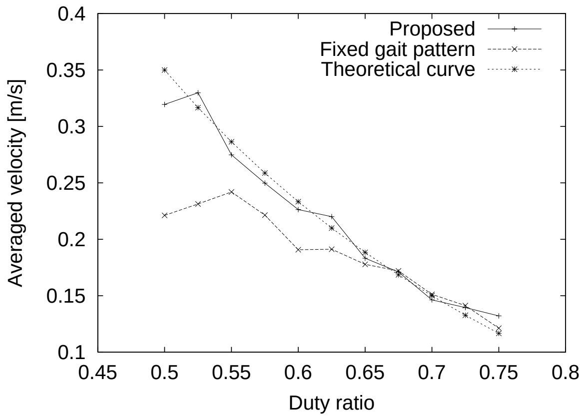
To the comparison, the case in which the nominal gait pattern is fixed to transverse walk is also simulated. Figures 4 show the simulation results in terms of a quadruped locomotion robot. Figures 4.(a) show the averaged walking velocity V. Dotted line indicates the theoretical curve. The proposed controller established the walking velocity which coincides with the theoretical value in almost all parameter area. Figure 4.(b) shows $\Gamma_{(ii'),(jj')}$, the phase difference between oscillator (i,j) and (i',j'). The proposed controller realized a gait pattern similar to transverse walk when duty ratio β is large value and also realized a gait pattern similar to trot when duty ratio β is small value. Figure 4.(c) shows energy consumption E, which shows that the proposed controller suppresses energy consumption in almost all parameter area.

4.2 Ten-legged locomotion robot

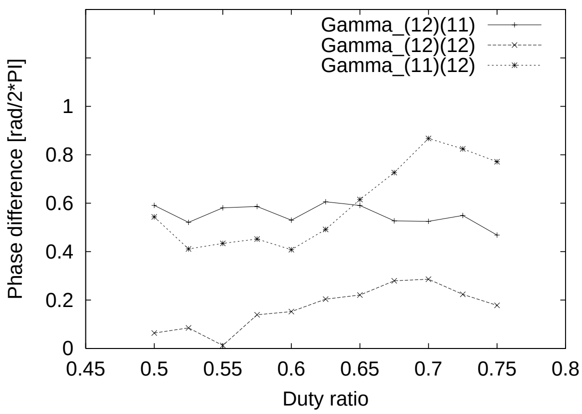
Next, the proposed controller is applied to a ten-legged locomotion robot. The angle $\theta^{(j)}_i$ $(i = 1, 2)$ of gimbal between module $j-1$ and j is controlled by PD feedback to be zero. The angular velocity of oscillators is fixed to 2π [rad/sec]. Stride is fixed to 7.0[cm]. The nominal phase difference is designed as follows;

$$\Gamma^{(m)}_{(ii),(12)} = 0 \ \ (i = 1, \cdots, 5) \tag{18}$$

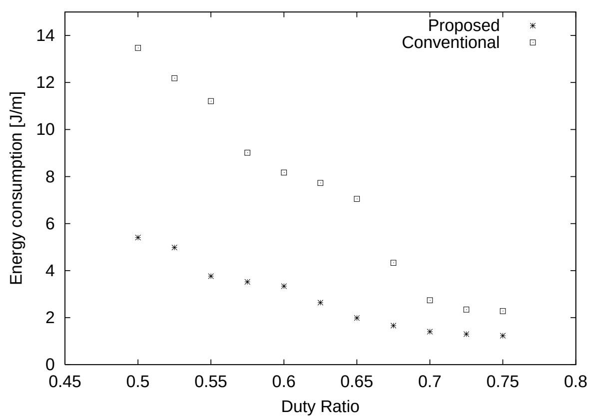
To the comparison, the other case in which the nominal gait pattern is fixed to metachronal wave is also simulated. Figures 5 show the simulation results in terms of a ten-legged locomotion robot. Figure 5.(a) shows the averaged walking velocity V. Dotted line indicates the theoretical curve. The proposed controller established the walking velocity which coincides with the theoretical value in almost all parameter area. Figure 5.(b) shows $\Gamma_{(ii'),(jj')}$, the phase difference between oscillator (i,j) and (i',j'). The proposed controller realized a gait pattern similar to transverse walk when duty ratio β is large value and also realized a gait pattern similar to trot when duty ratio β is small value.



(a) Averaged walking velocity

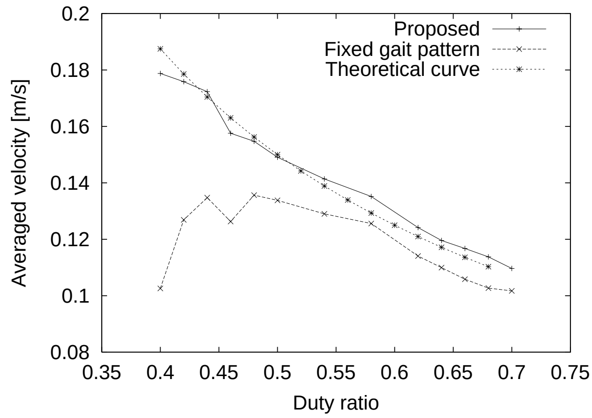


(b) Phase differences among oscillators

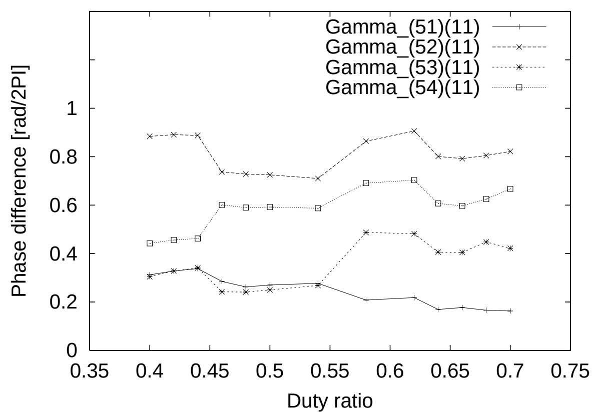


(c) Energy consumption

Fig.4: Quadruped locomotion robot



(a) Averaged walking velocity



(b) Phase differences among oscillators

Fig.5 Ten-legged locomotion robot

5. CONCLUSIONS

In this paper, we proposed a controller of a legged locomotion robot based on CPG principle. Oscillators are assigned to each leg and drive the periodic motion of legs. The phases of the oscillators are regulated impulsively by the feedback signals from the touch sensors at the tips of the legs. This type of system is shown numerically to form phase patterns adaptively to the change of environment. It is also shown that the controller designed by the same method of design can realize stable locomotion for two types of legged locomotion robot, quadruped locomotion robot and ten-legged locomotion robot.

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