Locomotion Control of a Biped Locomotion Robot using Nonlinear Oscillators

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Abstract

This paper proposes the locomotion control system for a biped locomotion robot. The proposed control system is composed of motion generator system and motion control system. Motion generator system is composed of nonlinear oscillators which generate the commanded trajectories of the joints as functions of phases of oscillators. Motion control system is composed of motors with controllers installed at joints which control motions of joints. The oscillators tune the phases through the mutual interactions and the feedback signals from the touch sensors at the tips of the legs. As a result, the robot with the controller walks stably by changing its period of locomotion in a changing environment. The performance of the proposed control system is verified by numerical simulations and experiments.

1 Introduction

Locomotion control of a biped locomotion robot is the motion control of a multi-linked mechanical system. Many researches on motion control of this class of mechanical system have been progressed. A standard method developed is as follows; First, in motion planning, the nominal trajectories of joints are computed to realize a given motion. Then, in motion control, the control system of joints control the joints to realize the nominal trajectories.

Steady biped locomotion is a periodic motion, a certain period of which the motion becomes to be unstable statically. Then, motion control of a biped locomotion robot is to establish a steady stable periodic motion. The following method is often used for this purpose; First, the nominal trajectories of the joints are designed as functions of time so that the generated motion of a biped robot is stable at a nominal condition. Then, the control system of joints controls the joints to realize the nominal trajectories. This method has a serious drawback when a robot walks in a real world, that is, the robot with this controller cannot adapt to a changing environment. A method of motion control of locomotion robots using nonlinear oscillators have been proposed and verified by hardware models (quadruped robot[1][2][3], hexapod robot[4][5]). To our knowledge, a method of motion control using nonlinear oscillators for biped locomotion robot has not been proposed and has not been applied to a real robot. In this paper, we will propose a method of motion control of a biped locomotion robot using nonlinear oscillators. The proposed control system is composed of motion generator system and motion control system. Motion generator system is composed of nonlinear oscillators which generate the commanded trajectories of the joints as functions of phases of oscillators. Motion control system is composed of motors with controllers installed at joints which control motions of joints. The oscillators tune the phases through the mutual interactions and the feedback signals from the touch sensors at the tips of the legs. As a result, the robot with the controller walks stably by changing its period of locomotion in a changing environment. The effectiveness of the proposed control system is verified by the numerical simulations and the experiments.

2 Equations of Motion

We consider the biped locomotion robot shown in Fig.1. The robot consists of a body, a pair of arms composed of four links and a pair of legs composed of six links. Each link is connected to each other through a one degree of freedom rotational joint. A motor is installed at each joint. Left and right arms are numbered as arm 1 and arm 2, respectively. The joints and the links of arms are numbered as joint 1,2,$\cdots$, and link 1,2,$\cdots$ in order from the side of the body. The legs are numbered in a similar manner. There are four touch sensors at the tips of each leg. The inertial fixed coordinate system is defined as $[\boldsymbol{a}_0] = [\boldsymbol{a}_{01}, \boldsymbol{a}_{02}, \boldsymbol{a}_{03}]$. The coordinate system fixed on the body is defined as $[\boldsymbol{a}_1] = [\boldsymbol{a}_{11}, \boldsymbol{a}_{12}, \boldsymbol{a}_{13}]$. Axes 1,2 and 3 coincide with the direction of roll, pitch and yaw, respectively. The position vector from the origin of $[\boldsymbol{a}_0]$ to the origin $[\boldsymbol{a}_1]$ is defined as $\boldsymbol{r}_0 = [\boldsymbol{a}_0] r_0$. We define θ_0 as 3-1-2 Euler angle from $[\boldsymbol{a}_0]$ to $[\boldsymbol{a}_1]$, we define also $\theta_{Aj}^{(i)}$ as the joint angle of link j of arm i and $\theta_{Lk}^{(i)}$ as the joint angle of link k of leg i.

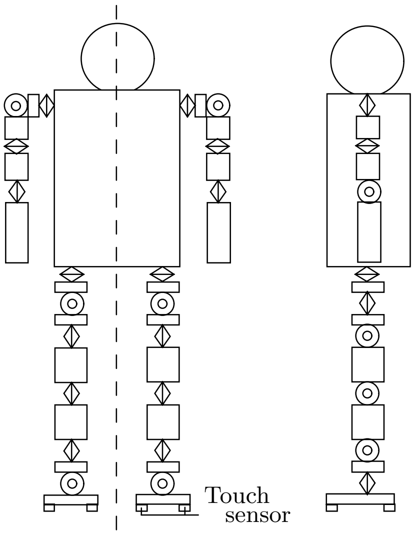

Figure 1: *Schematic model of biped locomotion robot*

The state variable is defined as follows;

$$q^T = [\ r_0\ \theta_0\ \theta_{Aj}^{(i)}\ \theta_{Lk}^{(i)}\ ] \qquad (1)$$
$$i = 1, 2,\ j = 1, \cdots, 4,\ k = 1, \cdots, 6$$

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

$$M\ddot{q} + H(q, \dot{q}) = G + \sum(\tau_{Aj}^{(i)} + \tau_{Lk}^{(i)}) + \Lambda \qquad (2)$$

where M is the generalized mass matrix. $H(q, \dot{q})$ is the nonlinear term which includes Coriolis forces and centrifugal forces. G is the gravity term. $\tau_{Aj}^{(i)}$ and $\tau_{Lk}^{(i)}$ are the input torques at joint j of arm i and joint k of leg i. Λ is the reaction force from the ground. The floor is modeled as a spring with damper.

3 Locomotion control

3.1 Locomotion control system

Locomotion control system is composed of motion control system and motion generator system (Fig.2). Motion control system is composed of motors with controllers installed at joints, which control the motions of joints corresponding to the desired motions commanded by motion generator system. Motion generator system is composed of pacemaker oscillator and motion oscillators. Motion oscillators are body, arm 1 and 2 and leg 1 and 2 oscillators which generate the commanded trajectories of the body, arm 1 and 2 and leg 1 and 2 and send them to motion control system (Fig.3). Motion oscillators are interacted with pacemaker oscillator; Arm 1 and 2 oscillators and body oscillator are affected unidirectionally from pacemaker oscillator, and leg 1 and 2 oscillators are bidirectionally interacted with pacemaker oscillator. Leg 1 and 2 oscillators receive the feedback signals from the touch sensors at the tips of the legs.

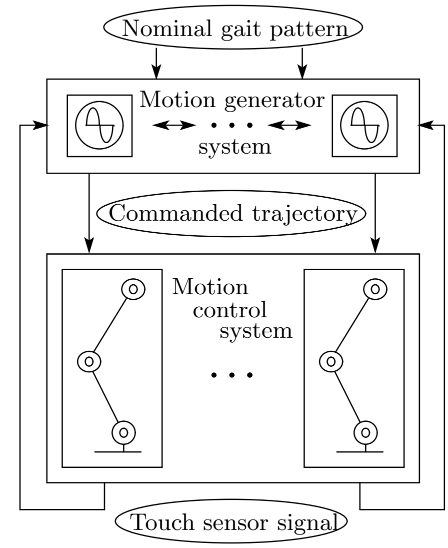

Figure 2: *Locomotion control system*

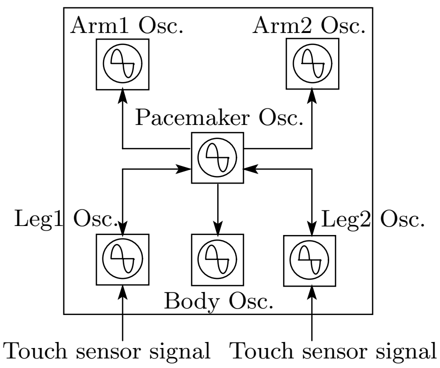

Figure 3: *Motion generator system*

3.2 Design of nominal trajectory of joint

The state of each oscillator is expressed as follows;

$$\begin{aligned} z_P = r_P \exp(\boldsymbol{j}\phi_S), &\quad z_B = r_B \exp(\boldsymbol{j}\phi_B) \\ z_A^{(i)} = r_A^{(i)} \exp(\boldsymbol{j}\phi_A^{(i)}), &\quad z_L^{(i)} = r_L^{(i)} \exp(\boldsymbol{j}\phi_L^{(i)}) \end{aligned} \qquad (3)$$

where z_P and z_B are the states of pacemaker and body oscillators and $z_A^{(i)}$ and $z_L^{(i)}$ are the states for arm i and leg i oscillators (i=1,2). Dynamics of the oscillators are set as;

$$\dot{\hat{r}} = 0, \quad \dot{\hat{\phi}} = \hat{\omega} \tag{4}$$

The nominal trajectories of the joints are given as functions of nominal phases of the oscillators. First, we define two positions of the tips of the legs, the anterior extreme position (AEP) and the posterior extreme position (PEP). The nominal PEP and the nominal AEP are expressed as $\hat{\eta}_{PEP}^{(i)}$, $\hat{\eta}_{AEP}^{(i)}$ in $[\,\boldsymbol{a}_1\,]$. The nominal trajectory for the swinging stage is designed as a closed curve $\hat{\eta}_{Sw}^{(i)}$ which involves the points $\hat{\eta}_{AEP}^{(i)}$ and $\hat{\eta}_{PEP}^{(i)}$, and the nominal trajectory for the supporting stage is given as a straight line $\hat{\eta}_{Sp}^{(i)}$ which also involves the points $\hat{\eta}_{AEP}^{(i)}$ and $\hat{\eta}_{PEP}^{(i)}$ (Fig.4). The nominal trajectory $\hat{\eta}_L^{(i)}$ of the tip of the leg i is generated by using one of these two trajectories alternatively; A swinging stage changes to a supporting stage at PEP and a supporting stage changes to a swinging stage at AEP. The nominal trajectories $\hat{\eta}_{Sw}^{(i)}$ and $\hat{\eta}_{Sp}^{(i)}$ are given as the functions of the nominal phase $\hat{\phi}_L^{(i)}$ of leg i oscillator. The nominal phases $\hat{\phi}_L^{(i)}$ of leg i oscillator at AEP and PEP are determined as follows;

$$\hat{\eta}_{Sw}^{(i)}(\hat{\phi}_{AEP}^{(i)}) = \hat{\eta}_{AEP}^{(i)}, \quad \hat{\eta}_{Sp}^{(i)}(0) = \hat{\eta}_{PEP}^{(i)} \tag{5}$$

The nominal trajectory $\hat{\eta}_L^{(i)}$ of the tip of the leg is expressed as follows;

$$\hat{\eta}_L^{(i)}(\hat{\phi}_L^{(i)}) = \begin{cases} \hat{\eta}_{Sw}^{(i)}(\hat{\phi}_L^{(i)}) & 0 \le \hat{\phi}_L^{(i)} < \hat{\phi}_{AEP}^{(i)} \\ \hat{\eta}_{Sp}^{(i)}(\hat{\phi}_L^{(i)}) & \hat{\phi}_{AEP}^{(i)} \le \hat{\phi}_L^{(i)} < 2\pi \end{cases} \tag{6}$$

The nominal duty ratio $\hat{\beta}^{(i)}$ of leg i is the ratio between the nominal time for the supporting stage and the period of one step of the nominal locomotion, which is given by

$$\hat{\beta}^{(i)} = 1 - \frac{\hat{\phi}_{AEP}^{(i)}}{2\pi} \tag{7}$$

Then, the nominal angular velocity $\hat{\omega}$ of each oscillator, the nominal stride $\hat{S}^{(i)}$ of leg i and the nominal locomotion velocity $\hat{v}$ are given as follows;

$$\omega = 2\pi \frac{1 - \hat{\beta}^{(i)}}{\hat{T}_{Sw}} \tag{8}$$

$$\hat{S}^{(i)} = \hat{\eta}_{AEP1}^{(i)} - \hat{\eta}_{PEP1}^{(i)}, \quad \hat{v} = \frac{1 - \hat{\beta}^{(i)}}{\hat{\beta}^{(i)}} \frac{\hat{S}^{(i)}}{\hat{T}_{Sw}} \tag{9}$$

Then, from the geometric relation, the nominal trajectory $\hat{\theta}_{Lj}^{(i)}$ of joint j(=3,4,5) of leg i is given as the function of the nominal phase $\hat{\phi}_L^{(i)}$ of leg i oscillator.

$$\hat{\theta}_{Lj}^{(i)} = \hat{\theta}_{Lj}^{(i)}(\hat{\phi}_L^{(i)}) \quad j = 3, 4, 5 \tag{10}$$

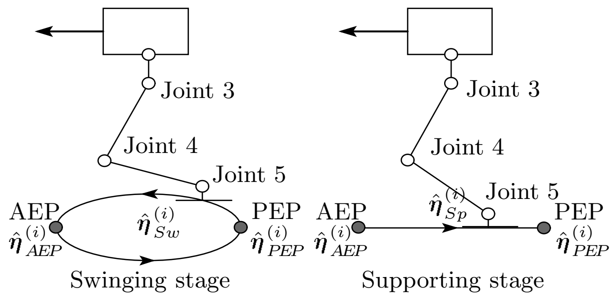

Figure 4: *Nominal trajectory of the leg*

Next, the nominal trajectories of the arm joints are designed as follows; In this paper, for the simplicity, the trajectories of the arm joints are given in order that the arms oscillate simply in phase with the contralateral legs. Then, the trajectory $\hat{\theta}_{A1}^{(i)}$ of joint 1 of arm i is given as the function of the nominal phase $\hat{\phi}_A^{(i)}$ of arm i oscillator;

$$\hat{\theta}_{A1}^{(i)} = \hat{\theta}_{A1}^{(i)}(\hat{\phi}_A^{(i)}) = \hat{A}\cos\hat{\phi}_A^{(i)} \tag{11}$$

where $\hat{A}$ is the nominal amplitude.

At last, the nominal trajectories of the hip and ankle joints are designed in order that the roll motion of the upper body is to be a periodic motion and the pitch and yaw motion are to be fixed to the inertial space. Then, the nominal trajectories $\hat{\theta}_{L2}^{(i)}$ of joint 2 and $\hat{\theta}_{L6}^{(i)}$ of joint 6 of leg i are given as the functions of the nominal phase $\hat{\phi}_B$ of body oscillator.

$$\begin{aligned} \hat{\theta}_{L2}^{(1)} &= \hat{\theta}_{L2}^{(1)}(\hat{\phi}_B) = \hat{B}\cos(\hat{\phi}_B + \hat{\psi}) + \hat{\delta} \\ \hat{\theta}_{L2}^{(2)} &= \hat{\theta}_{L2}^{(2)}(\hat{\phi}_B) = \hat{B}\cos(\hat{\phi}_B + \hat{\psi}) - \hat{\delta} \\ \hat{\theta}_{L6}^{(1)} &= \hat{\theta}_{L6}^{(1)}(\hat{\phi}_B) = -\hat{B}\cos(\hat{\phi}_B + \hat{\psi}) - \hat{\delta} \\ \hat{\theta}_{L6}^{(2)} &= \hat{\theta}_{L6}^{(2)}(\hat{\phi}_B) = -\hat{B}\cos(\hat{\phi}_B + \hat{\psi}) + \hat{\delta} \end{aligned} \tag{12}$$

where $\hat{B}$ is the nominal amplitude, $\hat{\psi}$ is the phase and $\hat{\delta}$ is a bias value. The nominal trajectory $\hat{\theta}_{L3}^{(i)}$ of joint 3 of leg i is modified so that the upper body keeps the pitch angle $\hat{C}$ to the inertial space.

$$\theta_{L3}^{(i)} = \hat{\theta}_{L3}^{(i)}(\hat{\phi}_L^{(i)}) - \hat{C} \tag{13}$$

The nominal trajectory $\hat{\theta}_{L1}^{(i)}$ of joint 1 of leg i is given so that the yaw motion of the upper body do not occur to the inertial space.

$$\hat{\theta}_{L1}^{(i)} = 0 \tag{14}$$

These nominal trajectories contain parameters $\hat{A}, \hat{B}, \hat{C}, \hat{\psi}, \hat{\delta}$. These parameters are determined so that the generated locomotion of a biped locomotion robot becomes to be stable at a nominal state.

3.3 Design of nominal gait pattern

Here, we design the nominal gait pattern, the phase relations of the oscillators. This is determined by the phase relations between pacemaker oscillator and motion oscillators. As the nominal gait pattern, the gait patterns of both arms and both legs are given in order that both arms and both legs move out of phase relatively, and one arm and the contralateral leg move in phase. That is, leg i oscillator $\hat{\phi}_L^{(i)}$ and arm i oscillator $\hat{\phi}_A^{(i)}$ are designed in terms of pacemaker oscillator $\hat{\phi}_P$ as follows;

$$\begin{cases} \hat{\phi}_A^{(1)} &= \hat{\phi}_P + \pi/2 \\ \hat{\phi}_A^{(2)} &= \hat{\phi}_P - \pi/2 \\ \hat{\phi}_L^{(1)} &= \hat{\phi}_P - \pi/2 \\ \hat{\phi}_L^{(2)} &= \hat{\phi}_P + \pi/2 \end{cases} \tag{15}$$

On the other hand, body oscillator $\hat{\phi}_B$ is designed as follows;

$$\hat{\phi}_B = \hat{\phi}_P \tag{16}$$

3.4 Trajectory control

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

$$\begin{aligned} \tau_{Aj}^{(i)} &= K_{PAj}^{(i)}(\hat{\theta}_{Aj}^{(i)} - \theta_{Aj}^{(i)}) + K_{DAj}^{(i)}(\dot{\hat{\theta}}_{Aj}^{(i)} - \dot{\theta}_{Aj}^{(i)}) \\ \tau_{Lj}^{(i)} &= K_{PLj}^{(i)}(\hat{\theta}_{Lj}^{(i)} - \theta_{Lj}^{(i)}) + K_{DLj}^{(i)}(\dot{\hat{\theta}}_{Lj}^{(i)} - \dot{\theta}_{Lj}^{(i)}) \end{aligned} \tag{17}$$

where $\tau_{Aj}^{(i)}, \tau_{Lj}^{(i)}$ are the actuator torques at joint j of arm i and leg i, and $K_{PAj}^{(i)}, K_{DAj}^{(i)}, K_{PLj}^{(i)}, K_{DLj}^{(i)}$ are the feedback gains.

3.5 Posture control

The posture of the robot are controlled adaptively by tuning the phases of the oscillators and thereby the real trajectories change corresponding to the phases.

For that purpose, the phase dynamics of each oscillator is designed as follows;

$$\begin{cases} \dot{\phi}_P &= \omega + g_{1P} \\ \dot{\phi}_B &= \omega + g_{1B} \\ \dot{\phi}_A^{(i)} &= \omega + g_{1A}^{(i)} \\ \dot{\phi}_L^{(i)} &= \omega + g_{1L}^{(i)} + g_{2L}^{(i)} \end{cases} \tag{18}$$

where g_1 are the terms which are derived from the interactions with other oscillators and g_2 are the terms caused by the feedback signals of the touch sensors at the tips of the legs.

Functions g_1 are designed in the following way; First, the following potential functions V are defined according to the nominal gait pattern in order that arm and body oscillators are acted unidirectionally from pacemaker oscillator and leg oscillators are bidirectionally.

$$\begin{cases} V_P &= -\sum_i K_L \cos(\phi_P - \phi_L^{(i)} + (-1)^i \pi/2) \\ V_B &= -K_B \cos(\phi_B - \phi_P) \\ V_A^{(i)} &= -K_A \cos(\phi_A^{(i)} - \phi_P + (-1)^i \pi/2) \\ V_L^{(i)} &= -K_L \cos(\phi_L^{(i)} - \phi_P - (-1)^i \pi/2) \end{cases} \tag{19}$$

where K_L, K_A, K_B are the gain constants. Functions g_1 are then derived from the potential functions V as follows;

$$g_1 = -\frac{\partial V}{\partial \phi}$$

Then, written as;

$$\begin{cases} g_{1P} &= -\sum_i K_L \sin(\phi_P - \phi_L^{(i)} + (-1)^i \pi/2) \\ g_{1B} &= -K_B \sin(\phi_B - \phi_P) \\ g_{1A}^{(i)} &= -K_A \sin(\phi_A^{(i)} - \phi_P + (-1)^i \pi/2) \\ g_{1L}^{(i)} &= -K_L \sin(\phi_L^{(i)} - \phi_P - (-1)^i \pi/2) \end{cases} \tag{20}$$

Function $g_{2L}^{(i)}$ is designed in the following way; Suppose that $\phi_{AEP}^{(i)}$ is the phase of leg i at the instant when leg i touches the ground, and $\eta_{AEP}^{(i)}$ is the position of leg i at that instance. When leg i touches the ground, the following procedure is undertaken.

1. Set the phase of leg i oscillator from $\phi_{AEP}^{(i)}$ to $\hat{\phi}_{AEP}^{(i)}$.
2. Switch the nominal trajectory of leg i from the swinging trajectory $\hat{\eta}_{Sw}^{(i)}$ to the supporting trajectory $\hat{\eta}_{Sp}^{(i)}$.
3. Replace the parameter $\hat{\eta}_{AEP}^{(i)}$ in the nominal trajectory $\hat{\eta}_{Sp}^{(i)}$ with $\eta_{AEP}^{(i)}$.

Function $g_{2L}^{(i)}$ is then given as follows;

$$g_{2L}^{(i)} = (\hat{\phi}_{AEP}^{(i)} - \phi_{AEP}^{(i)})\delta(t - t_{hs}^{(i)}) \tag{21}$$

where $t_{hs}^{(i)}$ is the time when leg i touches the ground. As a result, the nominal trajectory $\hat{\eta}_L^{(i)}$ of the tip of the leg is modified as shown in Fig.5; The tip of the leg moves on the trajectory in swinging stage. At $\eta_{AEP}^{(i)}$ the tip of the leg touches the ground and then changes to the trajectory in modified supporting stage.

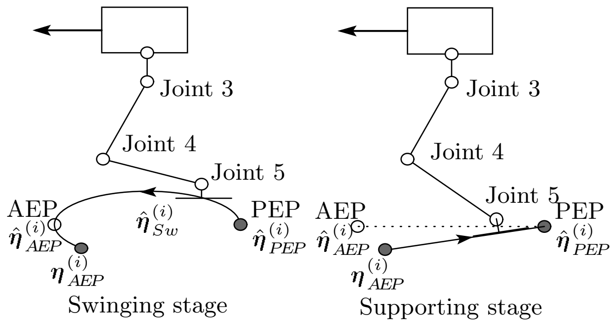

Figure 5: *Modified trajectory of the leg*

4 Numerical analysis

Here, the effectiveness of the proposed control system is verified by the numerical simulations. Especially whether the proposed control system is effective to the change of the environments is investigated.

The nominal trajectories of joints are determined so that the biped locomotion robot can walk stably in a certain fixed environment. While a certain environment changes, whether the robot can continue to walk adaptively using the proposed control system is investigated. In order to verify the effectiveness of the proposed control system, not only the simulations of the proposed control system (Proposal) but also the simulations of the conventional control system without tuning phases (Conventional) are investigated.

The physical parameters of the biped locomotion robot, HOAP-1(Fujitsu Fig.8), are used.

Change of locomotion speed. The nominal states are given as follows; $\hat{S}$=2[cm], $\hat{\beta}$=0.5, $\hat{T}_{Sw}$=0.3[s]. As a change of the environment, the nominal locomotion speed are changed gradually by changing the nominal stride $\hat{S}$. The results are shown in Fig.6. This figure shows the period of locomotion, the time intervals between the times when the left leg makes contact with the ground.

Change of slope angle of floor. The nominal states are given as follows; $\hat{S}$=5[cm], $\hat{\beta}$=0.5, $\hat{T}_{Sw}$=0.3[s]. As a change of the environment, the slope angle of the floor are changed gradually. The results are shown in Fig.7. This figure shows the period of locomotion, the time intervals (periods) between the times when the left leg makes contact with the ground.

From these figures, it is revealed that in the proposed control system the robot can walk in a wide velocity and a wide slope angle of the floor while in the conventional control system the robot soon falls. That is, in the proposed control system the robot can walk more adaptively to these changes of the environments than in the conventional control system. Moreover, compared with the conventional control system, in the proposed control system the robot can walk adaptively by changing the period of the locomotion.

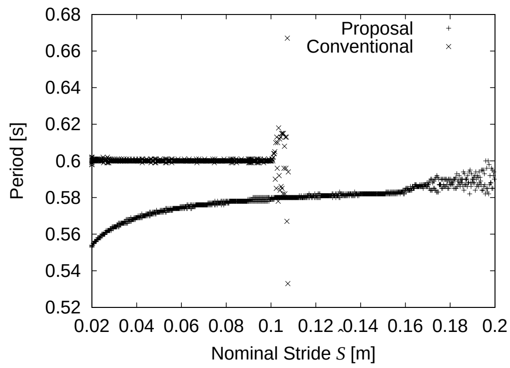

Figure 6: *Period of locomotion (In the case of the change of the locomotion speed)*

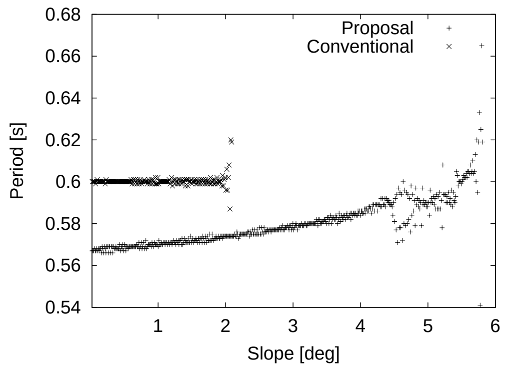

Figure 7: *Period of locomotion (In the case of the change of the slope angle)*

5 Hardware experiment

We experiment with the biped locomotion robot, HOAP-1(Fujitsu Fig.8), using the proposed control system. The nominal trajectories are given by determining the adjustment parameters in order that the robot can walk stably in a certain environment by trial and error experimentally.

Change of locomotion speed. As the nominal trajectories, the adjustment parameters are given as follows; $\hat{S}$=2[cm], $\hat{\beta}$=0.70, $\hat{T}_{Sw}$=0.3[s]. As a change of the environment, the nominal locomotion speed are changed gradually by changing the nominal stride $\hat{S}$. The results are shown in Fig.9. This figure shows the profiles of the period of pacemaker oscillator.

Change of slope angle of floor. As the nominal trajectories, the adjustment parameters are given as follows; $\hat{S}$=3[cm], $\hat{\beta}$=0.7, $\hat{T}_{Sw}$=0.3[s]. As a change of the environment, the slope angle of the floor are changed discontinuously. At first, the robot walks on the flat terrain, next on the up-slope and at the last on the flat terrain again. The slope angle of the up-slope is about 2.35[deg]. The results are shown in Fig.10. This figure also shows the profiles of the period of pacemaker oscillator.

From these figures, it is revealed that the robot with proposed control system can walk adaptively to these changes of the environments by changing the period of the locomotion.

Acknowledgments

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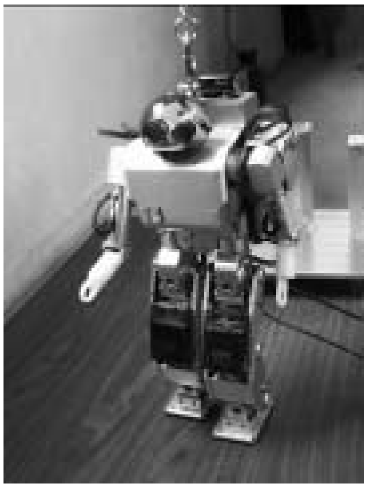

Figure 8: *HOAP-1(Fujitsu)*

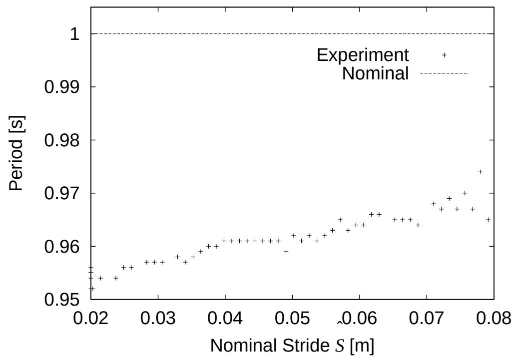

Figure 9: *Period of locomotion (In the case of the change of the locomotion speed)*

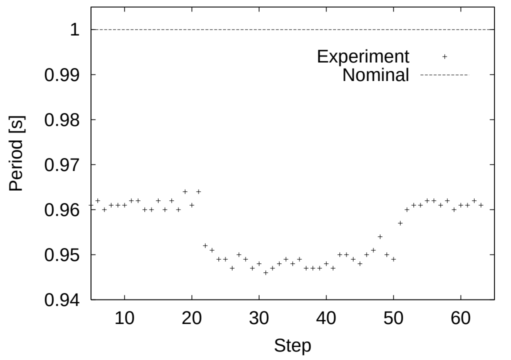

Figure 10: *Period of locomotion (In the case of the change of the slope angle)*