Abstract—In this paper, we investigate the locomotor behaviors of a biped robot on a splitbelt treadmill using a locomotion-control system composed of nonlinear oscillators with phase resetting. Our results show that the robot establishes stable walking on the treadmill at various speeds of the belts due to modulation of the rhythm and phase by phase resetting. In addition, the phase differences between the leg movements shifted from out of phase, and duty factors were autonomously modulated depending on the speed discrepancy between the belts occurring through dynamic interactions among the robot’s mechanical system, the oscillator control system, and the environment. Such shifts of phase differences between the leg movements and modulations of duty factors are observed during human splitbelt treadmill walking, and our results suggest that our dynamic model using the robot and oscillator control system reflects a certain essence of the ability to produce adaptive locomotor behaviors.

I. INTRODUCTION

Humans and animals produce adaptive walking in diverse environments by cooperatively and skillfully manipulating their complicated and redundant musculoskeletal systems. To elucidate the neuro-control mechanisms producing adaptive locomotor behaviors, physiological studies have investigated locomotor mechanisms by examining the configurations and activities of neural systems. However, it is difficult to fully clarify the mechanisms in terms of the nervous system alone because locomotion is a well-organized motion generated through dynamic interactions of the body, its nervous system, and the environment. To surmount such limitations, constructive approaches using robots have recently attracted attention, since robots have become effective tools for testing hypotheses of locomotor mechanisms and control systems by demonstrating real-world dynamic characteristics [10–13], [19], [21].

In robotic studies, there has been increasing interest in the study of legged robots. However, unlike humans and animals, these robots still have difficulties in achieving adaptive behaviors in various situations, and a huge gap remains between them. Therefore, to create new control strategies, it is natural to use ideas inspired from biological systems, and thus many biologically-inspired robots have been developed. In particular, the physiological concept of central pattern generators (CPGs) has been widely used in the locomotion control of legged robots [1], [2], [10], [12], [13], [16], [17]. CPGs can produce oscillatory behaviors even without rhythmic input and proprioceptive feedback. However, they must use sensory feedback to produce effective locomotor behavior. Physiological studies have shown that locomotor rhythm and its phases are modulated through resetting the locomotor rhythm induced by a shift in phase, based on sensory afferents and perturbations (phase resetting) [8], [9], [14], [22]. Such rhythm and phase modulations in phase resetting have for the most part been investigated during fictive locomotion in cats, and their functional roles during actual locomotion remain largely unclear. However, recent simulation studies have demonstrated that phase resetting plays an important role in generating adaptive human locomotion [5], [17]. In addition, our previous works developed a locomotion control system for biped robots using nonlinear oscillators with phase resetting based on the concept of CPG, and they showed that phase resetting contributes to the generation of adaptive walking [1], [2]. Furthermore, stability analysis with simple biped models has demonstrated the usefulness of the phase-resetting mechanism [4], [6]. To create adaptive locomotor behavior, interlimb coordination of the legs is a crucial factor. To investigate the mechanism controlling the interlimb coordination, a split-belt treadmill is a useful tool [7], [15], [18], [20]. It is equipped with two belts that each has its own motor, and thus their speeds can be controlled independently. Various speed conditions, such as the same speed (tied configuration) and different speeds (splitbelt configuration) between the belts, are used to investigate how humans adapt to various situations.

In this paper, we use our developed locomotion control system and a splitbelt treadmill to investigate how a biped robot generates adaptive walking behaviors through dynamical interactions among the robot’s mechanical system, the oscillator control system, and the environment under various speed conditions of the splitbelt. In particular, we examined how the roles of phase resetting control the interlimb coordination in this particular environmental situation.

II. EXPERIMENTAL SETUP

A. Biped robot

We used a biped robot developed in [3] (Fig. 1), which consists of a trunk composed of two parts, a pair of arms composed of two links, and a pair of legs composed of...
five links. Each link is connected to the others through a rotational joint with a single degree of freedom. Each joint has a motor and encoder to manipulate the angle. Four touch sensors are attached to the corners of the sole of each foot.

The left and right legs are numbered Legs 1 and 2, respectively. The joints of the legs are also numbered: Joints 1 \( \cdots \) 5 from the side of the trunk. The arms are numbered in a similar manner. The joint that connects the upper and lower parts of the trunk is named Waist Joint. To describe these configurations, we introduce angles \( \theta_W \), \( \theta^{i}_{Aj} \), and \( \theta^{i}_{Lk} \) (\( i = 1, 2 \), \( j = 1, 2 \), \( k = 1, \ldots, 5 \)), which are the rotation angles of the Waist Joint, Joint \( j \) of Arm \( i \), and Joint \( k \) of Leg \( i \). Table I shows the physical parameters of the robot.

The electric power is externally supplied and the robot is controlled by an external host computer (Intel Pentium 4 2.8 GHz, RT-Linux), which calculates the desired joint motions and solves the oscillator phase dynamics in the locomotion control system. It receives the command signals at intervals of 1 ms. The robot is connected with the electric power unit and the host computer by cables that are held up during the experiment to avoid influencing the walking.

B. Splitbelt treadmill

We developed a splitbelt treadmill (Fig. 2) with two parallel belts (Belts 1 and 2) and two motors with encoders, a structure that allows independent control of the belts’ speeds. The width of each belt is 15 cm and the length between the rotation axes is 64 cm. The robot walks on this treadmill under various speed conditions.

III. LOCOMOTION CONTROL SYSTEM

In this study, we used the same locomotion-control system using nonlinear oscillators, as in our previous studies [1–3], and changed the environmental setting using the splitbelt treadmill. This approach allowed us to investigate the adaptability in interlimb coordination through dynamical interactions among the robot’s mechanical system, the oscillator control system, and the environment. Therefore, here we briefly explain our locomotion control system.

The locomotion control system consists of a motion generator and a motion controller (Fig. 3A). The motion generator is composed of a rhythm generator and a trajectory generator to produce the desired leg motions based on the desired locomotion speed. The rhythm generator produces basic locomotor rhythm and phase for the leg movements using four oscillators (Leg 1, Leg 2, Trunk, and Inter oscillators) and touch sensor signals (Fig. 3B). The trajectory generator produces the desired leg joint movements from the oscillator phases. The motion controller consists of motor controllers to control the joint angles by motors based on the desired movements. We explain the details of each system below.

A. Trajectory generator

The desired leg movements are designed by the desired trajectory of Joint 4 relative to the trunk in the pitch plane, which consists of the swing and stance phases (Fig. 4). For the swing phase, the desired trajectory is composed of a simple closed curve that includes an anterior extreme position (AEP) and a posterior extreme position (PEP). It starts from the PEP and continues until the foot touches the ground. During the stance phase, Joint 4 traces out a straight line from the landing position (LP) to the PEP. In both the swing and stance phases, the angular movement of Joint 4 is designed so that the foot is parallel to the line that connects the AEP and PEP. The lower trunk is at an angle of \( \psi_H \) to the line perpendicular to the line connecting the AEP and
PEP. Distance between the AEP and PEP is given by $D$. We defined the swing and stance phase durations as $T_{sw}$ and $T_{st}$, respectively, for the case when the foot contacts the ground at the AEP ($LP = AEP$). The nominal duty factor $\beta$, the nominal stride length $S$, and the nominal locomotion speed $v$ are respectively then given by

$$\beta = \frac{T_{st}}{T_{sw} + T_{st}}, \quad S = \frac{T_{sw} + T_{st}}{T_{st}}D, \quad v = \frac{D}{T_{st}} \quad (1)$$

These two desired trajectories provide the desired motion $\dot{\theta}_{L,j}^i$ ($i = 1, 2, j = 2, 3, 4$) of Joint $j$ of Leg $i$ by the function of phase $\phi_j^i$ of Leg $i$ oscillator, where we use $\phi_j^i = 0$ at the PEP and $\phi_j^i = \phi_{AEP}(= 2\pi (1 - \beta))$ at the AEP.

To increase the stability of bipedal locomotion in three-dimensional space, we used roll joints in the legs. We designed the desired motions $\dot{\theta}_{L1}^1$ and $\dot{\theta}_{L5}^i$ ($i = 1, 2$) of Joints 1 and 5 of Leg $i$ by the functions of phase $\phi_T$ of Trunk oscillator by

$$\dot{\theta}_{L1}^1 = R \cos(\phi_T + \delta), \quad \dot{\theta}_{L5}^i = -R \cos(\phi_T + \delta) \quad (2)$$

where $R$ is the amplitude of the roll motion and $\delta$ determines the phase relationship between the leg movements in the pitch and roll planes.

In this study, we did not move the arm joints but fixed them during locomotion.

B. Rhythm generator

The rhythm generator produces the basic locomotor rhythm using four simple phase oscillators (Leg 1, Leg 2, Trunk, and Inter oscillators) and receives touch sensor signals to modulate the rhythm by phase resetting (Fig. 3B). We define $\phi_L^i$, $\phi_T$, and $\phi_{H}^i$ ($i = 1, 2$) as the phases of Leg $i$, Trunk, and Inter oscillators, respectively, and employ the following phase dynamics:

$$\dot{\phi}_L = \omega + g_{1L} \quad \dot{\phi}_T = \omega + g_{1T} \quad \dot{\phi}_{H}^i = \omega + g_{1L}^i + g_{2L}^i \quad i = 1, 2 \quad (3)$$

where $\omega$ is the basic oscillator frequency that uses the same value among the oscillators ($\omega = 2\pi/(T_{sw} + T_{st})$); $g_{1L}$, $g_{1T}$, and $g_{1L}^i$ ($i = 1, 2$) are functions related to the interlimb coordination shown below; and $g_{2L}^i$ ($i = 1, 2$) is a function related to the phase and rhythm modulation based on phase resetting in response to touch sensor signals given below.

C. Interlimb coordination

The aim of this paper is to investigate how to create adaptive walking through dynamical interactions among the robot mechanical system, the oscillator network system, and the environment under various speed conditions of the splitbelt by focusing on the interlimb coordination of the legs. Since the desired leg kinematics are designed by the corresponding oscillator phases, the interlimb coordination is represented by the phase relationship, that is, the phase difference, between the leg oscillators. Functions $g_{1L}$, $g_{1T}$, and $g_{1L}^i$ in (3) modulates the interlimb coordination and are given as follows by using the phase differences between oscillators based on Inter oscillator,

$$g_{1L} = -\sum_{i=1}^2 K_L \sin(\phi_T - \phi_L^i + (-1)^i \pi/2)$$

$$g_{1T} = -K_T \sin(\phi_T - \phi_H)$$

$$g_{1L}^i = -K_L \sin(\phi_L^i - \phi_T - (-1)^i \pi/2) \quad i = 1, 2 \quad (4)$$
where $K_L$ and $K_T$ are gain constants. Depending on gain parameter $K_L$, these functions move the phase relationship between the legs into the desired state in which two legs move out of phase to each other; $\phi^i_L - \phi^j_L = \pi$. Therefore, when we use a large value for gain parameter $K_L$, the phase difference $\phi^i_L - \phi^j_L = \pi$ will be satisfied. On the other hand, when we use a small value for gain parameter $K_L$, the phase difference between the legs can be shifted from out of phase and will be determined only through locomotion dynamics. These interactions are shown by the blue arrows in Fig. 3B.

D. Phase resetting

Phase resetting contributes to the generation of adaptive human walking by modulating motor commands based on sensory information [5], [17] and the phase resetting mechanism has been used for biped robots [1], [2], [16], [17]. To produce adaptive walking through dynamic interactions among the robot mechanical system, the oscillator control system, and the environment, we modulated the locomotor phase and rhythm by phase resetting based on touch sensor signals. Function $g^{i}_{2L}$ in (3) corresponds to this regulation. When the foot of Leg $i$ lands on the ground, phase $\phi^i_L$ of Leg $i$ oscillator is reset to $\phi_{\text{AEP}}$ from $\phi_{\text{land}}$ at the landing ($i = 1, 2$). Therefore, the functions $g^{i}_{2L}$ is written by

$$g^{i}_{2L} = (\phi_{\text{AEP}} - \phi_{\text{land}}) \delta(t - t_{\text{land}}) \quad i = 1, 2$$

(5)

where $t_{\text{land}}$ is the time when the foot of Leg $i$ lands on the ground ($i = 1, 2$) and $\delta(\cdot)$ denotes Dirac’s delta function. Note that the touch sensor signals not only modulate the locomotor rhythm and its phase but also switch the leg motions from the swing to the stance phase, as described in Section III-A.

E. Motor controller

The motor controller manipulates the joint angle based on the desired joint movement generated by the oscillator phases. The input torque $u^{i}_{t_{j}}$ ($i = 1, 2$, $j = 1, \ldots, 5$) for Joint $j$ of Leg $i$ is given by

$$u^{i}_{t_{j}} = -\kappa^{i}_{t_{j}} (\hat{\theta}^{i}_{t_{j}} - \hat{\theta}^{j}_{t_{j}} (\phi^i_L)) - \sigma^{i}_{t_{j}} \hat{\theta}^{i}_{t_{j}}$$

$i = 1, 2$, $j = 1, \ldots, 5$

(6)

where $\kappa^{i}_{t_{j}}$ and $\sigma^{i}_{t_{j}}$ ($i = 1, 2$, $j = 1, \ldots, 5$) are gain constants and we used adequately large values to establish the desired leg movements.

IV. RESULTS

A. Generation of walking under various speed conditions

To investigate how the robot establishes adaptive walking on the splitbelt treadmill, we prepared various conditions for the speeds of the left-side belt $v_1$ and the right-side belt $v_2$: 1) tied configuration with $v_1 = v_2$, 2) splitbelt configuration with $v_1 > v_2$, and 3) splitbelt configuration with $v_1 < v_2$. We used the following parameters without depending on the speed conditions of the splitbelt: $D = 2.5$ cm, $T_{\text{sw}} = 0.35$ s, $T_{\text{u}} = 0.35$ s, $R = 3^\circ$, $\delta = -170^\circ$, $\psi_{\text{H}} = 5^\circ$, $K_T = 10$, and $K_L = 1.5$, which results in $\beta = 0.5$, $S = 5$ cm, and $\nu = 7.1$ cm/s in (1). To clearly see the differences among various speed conditions, the robot first walked on the tied configuration. After the robot established steady walking, we changed the speed condition of the splitbelt from the tied to splitbelt configuration.

When we did not use phase resetting, the robot easily fell down. However, the robot with phase resetting achieved steady and straight walking on the splitbelt treadmill in a way that one foot contacts only the ipsilateral belt during locomotion, even when one belt speed is 1.6 times faster than the other belt speed ($v_1 = 8.5$, $v_2 = 5.4$ cm/s, see supplementary movie). When the speed discrepancy between the belts was larger than that, the robot did not fall down but it was difficult to establish a straight walk for a long time.

B. Emergence of adaptability

To investigate why the robot produced steady and straight walking without changing control parameters despite various speed conditions, we examined the phase differences between the leg oscillators $\phi^i_L - \phi^j_L$ and the duty factors of the legs.

Figure 5 shows the representative results, where we changed the speed condition from the tied configuration 1) $(v_1 = v_2 = 6.9$ cm/s) to the splitbelt configuration 2) $(v_1 = 8.5$, $v_2 = 5.4$ cm/s) and from the tied configuration to the splitbelt configuration 3) $(v_1 = 5.4$, $v_2 = 8.5$ cm/s). Figure 5A illustrates the phase differences between the leg oscillators $\phi^i_L - \phi^j_L$ during locomotion. For the tied configuration 1), although the phase differences fluctuate discretely due to phase resetting, they remain almost $\pi$ rad, meaning that the two legs move out of phase to each other during locomotion. However, for the splitbelt configurations 2) and 3), the average of the phase differences slightly shifted from $\pi$ rad (indicated by arrows), showing that the phase relationship between the leg movements changed from out of phase due to the discrepancy between the belt speeds. Figure 5B shows the duty factors of the legs during locomotion. Although the legs had almost the same value in the tied configuration 1), the values were slightly different between the legs for the splitbelt configurations 2) and 3) (indicated by arrows).

To more clearly see these effects, we conducted thorough investigations using various values of the belt speeds. Figure 6 shows the changes of the phase difference between the leg oscillators from the tied configuration to the splitbelt configuration (A) and the changes of the duty factors of the legs (B) relative to the speed discrepancy between the belts, calculated by averaging over ten gait cycles for each trial. Data points and error bars correspond to means and standard deviations of five experiments. This figure clearly shows that the phase difference shifted from $\pi$ rad and that duty factors changed depending on the speed discrepancy between the belts (indicated by arrows).

C. Role of phase resetting

As shown in the previous sections, the robot established stable walking on the splitbelt treadmill using phase resetting, where the phase difference between the leg oscillators
and the duty factors of the legs were autonomously modulated depending on the speed discrepancy between the belts. To investigate the reasons for these changes, we examined the reset values of the leg oscillators \( \phi_i \) (\( i = 1, 2, 3 \)) in (7) by phase resetting. Figure 7 shows the results, obtained from the experiments in Fig. 5, where we changed the speed condition from the tied configuration 1) to the splitbelt configurations 2) and 3). For the tied configuration 1), the oscillator phases are reset at the same value between the leg oscillators. On the other hand, for the splitbelt configurations 2) and 3), the oscillator phases are reset at different values between the leg oscillators (indicated by arrows). These results suggest that phase resetting modulates locomotor rhythm and its phase depending on the environmental situation and contributes to the generation of adaptive locomotor behaviors on the splitbelt treadmill.

D. Constraint on the interlimb coordination

As explained in Section III-C, when we used a large value for \( K_1 (= 10.0) \), the phase difference between the leg oscillators remained nearly \( \pi \) rad during locomotion, even on the splitbelt configurations, unlike Fig. 5(A). In addition, the duty factors of the legs did not change, unlike Fig. 5(B). Although the robot did not fall down, it was difficult to establish a straight walk for a large speed discrepancy between the belts. These findings suggest that the phase shift and the modulation of the duty factors contribute to the generation of adaptive walking.

V. DISCUSSION

In general, environmental variations, such as speed discrepancy between the belts, decrease the locomotion stability of a biped robot, unless the robot changes the control strategy or control parameters to cope with such variations. However, our robot established stable walking without changing control strategy and parameters, despite a large discrepancy between the belt speeds. Instead, the phase differences between the leg movements shifted from out of phase and the duty factors of the legs did not change, unlike Fig. 5(B). In addition, the duty factors of the legs did not change, unlike Fig. 5(A). Although the robot did not fall down, it was difficult to establish a straight walk for a large speed discrepancy between the belts. These findings suggest that the phase shift and the modulation of the duty factors contribute to the generation of adaptive walking.
of the foot contact between the legs. For example, since the stance leg on the belt with higher speed is pulled more backward than the contralateral leg, the robot falls forward and the foot contacts of the contralateral leg become earlier. Such temporal asymmetry resulted in changes of the reset values of the leg oscillator phases due to phase resetting (Fig. 7). These changes shifted the phase differences of the leg oscillators and modulated the phase relationship between the leg movements, creating spatial asymmetry of locomotor behaviors. These temporal and spatial asymmetries reflect the adaptability achieved during the splitbelt treadmill walking, which we did not specifically design. This adaptability emerged through dynamic interactions among the robot’s mechanical system, the oscillator control system, and the environment, which is not trivial. When the robot movements are completely predetermined, as in the case without phase resetting (Section IV-A), the robots cannot establish such adaptability.

Since we used only touch sensor signals to modulate the robot’s movements and did not use any vision or gyro sensors, the adaptability of our control system is limited. However, the shifts of the phase differences between the leg movements and the modulations of the duty factors of the legs are observed during human splitbelt treadmill walking [7], [15], [20], and our results suggest that our dynamic model using the robot and oscillator control system reflects some essence of the ability to produce adaptive locomotor behaviors.

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![Fig. 7. Phase reset values when changing the speed condition from the tied configuration $v_1 = v_2$ to the splitbelt configuration $v_1 > v_2$ or $v_1 < v_2$.](attachment:figure7.png)