Experimental Verification of Gait Transition from Quadrupedal to Bipedal Locomotion of an Oscillator-driven Biped Robot

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Abstract—This paper addresses the control of the gait change from quadrupedal to bipedal locomotion of a biped robot. In our previous work, we developed a locomotion control system using nonlinear oscillators that generate adaptive walking behavior verified by numerical simulations and hardware experiments. We extended it to deal with the gait change from quadrupedal to bipedal by designing kinematic coordination between these gait patterns, which was only verified by numerical simulations. In this paper, we create a biped robot and improve the control system to verify the performance of the proposed control system.

I. INTRODUCTION

Animals including humans can generate locomotor behaviors adaptively to diverse environments. They walk on level ground, walk up and down slopes, walk fast and slow, and turn to the left and right. Some animals crawl, walk quadrupedally, walk bipedally, run, hop, leap, and jump. One object of robotics is to reproduce such adaptive behaviors and elucidate the mechanisms inherent in their anatomical structure, control systems, and information processing. Furthermore, exploiting such findings in various fields is crucial. For that purpose, researchers have created various legged robots, such as biped and quadruped, and simulation models.

Such locomotor behaviors as walking and running are rhythmic motions. Therefore, a steady gait for a biped robot implies a stable limit cycle in its state space, indicating that we need to control the robot to achieve a limit cycle to produce a stable gait. In addition, to establish adaptive behavior, a robot must change its behavior depending on situations. Since different steady gaits have different stable limit cycles, a change of gait pattern implies that the state moves from one limit cycle to another. Even if a robot obtains steady gait patterns, the transition is not always completed. That is, the trajectory between limit cycles is not necessarily stable. Although many studies have investigated how to establish limit cycles for various gait patterns, their transitions have not really been examined; they remain difficult.

In our previous work, we investigated the turning behavior of a biped robot based on numerical simulations and hardware experiments by establishing the turning motion by straight and curved walking [3], where the turning consisted of two types of limit cycles (straight and curved walking) and the transition between them. In this paper, we deal with the gait transition from quadrupedal to bipedal of a biped robot while walking. These gait patterns originally suffer from poor stability, and the transition requires drastic changes in robot posture from the gait change between straight and curved walking, which aggravates the difficulty of establishing the transition without falling over. Our previous work developed simple control systems for quadruped and biped robots using nonlinear oscillators and revealed that they achieved steady and robust walking verified by numerical simulations and hardware experiments [2], [19]. Furthermore, we extended the control systems to cope with the gait transition from quadrupedal to bipedal by designing kinematic coordination between these gait patterns, which was only verified by numerical simulations [4], [5]. It is important to verify the performance of the proposed control system by using an actual robot. In this paper, we developed a biped robot and improved the control system to do it.

II. BIPED ROBOT

We developed a biped robot that consists of a trunk composed of two links, a pair of arms composed of two links, and a pair of legs composed of five links (Figs. 1A and B). Figure 2A shows the schematic model of the robot. Each link is connected to the others through a single degree of freedom rotational joint. Each joint has a motor to manipulate the angle. Four touch sensors are attached to the corners of the sole of each foot and one touch sensor is attached to the tip of the hand of each arm. 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, where Joints 1 and 2 are the roll and pitch hip joints, respectively, Joint 3 is the pitch knee joint, and Joints 4 and 5 are the pitch and roll ankle joints, respectively. The arms are also numbered in a similar manner. Joint 1 is the pitch shoulder joint and Joint 2 is the pitch elbow joint. The trunk consists of the upper and lower parts and has the waist joint.
Computations. The difficulty of establishing adaptability to various environments in the real world is often pointed out, indicating that these robots are too rigid to adequately react to environmental changes. Therefore, the key issue is establishing a supple robot by adequately changing its internal structure and response based on interactions between the robot and the environment.

In contrast to robots, animals adapt themselves to various environments by cooperatively manipulating their complicated and redundant musculoskeletal systems. Many studies have elucidated the mechanisms in their motion generation and control. In particular, neurophysiological studies have revealed that animal walking is generated by central pattern generators (CPGs) [14] that are widely modeled using nonlinear oscillators [18]. Based on such CPG models, many biped robots and their control systems have been developed [2–5], [12], [13], [16].

CPGs, which generate signals delivered to motoneurons that control the activity of corresponding muscles, can produce oscillatory behaviors in the absence of rhythmic input and proprioceptive feedback. Physiological findings imply that CPGs consist of hierarchical networks through interneurons: Rhythm Generator (RG) and Pattern Formation (PF) networks [8], [17]. The RG network generates a basic rhythm and alters it by producing phase shift and rhythm resetting affected by sensory afferents and perturbations. The PF network shapes the rhythm into spatiotemporal patterns of signals to be delivered to motoneurons through interneurons. CPGs separately control the locomotor rhythm and motoneuron activation pattern.

To establish adaptive walking behavior, we designed a locomotion control system with an internal structure that adapts to environmental changes by referring to such CPG characteristics [2–5]. We employed nonlinear oscillators as internal states that generate rhythmic signals appropriately responding to sensory signals and designed desired joint motions from the rhythmic signals. In the walking behavior, one crucial factor is the interaction between the feet and the ground. Since the leg motion consists of swing and stance phases, it is essential to adequately switch from one phase to another so that the robot creates kinematically and dynamically appropriate motion. Therefore, the control system focused on this point by modulating the signal generation of the oscillators and appropriately changing the leg motions from the swing to the stance phase based on touch sensors. We investigated the performance of the control system not only by numerical simulations and hardware experiments but also by theoretical analyses [6], [7].

2) Architecture of the locomotion control system: In the following sections, we describe the developed locomotion control system (see our previous work [2], [3] for further details) that establishes quadrupedal and bipedal walking.

The locomotion control system consists of a motion generator and a motion controller (Fig. 3A), which controls the robot based on upper commands that contain the desired locomotion speed and gait pattern. The motion generator is comprised of rhythm and trajectory generators. The rhythm
generator employs six oscillators: Leg 1, Leg 2, Arm 1, Arm 2, Trunk, and Inter oscillators (Fig. 3B). The oscillators create basic rhythm and interact with each other as shown by the blue arrows. Some receive touch sensor signals as shown by red arrows and modulate the rhythm and phase. The trajectory generator creates the desired trajectories of the robot joints using the oscillator phases, which means that it generates the physical kinematics based on the rhythmic signals from the oscillators. The desired trajectories are sent to the motion controller where the motor controllers manipulate the joint angles to follow the desired trajectories. Note that although the physical kinematics is different between quadrupedal and bipedal walking, we used the same control system regardless of gait patterns, except for the kinematics.

3) Trajectory generator: The trajectory generator creates the desired trajectories of all joints using the oscillator phases. First, let \( \phi_L, \phi_A, \phi_T, \) and \( \phi_i (i = 1, 2) \) be the phases of Leg \( i \), Arm \( i \), Trunk, and Inter oscillators, respectively.

The desired trajectories of the leg joints are determined by designing the desired trajectory of the foot, specifically Joint 4, relative to the trunk in the pitch plane, which consists of the swing and stance phases (Fig. 4A). The former is composed of a simple closed curve that includes an anterior extreme position (AEP) and a posterior extreme position (PEP). It starts from point PEP and continues until the leg touches the ground. The latter consists of a straight line from the foot landing position (LP) to point PEP. Therefore, this trajectory depends on the timing of the foot contact with the ground in each step cycle. Both in the swing and stance phases, desired foot movement is designed to be parallel to the line that involves points AEP and PEP. The height and forward bias from the center of points AEP and PEP to Joint 2 of the leg are defined as parameters \( \Delta_L \) and \( H_L \), respectively. These two desired foot trajectories provide desired trajectories \( \theta_L (i = 1, 2, j = 2, 3, 4) \) of Joint \( j \) (hip, knee, and ankle pitch joints) of Leg \( i \) by the functions of phase \( \phi_L \) of Leg \( i \) oscillator written by \( \theta_L (\phi_L) \), where we used \( \phi_L = 0 \) at point PEP and \( \phi_L = \phi_{AEP} \) at point AEP. Note that desired stride \( \hat{S} \) is given by the distance between points AEP and PEP, and duty factor \( \beta \) is given by the ratio between the desired stance phase and step cycle durations.

The desired trajectories for the arm joints are designed as the leg joints except for the bend direction between Joint 2 of the arm and Joint 3 of the leg (Fig. 4B), where the desired trajectory of the hand, specifically the touch sensor at the tip of the arm, is designed relative to the trunk in the pitch plane. From the inverse kinematics, desired trajectories \( \theta_{\alpha j} (i, j = 1, 2) \) of Joint \( j \) of Arm \( i \) are given by the functions of phase \( \phi_A \) of Arm \( i \) oscillator. These desired trajectories have parameters \( \Delta_A \) and \( H_A \) and use the same desired stride \( \hat{S} \) and duty factor \( \beta \) as the legs.

To achieve the desired joint trajectories, the motor controllers in the motion controller manipulate the angles using high-gain feedback control.

4) Desired kinematics and parameters: The desired robot kinematics are designed using the desired trajectories for the legs and arms described above. Figures 5A and B show the schematics and kinematic parameters for quadrupedal and bipedal locomotion, respectively, where COM indicates the center of the mass of the upper trunk, \( l_U \) and \( l_T \) are the lengths from COM to Joint 1 of the arm and Joint 1 of the trunk in the pitch plane, respectively, \( l_W \) is the length from Joint 1 of the trunk to Joint 1 of the leg, \( L_A \) and \( L_L \) are the forward biases from COM to the centers of the desired foot and hand trajectories, respectively, \( \psi_H \) is the pitch angle of the lower trunk relative to the perpendicular line to the line that involves points AEP and PEP of the foot or the hand trajectory, \( \psi_W \) is the pitch angle of the upper trunk relative to the lower trunk, and \( \beta_A \) and \( \beta_B \) indicate the parameter for quadrupedal and bipedal walking, respectively. Note that parameters \( L_A \) and \( L_L \) are kinematically determined by parameters \( \Delta_A, \Delta_L, \psi_H, \) and \( \psi_W \) as follows:

\[
\begin{align*}
L_A &= l_U \sin(\psi_H + \psi_W) + \Delta_A \\
L_L &= l_L \sin(\psi_H + \psi_W) + l_W \sin \psi_H + \Delta_L
\end{align*}
\]

(1)

Also note that \( L_A^B \) and \( L_L^B \) are both set to 0, as shown in Fig. 5B. Since the hands do not touch the ground during bipedal walking, the trajectory just follows the closed curve.
5) Rhythm generator: The rhythm generator creates the basic rhythm for the locomotor behavior. The oscillators produce rhythmic behaviors by following the phase dynamics

\[
\begin{align*}
\phi_i &= \tilde{\omega} + g_{11} \\
\phi_T &= \tilde{\omega} + g_{1T} \\
\phi_A^i &= \tilde{\omega} + g_{1A}^i + g_{2A}^i \quad i = 1, 2 \\
\phi_L^i &= \tilde{\omega} + g_L^i + g_{2L}^i \quad i = 1, 2
\end{align*}
\]  

where \( \tilde{\omega} \) is the basic oscillator frequency that uses the same value between the oscillators, \( g_{11}, g_{1T}, g_{1A}^i, \) and \( g_{1L}^i \) (\( i = 1, 2 \)) are functions regarding the desired phase relationship shown below, and \( g_{2A}^i \) and \( g_{2L}^i \) (\( i = 1, 2 \)) are functions arising from the sensory signals given below. As mentioned above, the desired locomotion speed is determined from the descending upper commands. Since locomotion speed is determined from three independent parameters (stride, step cycle, and duty factor), we used desired stride \( \tilde{S} \), swing phase duration \( T_{sw} \), and duty factor \( \beta \), where oscillator frequency \( \tilde{\omega} \) and locomotion speed \( \tilde{v} \) are obtained from

\[
\begin{align*}
\tilde{\omega} &= 2\pi \frac{1 - \beta}{T_{sw}}, \\
\tilde{v} &= \frac{1 - \beta}{\beta} \frac{\tilde{S}}{T_{sw}}
\end{align*}
\]  

Note that they are satisfied regardless of gait pattern.

The coordination of joint motions, especially, the interlimb coordination is essential. For example, both legs must move out of phase to prevent the robot from toppling during bipedal locomotion. Since the desired joint motions are designed by oscillator phases, interlimb coordination is given by the phase differences between oscillators. To cope with it, functions \( g_{11}, g_{1T}, g_{1A}^i, \) and \( g_{1L}^i \) in Eq. (2) are introduced by using the phase differences between oscillators based on Inter oscillator as follows:

\[
\begin{align*}
g_{11} &= -\sum_{i=1}^{2} K_L \sin(\phi_i - \phi_L^i + (-1)^i \pi/2) \\
g_{1T} &= -K_T \sin(\phi_T - \phi_L^i) \\
g_{1A}^i &= -K_A \sin(\phi_A^i - \phi_L^i + (-1)^i \pi/2) \quad i = 1, 2 \\
g_{1L}^i &= -K_L \sin(\phi_L^i - \phi_L^i - (-1)^i \pi/2) \quad i = 1, 2
\end{align*}
\]

where desired phase relations are given so that both the arms and legs move out of phase and one arm and the contralateral leg move in phase: \( \phi_A^i - \phi_L^i = \pi, \phi_A^i - \phi_L^i = \pi, \) and \( \phi_A^i - \phi_L^i = 0, \) and \( K_L, K_A, \) and \( K_T \) are gain constants.

The modulation of walking rhythm and phase is another important factor. Functions \( g_{2A}^i \) and \( g_{2L}^i \) modulate them by resetting the oscillator phases based on touch sensor signals. When the hand of Arm \( i \) (the foot of Leg \( i \)) lands on the ground, phase \( \phi_A^i \) of Arm \( i \) oscillator (phase \( \phi_L^i \) of Leg \( i \) oscillator) is reset to \( \phi_{AEP} \) from \( \phi_L^i \) at the landing (\( i = 1, 2 \)). Therefore, functions \( g_{2A}^i \) and \( g_{2L}^i \) are written by

\[
\begin{align*}
g_{2A}^i &= (\phi_{AEP} - \phi_L^i) \delta(t - t_{land}^i) \quad i = 1, 2 \\
g_{2L}^i &= (\phi_{AEP} - \phi_L^i) \delta(t - t_{land}^i) \quad i = 1, 2
\end{align*}
\]

where \( \phi_{AEP} = 2\pi(1 - \beta), t_{land}^i \) is the time when the hand of Arm \( i \) (the foot of Leg \( i \)) lands on the ground (\( i = 1, 2 \)) and \( \delta(\cdot) \) denotes Dirac’s delta function. Note that touch sensor signals not only modulate the walking rhythm and phase but also switch the leg motions from the swing to the stance phase, as described above.

B. Gait change control system

In this section, we explain the control system to obtain gait change from quadrupedal to bipedal.

1) Control strategy: Joint movements are different between quadrupedal and bipedal. To change the gait patterns, we need to design additional joint movements to connect these gait patterns. Since a biped robot walks quadrupedally and bipedally while manipulating many degrees of freedom, there are a million ways to design them, which is critical.

As described in the last section, we created desired robot motions using the kinematic parameters \( \Delta_A, \Delta_L, H_A, H_L, \psi_H, \) and \( \psi_W \) for quadrupedal and bipedal, indicating that the differences in these parameters explain the gait patterns. Therefore, from a kinematic viewpoint, gait transition is achieved by changing these parameters from \( \Delta_A^Q, \Delta_L^Q, H_A^Q, H_L^Q, \psi_H^Q, \) and \( \psi_W^Q \) to \( \Delta_A^B, \Delta_L^B, H_A^B, H_L^B, \psi_H^B, \) and \( \psi_W^B \), while the robot is walking. However, many parameters must still be changed, and it is necessary to determine how.

Animals, which generate various motions and smoothly change them, cooperatively manipulate their complicated and redundant musculoskeletal systems. To elucidate these mechanisms, many studies have investigated recorded electromyographic (EMG) activities, revealing that muscle activity patterns are expressed by the combination of several patterns, despite their complexity [9], [10], [15]. In addition, various motions share some muscle activity patterns and different motions only have a few different specific patterns, suggesting that only a few patterns provide cooperation in different complex movements. As well as muscle coordination, kinematic coordination plays an important role [1], [11].

This paper reduces the kinematic parameters by designing the coordination during gait change by cooperatively changing the physical kinematics from quadrupedal to bipedal.

The crucial issue is the change of the number of limbs that support the body. When the robot implements the gait change, its arms and legs must adequately support its body to prevent from falling over. Therefore, the hand and foot positions on the same side must be close together when the hands leave the ground and the robot starts to walk bipedally. Not only this kinematic element but also the trunk
posture is key, since the robot must raise its trunk during the gait transition. To manipulate these kinematic elements, we introduce two parameters, $ξ_1$ and $ξ_2$, and encode kinematic parameters $ΔA$, $ΔL$, $H_A$, $H_L$, $ψ_H$, and $ψ_W$ by

$$ΔA(ξ_1, ξ_2) = ΔA^Q - (l_1 sin(ψ_H(ξ_1, ξ_2) + ψ_W(ξ_1, ξ_2)) + ΔA^Q)ξ_1$$
$$ΔL(ξ_1, ξ_2) = ΔL^Q - (l_2 sin(ψ_H(ξ_1, ξ_2) + ψ_W(ξ_1, ξ_2)) + ΔL^Q)ξ_2$$
$$H_A(ξ_1, ξ_2) = H_A^Q + (H_A^R - H_A^Q)ξ_2$$
$$H_L(ξ_1, ξ_2) = H_L^Q + (H_L^R - H_L^Q)ξ_2$$
$$ψ_H(ξ_1, ξ_2) = ψ_H^Q + (ψ_H^R - ψ_H^Q)ξ_2$$
$$ψ_W(ξ_1, ξ_2) = ψ_W^Q + (ψ_W^R - ψ_W^Q)ξ_2$$

(6)

These functions mean that parameters $ξ_1$ and $ξ_2$ are used to change the distance between the foot and hand trajectories and the posture of the trunk, respectively. Using this controller, gait transition is achieved by simply changing the introduced parameters ($ξ_1, ξ_2$) from (0, 0) to (1, 1).

2) Design of gait change: The robot implements the gait change, when the robot receives an upper command to do it. In particular, we changed parameters $ξ_1$ and $ξ_2$ by following two successive steps (see Fig. 6):

Step 1: when the robot receives the command, parameter $ξ_1$ is linearly increased from 0 to $ξ_1$ ($0 ≤ ξ_1 ≤ 1$) during time interval $T_1$ s.

Step 2: after the left arm (Arm 1) starts the swing phase, $ξ_1$ and $ξ_2$ are linearly increased from $ξ_1$ to 1 and from 0 to 1, respectively, during time interval $T_2$ s.

This strategy aims to move the foot and hand trajectories closer during Step 1 while it walks quadrupedally. During Step 2, the robot raises its trunk to start walking bipedally.

IV. EXPERIMENTAL RESULTS

This section examines if the proposed control system establishes gait transition using the developed biped robot.

We used the following parameters: $ξ_1 = 0.7$, $T_1 = 2.0$ s, $T_2 = 4.5$ s, $S = 4.5$ cm, $β = 0.5$, $T_{sw} = 0.5$ s, $K_T = 20$, $K_A = 10$, $K_L = 10$, $l_U = 8.0$ cm, $h_I = 7.0$ cm, and $l_W = 6.2$ cm; the remaining parameters are shown in Table II. Figure 7 shows the joint angles (pitch angles of trunk, left arm, and left leg) during the gait transition, where the solid and dotted line are actual and desired angles, respectively. Figure 8 shows snapshots of the gait transition (see attached movie). The robot started to walk quadrupedally. When 17 s passed, the robot received an upper command and changed the gait pattern from quadrupedal to bipedal through Steps 1 and 2. These results demonstrate that the proposed control system establishes the gait transition.

V. CONCLUSION

In this paper, we developed a biped robot and verified the performance of the proposed control system to change the gait pattern from quadrupedal to bipedal. Although the robot successfully established the gait change, we must investigate the contributions of the oscillator behaviors with phase modulation to the gait transition for further details.

### Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quadrupedal ($ξ_1^Q$)</th>
<th>Bipedal ($ξ_1^B$)</th>
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<tr>
<td>$ΔA$ [cm]</td>
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<tr>
<td>$ΔL$ [cm]</td>
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<td>$ψ_H$ [deg]</td>
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<tr>
<td>$ψ_W$ [deg]</td>
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<td>5.0</td>
</tr>
</tbody>
</table>

Fig. 6. Designed trajectory in $ξ_1$-$ξ_2$ plane to change gait pattern from quadrupedal to bipedal walking.

Fig. 7. Joint angles during gait transition.

Fig. 8. Snapshots of the gait transition (see attached movie).
Fig. 8. Snapshots of gait transition from quadrupedal to bipedal walking

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