Shuffle Traveling of Humanoid Robots

Masanao Koeda, Masayuki Ueno, and Takayuki Serizawa

Abstract—Recently, many researchers have been studying methods for the stepless slip motion of humanoid robots. However, the control mechanism is not clear. In this paper, we propose a simple feedback control method for slip motion based on the forward and backward tilting of the body. We verified this control method by using a life-size humanoid dynamic simulator that was constructed with Open Dynamics Engine. By controlling the body tilt using a proportional controller, the robot can reach the target position with stepless motion.

I. INTRODUCTION

Conventionally, biped robots perform walking and turning motions by stepping with their feet. As illustrated in Fig. 1, conventional motion loops of humanoid robots are generated using only two states: standing and stepping. The motions generated by combining these two states are suitable for long-range movements. However, they are inefficient and generally unsuitable in narrow spaces with constrained postures, as shown in Fig. 2. Biped robots are expected to be used in energy plant inspection/demolition, kitchens, and search and rescue tasks in disaster areas. These are all tasks that take place in narrow spaces with constrained postures.

Recently, we have been focusing on a method that involves the stepless and swingless slip motion of humanoid robots to realize smooth, quick, and high-stability movement [1-6], which we call shuffle motion. Other researchers have also examined the narrow space motions and slip motions of biped robots. Harada et al. [7] realized narrow space movements with a conventional stepping motion by having the robot hold onto the environment. Miura et al. [8-10] reported a model in which a minimal amount of energy is consumed from floor friction when both feet are in a slip turning motion. They conducted their experiments by using a humanoid robot and simulator and concluded that the friction coefficient of the floor has no effect on slip turning. Nishikawa [11] developed a humanoid robot with an extrusion pin on each foot to realize a stepless turning movement. However, the proposed robot requires a specialized mechanism on its feet. Hashimoto et al. [12] investigated a quick slip turn for a humanoid robot using a passive toe joint and demonstrated the high-energy efficiency of a slip turn. Research has been conducted on step walking on low-friction floors [13-16].

In this study, we investigated a method for medium- to long-range movements using only shuffling motions. We developed a feedback controller for shuffle motion based on the forward and backward tilting of the body. We used a life-size humanoid dynamic simulator to verify that the robot can reach the target position and attitude through only stepless and swingless motion.

Fig. 1 State transition diagram for humanoid robots

Fig. 2 Humanoids are expected to act in narrow spaces under constrained postures

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II. VARIETY OF SHUFFLE TRANSLATIONS

As shown in Fig. 3, shuffle translation can be classified into three types based on the foot motion:
(a) Sequential side-slipping motion
(b) Simultaneous nonparallel shuffling motion
(c) Simultaneous parallel shuffling motion.

In this study, we used the simultaneous nonparallel shuffling motion depicted in Fig. 3(b), which is considered more balanced and stable than the others because it can be generated without swinging the body.

III. VARIETY OF LOAD DISTRIBUTIONS

Almost every humanoid robot has flat and square soles. There are a number of combinations that can be used to distribute loads across the soles. Typical load distributions are listed in [1]; their features are presented in Fig. 4. These patterns should be selected as the situation dictates. In this study, we focused on pattern (a) (non-uniform distribution) because of its stability and symmetry.

IV. SIMULATION

Open Dynamics Engine (ODE) is an open-source, high-performance library for dynamic simulations. We used ODE ver. 0.11-1 (double-precision type) to simulate humanoid robot dynamics. We ran our simulation on a computer with the following specifications: a CPU with an Intel Core2 Duo 1.2-GHz processor and 4 GB of RAM running the Windows 7 Professional 32-bit OS.

The simulated robot had 12 degrees of freedom (DOFs) in the lower body, as illustrated in Fig. 5. The foot size, link length of the leg, and weight of the body parts were determined by referring to [17] for a 24–29 year old male Japanese. Table 1 lists the parameters in detail. In this simulation, the dynamic friction coefficient of the floor was set to 0.2 based on empirical data. Fig. 6 shows an overview of the humanoid model in this simulation.

The initial position was set to the origin point \( (x, y, z) = (0, 0, 0) \), the initial joint angles were set to upright standing, and the initial frontal direction was in the \(-y\) axis direction.
Table 1 Parameters of humanoid model in simulator

<table>
<thead>
<tr>
<th>Name</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body height</td>
<td>1706 [mm]</td>
</tr>
<tr>
<td>Knee height</td>
<td>429.6 [mm]</td>
</tr>
<tr>
<td>Crotch height</td>
<td>759.7 [mm]</td>
</tr>
<tr>
<td>Side neck height</td>
<td>1440 [mm]</td>
</tr>
<tr>
<td>Hip breadth</td>
<td>340.3 [mm]</td>
</tr>
<tr>
<td>Hip depth</td>
<td>255.3 [mm]</td>
</tr>
<tr>
<td>Thigh circumference</td>
<td>536.4 [mm]</td>
</tr>
<tr>
<td>Calf circumference</td>
<td>366.8 [mm]</td>
</tr>
<tr>
<td>Foot depth length</td>
<td>249.4 [mm]</td>
</tr>
<tr>
<td>Projected foot breadth</td>
<td>96.3 [mm]</td>
</tr>
<tr>
<td>Foot circumference</td>
<td>247.8 [mm]</td>
</tr>
<tr>
<td>Cervical height, sitting</td>
<td>653.2 [mm]</td>
</tr>
<tr>
<td>Head height</td>
<td>237.1 [mm]</td>
</tr>
<tr>
<td>Body weight</td>
<td>64.9 [kg]</td>
</tr>
<tr>
<td>Trunk weight</td>
<td>44.9 [kg]</td>
</tr>
<tr>
<td>Leg weight</td>
<td>10.0 [kg]</td>
</tr>
</tbody>
</table>

V. MOTION SEQUENCE OF SHUFFLE TRANSLATION

For the robot to translate leftward by repeated shuffling motions, it processes four states of the feet motion sequentially, as illustrated in Fig. 7:

1. Change load distribution to pattern (a) in Fig. 4 by controlling the sole angles.
2. Shuffle turn by +30 [deg] with the right foot and -30 [deg] with the left foot along the z axis.
3. Change the load distribution to the opposite corners of pattern (A) in Fig. 4 by controlling sole angles.
4. Shuffle turn by -30 [deg] with the right foot and +30 [deg] with the left foot along the z axis.

To change the moving direction to rightward, only the sole angle control (states 1 and 3) has to be changed.

If the conditions are successfully managed, the ideal moving distance can be calculated by the following equation:

$$d = 2L \sin(q_r)$$

where $L$ is the depth length of the sole. In this simulation, $L = 249.4$ [mm] and $q_r = 30$ [deg]. Under these conditions, the ideal moving distance was calculated to be 249.4 [mm/step].
body tilt angle and traveling direction. In this experiment, the angle of the body tilt was set to -5, 0, and +5 [deg] along the x axis before the shuffle translation was started. Shuffle translation was performed in both the left and right directions while the body tilt was maintained.

Fig. 11 shows the experimental results, and Fig. 12 shows snapshots of the robot traveling. Over four shuffle steps, the translation distance was approximately 1 [m], and the change in direction was approximately 90 [deg]. Thus, this fairly simple control was demonstrated to be effective for the shuffle traveling of humanoid robot.

VII. POSITION AND ATTITUDE CONTROL BY BODY TILT

Next, we tried to control the position and attitude of the robot through body tilting. The difference between the current direction \( g_c \) and current target direction \( g_d \) was feedback to the forward / backward body tilt angle \( \theta \). The target attitude was calculated through the following equation:

\[
y = \left( \frac{g_f x_f - 2 y_f}{x_f^3} \right) x + \left( g_f x_f + 3 y_f y_x \right) x^2
\]

where \( x_f, y_f \) is the final position, \( g_f = \frac{dy}{dx} \bigg |_{x=x_f} \) and \( g_c = \frac{dy}{dx} \bigg |_{x=x_c} \) are the final and current direction of the robot respectively. This equation creates a cubic curve that smoothly connects two points: the origin (0, 0) and \((x_f, y_f)\).

Experiments were conducted under the following three conditions;

Condition 1: \((x_f, y_f) = (3, 1) \text{ [m]}, g_d = 0 \text{ [deg]}\)
Condition 2: \((x_f, y_f) = (3, 0) \text{ [m]}, g_d = 0 \text{ [deg]}\)
Condition 3: \((x_f, y_f) = (3, -1) \text{ [m]}, g_d = 0 \text{ [deg]}\)

The robot was continuously translated along the x axis by shuffling until the current position of the robot \( x_c \) was over \( x_d \). The calculated \( d = g_d - g_c \) was fed back to the body tilt angle \( \theta_{t+1} = \theta_t + K_p d \), where \( K_p \) is the proportional gain for feedback and was set to \( K_p = 0.1 \) empirically. To avoid rollover, \( \theta \) was limited to \(-5 \leq \theta \leq 5\).

Fig. 13 shows the experimental results. Fig. 13(a) and (b) show the traveling trajectory and direction change of the robot, respectively. Under experimental conditions 1 and 3, both the trajectory and direction nearly stayed on the target curve until the end of the travel. However, under condition 2, large deviations in both the position and direction occurred. This deviations may have been caused by the simple P controller and can be solved by using a PI or PID controller.

VIII. CONCLUSION

We proposed a control scheme for controlling the direction of a robot during shuffle translation based on forward/backward tilting of the body. Although the scheme is quite simple, it can dynamically control the direction of shuffle translation by changing the tilt angle of the body. We also demonstrated that the scheme can be used for long-range traveling control through continuous shuffle motion for the robot to reach the target position and attitude. This control is...
still in the rough design stages, and there is still much to improve on. In future work, we will try to realize more robust control by using sensors, such as foot-mounted force/torque sensors to determine the zero moment point. We will also conduct experiments not only with simulators but also real humanoid robots to confirm the scheme’s wide range of applicability.

REFERENCES


Fig. 12 Snapshots of direction control by body tilting