Shuffle Turn and Translation of Humanoid Robots

Masanao Koeda, Yumi Uda, Seiji Sugiyama, and Tsuneo Yoshikawa

Abstract—This paper proposes a novel shuffle-translating method that combines shuffle turns repeatedly for a humanoid robot. Conventionally, the walking motion of a humanoid robot is performed through a repeated foot stepping motion. However, this motion is inefficient and has low stability. Previously, we have studied the shuffle-turning method for a humanoid robot, which can perform a stepless and stable turning.

In this paper, we present a precise shuffle turn with feedback control and a new shuffle translation method by repeating shuffle turns. Experiments using a humanoid robot were conducted and the results revealed that the proposed method was effective for shuffle translation.

I. INTRODUCTION

Humans routinely move within narrow spaces and in constrained postures during their everyday activities. When working in a kitchen, for example, cooking, washing dishes, fetching a piece of cookware, or doing some other task related to their work, cooks move around a sink area in a stooped or knee-bent position. In automobile assembly lines, workers move within narrow spaces and in constrained postures when assembling car parts. In nursing care, support personnel may lift a patient from his or her bed with their arms in a constrained position when turning to place the patient in a wheelchair within a narrow medical ward. Finally, in plant construction tasks, field workers perform much of their work in narrow spaces and constrained postures.

Biped robots conventionally perform walking and turning motions through repeated foot stepping as they move around their environment. These kinds of motions are easy to generate because they can be treated similarly to walking motions. However, foot stepping is inefficient, time consuming, unstable, and generally unsuitable for use in narrow spaces under constrained postures, as illustrated in Fig. 1.

Recently, we have been studying a method that involves the stepless shuffle motion of humanoid robots to realize smooth, quick, and high stability moving [1][2]. The main feature of the shuffle motion is that the load distributions of each sole are controlled to be nonuniform to take into account the effect of floor friction. As illustrated in Fig. 2, the 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 mid- and long-range movements. However, they are not suitable for narrow spaces in constrained positions. Shuffling is a newly developed state but one that has received little attention from researchers thus far.

As shown in Fig. 3, the shuffling motion is not generated by stepping, but by rotating the legs while maintaining contact with the soles and the floor. This is suitable for short-range movement with high stability and low energy consumption because of the stepless motion, and it is useful in a narrow space in a constrained posture because it takes advantage of stepless motion.

There has been a great deal of research on the narrow space motions and slip motions of biped robots. Harada et al. [3] realized a narrow space movement with a conventional stepping motion by grasping the environment. Miura et al. [4] reported a model in which a minimal amount of energy was consumed from floor friction when both feet were in a slip turning motion. They conducted their experiments using a humanoid robot and a simulator, and they concluded that the friction coefficient of the floor had no effect on slip turning.
Afterward, the model was extended to study asymmetric load balance, and a friction coefficient was input into the model equation [5]. They concluded that the model error was not negligible for a large velocity motion and that standing on tiptoes to reduce the ground contact area may solve the problem. Nishikawa [6] developed a humanoid robot that has an extrusion pin on each foot, and can thus realize a stepless turning movement. However, the proposed robot requires a specialized mechanism on its feet. Hashimoto et al. [7] 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 the walking movements of biped robots on low-friction floors [8][9][10][11]. However, these studies did not report on the turning motions of biped robots.

Previous research has been carried out on the turning motion with shuffling; however, the translation motion was not mentioned. Our end goal is to realize full moving motion of humanoid robots using shuffling under various situations, to integrate the shuffle motion into the conventional stepping motion, and to select the most suitable motion depending on the situation. In this paper, we describe shuffle turning with feedback control, and shuffle translation by controlling the load distributions of soles.

II. CONTROL SCHEME FOR PRECISE SHUFFLE TURNING

A. Variety of shuffle translation

In terms of foot motion, shuffle translation can be classified into the following three typical patterns illustrated in Fig. 4 (note that, in Fig. 4, the soles of the feet are always fully touching the ground):

(a) sequential side-slipping motion
(b) simultaneous nonparallel shuffling motion
(c) simultaneous parallel shuffling motion

In this paper, we target the simultaneous parallel shuffling motion depicted in Fig. 4-(c), which requires the same motion for both legs. The load distributions are easy to control in this method.

To realize this motion, shuffle turn must be realized repeatedly and precisely. Therefore, we apply a proportional-integral (PI) control scheme and its efficiencies are a priori investigated by experiments using a humanoid robot.

B. Control scheme

The coordination system of the feet $\Sigma_B$ is illustrated in Fig. 5-(a),(b). The origin position of the coordination system $\Sigma_B$ is arranged in the middle between the rotational center points. The positions of the rotational center of the right and left sole in the initial state are described as

\[
\begin{align*}
\mathbf{r}_s &= \begin{bmatrix} r_{sx} & r_{sy} \end{bmatrix}^T \quad (1) \\
\mathbf{l}_s &= \begin{bmatrix} l_{sx} & l_{sy} \end{bmatrix}^T \quad (2)
\end{align*}
\]

(a) Sequential side-slipping motion

(b) Simultaneous nonparallel shuffling motion

(c) Simultaneous parallel shuffling motion

Fig. 4. Feet motion of shuffle translation

(a) Start feet position

(b) End feet position

(c) Body

Fig. 5. Coordination system and rotational center

Fig. 3. Shuffle turn
After the shuffle turn by $q_r$ is conducted, the positions of the rotational centers in $\Sigma_H$ can be written as:

$$ r_c = R r_s $$  
$$ l_c = R l_s $$  
$$ R = \begin{bmatrix} \cos q_r & \sin q_r \\ -\sin q_r & \cos q_r \end{bmatrix} $$

The coordination system $\Sigma_H$, which is shown in Fig.5-(c), is settled on the center of the hip joint of the robot. The joint angles of legs on $\Sigma_H$ are calculated from $r_c$ and $l_c$ by solving the inverse kinematics problem.

The error value between the current angle and the target angle can be measured using the PI feedback algorithm. The control scheme is given by:

$$ q_c(t) = q_r(t) - q_c(t) $$  
$$ q_r(t+1) = q_r(t+1) + K_p q_c(t) + K_i \int q_c(t) dt $$

where $q_r(t+1)$ is the target angle at $t+1$, $q_c(t)$ is the rotated angle at $t$, $q_r(t)$ is the angular error at $t$, $q_r(t+1)$ is the modified target angle at $t+1$, and $K_p (= 0.054)$ and $K_i (= 0.054)$ are the proportional and integral gain respectively.

Following the $q_c$, which is given by Eq. (7), the rotation motion is generated by Eqs. (3), (4) and (5). $q_r$ is calculated by integration of the value of the angular velocity sensor that is mounted on the robot. We proved that this method can measure the angle between $\Sigma_H$ and $\Sigma_B$ in advance.

### C. System configuration

Our experimental system consists of a humanoid robot HOAP-2 and a host PC. HOAP-2 is a commercial humanoid robot that was developed by Miyachi Systems Corporation; the robot has 25[DOF] in total. The height of the robot is 500[mm] and the weight is 7[kg] approximately. The size of foot is 98[mm] by 63[mm]. The distance between feet is 47[mm] at the initial standing posture. In each foot, 4 force sensors are mounted, and 3 axis acceleration/angular sensors are equipped in its body. The soles of the foot are made of POM. The robot is controlled in [ms] through the PC which is running RT-Linux OS.

In the following experiments, two kinds of floors with different friction coefficients are used. The friction coefficients were measured using the measurement device depicted in Fig. 6. The device has a vice bench with a tiltable clump, and the tilt angle can be measured using a scale. The floorboard was clamped using the vice and a piece of plastic of the same material and size of the sole was put on the floorboard.

When tilting the vice, the piece of plastic started slipping on the board. The static friction coefficient $\mu$ was calculated by the following equation:

$$ \mu = \tan \theta $$

where $\theta$ is the tilting angle of the clamp.

In addition, on the assumption that the piece of plastic has a constant acceleration, the dynamic friction coefficient $\mu'$ can be calculated using

$$ \mu' = \tan \theta - \frac{2s}{t^2 y \cos \theta} $$

where $\theta$ is the tilting angle of the clamp, $s$ is the slipping length, $t$ is the slipping time, and $g (= 9.81[\text{m/s}^2])$ is the acceleration of gravity.

Using these equations, the friction coefficients of the two kinds of floor material used in the following experiments were measured, the results of which are presented in Table I. The values in the table are the averaged value of 10 measurements.

### D. Experimental conditions

There are a number of varying combinations for how loads can be distributed across the soles. Most humanoid robots have flat and square soles; patterns of their typical load distribution are depicted in Fig. 7. These patterns should be selected as the situation dictates.

In this paper, we focus on the following two characteristic load patterns:

- Pattern (a): nonuniform and symmetrical distribution
- Pattern (e): uniform distribution

To change the load distribution in pattern (a), the joints of the ankle are rotated by +1[deg] about the $x, y$ axis in the

<table>
<thead>
<tr>
<th>Flooring</th>
<th>Static Friction Coef.</th>
<th>Dynamic Friction Coef.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cork</td>
<td>0.420 (0.025)</td>
<td>0.226 (0.095)</td>
</tr>
<tr>
<td>Static Coef.</td>
<td>0.467 (0.019)</td>
<td>0.431 (0.019)</td>
</tr>
</tbody>
</table>

Fig. 6. Measurement of coefficient of floor friction
right foot, and by -1[deg] about the \( x, y \) axis in the left foot, before turning. In actuality, these tilts are not discernible to the eye because of the backlash of the joints, and the stability is not impaired practically. In pattern (e), the ankle joints are maintained in a constant horizontal position.

On the low and high friction floor, experiments with and without feedback control were conducted 5 times respectively, and the averaged rotation angle was compared. The target angle was set to 30[deg] for 4[s] and a constant angular velocity of 7.5[deg/s]. The rotation angle was measured by the integration of an angular velocity sensor mounted on the robot.

E. Effect of feedback control for shuffle turning

Figs. 8 and 9 depict the rotation angle at the end of the motion of each pattern. The results reveal that the rotation angle was closer to the target angle with feedback control than that without feedback control. This reveals that the control scheme performs effectively for precise shuffle turning.

III. SHUFFLE TRANSLATION

A. Experimental Conditions

Shuffle translation is conducted by performing shuffle turn in opposite directions repeatedly, as depicted in Fig. 10. To move rightward by shuffle translation, the motion sequence of feet is in the following order:

1) change load distribution to left front of the sole
2) shuffle turn by +\( q_r \)
3) change load distribution to left rear of the sole
4) shuffle turn by -2\( q_r \)
5) change load distribution to left front of the sole
6) shuffle turn by +\( q_r \)
If the conditions are successfully managed, the moving distance $d$ can be:

$$d = 2L \sin q_r$$  \hspace{1cm} (10)

where $L$ means the length of the sole. The length of the sole of the robot is 98[mm], so $d$ can be calculated as 51[mm].

In these experiments, $q_r=15[\text{deg}]$ in 3.5[s] was employed because of the limitation of the joint movement of the robot. The experiments were conducted 5 times on the low and high friction floor, with and without the feedback control, respectively. The average of the moving distance was compared.

**B. Results**

Fig. 11 depicts the snapshots of the experiment while shuffle translating with feedback control on the low friction floor. The grid lines on the floor were drawn at 10[mm] intervals, and the translating motions of the feet were measured using the grid in this experiment. The rotation angle was measured by integration of an angular velocity sensor mounted on the robot.

The averaged value and the standard deviation of the moving distance are shown in Fig. 12, and the time-series data of the rotation angle when shuffle translating is also shown in Fig. 13. The green lines in the figures indicate the target values.

From the results, the rotation angles were closer to the target angles with feedback control, and the moving distance was also nearer the desired value with feedback control than that without feedback control; with feedback control, the moving distance was nearly constant regardless of the floor friction. However, without feedback control, the distance varied by the friction. The main causes of the error of the distance were the effect of the floor friction and the misalignment of the rotational center.

**IV. CONCLUSION**

In this paper, we proposed a shuffle translating method using repeated shuffle turns for a humanoid robot. The precise shuffle turning with feedback control was described and the experimental results revealed that the control scheme performs effectively. Experiments of shuffle translation were also conducted on a low and high friction floor, with and without feedback control, respectively. With feedback control, the moving distance was nearly constant on both floors; however, without feedback control, the distance was affected by the friction. This revealed that the shuffle translation performed properly, and that feedback control was needed to achieve fewer effects from the material or condition of the floor.

In future work, we plan to implement another shuffle translating pattern, to analyze the relationship between friction and motion, to investigate the zero moment point (ZMP) trajectories, to evaluate the stability while shuffling quantitatively, and to develop a comprehensive method for moving by combining the conventional step walk and the shuffling motions presented herein.

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**REFERENCES**

Fig. 11. Snapshots of right shuffle translation on low friction floor (upper: whole body, lower: feet in closeup)

(a) Initial position
(b) Change load distribution to left front
(c) Turn left by 15 [deg]
(d) Change load distribution to left rear
(e) Turn right by 30 [deg]
(f) Change load distribution to left front
(g) Turn left by 15 [deg]
(h) Change load distribution to center

Fig. 13. Time series of turning angle while shuffle translating

(a) on low friction floor
(b) on high friction floor