Load Gradient Model in Foot Soles for Non-Parallel Shuffling Humanoid Walk

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Abstract—Natural disaster prevention and reduction strategies are of national importance. In Japan, earthquakes occur frequently and are often of a significant magnitude. Such occurrences of natural disasters require adequate preparations, and robots are the preferred choice of personnel for disaster-related search and rescue tasks. Humanoid robots, in particular, can modify their behavior depending on the situations or conditions, and are expected to be used in disaster-affected areas for search and rescue activities. This study focuses on the humanoid robot shuffling walk, which is expected to be advantageous when moving around a narrow area with a constrained posture, as is often required for rescue operations in the devastated area. This report will propose a new load gradient model in foot soles for the synchronous, non-parallel shuffling walk of humanoid robots, for efficient movement.

Keywords—humanoid robot; slip; load gradient model; non-parallel shuffling humanoid walk

I. INTRODUCTION

During rescue operations within devastated areas, rescue operators are required to access narrow areas to reach victims in distress. Wheel-based mobile robots such as PackBot [1] are used for search activities in such confined spaces. Mobile robots have low flexibility and versatility when compared with humanoid robots. However, humanoid robots have low mobility in confined spaces. There are several previous studies investigating this issue [2]-[5]. Previous research papers focusing on robot sliding motion are limited in number, with such studies proposing the models of sliding mechanism and dynamic control [6],[7].

Our team has also studied about this activity, focusing on the robot shuffling motion [8]-[14]. It is important to control the support points and slide, while shuffling. In critical situations such as during an emergency rescue, static control is superior from the point of view of safety.

In this report, we propose a new load gradient model to investigate the motion of the soles of robotic feet. In addition, we will investigate a static control method for the synchronous, non-parallel shuffling walk of humanoid robots. We show some preliminary experimental results obtained by using the proposed methods. The results indicate the effectiveness of the proposed methods.
II. CATEGORIZATION OF THE SHUFFLING WALK

The shuffling walk is generated by stepless motion and sliding soles. The shuffling walk is described in [11], [12] (Fig. 1). Three types of shuffling walk are described in [15] and the following descriptions are partially quoted from [15].

- Asynchronous shuffling walk (Fig. 2-(a)): The asynchronous shuffling walk is generated by sliding one foot at a time. It can help the robot take long steps. However, it is relatively unstable because the center of gravity needs to be shifted dynamically.
- Synchronous, parallel feet shuffling walk (Fig. 2-(b)): The synchronous shuffling walk is generated by sliding both feet simultaneously and in parallel. It is relatively slow and needs to have controlled weight distribution on each foot. Therefore, it is unstable for the same reason as asynchronous shuffling walk.
- Synchronous, non-parallel feet shuffling walk (Fig. 2-(c)): The synchronous, non-parallel feet shuffling walk is generated by sliding both feet simultaneously and non-parallelly. It is relatively stable because the change in the center of gravity during movement is relatively small as compared to the two previously described shuffling walk methods.

In this study, we intend to focus on the load gradient model of the synchronous, non-parallel feet shuffling walk (Fig. 3), because of its stability.

III. LOAD GRADIENT MODEL

The total weight of the robot is assumed to be $W$, the size of each sole of the robot’s feet is given by $x_l, y_l$, and the sole of the robot’s foot is assumed to be rectangular in shape with a rigid plane (Fig. 4). The origin point is defined at the load position. For the coordinate axes, the left-right and front-back directions of the soles are assumed to be the $x$ and $y$ axes, respectively. The pressure, $N$, applied to the load position is set as the maximum, and at the diagonal point of the load position, the pressure is assumed to 0. Let $F_{xy}$ be the normal vector of the sole pressure gradient applied to a certain point $(x, y)$. With a coefficient of friction $\mu$, the friction force added to $(x, y)$ is $\mu N_{xy}$. Let the normal force at $(x, y)$ be $f(x, y)$, and set the following constraint conditions.

\[
\begin{align*}
    f(x_l, y_l) &= 0 \quad (1) \\
    f(x_l, 0) &= f_x \quad (2) \\
    f(0, y_l) &= f_y \quad (3)
\end{align*}
\]

The shuffling motion is slow and is not affected by inertia. From the constraints above, the equation of the sole force gradient is as follows.

\[
f(x, y) = -\frac{f_x}{x_l} x - \frac{f_y}{y_l} y + (f_x + f_y) \quad (4)
\]

This equation shows $f(0, 0) = f_x + f_y$ at the load position.

When calculating the multiple integral of $f(x, y)$ over the entire sole of the foot,
$V = \int f(x, y) \, dx \, dy = \frac{x_l y_l}{2} (f_x + f_y)$ (5)

For synchronous, non-parallel feet shuffling walk, $W$ is equally divided over the right and left legs, so $V = W/2$ for one foot.

$$\frac{x_l y_l}{2} (f_x + f_y) = \frac{W}{2}$$ (6)

$$f_x + f_y = \frac{W}{x_l y_l}$$ (7)

We adjust $f_x, f_y$ in the following expression;

$$f_x = \alpha F$$ (8)

$$f_y = (1 - \alpha) F$$ (9)

where $\alpha (0 \leq \alpha \leq 1)$ is the control parameter.

One model of translational friction and frictional rotation constraint was proposed in [16]. The model in this study will consider the corner pivoting motion, and does not take rotational friction into account.

IV. CONTROL METHOD

We define the coordinate systems of the robot body and foot sole as $\Sigma_{body}$, $\Sigma_{sole}$, respectively. The normal vector of the force plane is calculated from Eq.4,

$$\n_{xy} = \begin{pmatrix} -f_y/x_l \\ -f_x/y_l \\ f_x + f_y \end{pmatrix}$$ (10)

and the gradient vector $\nabla f$ of $f(x, y)$ is calculated using the equation below;

$$\nabla f = \begin{pmatrix} -f_y/x_l \\ -f_x/y_l \end{pmatrix}$$ (11)

Let $\theta_x$ be the angle between the vector of $\nabla f$ projected on the $xy$ plane and the $x$ axis of $\Sigma_{sole}$,

$$\tan \theta_x = \frac{-f_x/y_l}{-f_y/x_l} = \frac{\alpha F \cdot x_l}{(1 - \alpha) F \cdot y_l}$$ (12)

When solving with $\alpha$,

$$\alpha = \frac{y_l \cdot \tan \theta_x}{y_l \cdot \tan \theta_x + x_l}$$ (13)

For efficient lateral movement by synchronous, non-parallel feet shuffling, the frictional force is generated in the lateral direction by adjusting $\alpha$ to satisfy the following formula:

$$\theta_x = \theta_c$$ (14)
where $\theta_r$ is the relative angle of $\Sigma_{\text{sole}}$ to $\Sigma_{\text{body}}$.

V. SYSTEM OVERVIEW AND MOTION GENERATION

A commercially available humanoid robot, Robovie-X PRO (manufactured by Vstone Co., Ltd.), was used for this experiment. The robot has 19 degrees-of-freedom (DOF) (1 DOF in the head, 3 DOF in each arm, and 6 DOF in each leg), an approximate dimension of 380 mm (height) $\times$ 180 mm (width) $\times$ 73 mm (depth), an approximate weight of 2 kg, and an approximate foot sole size of 72 mm (width) $\times$ 123 mm (depth).

To measure the load on soles, an LL sensor (manufactured by Xiroku Inc.) was used [17]. LL sensor is shaped in the form of a sheet and can measure pressure distribution by detecting electromagnetic induction. The size of the sensor used is 580 mm $\times$ 480 mm. The gap of each sensor element is 12.5 mm and the number of sensor elements is 1660. The frame rate is 100 Hz.

RobovieMaker2 was used for the generation of robot motion. In the following experiments, robotic shuffling motions are created beforehand by following the ideal load gradient by observing the LL sensor output. Please note that the robot control is not given feedback from the sensors and is not in real time control.

Fig. 6 shows four possible load point patterns for synchronous, non-parallel feet shuffling movement toward the right direction. Each of the footstep shown progress from the upper to the lower image. In order to satisfy Eq. 14, the pivot points of each foot are moved according to the foot rotation. The angle $\theta$ of the foot rotation shown in Fig. 6 is set 5 degrees in the following experiments.

VI. EXPERIMENT AND RESULT

For each of the patterns described in Fig. 6, 20 steps of shuffling feet were performed five times, and the moving distance and the angle of rotation were measured. Fig. 7 shows snapshots of the robot sole loads while moving in the “loaded right side” pattern. The detail of all the joint angles for all the motions cannot be listed here due to document size constraints. In this paper, we present the one output from LL sensor while moving rightwards in loaded “right side” pattern in Fig. 8. The results of the moving trajectory of each load pattern are shown in Fig. 9. The results of the moving distance in the x and y directions and the angle of rotation are shown in Fig. 10.

In the case of the inner loaded pattern, the robot moved significantly in the longitudinal direction and negligibly in the lateral direction. The angle of rotation was also large.

In the case of the outer loaded pattern, the amount of movement and the angle of rotation were negligible. It is thought that the cancellation of the forces generated at the soles of both feet is the reason for the difficulty in lateral movement.

In the case of the leftward loaded pattern, the robot moved slightly to the right and also rotated slightly. The longitudinal forces generated at the soles of both feet are canceled, and leftward forces are generated; it is thought that this loading pattern produces inefficient lateral movement.

In the case of the rightward loaded pattern, the robot moved only to the right and the amount of movement was the greatest, when compared with the other loading patterns. The rotation angle was negligible. The longitudinal forces generated at the soles of both feet are canceled and rightward forces are synchronized. It is thought that it is efficient to move laterally with this loading pattern.

VII. CONCLUSION

In this study, we proposed a load gradient model and control strategy for the synchronous, non-parallel shuffling walk of a humanoid robot. Using the proposed methods, the results for the robot’s moving distance and angle of rotation differed greatly, depending on the loading pattern, and so the differences in effectiveness of the proposed method were confirmed.

For future study, we will seek to control the optimal contact state of robot feet soles using sole mounted sensors.

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Figure 6. Four load patterns for synchronous, non-parallel feet shuffling walk

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Figure 7. Snapshots of the shuffling motion when loaded on the right side

Figure 8. Snapshots of sole load measured by the LLsensor, while moving (loaded right side)

Figure 9. Moving trajectory of four load patterns

Figure 10. Moving distance and rotation angle (Error bars show standard deviation.)