Stability Improvement Using Soft Sole on Humanoid Robot

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Abstract — This paper shows the effect of a stability improvement of humanoid robot with a soft sole of feet which is aimed at walking on an uneven terrain. Generally, it was thought that the soft sole absorbs shocks but decrease stability at the same time. We conducted preliminary experiments of shifting center of gravity, stepping motions, and walking on an even/uneven terrain with and without soft sole of the feet. The experimental results show that the soft sole increases the stability in certain conditions.

Keywords — Humanoid Robot, Soft Sole, Stability, Uneven Terrain

I. Introduction

RECENTLY, various humanoid robots have been developed[1], [2]. For humanoid robots, walking skill is one of the most important and basically functions. However, at this time, it is difficult for humanoid robots to walk adaptively on the floor conditions such as a deformable floor like a grass plot or a sandy place, or an uneven terrain like a gravel road. Researches to walk on an uneven terrain by a humanoid robot can be classified into category; Active and Passive. The former aims for recognition of the condition of the floor using a sensor such as a stereo camera, or an ultrasonic sensor [3], [4], and generation of gait pattern depending on the floor condition [5], [6], [7]. Yamaguchi et al.[8] developed mechanical foot with shock absorbing material and investigated its stability.

Generally, it is known empirically that the soft sole absorbs shocks but decrease stability at the same time. We investigated the stability of a humanoid robot with a soft sole at the feet’s bottom. Experiments were conducted in following 3 motions; shifting the center of gravity, stepping, and walking on an even/uneven terrain, and stability margin was compared each of them with the case of not using any rubber foam. Finally, we show that the stability was improved in a certain condition contrary to our expectations.

II. System Overview

Our system consists of a humanoid robot HOAP-2(Fig.1) and a host PC. The system overview is shown in Fig.2.

A. HOAP-2

HOAP-2 is a commercial humanoid robot which is developed by FUJITSU AUTOMATION Ltd. Its height is 50[cm] and weight is 7[kg] approximately. The size of foot is 98[mm] by 63[mm]. Detailed specification is shown in TABLE I. In each foot, 4 force sensors are mounted, and 3 axis acceleration/angular sensors are equipped in its body. Fig.4 illustrates the size of the feet and the position of the force sensors. CH.0, 1, 2 and 3 show the position of the force sensors.

B. Host PC

The robot is controlled in 1[ms] through a host PC which is running RT-Linux OS. They are connected by USB interface. The PC sends control commands to the robot, and the robot transmits acquired data from several sensors. A wireless network based on 802.11b can be used for communication between the PC and the robot. However, we selected the wire communication because the moving range of the robot is not so large in this study.
C. Soft Sole

6 kinds of rubber foams of 5, 10, 15, 20, 25, and 30[mm] thickness were used as the soft material. The Young’s modulus of the rubber foam is 45.3[Pa]. The foams are cut in the same size as the robot’s foot and attached to the sole by a thin two-sided tape. Fig.3 shows the feet which is attached with 10[mm] rubber foam. When no rubber foam is attached, it is called “0[mm] thickness” afterward.

III. Evaluating Method

A. Stability Margin

To calculate stability of the robot quantitatively, "Stability margin" is defined as the following equation for evaluation criteria.

\[
(Stability \ Margin) = \min \{d_i \mid i = 1, 2, 3, 4\}
\]  \hspace{1cm} (1)

where \(d_i\) means the distance between ZMP(Zero Moment Point)[9] to each edge of the sole. In Fig.5, \(d_3\) becomes stability margin because of the shortest distance from ZMP to the right edge. It can be said that the stability is improved when the stability margin becomes large.

TABLE I

Specifications of HOAP-2

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>50[cm]</td>
</tr>
<tr>
<td>Weight</td>
<td>7[kg]</td>
</tr>
<tr>
<td>DOF</td>
<td>6 in Leg × 2</td>
</tr>
<tr>
<td></td>
<td>4 in Arm × 2</td>
</tr>
<tr>
<td></td>
<td>1 in West × 1</td>
</tr>
<tr>
<td></td>
<td>1 in Hand × 2</td>
</tr>
<tr>
<td></td>
<td>2 in Neck × 1</td>
</tr>
<tr>
<td>(Total 25DOF)</td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td></td>
</tr>
<tr>
<td>Joint Angle Sensor</td>
<td>Resolution: 0.01[deg/pulse]</td>
</tr>
<tr>
<td>3 Axis Accelerometer</td>
<td>Measuring Range: ±2[G]</td>
</tr>
<tr>
<td></td>
<td>Resolution: 0.005[G]</td>
</tr>
<tr>
<td>3 Axis Gyrometer</td>
<td>Measuring Range: ±60[deg/s]</td>
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<tr>
<td></td>
<td>Resolution: 0.25[deg/s]</td>
</tr>
<tr>
<td>Foot Load Sensor</td>
<td>4[ch/foot]</td>
</tr>
<tr>
<td>PC</td>
<td>OS: RT-Linux</td>
</tr>
<tr>
<td></td>
<td>CPU: Pentium4 2[GHz]</td>
</tr>
<tr>
<td></td>
<td>Memory: 1[GB]</td>
</tr>
<tr>
<td></td>
<td>Sampling Rate: 1[ms]</td>
</tr>
</tbody>
</table>

IV. Experiments and Results

We conducted the following 4 set of experiments; shifting center of gravity, stepping motions, and walking on an even/uneven terrain with and without the soft sole of the feet. To compare the experimental results easily, all motions were generated by a complete open loop without feedback from any sensors.

A. Shifting Center of Gravity

A.1 Right and Left

To move the center of gravity to the right and to the left, the leg was tilted slowly by 10[deg] without lifting the foot while the body was horizontal. This motion was operated for 20[sec]. Fig.7 shows the sequential images of this motion. This motion was operated 3 times in the
conditions that 7 kinds of rubber foam (from 0[mm] to 30[mm] thickness) was attached. Fig.6 shows temporal changes of the stability margin while 3 kinds of sole (0, 5, and 10[mm]). The horizontal axis shows time and the vertical axis shows the stability margin. In consideration of the measuring range of the force sensor, ZMP of the right foot in 0-10[sec] and ZMP of the left foot in 10-20[sec] were used to calculate the stability margins. The stability margins have decreased along with the shifting center of gravity. Moreover, the lowest value of the stability margin increases by attaching rubber foams. In the following experiments, the lowest values of the stability margin are compared. Fig.9-(a) shows the average of minimum stability margin in 7 kinds of soles. The stability margin became the maximum at 20[mm], and it tended to decrease in thicker rubber.

A.2 Backward and Forward

To move the center of gravity to backward and forward, the leg was tilted slowly by 5[deg] without lifting the foot while the body was horizontal. This motion was operated for 20[sec], and Fig.8 shows the sequential images of this motion. Fig.9-(b) shows the average of minimum stability margin in 7 soles. It shows that the rubber does not influence the stability margin so much in this motion.

B. Stepping Motion

Next, the stability margins while the spot stepping motion were compared. Experimental conditions were that one step took 8[sec] and each foot was lifted by 20[mm]. Fig.10 shows the sequential images of this motion. The averages of minimum stability margins while the motion was measured for 7 kinds of sole in 5 times respectively. The results are shown in Fig.11. To calculate the stability margin in the measuring range of the force sensor, the ZMP of the landing foot was calculated in 0-2[sec], 6-8[sec], 8-10[sec], and 14-16[sec]. The results shows that the stability had decreased when over 25[mm] thickness rubber was attached, and the same tendency appeared as the previous experiments.
C. Walking Motion

C.1 On Even Terrain

Experimental conditions were that one step took 6[sec], each foot was lifted by 20[mm], the length of stride was 30[mm], and the robot took 8 steps forward. The experiments were conducted 7 times in each sole respectively, and the stability margin and the number of non-fall were compared. Fig.12 shows the sequential images of this motion. Fig.13 shows the average of minimum stability margin of each experiment. Same as in
the case of the stepping motion, the ZMP of the landing foot was used. In whole of the conditions, the stability margin became small since the walking motion was unstable itself, and it shows a similar tendency as the previous experiments. Fig.17-(a) shows the number of non-fall while the robot takes 8 steps in 7 trials. The robot did not fall over when the rubber foam below 15[mm] thickness was attached on the sole. However, when the rubber was over 20[mm] thickness, the robot tended to become unstable and fall over.

C.2 On Uneven Terrain

Finally, we confirm the effect of the soft sole while walking on an uneven terrain. The motion is the same as the previous one. Fig. 14 shows the condition of the constructed uneven terrain for this experiment. Hemispheric convex objects of 5[mm] in diameter are arranged by every 80[mm] on a woody board. The character S in Fig.14 indicates the starting position and the 7 arrows which were drawn every 15[deg] mean the starting pose of the robot. Fig. 15 and 16 are the experimental snapshots when the robot which has 0 or 10[mm] rubber sole is walking in the direction of the red arrow in Fig.14. The numbers of non-fall in 7 trials are indicated in Fig.17-(b).

The experimental results shows that the excessive thickness of the rubber makes stability decrease, and the thickness about 10[mm] is suitable for walking on an uneven terrain.

V. CONCLUSION

In this paper, we described the stability improvement of a humanoid robot which was attached soft materials on its soles. We conducted experiments of shifting center of gravity, stepping motions, and walking on an even/uneven terrain with and without soft sole of the feet. As a result, comparing the soft sole with the hard sole in the point of view of the stability margin, soft soles increase stability in certain conditions. Proposed method is quite simple remodeling to improve the stability, and it is effective for an irregular terrain.

In the future, we will analyze this effect mathematically, and investigate the optimal thickness, hardness and shape of the sole, and we will also establish a suitable control method.

REFERENCES


Fig. 15. Uneven terrain walking with 0[mm] sole

Fig. 16. Uneven terrain walking with 10[mm] sole

Fig. 17. Number of non-fall while walking

