A sliding walk method for humanoid robots using ZMP feedback control

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Abstract—In this paper, we propose two methods for a highly stable sliding walk for humanoid robots working in narrow areas under constrained postures. The first method uses a new displacement of the center of gravity with Zero Moment Point (ZMP) feedback control. ZMP is a force distribution on the soles of the feet. This method is faster and more stable than previous techniques. The second method utilizes sliding forward movements using the inverse kinematics of the leg mechanism, which are calculated from the positions variation of the sole. The sliding walk is experimentally demonstrated using the humanoid robot HOAP-2, and an evaluation of the lateral variations in ZMP and the lateral acceleration variations are shown.

I. INTRODUCTION

Recently, humanoid robot research has prospered in an attempt to integrate humans and robots by taking into consideration the places where they could be most useful to society. As humanoid robots have similar physical characteristics, they can easily adapt to human environments. Another advantage is that due to their physical appearance, humans can easily become familiar with them and develop a friendlier relationship [1].

One scenario where humanoid robots can be useful is in health–care. Besides it is difficult to foresee all possible disturbances in such situations, humanoid robots must navigate through narrow places, move under constrained postures with balance difficulties, and transport heavy objects. In such cases, it is difficult for humanoid robots to move using a conventional stepping walk, as higher stability is necessary. It has been suggested that walking and turning using a foot sliding motion could provide this stability. In a sliding walk, it is not necessary to lift the legs or stand on one leg. Using a sliding walk, the robot also has a larger support polygon in terms of its Zero Moment Point (ZMP)[2]. As the target ZMP becomes wider, it is possible to achieve a smaller swinging motion, in comparison to conventional stepping walk (Fig. 1(a)). Besides, as the robot is supported by both legs during the sliding walk(Fig. 1(b)), it is possible to walk with a small displacement of the center of gravity, resulting in a shorter robot movement time.

Recently, there has been a great deal of research on narrow space motions and slip motions of biped robots. Harada et al. [3] realized narrow space movement with a conventional stepping motion. Miura et al. [4] reported a model in which a minimal amount of energy was consumed by 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. Afterwards, the model was extended to study an asymmetric load balance, and a friction coefficient was input into the model equation [5]. Hashimoto et al. [6] investigated a quick slip turn for a humanoid robot using a passive toe joint, and demonstrated the high energy efficiency of such a slip turn. The research has also been conducted on the walking movements of biped robots on low-friction floors [7]. There have been attempts to achieve a sliding walk and turn instead of lifting the legs. Koeda et al. [8] suggested a sliding turn considering the floor friction, and proved its effectiveness by conducting experiments with a humanoid robot. Miura et al. [9] proposed a modeling method for a 360 [deg] turn that led to the minimization of the loss of power ("power rate", in physics) during robot motion. Uda et al. [10] [11] extended the research of Koeda on sliding turns by implementing lateral motion in a humanoid robot.

In addition, Uda implemented forward motion using a sliding walk. Nevertheless, due to the experimentally obtained value of the center of gravity, and since Uda did not take into consideration the state of the ground, it is hard to say that the resulting motion can be always stable.

In this research, we implemented a sliding walk method that is always stable. This is achieved using the center of gravity displacement from the ZMP feedback control, obtained from pressure sensors located on the sole of each foot. The ZMP expresses the robot’s balance as a force distribution on each foot’s sole. In the following section we describe the PI control with ZMP on moving the center of gravity. In section III we present a forward, linear, and
parallel–to–the–floor sole movement for a humanoid robot.
In section IV we shortly introduce our research platform and
the ZMP on the soles of the feet. In section V we describe
experimental procedures and results from section II and III.
Finally, in section VI we summarize the presented methods
and results.

II. PI CONTROL OF THE DISPLACEMENT OF CENTER
OF GRAVITY WITH ZMP AS REFERENCE

Fig. 2 shows the methods of controlling the displacement
of the center of gravity used by Uda [10] and in this
research. Most existing humanoid robots perform a lateral
displacement of their center of gravity by controlling the
rotation of the X axis of hips and ankles at the same
time, as shown in Fig. 2(a). Nevertheless, this method of
controlling two joints at the same time has a high lateral
inertia that causes big variations in the ZMP, making control
very difficult. The method where each joint moves discretely
and successively has a smaller inertia and less variations
in ZMP. Besides, when a joint on one side is moving to
its desired position, the inertial force and the ZMP will
variations decrease on the other side and since the angle
difference between the hip joint and the ankle is big, the
sole tends to get separated from the floor surface. In a similar
way, if a variation is introduced in the displacement of each
joint, the sole will become separated from the floor.

In this research, after controlling the ankle joint with the
ZMP in each cycle, only the angle that caused a displacement
in the ankle will be used to control the hip joint, as shown in
Fig. 2(b). It is possible to move the center of gravity using
ZMP feedback with this method, as it reduces the variation
in the ZMP.

In addition, the center of gravity PI controlled to provide
the ZMP feedback. Let us consider \( p(t) \) as the current ZMP,
\( p_0 \) as the target ZMP, \( E(t) \) as the variation between them,
and \( \psi_{roll}(t) \) as the manipulation variable of the rotation over
the X axis needed to perform the control, as shown in Fig.
2(b). The center of gravity moves using PI control of the
ankle joint, as described in the block diagram in Fig. 3. The
control equation can be expressed as

\[
E(t) = p_0 - p(t),
\]

\[
\psi_{roll}(t) = K_P E(t) + K_I \int_0^t E(t) dt.
\]

In this research, we consider the proportional gain \( K_P \) as
0.0125, the integral gain \( K_I \) as 0.00025, and the sampling
time as 0.001 [s].

III. INVERSE KINEMATICS OF LEG MECHANISM

Within the present research, we implemented a forward,
linear, and parallel–to–the–floor sole movement for a hu-
manoid robot. To move the foot forward, it is necessary to
move the center of gravity; after that, we must rotate the leg
over both the Y axis and the X axis, performing a three–
dimensional movement. A model of the right leg mechanism
of a humanoid robot is shown in Fig. 4. A front view of the
humanoid robot right leg is shown in Fig. 4(a), the right side
view is shown in Fig. 4(b). In these leg mechanism models,
we consider the hip joint to have three degrees of freedom
(DOF) \((x,y,z)\), the knee to have one DOF \((x)\), and the ankle
joint to have two DOF \((x,y)\).

The \( \Sigma_{RF} \) coordinate system is defined using the hip joint
as the origin, and considers the forward direction to be the
X axis, the left direction to be the Y axis, and the vertical
line directed at the floor to be the Z axis, as shown in Fig.
4. We consider the position of the humanoid robot’s hip joint as
\( p_1 \), the position of the knee as \( p_2 \), the position of the ankle as
\( p_3 \), and the position of the foot as \( p_4 \). The length of the
humanoid robot’s thigh is \( l_1 \), the length of the calf is \( l_2 \), and the
distance from the ankle joint to the sole is \( l_3 \). As shown in
Fig. 2, the rotation of the hip joint and the ankle over the X
axis are given by \( \psi_1 \) and \( \psi_3 \), respectively, and observing this
from the \( XZ \) plane it is possible to obtain the line segments
as the product of \( \cos \psi_1 \), \( l_1 \), and \( l_2 \), respectively. We donate
the rotation angle over the Y axis as \( \theta_1 \) for the hip joint, \( \theta_2 \)
for the knee, and \( \theta_3 \) for the ankle joint. Considering a sliding
walk, the rotation over the \( x \) and \( y \) axes of \( p_4 \) will always
be 0 [rad]. Using forward kinematics, \( p_4 \) is given by

\[
p_4 = \begin{bmatrix}
    x_4 \\
    y_4 \\
    z_4
\end{bmatrix} = \begin{bmatrix}
    l_1 c_{\psi_3} s_{\theta_1} + l_2 c_{\psi_3} s_{\theta_1} \\
    (l_1 c_{\psi_3} c_{\theta_1} + l_2 c_{\psi_3} c_{\theta_1}) \psi_3 \\
    l_1 c_{\psi_3} c_{\theta_1} + l_2 c_{\psi_3} c_{\theta_1} + l_3
\end{bmatrix}.
\]

In this equation, the following abbreviations are used: \( c_{\psi_1} = 
\cos \psi_1 \), \( s_{\theta_3} = \sin (\theta_1 + \theta_2) \), and \( \tan \psi_2 \).

The coordinates of the current position of the foot can be
explained using Eq. (2), where angles \( \psi_1, \psi_3, \theta_1, \theta_2, \theta_3 \) can
be retrieved from the angle sensors of each joint.

As the foot coordinates obtained from Eq. (2) are added
to the variation caused by one step of the sliding walk, it
is possible to use inverse kinematics to calculate the angle
values after each step. According to the Fig. 4(a), we have

\[ \psi_1 = \text{atan2}(y_4, z_4 - l_3), \]
\[ \psi_3 = -\psi_1, \]

therefore with \( l_r = \sqrt{x_4^2 + (z_4 - l_3)^2} \), as shown in Fig. 4(b), it is possible to obtain

\[ \theta_1 = \cos^{-1} \left( \frac{l_1 \cos \psi_1^2 + l_2^2 - (l_3 \cos \psi_1)^2}{2l_1 \cos \psi_1 l_r} \right) + \text{atan2}(x_4, z_4 - l_3), \]  
\[ \theta_2 = -\pi + \cos^{-1} \left( \frac{l_1 \cos \psi_1^2 + (l_2 \cos \psi_1)^2 - l_3^2}{2l_1 \cos \psi_1 l_2 \cos \psi_1} \right), \]  
\[ \theta_3 = -(\theta_1 + \theta_2). \]  

If we divide the distance between the current position and the subsequent position into 500 equal parts, and solve Eqs. (3), (4), (5), (6), and (7) for each part, then, using the variations, it is possible to perform a sliding walk.

IV. SYSTEM CONFIGURATION

A. Humanoid robot HOAP–2

Fig. 5(a) shows the initial state of the robot, and Fig. 5(b) shows the state of the robot after a displacement of its center of gravity. The robot specifications are: 500 [mm] height, 6.5 [kg] weight, 25 DOF (two in the neck, four in the right arm, four in the left arm, one in the right hand, one in the hip, six in the right leg, and six in the left leg). It has four types of sensor: joint angle sensors, three-axis acceleration sensors, 3-axis angular velocity sensors, and pressure sensors located in its soles. The robot uses a standard USB1.0, capable of transmitting up to 12 [Mbps] with a control cycle of 1 [ms], to communicate.

B. Foot–pressure sensors

The position of the pressure sensors is indicated in Fig. 6. The sole of each foot of HOAP–2 is 98 [mm] of high, 63 [mm] wide, and, when the robot is standing, the distance between the soles is 15 [mm]. As shown in Fig. 6, the coordinates of the pressure sensors are indicated as CH.0, CH.1, CH.2, and CH.3, so each foot has four sensors, having one axis per sensor. Once the ZMP is calculated from the
foot pressure sensors, the coordinate system of each foot can be determined with the center of the foot as the origin and the X and Y axes parallel to the world coordinate system of the humanoid robot, i.e., the X axis in the forward direction and the Y axis extending to the robot’s left. Regarding the ZMP calculation, the origin of each foot can be matched to the origin of the world coordinate system, so the axes turn but to be the same.

We first conducted a preliminary experiment to verify the accuracy of the ZMP values retrieved from the pressure sensors. The results obtained from the left foot are shown in Fig. 7(a), and those obtained from the right foot are shown in Fig. 7(b).

For the experiment, the angle values for both sides of the HOAP–2 were set as follows: 0 [deg] for the hip joints’ torsion, 0 [deg] for the right and left directions of shoulder joints, 0 [deg] for knee joints, 0 [deg] for the forward and backward directions of ankle joints, 0 [deg] for hip joints’ torsion, 0 [deg] for the right and left directions of hip joints, 0 [deg] for the forward and backward directions of ankle joints, 0 [deg] for the forward and backward directions of shoulder joints, 0 [deg] for elbow joints, 0 [deg] for head joint, and 0 [deg] for the head joint.

An explanation of each point in Fig. 7 is given below. The transitions of the ZMP for each point where force is applied are differentiated using four colors.

(a) ×: Point where force is applied
(b) ■: ZMP when not carrying any weight
(c) ▲: ZMP using a load of 16 [N]
(d) ◆: ZMP using a load of 32 [N]
(e) ●: ZMP using a load of 64 [N]

Without any load, and considering half of the robot’s own weight, approximately 32 [N] was correctly obtained from the foot sensors. When a load of 16 [N] was applied to the point in the upper right corner of Fig. 7(b), the resulting distance from ■ to ▲ was 13.1 [mm] and the resulting distance from ▲ to × was 26.0 [mm]. Thus, the load of 16 [N] is approximately equal to the inverse ratio of the robot’s own weight of 32 [N]. From this, it is possible to conclude that the ZMP of both feet is accurate.

This research also seeks to stabilize the walking motion, taking into account the whole balance of the humanoid robot during a sliding walk. To do so, it is necessary to match the origin of the world coordinate system to a single origin for the ZMP of both feet. In that way, a stability index can be created and used to verify the robot’s balance in real time. The ZMP of both feet together can be derived from the ZMP of each individual foot and the normal force. As shown in Fig. 8, considering the center of pressure on the sole, the ZMP of the right foot is \( p_R = (p_{R_L}, p_{R_T})^T \), the ZMP of the left foot is \( p_L = (p_{L_L}, p_{L_T})^T \), the normal force affecting the right foot is \( f_R \), the normal force affecting the left foot is \( f_L \), and the ZMP of both feet is \( p \). It is then possible to match the origin of the world coordinate system to the origin of the ZMP of both feet. By doing this, the X axis will be in the forward direction of the robot, the Y axis will be in the left direction, and the Z axis will be in the upward direction. As shown in Fig. 8, using the formula of the dividing point, the ZMP of both feet is given by

\[
\begin{bmatrix}
  p_x \\
  p_y 
\end{bmatrix} = \begin{bmatrix}
  p_{R_L} f_R + p_{L_L} f_L \\
  p_{R_T} f_R + p_{L_T} f_L 
\end{bmatrix} .
\tag{8}
\]

In this research, we move the center of gravity using the ZMP of both feet.
V. Experiments

A. Displacement of the center of gravity using PI control and ZMP feedback

In this section, we compare the two methods for moving the center of gravity shown in section 2. Using Eq. (1) with a value of 25 [mm] for \( \rho_0 \), the PI control with displacement of the HOAP-2’s center of gravity is performed. The results of transition the \( Y \) coordinate in ZMP of both feet obtained from previous method are shown in Fig. 9(a), and those obtained from proposed method are shown in Fig. 9(b).

From Fig. 9(a), it can be seen that a maximum variation of approximately 8 [mm] in the ZMP of both feet occurs, regardless of a funnel time of 8 [s]. However, from Fig. 9(b), the ZMP of both feet mainly change to the direction of the displacement of the center of gravity, and it can be seen that a maximum variation of approximately 3 [mm] in the ZMP of both feet occurs, regardless of a funnel time of 4 [s].

B. Sliding walk

In this section, the sliding walk was performed by implementing the methods described in sections 2 and 3, as shown
in Figs. 12(a–h). A total of two steps were performed (two forward sliding steps) by moving the center of gravity with the ZMP control.

In order to compare the present research, an additional experiment was also conducted using the method proposed by Uda [10]. Fig. 10 shows a comparison of the $Y$ coordinate of the ZMP of both feet after the first step has been completed. Fig. 11 shows a comparison of the acceleration change over the $Y$ axis.

The sliding walk of Uda [10] is shown in Fig. 10(a) and Fig. 11(a), while the sliding walk proposed in this research is shown in Fig. 10(b) and Fig. 11(b). For the sliding walk method of Uda [10], the displacement of the center of gravity is observed from time 0 [s] to 2 [s], and the sliding walk stage is observed from 2 [s] to 4 [s]. Regarding the sliding walk proposed in the present research, the displacement of the center of gravity is observed from 0 [s] to 12 [s], and the sliding walk stage is observed from 12 [s] to 14 [s]. From Fig. 10 and Fig. 11, it can be seen that the present method gives a smaller variation in both the displacement of the center of gravity and the sliding walk stage. Even though the speed does not change in the sliding walk stage, it is possible to keep the variation of the ZMP of both feet over the $Y$ axis below 0.4 [mm] and the variation of the acceleration over the $Y$ axis under 0.4 [m/s$^2$].

VI. CONCLUSION

In this research, a PI control was implemented during the displacement of the center of gravity following the ZMP criteria. By doing this, a sliding walk was accomplished and, during the walk, the variation in ZMP of both feet and the variation of acceleration over the $Y$ axis were minimized. As future work, a barycentric correction using ZMP control over the $X$ axis could be added, as well as transition planning of ZMP on a two-dimensional plane.

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