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Biped Robot Walking on Uneven Terrain Using Impedance Control and Terrain Recognition Algorithm

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Abstract— **This paper proposes a control method for biped robot locomotion on uneven and uncertain terrain based on the impedance control with impedance modulation at the ankle joints and terrain recognition using force sensors at the soles. The impedance parameters are changed depending on unexpected contact forces. To reduce the size of the peak ground reaction force and to guarantee soft footing on the ground, the stiffness coefficient of the impedance of the landing foot is drastically reduced. Also, the orientation of landing foot is updated for the next phase of walking trajectory. A series of computer simulations of a 12-degree-of-freedom (DOF) biped robot with an uneven and uncertain terrain showed the effectiveness of the proposed control method.**

Index Terms – Biped robot, impedance control, uneven terrain, terrain recognition.

I. INTRODUCTION

There has been so much progresses in humanoid robots and their capabilities are increasing year by year. Despite of it, there are still many challenging issues remained to be solved, including their ability to walk stably on uneven terrains. Since bipedal locomotion is unstable in nature similar to the motions of an inverted pendulum, it is very important to make biped robots walk stably. So, there has been intensive research in the related areas including designing a dynamically stable trajectory and controlling stable locomotion.

In generating stable trajectories, the inverted pendulum mode (IPM) is the most common method used to generate a locomotion trajectory. Its main advantage is that it can generate a relatively stable trajectory by modeling a biped robot as an inverted pendulum model. Many different varieties on it including the linear inverted pendulum mode (LIPM), the gravity compensated inverted pendulum model (GCIPM) and the moving inverted pendulum model (MIPM) were proposed [1], [2], [3]. In these methods, a biped robot is assumed as a particle or a set of particles and the trajectories of these masses are generated only for the motion during a single-support phase. However, a double-support phase and flight phase also play an important role. Shibuya et al. proposed a method to generate a trajectory during the double-support phase by using a linear pendulum model [4].

In controlling for stable locomotion, the most conventional and classical method is to control the zero moment point (ZMP) [5], [6], which is defined as the center of the pressure on the feet (or a foot) on the ground, applied by the ground. It is important to control the motion of a biped robot such that its ZMP is located always within the foot-supporting polygon.

Locomotion of a biped robot on an uneven terrain has been studied by many researchers. Stabilizing aperiodic orbits of insufficient robots was proposed in [7], based on transversal linearization for a target motion and hip motions, but its effectiveness was verified experimentally only with a compass walking aid that points to a pointed leg in bipedalism with 2 DOF. Even vision sensors are highly effective in find the pattern of a terrain, their performance is strongly affected by the surrounding environment. For example, if the sunlight becomes too strong, it will not be possible to obtain information about the terrain, and it will be difficult to use the vision sensor even in a disaster environment covered with dust or ashes. Therefore, a biped robot needs to be able to walk stably on the uneven terrain even when there are some errors in visual information on the terrain. The idea of controlling the impedance of a biped robot for its locomotion on an uneven and uncertain terrain and modulating the impedance parameters was originally proposed in [9].

In this paper, a method to make the biped robot walk stably on an uneven and uncertain terrain is proposed when the information on the terrain obtained by the vision sensor is inaccurate. A walking strategy based on impedance control and impedance modulation and an algorithm to get the information on the local terrain by using force-sensitive-resistor (FSR) sensors are proposed.

This paper is organized as follow. In Section II, the trajectory generation method to make a biped robot walk on the flat surface during the single-support phase and the double-support phase is explained. In Section III, the impedance control with an impedance modulation strategy is explained. In Section IV, a terrain recognition algorithm based on FSR sensors attached to the soles of the robot is explained, followed by computer simulations in Section V. Finally, a few conclusions are drawn in VI.

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II. Trajectory Generation

A locomotion cycle of a biped robot can be separated into two phases depending on the number of feet on the ground: single-support phase and double-support phase. A motion trajectory will be generated for each of the single-support phase and the double-support phase. For the basic time, we first define the followings.

$$T = T_s + T_d$$
$$S = S_s + S_d,$$

where T and S denote the duration of the whole period and the length of a single stride, respectively. Here, subscripts s and d denote the single-support phase and double-support phase, respectively. The locomotion periods and strides are set before a biped robot walks. One cycle of locomotion starts with a single-support phase and ends with a double-support phase.

A. Trajectory Generation Method

To generate the locomotion trajectory, a biped robot is modeled as a single-particle model. It is assumed that this mass is located at the hip of the biped robot as shown in Fig. 1. In the figure, particle M denotes the mass representing the total mass of the biped robot, which is M; $\vec{q}$ denotes the position vector from the supporting point to the center of mass (COM) of the robot; $\vec{P}_{ZMP}$ denotes the position vector of the ZMP of the robot; and $\vec{P}$ denotes the position vector from the ZMP of the robot to the COM of the robot. The global coordinate frame is attached at the ground where the center of the supporting foot is located.

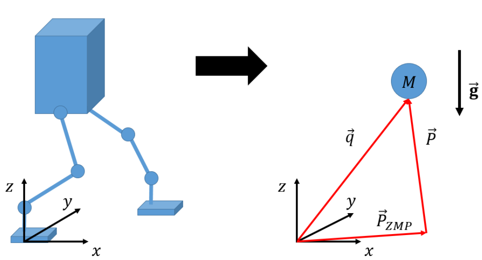

Fig. 1. A simplified robot model

To generate the walking trajectory in the sagittal and lateral plane, the angular momentum equation about the ZMP is used:

$$\vec{P} \times (M\ddot{\vec{q}}) = \vec{P} \times (M\vec{g}) \tag{1}$$

where

$$\vec{P} = \vec{q} - \vec{P}_{ZMP}$$
$$\vec{q} = \begin{bmatrix} X & Y & Z \end{bmatrix}^T$$
$$\vec{P}_{ZMP} = \begin{bmatrix} X_{ZMP} & Y_{ZMP} & Z_{ZMP} \end{bmatrix}^T$$
$$\vec{g} = \begin{bmatrix} 0 & 0 & -g \end{bmatrix}^T$$

Under the assumption that $Z = Z_0$, which is constant, Eq. (1) yields

$$\ddot{X} = \omega^2 X - \omega^2 X_{ZMP} \tag{2}$$
$$\ddot{Y} = \omega^2 Y - \omega^2 Y_{ZMP} \tag{3}$$

where

$$\omega = \sqrt{\frac{g}{Z_0}}$$

B. Single-Support Phase

When locomotion of a biped robot is in the single-support phase, it is assumed that the desired ZMP is fixed at the center of the supporting foot. So, the desired ZMP trajectory is zero. From Eq. (2), a walking trajectory is obtained in the sagittal direction.

$$X_s(t) = C_1 e^{\omega t} + C_2 e^{-\omega t} \tag{4}$$

where

$$C_1 = \frac{1}{2}\left(X_s(0) + \frac{\dot{X}_s(0)}{\omega}\right)$$
$$C_2 = \frac{1}{2}\left(X_s(0) - \frac{\dot{X}_s(0)}{\omega}\right)$$

Here, $X_s(0)$ and $\dot{X}_s(0)$ represent the initial position and velocity of the COM with respect to the center of the supporting foot. In order to walk in steady and cycles, the initial velocity should be equal to the final velocity.

$$\dot{X}_s(0) = \dot{X}_s(T_s) \tag{5}$$

From Eqs. (4) and (5), the initial velocity of $\dot{X}_s(0)$ can be obtained.

$$\dot{X}_s(0) = \frac{1 + e^{\omega t}}{1 - e^{\omega t}}\, \omega X_s(0) \tag{6}$$

Here, the trajectory in the lateral plane is made in the same procedure as in the sagittal plane, except for a different velocity condition:

$$\dot{Y}_s(0) = -\dot{Y}_s(T_s) \tag{7}$$

C. Double-Support Phase

When locomotion of a biped robot is in a double-support phase, it is assumed that the desired ZMP moves. This means that the desired ZMP should move from the center of the current supporting foot to the center of next supporting food during a double-support phase. And the trajectory of the double-support phase has to be connected smoothly by considering the final condition of the previous single-support phase and the initial condition of the next single-support phase. So, the initial, last position, initial and last velocities of single-support phase are used to generate the trajectory of a double-support phase. Also, initial and last positions of the desired ZMP of the double-support phase are used. These six conditions of the sagittal plane can be expressed the following equation.

$$
\begin{aligned}
X_d(t'=0) &= X_s(T_s) && \text{(7a)}\\
\dot{X}_d(t'=0) &= \dot{X}_s(T_s) && \text{(7b)}\\
X_d(t'=T_d) &= X_s(T_s)+S_d && \text{(7c)}\\
\dot{X}_d(t'=T_d) &= \dot{X}_s(0) && \text{(7d)}\\
X_{ZMP}(t'=0) &= 0 && \text{(7e)}\\
X_{ZMP}(t'=T_d) &= S_s+S_d && \text{(7f)}
\end{aligned}
$$

where

$$t' = t - T_s$$

Therefore, the desired ZMP trajectory in the X-direction during a double-support phase is designed as 3rd-order polynomial to generate the walking trajectory which satisfy these six conditions in Eq. (7).

$$X_{ZMP}(t') = a_x t'^3 + b_x t'^2 + c_x t' + d_x \tag{8}$$

So, the trajectory of the double-support phase can be obtained by solving a differential equation, Eq. (2).

$$
\begin{aligned}
X_d(t') = {} & C_1 e^{\omega t'} + C_2 e^{-\omega t'} + a_x t'^3 + b_x t'^2 \\
& + \frac{6a_x + \omega^2 c_x}{\omega^2} t' + \frac{2b_x + \omega^2 d_x}{\omega^2}
\end{aligned} \tag{9}
$$

In Eq. (9), the trajectory of the double-support phase has unknown variables C_1, C_2, a_x, b_x, c_x and d_x. These unknown variables should be obtained by using Eq. (7).And, that can be expressed as a matrix form as follows.

$$C_x = A_x B_x \tag{10}$$

where

$$
C_x = \begin{bmatrix} X_d(t'=0) \\ \dot{X}_d(t'=0) \\ X_d(t'=T_d) \\ \dot{X}_d(t'=T_d) \\ X_{ZMP}(t'=0) \\ X_{ZMP}(t'=Td) \end{bmatrix}
$$

$$
A_x = \begin{bmatrix}
1 & 1 & 0 & \frac{2}{\omega^2} & 0 & 1 \\
\omega & -\omega & \frac{6}{\omega^2} & 0 & 1 & 0 \\
e^{\omega T_d} & e^{-\omega T_d} & (T_d^3 + \frac{6}{\omega^2} T_d) & (T_d^2 + \frac{2}{\omega^2}) & T_d & 1 \\
\omega e^{\omega T_d} & -\omega e^{-\omega T_d} & (3T_d^2 + \frac{6}{\omega^2}) & 2T_d & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & T_d^3 & T_d^2 & T_d & 1
\end{bmatrix}
$$

$$B_x = \begin{bmatrix} C_1 & C_2 & a_x & b_x & c_x & d_x \end{bmatrix}$$

The elements of the matrices C_x and A_x are known from the walking period and Eq. (7). So, the elements of matrix B_x can be found by multiplying both sides of Eq. (10) by the inverse matrix, A_x^{-1}.

$$B_x = A_x^{-1} C_x \tag{11}$$

Therefore, the desired trajectory of the double-support phase can be obtained.

Likewise, the trajectory in the lateral plane is skipped because it is the same method except for the explained conditions.

$$
\begin{aligned}
Y_d(t'=0) &= i \cdot Y_s(T_s) && \text{(12a)}\\
\dot{Y}_d(t'=0) &= i \cdot \dot{Y}_s(T_s) && \text{(12b)}\\
Y_d(t'=T_d) &= i \cdot Y_s(0) && \text{(12c)}\\
\dot{Y}_d(t'=T_d) &= i \cdot \dot{Y}_s(0) && \text{(12d)}\\
Y_{ZMP}(t'=0) &= i \cdot 0 && \text{(12e)}\\
Y_{ZMP}(t'=T_d) &= i \cdot S_{lp} && \text{(12f)}
\end{aligned}
$$

Eq. (12) is used instead of Eq. (7) for generating the trajectory in lateral plane. In Eq. (12), i is 1 when the supporting foot is that right foot and i is -1 when it is the left foot. And S_{lp} is the stride in the lateral plane.

III. Impedance Control for Walking on Uneven Terrain

The biped robot is always in contact with the ground, sometimes with one foot and other times with two feet. Therefore, the reaction force between the ground and the sole of the biped robot is always applied and it affects the walking stability of the biped robot. For this reason, if the information about the condition of the ground contact with the biped robot is not considered to generate the walking trajectory of the biped robot, an unexpected ground reaction force is occurred and it make the biped robot unstable.

A. Virtual Impedance of Ankle Joint

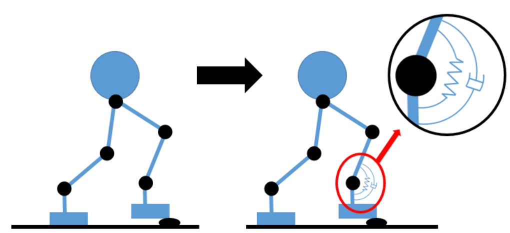

Fig. 2. Virtual impedance of the ankle joint

In this paper, an impedance control is applied to the ankle joint of the biped robot to reduce the ground reaction force. Suppose that the desired impedance of the each ankle as shown in Fig. 2 is expressed by

$$(d/2)(f_r - f_d) = I(\ddot{\theta}_r - \ddot{\theta}_d) + B(\dot{\theta}_r - \dot{\theta}_d) + K(\theta_r - \theta_d) \tag{13}$$

Here, f_r and f_d are the measured contact force and the desired contact force between the sole of the robot and the ground.

And, the dynamics of the foot of the robot can be expressed by

$$\tau - (d/2)(f_r - f_d) = I\ddot{\theta}_r \tag{14}$$

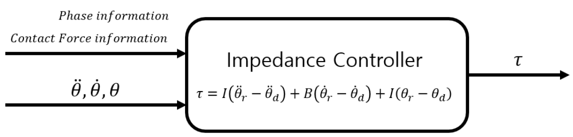

Fig. 3. Configuration of impedance controller

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From Eqs. (13) and (14), the torque acted on the ankle joint can be obtained as

$$\tau = I\ddot{\theta}_d - B(\dot{\theta}_r - \dot{\theta}_d) - K(\theta_r - \theta_d) \tag{15}$$

where I is the inertia of the foot of robot. Gains B and K are set as high values for tracking the desired trajectory of the ankle joint well.

B. Impedance Modulation

When a biped robot walks on the uneven terrain, the unexpected ground reaction force can be applied to the robot. If this situation is occurred, the stiffness component of the impedance model in Eq. 15 should be softened to reduce the contact force and to make the sole of the robot land stably on the walking surface.

$$K = (m \cdot g \cdot d)/(8 \cdot \theta_{ar}) \tag{16}$$

$$B = 2\sqrt{MK}. \tag{17}$$

where m, g and d denote the total mass of the biped robot, the acceleration of gravity and the length of the sole, respectively; and, θ_{ar} denotes the maximum allowable angle of the ankle in adapting to the uneven surface, which is set as 30 degree in this work.

During the single-support phase, the desired contact force of the swing leg should be zero, i.e. $f_d = 0$ in Eqs. 13 and 14. However, the foot of the swing leg may be contacted with the ground during the single-support phase because the robot walks on the uneven terrain. In this case, the walking strategy is shown as in Fig. 4 in order that the biped robot walks stably and the foot lands on the walking surface stably. In Fig. 4, F is the contact force measured from the FSR sensor attached on the foot. And, t and T_s mean the current time and the period of the single-support phase. If the contact force is detected during the single-support phase, the stiffness coefficient, K, is reduced.

The initial state of the foot when the double-support phase starts can be divided into three cases depending on the final state of the single-support phase, and these cases are shown in Fig. 5. In Fig. 5(a), the front and rear points of the sole contact with the ground. In this case, the biped robot can walk stable during the subsequent double-support phase.

In the case of Fig. 5(b) or Fig. 5(c), where the front side of sole based on the center point and the whole side of the sole do not contact with ground, the biped robot will tilt to the walking direction during double-support phase and the front

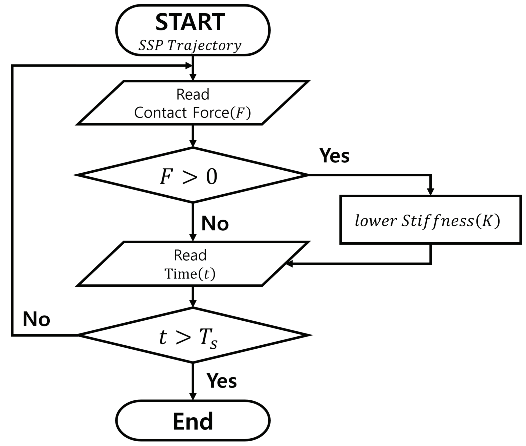

Fig. 4. Flow chart for impedance control during a single-support phase

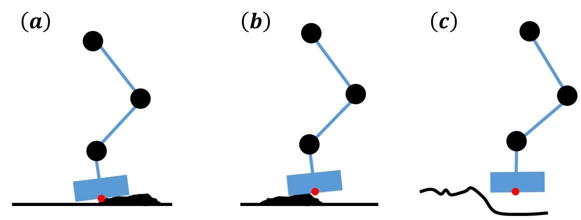

Fig. 5. Three cases of the state of landed foot

side of the foot will collide with the ground. It causes the unexpected contact force and the bad influence on the biped robot. In order to resolve this problem, the walking strategy during the double-support phase is presented in Fig. 6

F_c and F_f are respectively the contact force for the center point of the sole and the front of the sole in Fig. 6. If the values of F_f and F_c measured from the FSR sensor are 0, it can be decided that the current state of the foot is the state of (b) and (c) in Fig. 5. So, the stiffness, K, should be reduced for stable landing of another side of the sole which does not contact during the double-support phase. On the other hand, if F_f is higher than 0, the state of the landed foot is assumed to be the case shown in Fig. 5(a); therefore, the biped robot would move stably during the following double-support phase.

IV. Terrain Recognition Method

Terrain recognition is important when a biped robot walks on uneven terrain. It is impossible to get precise information on the geometry of the uneven terrain due to the environmental factors or limitations of the sensors used. Therefore, a method to improve the measurement of the information of the walking surface should be developed. In this section, the terrain recognition method proposed to obtain the local terrain information with FSR sensors is explained.

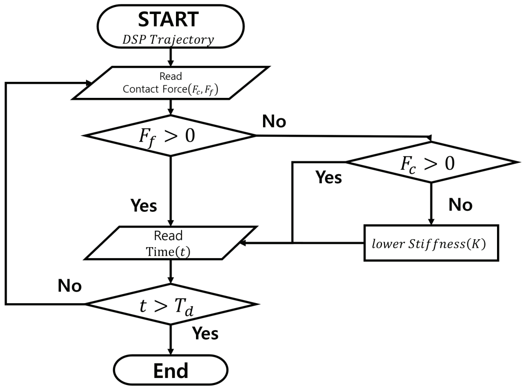

Fig. 6. Flow chart for impedance control during a double-support phase

A. Recognition of Terrain Inclination

If the biped robot walks on the uneven terrain, the desired trajectory for the walking should be modified based on the shape of the walking surface. To do this, the joint trajectory of the ankle is corrected by considering the angle of surface.

When the foot of the biped robot lands stably on the uneven surface by using the impedance control explained in section III, the angle of the slope, θ_p is shown in Figs. 7 and 8, can be obtained. The obtained inclination is reflected on the ankle joint of the biped robot to change the orientation of the foot.

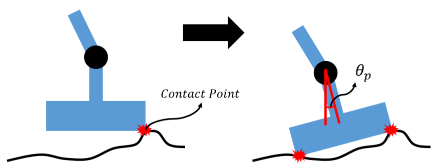

Fig. 7. Recognition terrain during a single-support phase

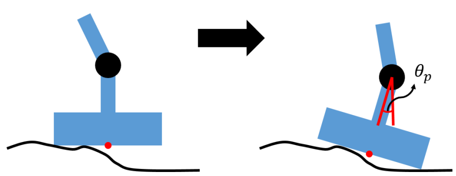

Fig. 8. Recognition terrain during a double-support phase

V. Simulation

A. Simulation Model and Conditions

To show the effectiveness and performance of the proposed method, a computer simulation was conducted using a commercial software called RecurDyn and Matlab. The biped robot model used in the simulation has six joints in each leg as shown in Fig. 9. The weight of the robot is 2.93 kg and its height is 0.46 m.

The block diagram of the control system used in the simulation is shown in Fig. 10. The environment used to verify the proposed method consists of several surfaces which have different heights between 0 and 0.025 meters and different slopes between 0 and 15 degrees as shown in Fig. 11.

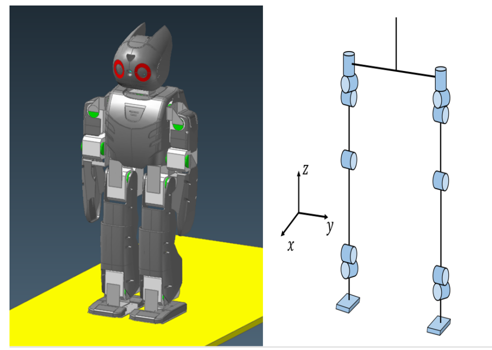

Fig. 9. Biped robot model used in the simulation

B. Simulation Result

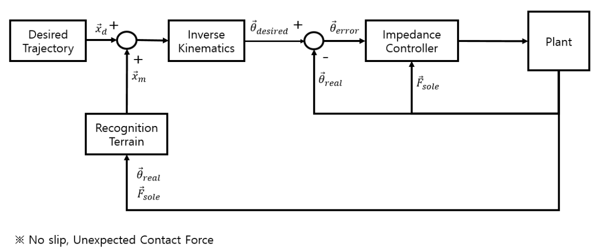

Fig. 10. Black diagram of controller

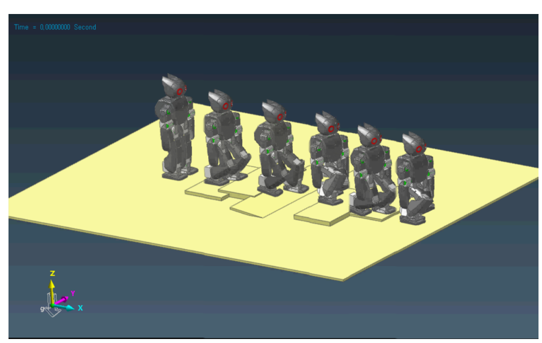

Fig. 11. Walking simulation on uneven terrain

The contact forces measured from the FSR sensors of the left and right foot are shown in Figs. 12 and 13. It can be seen that the ground reaction force increased due to the contact with unexpected terrain was reduced by the proposed method. And it is verified that the angle of the each ankle joint were changed as shown in Fig. 14 using the terrain recognition algorithm.

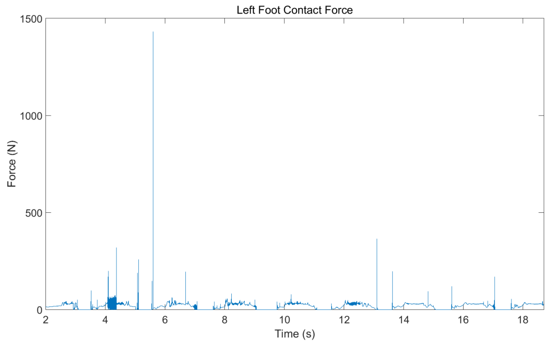

Fig. 12. Contact force at the left foot

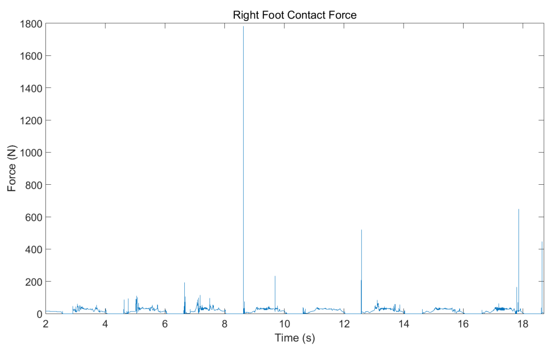

Fig. 13. Contact force at the right foot

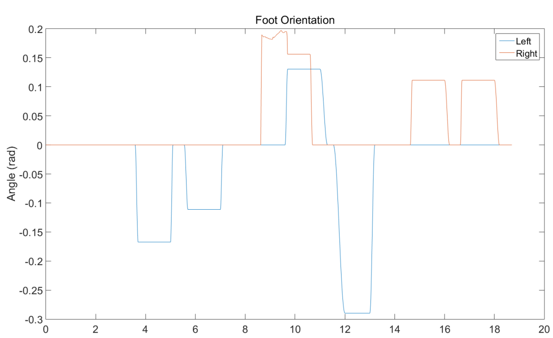

Fig. 14. Trajectory of the ankle joint angles

VI. Conclusion

In this paper, a walking strategy based on variable impedance control are proposed for walking of a biped robot on uneven terrain. For the stable walking of the robot on uneven terrain, terrain recognition algorithm is applied to detect the inclination of walking environment and the ground reaction force occurred when the swing foot land on the terrain is reduced based on variable impedance control. In order to verify the proposed method, walking on uneven terrain of a 12-DOF biped robot are carried out in computer simulation environment without topographic information. Through the computer simulation, it was shown that the biped robot walk stably on uneven terrain by applying the proposed method.

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