Development of the Modeling for Biped Robot using Inverse Kinematics

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Abstract: The legged robot can only walk very similar to human walking pattern. Therefore, many robots have been researched and developed in recent years. However, the biped robots still have many issues for the natural human walking in terms of the redundant degree of freedom, complexity of the kinematics, and stability. In this paper, we have described our biped robot modeling in the forward and inverse kinematics and gotten the results of the simulation for the proposed walking pattern. For the modeling and simulation, we apply some kind of theory such as ZMP, D-H notation, and forward or inverse kinematics to the biped robot.

Key-Words: Biped Robot, ZMP, D-H notation, Forward Kinematics, Inverse Kinematics.

1 Introduction

Legged or biped robots have much higher mobility than wheeled robots in environments with obstacles, stairs and rough terrains. And, the other reason why many researchers have been absorbed in field of the biped robot is that the legged robot can only walk very similar to human walking pattern. For these reasons, many biped robots have been developed in recent years [1][2][3] and so many people have studied its control development.[4][5][6].

Many biped robots have been developed in recent years [1], [2], [3] in various regions. Mc Geer [7] developed a passive dynamic walker and described a natural walking pattern generated by the passive interaction of gravity and inertia on a downhill slope. Zeng et al, have constructed a biped robot named SD-2[8]. A scheme to enable the robot to climb sloping surface and toe, the robot can detect the transition of the support terrain from a flat floor to a sloping surface. To extend the minimum-energy walking method to level ground and uphill slopes, Channon et al.[9], Rostami et al. [10], and Roussel et al. [11] have proposed methods of gait generation by minimizing the cost function of energy consumption. Silva et al.[12] have investigated the required actuator power and energy by adjusting walking parameters[13]. However, the biped robots still have many issues for the natural human walking in terms of the redundant degree of freedom, complexity of the kinematics, and stability. [14]

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In this paper, we analyze the biped robot from the basis of the forward and inverse kinematics. It is needed several theories to analyze the walking pattern of biped robot. Especially, we used the theory of the Denavit-Hartenberg (D-H) notation for the kinematics and of the zero moment point (ZMP) concept for the walking stability of biped robot. D-H notation is the standard approach in robotics to describe joint kinematics for computational applications. The computational versatility of the D-H notation representation of robotic joints makes it the logical choice for describing the complex manipulator with many links. [15].

The ZMP is applied for ensuring the dynamics stability of a biped robot by Takanishi[14][16], Shih[19], Hirai[20] et al. They have proposed methods of walking pattern synthesis based on ZMP. The ZMP is defined as the point on the ground about which the sum of all the moments of the active forces equals zero. If the ZMP is located the point between the sole and the ground, the biped robot is possible to walk and to be stationary. In order to achieve stable dynamic walking, the ZMP must be kept inside the support region. This criterion just ensures that the support foot is stationary on the ground in single support phase. Under such circumstances, the biped robot can be considered as a traditional manipulator for analysis purposes. [17]

This paper introduces the general biped robot and its control methods, which includes modeling and walking pattern. It is organized as follows. The walking pattern and cycle of biped robot will be described in section II. The modeling for biped robot in forward and inverse kinematics is introduced in section II. In section III, we show the result of the simulation based on section II.

2 Biped Robot Modeling in Kinematics

2.1 Zero Moment Point

The ZMP is the point on the ground around which the sum of all the moments of the active forces equals zero. In general, the ZMP can be defined with an equivalent pair of force N and vertical moment M that act on within the foot sole, as far as the dynamic motion of the whole mechanical system is concerned. That is to say, the ZMP is the point which vertical moment M becomes zero.

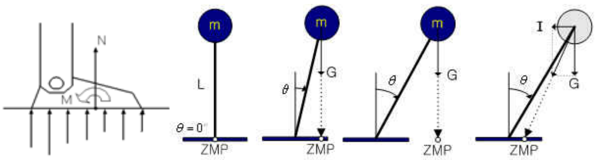


Fig. 1. Concept of ZMP

When biped robot is not moving, the ZMP is the point on the ground which the center of gravity (COG) is projected on the foot sole. But, if robot is moving with constant acceleration, the ZMP is defined with the point that the sum of moment of inertia and gravity is reflected on the ground. Figure 1 shows the several states of ZMP and the ZMP can be computed by [13]:

$$x_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i \ddot{x}_i z_i - \sum_{i=1}^{n} I_{iy}\ddot{\Omega}_{iy}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)}$$

$$y_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)y_i - \sum_{i=1}^{n} m_i \ddot{y}_i z_i - \sum_{i=1}^{n} I_{ix}\ddot{\Omega}_{iz}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)}$$

(1)

where m_i is the mass of link i, I_{ix} and I_{iy} are the inertial components, $\ddot{\Omega}_{ix}$ and $\ddot{\Omega}_{iy}$ are the absolute angular velocity components around x-axis and y-axis at the center of gravity of link i, g is the gravitational acceleration $(x_{zmp}, y_{zmp}, 0)$ is the coordinate of the ZMP, and (x_i, y_i, z_i) is the coordinate of the mass center of link i on an absolute Cartesian coordinate system.

2.2 Swing Leg & Foot Tip Trajectory

We considered a tip trajectory of swing leg for walking pattern for robot. It is determined the trajectory of the tip of a toe and then the angle of all joint is computed on the basis of the change of the position of the tip of a toe. Fig 3 shows the trajectory of the tip of the toe during walking of robot, and this proposed one was applied in our experiments.

- Organization for the determination of the walking pattern:

① Preparation posture before walking
② Change of the COG
③ Swing the one leg
④ Landing of the swing leg & Change of the COG
⑤ Swing the other leg & Landing

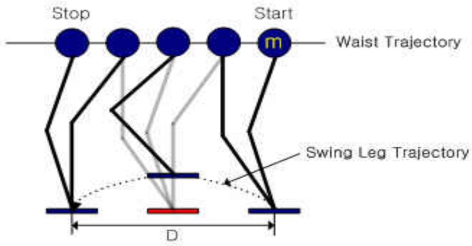


Fig. 2. Swing leg trajectory

As shown figure 2, the walking patterns are classified 4 steps and listed in table 1.

Table 1: Walking step of the biped robot

Step	Applied Pattern (Left, Right Foot)	Position of leg (Left, Right Foot)	Movement of COG
1	(A, O)	(D/2, 0)	-
2	(B, C)	(0, -D/2)	O
3	(O, D)	(0, D/2)	-
4	(C, B)	(-D/2, 0)	O
5	(D, O)	(D/2, 0)	-
6	Repeat from 2 to 5	-	-

* Proposed walking pattern lists

O: Stationary state. (Zero position)
A: A motion where in the robot raises one leg and takes a forward step from zero position by the distance of D/2.
B: A motion where in the robot pushes one leg backward with its sole put on the ground from D/2 position to the stationary state.
C: A motion where in the robot pushes one leg backward with its sole put on the ground from zero position to –D/2 position.

D: A motion where in the robot raises one leg and takes a forward step from –D/2 position by the distance of D/2.

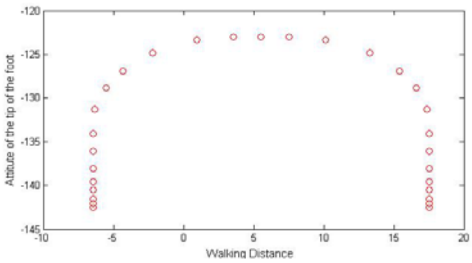


Fig. 3. Proposed the tip of the foot

2.3 Biped Robot Model in Forward Kinematics

For the kinematics analysis of the biped robot, the coordinate system was shown in Fig 4. This proposed model is composed of 12 degree of freedom (DOF) with 6 DOF to one leg: three DOF in the hip joint, one in the knee joint, and two in the ankle joint. And, the all link are a rigid body not twisted.

The D-H Notation adapted in this paper is widely used in the transformation of coordinate systems of linkages and robot mechanisms. It can be used to represent the transformation matrix between links. As long as the change of the foot tip trajectory, we can in 4 parameters of the D-H Notation.[18]

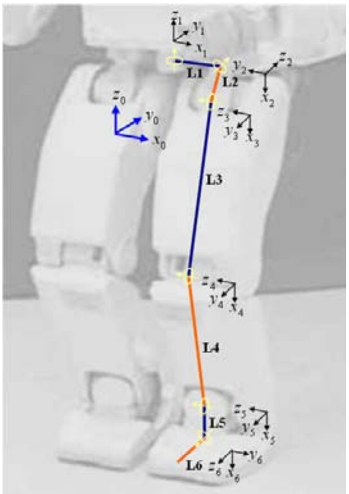


Fig. 4. Coordinate establishment for the analysis of the correlation between all links

Table 2: Each parameter computed from D-H notation.

Link	l (cm)	α (deg)	d (cm)	θ (deg
L1	15	-90	c(0)	-
L2	5	-90	0	-
L3	25	0	0	-
L4	25	0	0	-
L5	5	-90	0	-
L6	10	0	c(0)	-

The results of the D-H Notation are showed Table 2. And, from it, we can compute a transportation matrix A. It can be computed the following form:

$$A_i = Rot_{\theta_i} Trans_{d_i} Rot_{\alpha_i} Trans_{l_i}$$
$$A = A_1 A_2 A_3 A_4 A_5 A_6 \qquad (2)$$
$$P_o = AP_n$$

The final form of matrix A is:

$$A_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & l_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_i & -\sin\alpha_i & 0 \\ 0 & \sin\alpha_i & \cos\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & l_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & l_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

The transfer matrix A is composed of both the two rotation matrix and the two translation one. The position that we try to find, is the last coordinate of the tip of the foot. Therefore, it is acquired by multiplying all the matrix A. From the equation (3), we can compute the correlation between all links of the biped robot in the forward kinematics.

2.4 Inverse Kinematics

Using a forward kinematics we can calculate the position of the tip of the foot when there is presented all values of the angle of each joint. Whereas in the opposite case, that is, when we know the position of the tip of the foot and don't know all values of the angle of each joint, can't we use the inverse determinant of the matrix A. The inverse matrix A can't be used because the matrix A is composed of the non-linear factor. So, for the solving this problem, it is adapted with the theory of the Jacobian matrix.

It is the matrix of an unknown quantity that can be defined as q. These unknown matrix is included in the transfer matrix A. From the equation (2), all these descriptions can be represented by,

$$A = K_0^1(q_1)\cdot K_1^2(q_2)\cdot \ldots \cdot K_{n-1}^n(q_n)$$
$$A = K(q) \qquad (4)$$

The general form of the transfer matrix A is,

$$A = K(q) = \begin{bmatrix} R(q) & d(q) \\ 0 & 1 \end{bmatrix} \qquad (5)$$

R is the rotation factor and d means the translation factor in the matrix A. For that reason, we can't get the unknown matrix $K(q)$ using the inverse matrix of $K(q)$. For getting the solutions for this issue, we are adapted the concept of Jacobian matrix. In equation (4), if the equation is differentiated, the displacement of each joints, q can be converted to the region of the angular velocity, $\dot{q}$ that is to say, the domain q is changed to the domain $\dot{q}$. We can describe that,

$$\dot{x} = J(q)\dot{q} \tag{6}$$

$\dot{x}$: Velocity of the tip of the foot in the rectangular coordinates
$\dot{q}$: Velocity of each joint. (The domain)

As stated upper Jacobian theory, it will be applied to the equation (4). In equation (4), q is the function based on the time. Consequently, R and d is the same one. Translation with Jacobian is separately:

$$\begin{aligned} v &= J_v \dot{q} \\ \omega &= J_w \dot{q} \end{aligned} \tag{7}$$

It is described again using the matrix:

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} J_v \\ J_\omega \end{bmatrix} \dot{q} = J\dot{q} \qquad \dot{x} = J(q)\dot{q} \tag{8}$$

As shown equation (6) and (8), we can apply the Jacobian theory to get the variation of each joint angle when the biped robot walks.

3 Simulations

To compute the variation of each joint angle with the proposed the tip trajectory, simulations were executed.

A. Position of the leg in the forward kinematics

In the chapter 2.3, we can get the transfer matrix A. The matrix A means that it is possible to compute the final position of the tip of a toe, if each joint angle is presented. The simulation results in the figure 5 shows the change of the position of the robot leg.

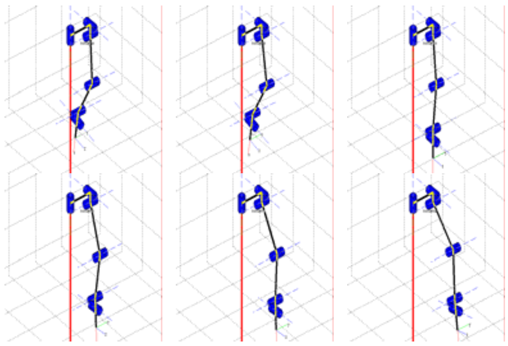
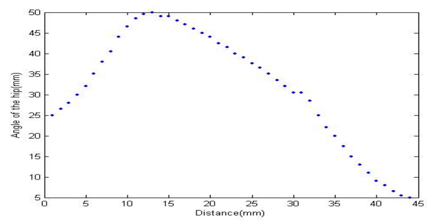


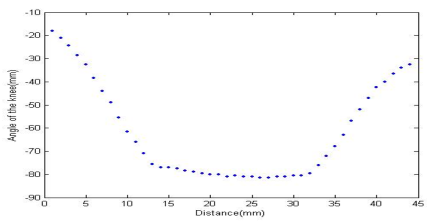
Fig. 5. Changes of the position of the robot leg

B. Variations of each joint angle in the inverse kinematics

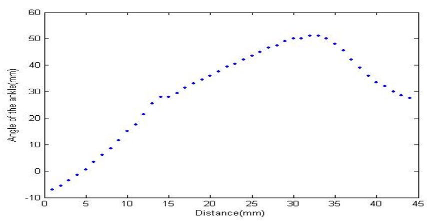
In this paper, we simulated the change of each joint of the biped robot when the robot has the tip trajectory of swing leg for walking pattern such as the figure 3. Figure 5 shows all the variations of each joint angle. The unit of all the axis is 'mm' and simulation is considered as only one phase of the robot. The x-axis is a distance of the forward walking and the y-axis presents the joint angle. Figure 5-(a) shows the changes of the hip joint and 5-(b) is of the knee. At last, figure 5-(c) is of the ankle joint.



(a) Hip joint angle



(b) Knee joint angle



(c) Ankle joint angle

Fig. 6. Variations of each joint angle

4 Conclusion

In this paper, we have described our biped robot modeling in the forward and inverse kinematics and gotten the results of the simulation for the proposed walking pattern. But, this paper was only considered about the static walking without due regard to the dynamic walking. In addition, we can't apply these results to the actual biped machine because we don't reserve the one. Hence, the control of the actual robot applied the dynamic walking will be needed to be reflected in the next experiments.

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