Modeling and Kinematic Analysis of the Biped Robot

Muhammad Rameez, and Dr. Liaquat Ali Khan

***Abstract*—**Biped robots are intricate in design, with more degrees of freedom (DOF) because of the challenging goal of imitating humanoid gait. This paper gives a very simple architecture of the biped robot have three degrees of freedom (DOF)in each leg, one DOF for hip joint and one corresponding to the knee and ankle joint respectively. Denavit-Hartenberg parameter is being used to obtain the solution for forward kinematics (FK). Furthermore the forward kinematics is also confirmed using Peter-Corke toolbox in this work. This gives the desired results of the different orientation. The CAD model is also made to give a better visual model of the biped robot.

***Keywords*—**Biped robot, Design, Denavit-Hartenberg parameters, Forward kinematics

I. Introduction

DURING 1970s the study of biped robots started. In recent years, many efforts have been employed on the focus of developing biped robots with different applications. Now a day's humanoid robot is the most interesting topics in the field of robotic.

The motivation behind building of the humanoid robots is to replicate the behavior of human motion and help people in performing different repetitive and difficult tasks. Recently, vast sum of technical and scientific efforts has been used on improving the development of two legged walking robots as due to the design, humanoid looks and artificial intelligence they have become the center of attraction for the society. The motivation is very simple but the task is a difficult one. For example, Engineers and researcher in Honda took many years to accomplish the invention of the most advanced humanoid robot i.e. Honda Asimo [1]-[3].
[1]

Fig. 1 Asimo (Honda)

For these objectives, kinematics is considered the most important factor for the locomotion control of biped robot and its gaits as well. The kinematic analysis of the two legged robot is very important because the control system for the robot needs to use these equations relatively in the dynamics and control domain. The kinematics of the system results are parameters i.e. velocities, accelerations and orientations needed for the mobility of the robot.

The kinematics of robot is of two types: Forward kinematics (FK) in which the length and angle of each link and joint respectively are given then the kinematic equations are used to determine the location of any point in the workspace of the robot and inverse kinematic (IK). In industry, animation and computer games kinematic equations are widely used [2]. In inverse kinematics the angles are computed to find the end-effector desired position of the robot.

Before starting the mathematical modeling of the robot some of the former and current work is presented in a brief description, as there are various works in solving the walking motion control and balancing of the robot by beginning with the kinematic and dynamic equations.

John. H. Park and K. D. Kim [6] generated the locomotion patterns of the biped using a mode called the gravity compensated inverted pendulum which is similar to the patterns that are generated by the linear inverted pendulum mode (LIPM). The kinematic analysis of the biped is described using Denavit-Hartenberg (DH) notation and the dynamics of the model is presented using the Lagrangian formulation.

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C. Hernández-Santos et al [5] proposed a new design of the biped robot having seven degrees of freedom (DOF) per each leg with an additional degree of freedom to mimic the toe joint in the robot. DH notation is used in this work to present the forward kinematics where the inverse kinematics (IK) is done for the sagittal and the frontal planes separately which results in a simple model which gave the closed form solution of equations for the leg orientation and position. The trajectories for the biped's legs motion are obtained using periodic gait functions. The required torque for the joints is computed by the Lagrangian dynamic principles and for control of the desired trajectories PD control with gravity compensation is used.

O. Narvez-Aroche el at [4] has obtained adequate kinematic model which generated the results for the position, velocity and acceleration of the biped that were satisfactory. The equations of dynamic of the robot are obtained by using the Euler-Lagrange approach.

In this paper forward kinematics of the biped robot is discussed which is organized as follow. In 2nd part, the proposed model of biped robot is presented. This is followed by section 3 includes the kinematic modeling for the biped robot legs which is obtained using the Denavit-Hartenberg (DH) notation. In section 4, the biped robot leg position for different angle is verified using Peter-Corke robotics toolbox in Matlab® to see the possible movement and determine that it can be used for further analysis in the next phases i.e. inverse kinematics, dynamics and control each angle to get the desired motion and the last section includes the conclusion of the work.

II. Mathematical Modeling

A. Model of the biped robot

Leg of human is an important organ of the body which extends from hip to the ankle. The proposed biped robot's model is shown in figure 2 as follow.

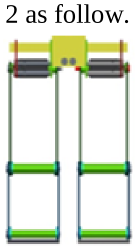

Fig. 2 Biped robot model

The proposed biped robot model is a very simple architecture. The aim beside the simple architecture is to keep the analysis simpler while deriving the kinematics and dynamics as well which will be done in the next phase of the work and to perform motion in one straight direction. The parameters of the two legged robot are shown in the table below.

TABLE I
BIPED ROBOT PARAMETERS

Parameters	Description (Link Lengths)	Values
$l_2 = l_5$	Upper leg	0.2 m
$l_3 = l_6$	Lower leg	0.2 m
l_w	Pelvic	0.03 m

III. Kinematic Modeling

Kinematics describes the motion of the point or articulated bodies without considering the causes of the motion. With kinematics, one studies the orientation (position), velocity and acceleration of the model. The kinematic modeling of the biped robot contains the forward kinematic derived by using the Denavit-Hartenberg (DH) notation.

A. Forward Kinematics

In literature of robotics, it is the study of determining the end-effectors' position and orientation by giving configuration of robot's joints. Prime focus of this paper is the lower body of two legged walking robot as we can see in Figure 1. It has two 3 DOF legs namely 1 DOF for the hip joint and one each for the knee and ankle respectively. Each leg of the biped robot can be modeled as a kinematics chain of with 4 links and 3 revolute joints.

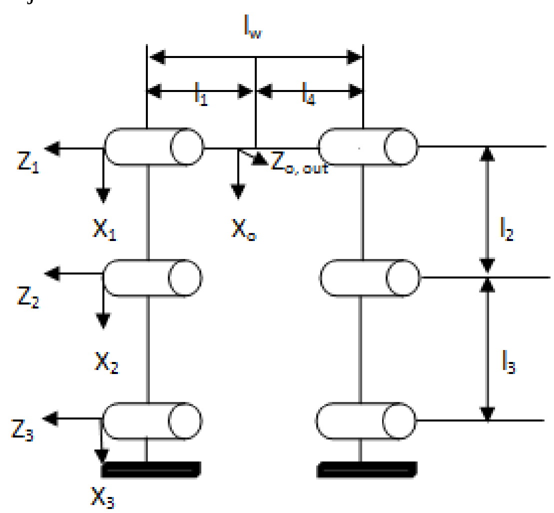

Fig. 3 Schematic model of the biped robot

The assigned local frames are $\{X_i, Y_i, Z_i\}$, which is illustrated in Figure 1. The frames are attached according to the names given as numbers. Assignment of the frames is done according to the convention known as DH-notation [7]-[8] which is illustrated in the figure. 4:

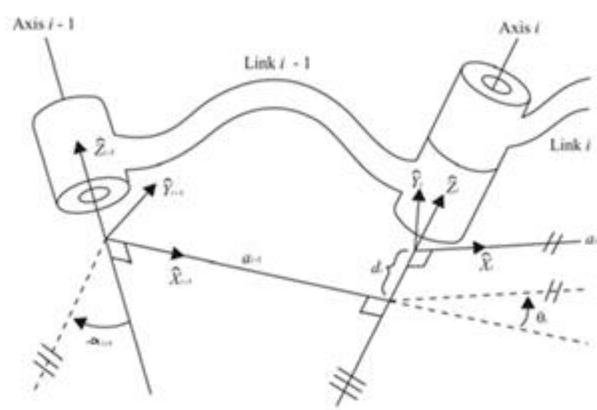

Fig. 4 Schematic of Denavit-Hartenberg (DH) convention

i. Z_i = Z-axis frame {i}, which is directed in the direction of joint axis of link {i}.
ii. Link's origin frame is assigned at the location of common perpendicular or at the point of intersection
iii. X_i axis is assigned long the common perpendicular and if the axes of two links intersect then X_i axis is assigned which is to be acting perpendicular to the plane formed by the two axes.
iv. Y_i axis is assigned to complete the right-hand rule.

As the frames attachment is according to the DH-notation, the definition of the valid parameters is given as follows:

i. (a_{i-1}) = distance (Z_{i-1} to Z_i).along X_i.
ii. (α_{i-1}) = angle (Z_{i-1} to Z_i) about X_{i-1}.
iii. (d_i) = distance (X_{i-1} to X_i) along Z_i.
iv. (θ_i) = angle (X_{i-1} to X_i) about X_i.

In this paper for convenience of analysis same coordinate frames are assigned for both right and left legs as the structure of the right leg is identical to that of the left leg. Figure 3 shows the frames attachment for the right-leg of the biped robot.

The parameters of the right leg and left leg are shown in table II and table III respectively.

TABLE II
RIGHT LEG DH-NOTATIONS

I	α_{i-1}	a_{i-1}	d_i	θ_i
1	90	0	l_1	θ_1
2	0	l_2	0	θ_2
3	0	l_3	0	θ_3

TABLE III
LEFT LEG DH-NOTATIONS

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	90	0	l_4	θ_4
2	0	l_5	0	θ_5
3	0	l_6	0	θ_6

As we can see both legs have three identical DH-parameters and θ_i is the only parameter that is changing (angle of each leg's joint). In figure 3 as convention used in paper, the joints position is shown for 0^o angle.

The transformation matrices are calculated from the given DH-tables using the following general form of transformation matrix [7].

$$ {}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$ {}^{0}_{i}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T \ldots {}^{i-1}_{i}T \quad (2)$$

Therefore, based on equation 1 the DH-parameters can be substituted for the link to link transformations are:

$$ {}^{0}_{1}T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ 0 & 0 & -1 & -l_1 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$ {}^{1}_{2}T = \begin{bmatrix} c_2 & -s_2 & 0 & l_2 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$ {}^{2}_{3}T = \begin{bmatrix} c_3 & -s_3 & 0 & l_3 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Where s (θ_i) = sin (θ_i), c (θ_i) = cos (θ_i), s (α_i) = sin (α_i), c (α_i) = cos (α_i), c_1 = cos (θ_1), c_2 = cos (θ_2), c_3 = cos (θ_3), s_1 = sin (θ_1), s_2 = sin (θ_2) and s_3 = sin (θ_3)

Hip to ankle matrix transformation is the combine link-to-link transformation (${}^{0}_{3}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T$). since the mathematical representation is identical both legs so, the transformation matrix is calculated only for one leg.

$$ {}^{0}_{3}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Where

P_x, P_y, P_z gives end-effecter's position

$r_{11} = c_{123}, r_{12} = -s_{123},\ r_{13} = r_{21} = 0,\ r_{22} = r_{33} = 0,$

$r_{23} = -1, r_{31} = s_{123}, r_{32} = c_{123},$

$p_x = c_{12}l_3 + c_1 l_2$

$p_y = -l_1$

$p_z = s_{12}l_3 + s_1 l_2$

Where $c_{(12)}$ = cos (θ_1+ θ_2), $s_{(12)}$ = sin (θ_1+ θ_2), $c_{(123)}$ = cos (θ_1+ θ_2+ θ_3) and $s_{(123)}$ = sin (θ_1+ θ_2+ θ_3)

IV. BIPED ROBOT ORIENTATIONS

The following section shows the biped robot leg orientation at different angles to show that the robot leg can move to different positions which are inside the workspace. Peter-Corke robotics toolbox [9] is being used to show the orientation of the biped robot leg at different angles.

A. Peter-Corke robotics toolbox

Peter-Corke robotics toolbox is a Matlab® toolbox which is used in research and teaching in the field of robotics. The robotics toolbox is very effective for the study and simulation of the classical arm type and mobile robotics.

B. Biped robot leg positions

As discussed earlier the Matlab® toolbox is being used to confirm the robot leg placement at different angles. Following figure 5 shows plot of the orientation of the robot leg at different angles.

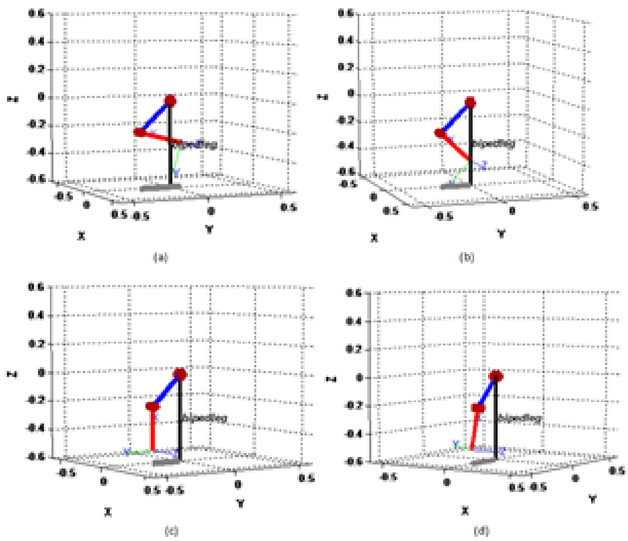

Fig. 5 Biped robot leg with different knee angles

Fig. 5 represents the results of the biped robot leg plotted for different values of angle. Fig. 5 (a) shows the plot for the knee at an angle of 2pi/3, Fig. 5 (b) represents the knee at an angle pi/2, Fig.5 (c) shows the knee at angle of pi/4 and Fig.5 (d) represents the knee at an angle of pi/6.

V. CONCLUSION & FUTURE WORK

Kinematics deal with the study of the mechanism's motion or any articulated series of bodies with respect to a rigid reference coordinates system fixed to the base without considering the force and moments that cause that motion. The kinematic model i.e. forward kinematics (FK) is dine successfully for the biped robot and validated using Peter-Corke robotics tool box.

Presently, we are solving the inverse kinematics (IK) in which finding the angles of the joints is studied for a desired position and orientation and the dynamics of the biped robot can be used to find the required torque to move the robot to a desired point.

Further, we will investigate about the gait and the controller to perform the desired gait which will be accomplished in the next phase of the research.

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