Simulation and Control of a Biped Walking Robot using Kinematic and Dynamic Modelling

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***Abstract*— In this article, we intend to consider the behavior and control of a biped walking robot using kinematic and dynamic relations. At first, by using simple model of humanoid robot and essentional equations the angles, angular velocities, accelerations of motors and required torques for moving on a straight line are find out. In the second step considering numerical values of the robot parameters and constructing the dynamic model the abilities of robot are examined and simulated.**

***Keywords*—Humanoid robot; simulation; control**

I. INTRODUCTION

The need for robots has recently been changed from industrial automation to human friendly robot system [1]. One of them is WABIAN constructed by Waseda University and WABOT which is the world's first life-sized humanoid robot with the ability of walking and dancing [2]. H6 and H7 are humanoid robots constructed by University of Tokyo [3]. JOHNNIE is an anthropomorphic autonomous biped robot constructed by Technical University of Munich [4]. MK.5 is a compact size humanoid robot with 24 D.O.F. constructed by Aoyma Gakuin University [5]. The most impressive humanoid robot should be HONDA humanoid robots. P2 is the world's first cable-less humanoid robot, which can walk and can go up/down stairs [6]. P3(height 1600 mm, width 600 mm, weight including batteries 130 kg, 6 D.O.F./Leg, 7 D.O.F./Arm, 1 D.O.F./Hand) appeared in 1997 with the same mobility as P2 [7]. In 2000, further downsizing P3, ASIMO that stands for Advanced Step in Innovative Mobility appeared with children-size (height 1200 mm, width 450 mm, weight including batteries 43 kg, 6 D.O.F./Leg, 5 D.O.F./Arm, 1 D.O.F./Hand, 2 D.O.F./Head) [8,9].

This work includes the simple model of ASIMO robot and simulates its motion using series of motors to establish automatically robot stability during its motion. This robot has 23 D.O.F. Six motors that move the robot on the straight direction, eight motors control robot's stability and the other motors are used for extra body movements and 3D motion.

II. EQUATIONS OF MOTION

A. Two dimensions dynamic equation

There are many and complex equations to control a biped walking robot accurately; therefore, it is difficult to achieve a standard control algorithm. So, the simple models are used. A simple 2D model which has 5 D.O.F is shown in Fig. 1 [10].

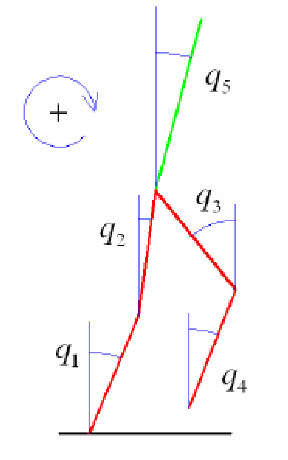

Fig. 1 absolute angels of 2D model with 5 D.O.F.

The dynamic model is given by:

$$B(q)\ddot{q} + c(q,\dot{q}) + g(q) = A\tau \tag{1}$$

Where $B(q)$ is the inertia matrix, $c(q,\dot{q})$ groups the coriolis and centrifugal terms, and $g(q)$ represents the gravitational term. The vector τ represents only the torques on the actuated motors, and matrix A is the mapping from the relative torques to the absolute torques. When only one foot is in contact with the ground, the system is said to be single support phase and when both feet are in contact with the ground is double support phase. Note that in this situation there is a closed kinematic chain formed by the two legs and the ground. The total number of degrees of freedom in this phase is three.

B. Impact model

The transition from the single support phase to the double support phase is assumed to occur with an anelastic collision of swing leg. This event results in a discontinuity of the joint velocities described by this equation [11].

$$\dot{q}^{+} = \Delta(q^{-}, \dot{q}^{-}) \tag{2}$$

Where the superscript ($^+$) indicates a value immediately after and ($^-$) immediately before the impact. The starting point is the extended dynamic model of the system that also includes the position and velocity of the stand foot. The new model has then 7 degree of freedom and can be represented as:

$$B(x)\ddot{x} + \hat{c}(x,\dot{x}) + g(x) = \begin{bmatrix} T \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} D_1(x) \\ D_2(q) \end{bmatrix} F \tag{3}$$

Where $x = (q_1, \ldots, q_n, x_p, y_p)^T$ is a new state vector that includes the Cartesian coordinate's x_p and y_p of the stand foot. On the right hand side there are the joint torques T and the constant forces $F = (F_0^t, F_0^n, F_c^t, F_c^n)$ are the forces exerted by the ground on the robot. The key idea is now to integrate the motion. With this integration, all forces that are not impulsive can be eliminated. Suppose that the stand foot gets fix on the ground and to be lifted after finishing impulse, by using collision theory, the velocity will be obtained after contacting the foot.

$$x^{+} - x^{-} = \hat{B}(x)^{-1} \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} \beta \tag{4}$$

That β is the integrated impulsive force.

C. Robotic linear control equation

By using four suitable outputs which are shown in Fig. 2 and *z5* which is moving of body on the *x* axis, we have [11]:

$$\begin{aligned} z_1 &= y_1 \\ z_2 &= y_2 \\ z_3 &= y_3 \\ z_4 &= y_4 \\ z_5 &= \eta(q, \dot{q}, \upsilon) \end{aligned} \tag{5}$$

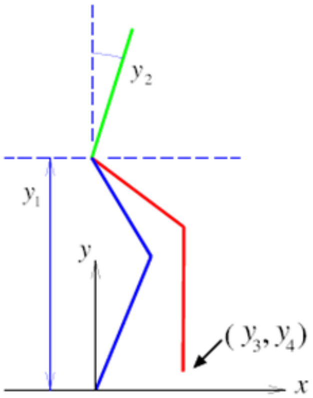

Fig. 2 Taken outputs from robot.

These values should be obtained by using absolute angles as follow:

$$\begin{aligned} y_1 &= l_1 c_1 + l_2 c_2 \\ y_2 &= q_5 \\ y_3 &= l_1 s_1 + l_2 s_2 - l_3 s_3 - l_4 s_4 \\ y_4 &= l_1 c_1 + l_2 c_2 - l_3 c_3 - l_4 c_4 \\ y_5 &= X_{hip} = l_1 s_1 + l_2 s_2 \end{aligned} \tag{6}$$

In this Equations l_i is length of each parts and $c_i = \cos(q_i)$, $s_i = \sin(q_i)$. If we derivate from above Equations to *t* will have:

$$\ddot{y} = J(q)\ddot{q} + n(q, \dot{q}) \tag{7}$$

The $\ddot{q}$ state should be obtained from dynamic model:

$$\ddot{q} = B^{-1}(q)[A\tau - c(q,\dot{q}) - g(q)] \tag{8}$$

The simpler form of Eq. 7 with substituting the above Equations is:

$$\ddot{y} = \tilde{J}(q)\tau + \tilde{n}(q, \dot{q}) \tag{9}$$

By applying this linear algorithm we express a new dynamic system:

$$\begin{aligned} \ddot{z}_1 &= \ddot{y}_1 = \upsilon_1 \\ \ddot{z}_2 &= \ddot{y}_2 = \upsilon_2 \\ \ddot{z}_3 &= \ddot{y}_3 = \upsilon_3 \\ \ddot{z}_4 &= \ddot{y}_4 = \upsilon_4 \\ \ddot{z}_5 &= \ddot{y}_5 = \varphi(z, \dot{z}, \upsilon) \end{aligned} \tag{10}$$

To obtain a linear system with static feedback position, we specify the torques value like this:

$$\tau = \tilde{J}(q)^{-1}(\upsilon - \tilde{n}(q, \dot{q})) \tag{11}$$

By choosing υ, this dynamic system will be stable and y_i will reach to the designed value to move on straight direction.

D. Motional constraint for controlling

The main duty of robot controller is ability to adjust robot's motion and speed. In this article, the time of swing foot trajectory is used for controlling walking and velocity. The velocity of walking is controlled by using of end in time of the swing foot trajectory or by ending phase of joint leg on the x axis direction. Therefore, an approximate simple dynamic system is assumed which is including inverted pendulum with variant length and concentrated mass in one point, as shown in Fig. 3 [12]. The pendulum mass (m) shows the total mass of the robot.

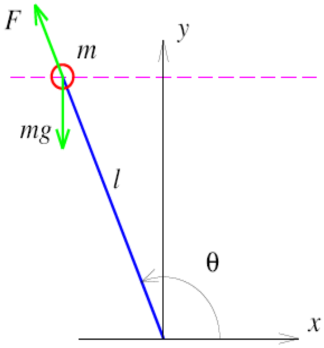

Fig. 3: Scheme of robot with assuming of concentrating mass and variant length.

If the most robot mass to be concentrated in the middle of the body, we can assume that the approximated mass of the inverted pendulum has always constant height. To keep y_1 constantly, the concentrated mass is desired to move on a parallel line with x axis. So we can do this by a linear motor and a control system. The motion of mass m, in x axis, is given as follows:

$$m\ddot{x} = T \qquad (12)$$

Where T is the horizontal component of F that is shown in Fig. 3 we conclude:

$$\ddot{x} - \gamma^2 x = 0\ ,\ \gamma = \sqrt{\frac{g}{y_0}} \qquad (13)$$

Where:

$$x(t) = C_1 e^{-\gamma t} + C_2 e^{\gamma t}$$
$$C_1 = \frac{\gamma x_0 - \dot{x}_0}{2\gamma} \qquad (14)$$
$$C_2 = \frac{\gamma x_0 + \dot{x}_0}{2\gamma}$$

$\dot{x}_0 = -\gamma x_0$ is the lowest initial speed that the mass should possess to reach to the point $x = 0$ so for continuing the motion on the x axis, the initial speed should be more than this value.

E. Swing foot rejection of robot

We approximate the swing foot trajectory by a cubic function including 2 functions on the y axis and one function for motion on the x axis that is shown in Fig. 4 and Eq. 15 [10].

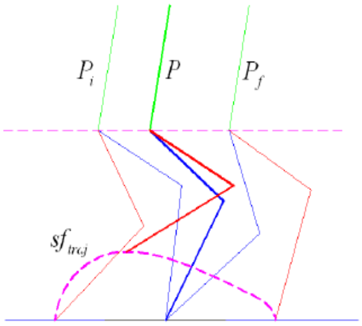

Fig. 4: Swing foot trajectory.

$$\begin{aligned} x_{sf}(s) &= a_x s^3 + b_x s^2 + c_x s + d_x \\ y_{sf1}(s) &= a_{y1} s^3 + b_{y1} s^2 + c_{y1} s + d_{y1} \quad s \in [0,c) \\ y_{sf2}(s) &= a_{y2} s^3 + b_{y2} s^2 + c_{y2} s + d_{y2} \quad s \in (c,1] \end{aligned} \qquad (15)$$

By using the boundary condition in single support phase these 3 functions are derived. Using robot dimensions, we can obtain the torque values in each motor. Thereafter with Eq. 11 and by applying obtained torques to the motors, robot moves on the defined direction.

III. NUMERICAL EXAMPLE

With considerate 2D robot model as shown in Fig. 5 and given dimensions and size in Eq. 16 we want to calculate the rotating angle values, angular accelerations, angular velocities and torques of each motor.

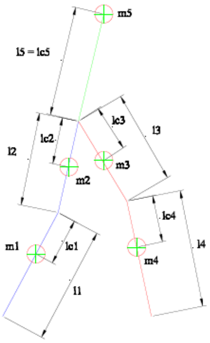

Fig. 5: Length and mass of each part in 2D model.

For doing this it needs to calculate the swing foot trajectory and body trajectory in single support phase which is used plastic contact assumption. A prepared program in Matlab-Simulink gives the trajectory of swing foot. The result is depicted in Fig.6. The numerical value of parameters are as follows:.

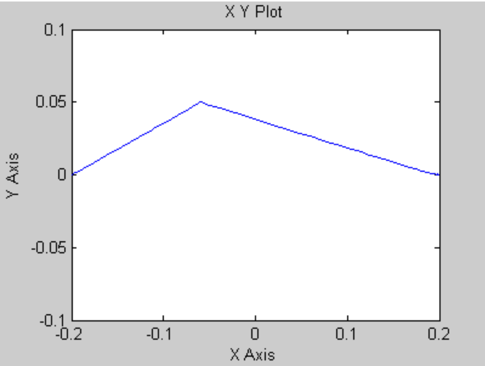

Fig. 6: The *x-y* diagram of swing foot trajectory in single support phase.

$$\begin{aligned} & m1 = 4; m2 = 4.6; m3 = 4.6; m4 = 4; m5 = 9 \\ & l1 = .41; l2 = .34; l3 = .34; l4 = .41; l5 = .67 \\ & I1 = .06; I2 = .04; I3 = .04; I4 = .06; I5 = .32 \\ & lc1 = .26; lc2 = .16; lc3 = .16; lc4 = .26; lc5 = .67 \end{aligned} \quad (16)$$

IV. OBTAINED SIMULATION

To evaluate results of motion on the straight direction the robot of Fig. 7 is considered and its motion is simulated [13,14].

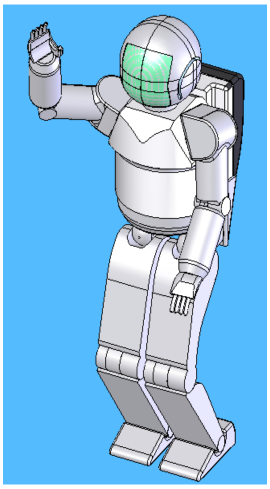

Fig. 7: Simulating 3D model of robot in the SOLID WORKS software.

The illustrated 3D model has 23 DOF which is as follows: 6 D.O.F in each leg, 4 D.O.F in each hand, 2 D.O.F in head, 1 D.O.F in waist.

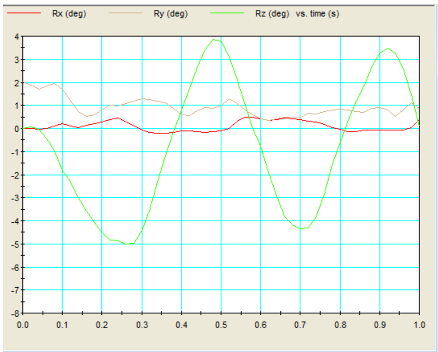

Fig. 8: The rate of rotating of robot's upper body in 3 directions of coordinate axis's.

To control the robot, joint angles of the upper body in 3 directions is obtained from motion simulation by using control systems in MATLAB software and also using feedback from the angles. The results are shown in Fig. 8.

Simulation of the robot motion on the straight direction is shown in Fig. 9 by MSC. Visual Nastran software and rotating angles, angular velocities and angular accelerations in simulating of motion of this robot are shown in Fig. 10:

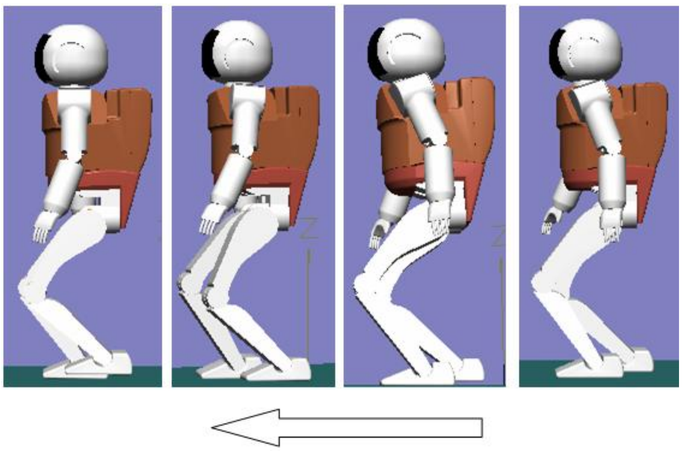

Fig. 9: Simulation of robot motion on the straight direction.

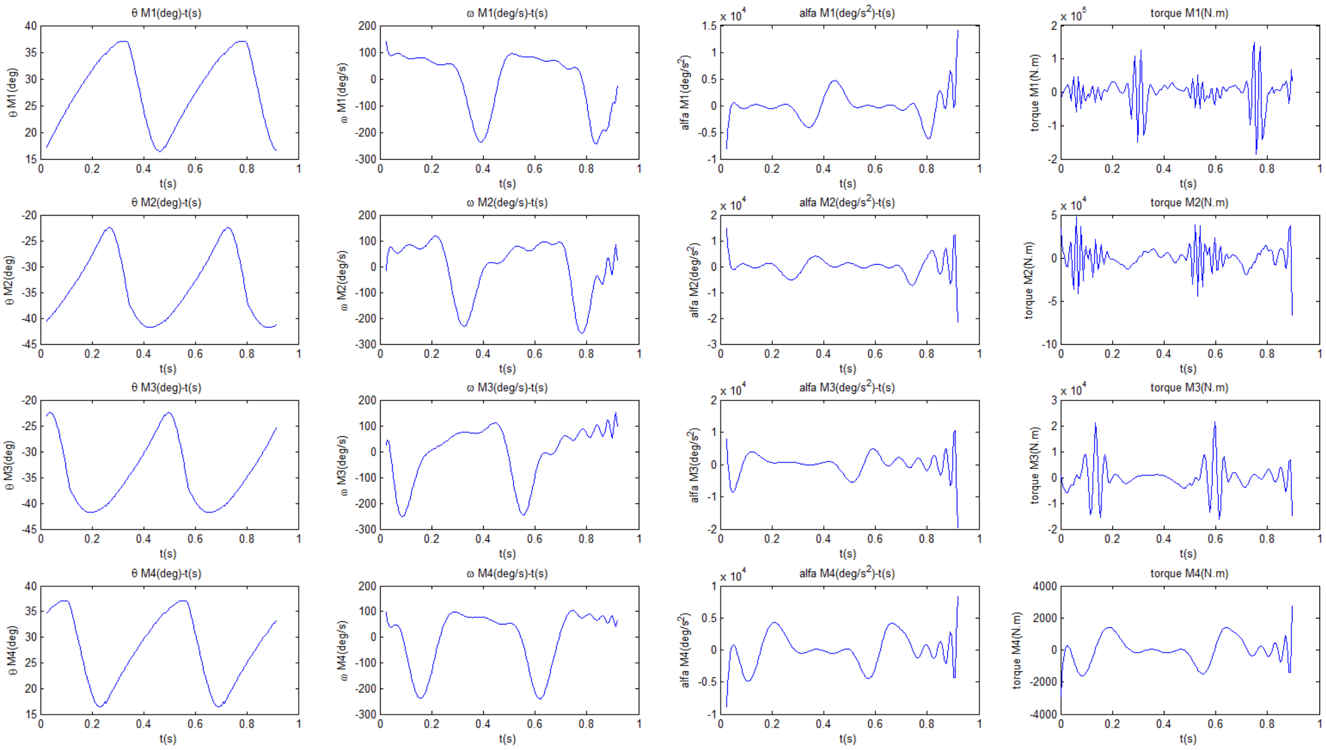

Fig. 10: Calculated values of the angles, angular velocity, angular acceleration and angular torque of the motors in 2D situation.

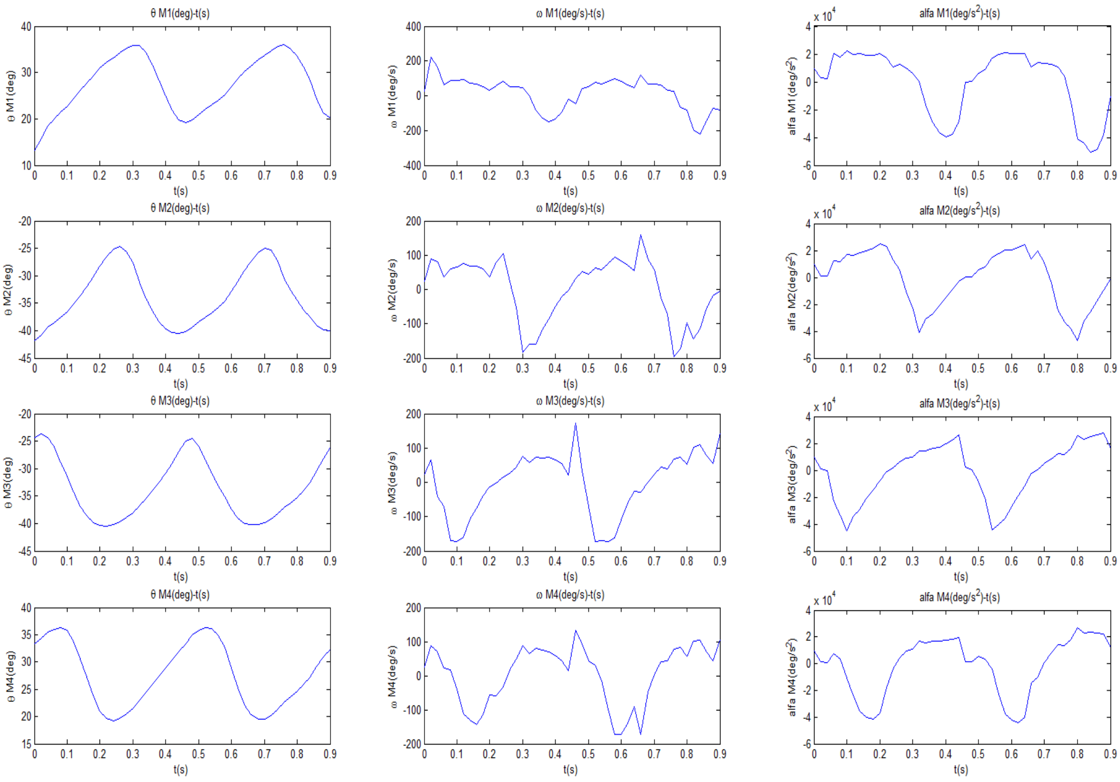

Fig. 11: Measured values of angles, angular velocities and angular accelerations in simulating of the motors in the 3D simulating situation.

V. CONCLUSION

Considering figures 10 and 11 the following results can be obtained:

The angular motion motors in 2D and 3D simulation are the same. During the contact time in simulation process there is jump discontinuity and jerk in angular acceleration of revolute joints which is due to the impulse between the ground and robot foot. Therefore the angular acceleration also takes variants to the 2D situation. The calculated torqueses are not comparable to each other because of different natures in 2D and 3D situations. Controlling the robot is done very well; during it moves on the straight direction in *x-y* plane and right on *z* direction. This matter is occurred because of keeping stability of the robot in single support leg of course as it is shown in Fig. 8 effect of the robot control as well as the movements of hands and feedback of upper part of the robot, the value of this revolute joint angles with respect to time can be investigated.

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