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The dynamic analysis of humanoid robot system

Yunn-Lin Hwang[1,a], Chien-Hsin Chen[1,b], Shen-Jenn Hwang[1,c], Wen-Huang Lin[2,d], Nguyen Xuan Mai[3,e]

[1]National Formosa University, Department of Mechanical Design Engineering, Yunlin 63201, Taiwan

[2]National Formosa University, Office of Physical Education, Yunlin 63201, Taiwan

[3]National Formosa University, Department of Mechanical & Electro-Mechanical Engineering, Yunlin 63201, Taiwan

[a]hwang@nfu.edu.tw, [b]chchen@nfu.edu.tw, [c]hwang6@nfu.edu.tw, [d]david@nfu.edu.tw, [e]xuanmai1711@gmail.com

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Abstract. The main objective of this paper is to simulate the mobility of humanoid robot. Simulation method implemented by using RecurDyn, one can analyze the kinematics and dynamics of BIOLOID humanoid robot. Moreover, the analysis of mobility will be discussed. In this paper, the Zero-Moment Point and Forward Dynamics methods are also introduced to the dynamic analysis of humanoid robot. Finally, the simulation results show that the algorithms developed in this paper can efficiently enhance the stability of the humanoid robot.

Introduction

Nowaday, robots are becoming more and more popular all over the world, expecialy humanoid-robot. A humanoid robot is a robot with its body shape is built like human body, design might be for many purposes such as interacting with human tools and environments, study of bipedal locomotion, etc. So the goal of this paper is find out more about the dynamic control analysis of humanoid robot system. During this paper, three softwares are used such as RoboPlus to control the real humanoid robot, SolidWorks and RecurDyn to construct and simulate the robot model. Human walking can be considered as a periodic phenomenon. A complete walking cycle is composed of two phases: a double support phase and a single support phase. The gait cycle is the period of time between any two identical events in the walking cycle [1]. During double support phase, both feet are in contact with the ground. This phase begins with the heel of the forward foot touching the ground, and ends with the toe of the rear foot leaving the ground. During the single support phase, one foot is stationary on the ground, and the other foot swings from the rear to the front [2]. When the heel of the forward foot touches the ground, the hip along the vertical direction is going to achieve the lowest point. Then in the middle of single support phase, called midstance in medical terminology, the hip will achieve the highest point [3]. There are two types of biped walking: static walking and dynamic walking. Static walking is easier to implement, but it is slow. Dynamic walking can achieve much faster walking speed but has more challenges [4]. Static walking means the projection of the center of mass (CoM) on the ground should be always inside the foot supported area during walking. In other words, a biped robot can move one foot forward only after it has its weight balanced on the other foot. Because it can only achieve slow speed, static walking has been seldom noticed.

The Lagrangian for an open-chain robot

To calculate the kinetic energy of an open-chain robot manipulator with n joints, we sum the kinetic energy of each link. For this, we can define a coordinate frame, L_i, attached to the center of mass of the ith link. Let

$$g_{sl_i}(\theta) = e^{\hat{\xi}_1\theta_1} \ldots e^{\hat{\xi}_i\theta_i} g_{sl_i}(0) \tag{1}$$

represent the configuration of the frame L_i relative to the base frame of the robot, S. The body velocity of the center of mass of the ith link is given by

$$V^b_{sl_i} = J^b_{sl_i}(\theta)\dot{\theta} \tag{2}$$

where $J^b_{sl_i}$ is the body Jacobian corresponding to g_{sl_i}. $J^b_{sl_i}$ has the form

$$J^b_{sl_i}(\theta) = \left[\xi^\dagger_1 \ldots \xi^\dagger_i\right] \tag{3}$$

where

$$\xi^\dagger_j = Ad^{-1}_{(e^{\hat{\xi}_j\theta_j} \ldots e^{\hat{\xi}_i\theta_i} g_{sl_i}(0))}\xi_j \qquad j \le i$$

is the jth instantaneous joint twist relative to the ith link frame. To streamline notation, we write $J^b_{sl_i}$ as J_i for the remainder of this section.

The kinetic energy of the ith link is

$$T_i(\theta,\dot{\theta}) = \frac{1}{2}(V^b_{sl_i})^T M_i V^b_{sl_i} = \frac{1}{2}\dot{\theta}^T J_i^T(\theta) M_i J_i(\theta)\dot{\theta} \tag{4}$$

The matrix $M(\theta) \in \mathbb{R}^{n\times n}$ is the manipulator inertia matrix. In terms of the link Jacobians, J_i, the manipulator inertia matrix is defined as

$$M(\theta) = \sum_{i=1}^{n} J_i^T(\theta) M_i J_i(\theta). \tag{5}$$

To complete our derivation of the Lagrangian, we must calculate the potential energy of the manipulator. Let $h_i(\theta)$ be the height of the center of mass of the ith link (height is the component of the position of the center of mass opposite the direction of gravity). The potential energy for the ith link is

$$V_i(\theta) = m_i g h_i(\theta) \tag{6}$$

where m_i is the mass of the ith link and g is the gravitational constant. The total potential energy is given by the sum of the contributions from each link:

$$V(\theta) = \sum_{i=1}^{n} V_i(\theta) = \sum_{i=1}^{n} m_i g h_i(\theta). \tag{7}$$

Combining this with the kinetic energy, we have

$$L(\theta,\dot{\theta}) = \sum_{i=1}^{n}(T_i(\theta,\dot{\theta}) - V_i(\theta) = \frac{1}{2}\dot{\theta}^T M(\theta)\dot{\theta} - V(\theta). \tag{8}$$

Dynamic equations of motion

The dynamic equations of motion among links can be written in a compact matrix form as

$$\underline{\boldsymbol{q}} = \underline{\boldsymbol{H}}^p \ddot{\underline{\boldsymbol{p}}} + \underline{\boldsymbol{\beta}} \tag{9}$$

where the vectors $\underline{\boldsymbol{q}}$, $\ddot{\underline{\boldsymbol{p}}}$ and $\underline{\boldsymbol{\beta}}$, and the matrix $\underline{\boldsymbol{H}}^p$ defined as following

$$\underline{\boldsymbol{q}} = \begin{bmatrix} \boldsymbol{q}_1^{\mathrm{T}} & \boldsymbol{q}_2^{\mathrm{T}} & \cdots & \boldsymbol{q}_{i-1}^{\mathrm{T}} & \boldsymbol{q}_i^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \tag{10}$$

$$\ddot{\underline{\boldsymbol{p}}} = \begin{bmatrix} \ddot{\boldsymbol{p}}_1^{\mathrm{T}} & \ddot{\boldsymbol{p}}_2^{\mathrm{T}} & \cdots & \ddot{\boldsymbol{p}}_{\mathrm{i-1}}^{\mathrm{T}} & \ddot{\boldsymbol{p}}_{\mathrm{i}}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \tag{11}$$

$$\underline{\boldsymbol{\beta}} = \begin{bmatrix} \hat{\boldsymbol{\beta}}_1^{\mathrm{T}} & \hat{\boldsymbol{\beta}}_2^{\mathrm{T}} & \cdots & \hat{\boldsymbol{\beta}}_{\mathrm{i-1}}^{\mathrm{T}} & \hat{\boldsymbol{\beta}}_{\mathrm{i}}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \tag{12}$$

where $\hat{\boldsymbol{\beta}}_i = \boldsymbol{\beta}_i + \boldsymbol{H}^q_{i,i-1}\hat{\boldsymbol{\beta}}_{i-1}$

$$\underline{\boldsymbol{H}}^p = \begin{bmatrix} \boldsymbol{H}^p_1 & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{H}^q_{i,i-1}\ldots\boldsymbol{H}^p_1 & \cdots & \boldsymbol{H}^p_i \end{bmatrix} \tag{13}$$

Clearly, the system equations of Eq. 13 (from link 1 to link $\boldsymbol{i}$) can be combined together in a compact matrix form

$$\underline{\boldsymbol{M}}^{g}\underline{\boldsymbol{a}} = \underline{\boldsymbol{f}}^{g} \tag{14}$$

where system acceleration vector $\underline{\boldsymbol{a}}$, system mass matrix $\underline{\boldsymbol{M}}^{g}$ and system force vector $\underline{\boldsymbol{f}}^{g}$ are defined as

$$\underline{\boldsymbol{M}}^{g} = \begin{bmatrix} \boldsymbol{M}_1^g & 0 & \cdots & 0 & 0 \\ 0 & \boldsymbol{M}_2^g & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \boldsymbol{M}_{i-1}^g & 0 \\ 0 & 0 & \cdots & 0 & \boldsymbol{M}_i^g \end{bmatrix} \tag{15}$$

$$\underline{\boldsymbol{f}}^{g} = \begin{bmatrix} \boldsymbol{f}_1^{g\mathrm{T}} & \boldsymbol{f}_2^{g\mathrm{T}} & \cdots & \boldsymbol{f}_{i-1}^{g\mathrm{T}} & \boldsymbol{f}_i^{g\mathrm{T}} \end{bmatrix} \tag{16}$$

Thus, the related acceleration vector $\underline{\boldsymbol{a}}$ can be solved using several numerical analysis methods if the mass matrix $\underline{\boldsymbol{M}}^{g}$ and the force vector $\underline{\boldsymbol{f}}^{g}$ are calculated and given.

Zero-Moment Point

The definition of ZMP was original introduced by Vokobratovic et al. in 1969, it is as follows: *"ZMP is defined as that point on the ground at which the net moment of the inertial forces and the gravity forces has no component along the horizontal axes."* In other words, ZMP is the point where Mx=0 and My=0. Mx and My represent the moments around x-axis (sagittal direction) and y-axis (lateral direction) generated by reation force, respectively. Vokobratovic also pointed out that COP (center of pressure) coincide with ZMP as the gait is dynamical balance. Here COP means a point within the foot where the resultant of the ground reation force acts. According to the definition, the ZMP equation can be represented as:

$$\sum_{i=1}^{N}\{m_i(p_{Gi} - ZMP)\times(\ddot{p}_{Gi} + g) + I_i\dot{\omega}_i \times I_i\omega_i\} = n_Z \tag{17}$$

$$\mathbf{n}_Z \times \mathbf{g} = 0 \tag{18}$$

where N is the number of links; m_i is the mass of link i; $\boldsymbol{I}_i$ is the inertia tensor of link i; $\mathbf{p}_{Gi} \equiv \left[x_{Gi} y_{Gi} z_{Gi}\right]^T$ is the center of gravity of link i; ω_i is the angular velocity of link i; $\boldsymbol{ZMP} \equiv \left[ZMP_x ZMP_y ZMP_z\right]^T$ is the position of ZMP; $\mathbf{n}_Z \equiv \left[n_{Zx} n_{Zy} n_{Zz}\right]^T$ is the moment around ZMP; and $\mathbf{g} \equiv [0\ 0\ -\mathrm{g}]^{\mathrm{T}}$ is the acceleration of gravity. If the height of the ground ZMP_z is given and the inertia of each link is ignored, Eqs.17 and 18 can be rewritten as:

$$ZMP_x = \frac{\sum\{m_i x_i(\ddot{z}_i + g) - m_i\ddot{x}_i(z_i - ZMP)\}}{\sum m_i(\ddot{z}_i + g)} \tag{19}$$

$$ZMP_y = \frac{\sum\{m_i y_i(\ddot{z}_i + g) - m_i\ddot{y}_i(z_i - ZMP_z)\}}{\sum m_i(\ddot{z}_i + g)} \tag{20}$$

If the position ZMP_x and ZMP_y computed from Eqs. 19 and 20, is within the support polygon, then the system is in dynamic equilibrium. Hence the primary task of the humanoid control systems is to constantly maintain the ZMP within the support area and prevent it from coming too close to the edge of support area so that a sudden disturbance would not cause a robot to lose its equilibrium and the to fall down [5].

Numerical example

As shown in Fig. 1, the Bioloid humanoid robot system is a 10-DOF system including several links connected by 10 revolute joints. The body reference coordinate systems are initially attached at the mass center of the respective links. In this study, these links are assumed to be rigid. The rationale is to develop a dynamic model which is based on previous formulation and capable of accurately predicting the behavior of the humanoid robot system. Figure 2 shows the Bioloid model was simulated by RecurDyn. Figure 3 shows the raise-hands, squatting down and standing up movements. Figure 4 indicates the displacement of mid point of human hipbone during one cycle.

Summary and Acknowledgement

In this paper, a general formulation is presented for solving the equations of motion of human biomechanical systems consisting of interconnected rigid and flexible bodies. The resulting system of equations of motion can be solved for the absolute, joint and elastic accelerations as well as the reaction forces. The whole multibody human biomechanical systems can be solved and simulated by using the nonlinear recursive formulation presented in this investigation. The authors would like to appreciate the finacial support of National Science Council of Taiwan under the grant contracts NSC-101-2511-S-150-002 and Research Center for Energy Technology and Strategy of National Cheng Kung University.

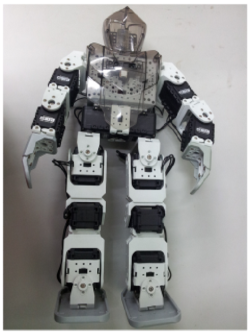

Fig. 1 Bioloid humanoid robot.

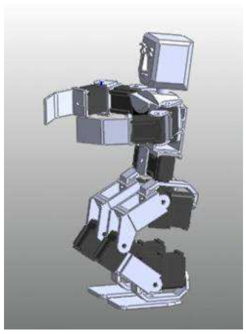

Fig. 2 Bioloid model simulated by RecurDyn

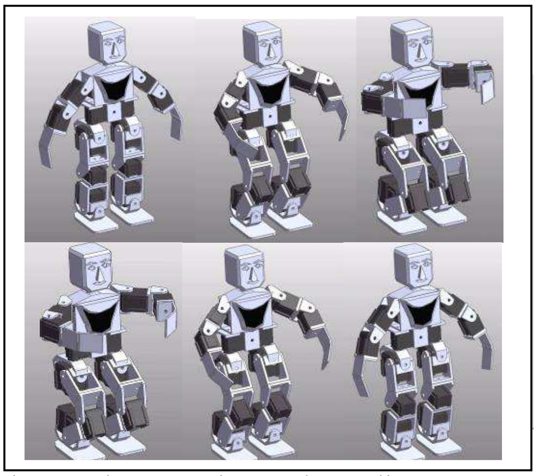

Fig. 3 The squatting and standing movements

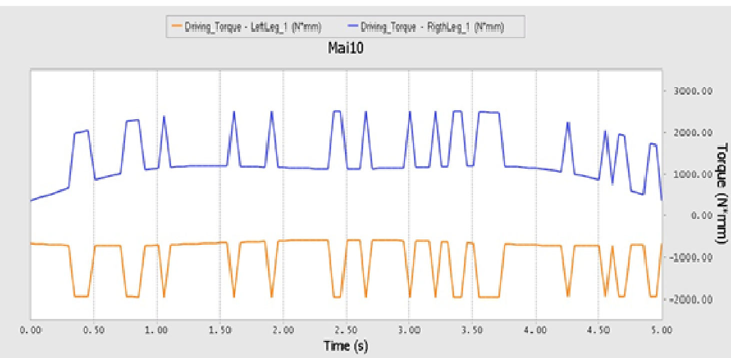

Fig. 4 The joint torques of right and left leg_1

References

[1] L. A. Gilchrist and D. A. Winter: IEEE, Vol. 5(1997), p. 290-8.
[2] A. J. Ijspeert: Int. J. of Neural Networks, Vol. 21(2008), p. 642–653.
[3] X. H. Duan, R. H. Allen, and J. Q. Sun: Med Eng Phys, Vol. 19(1997), p. 518-24.
[4] A. I. Botas: System Theory, Control, and Computing (ICSTCC2011), p.1-5.
[5] M. Vukobratovic, B. Borovac: Int. J. of Humanoid Robotics, Vol. 1, No. 1(2004), p. 157–173.