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BIPED ROBOT MODELING WITH REFLEX FUNCTION FOR STABILITY ANALYSIS AND CONTROL

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Abstract. *This work shows a typical 12 DOF biped robot model with a reflex function to overcome external perturbations with an articular control intended to maintain standing stability. A parameterized system is developed under SimMechanics 3D virtual environment from Matlab ®. Initially, an anthropomorphic model was configured with internal and external parameters for the study of body dynamics stability, such as link inertias, joint restrictions, ground interactions, and articular trajectory control. The reflex functions allow the robot to detect external perturbations which are modeled by measurement of the structure centroid and the identification of critical events that may destabilize the model. Next, the stability is reached through articular control of the lower limbs; relocation, their effects on the center of mass and pressure distribution on the contact surface. The system is evaluated to determine the ways in which the modeling method is able to find the sensibility of any dynamic biped model under external perturbations or initial pose conditions. The studied biped model is able to control its pose and maintain standing stability through multiples dynamic perturbations.*

Keywords: *Biped Robot, Stability Control, Reflex, Humanoid Robot*

1. INTRODUCTION

The study of biped robots has evolved in the pass years to become one of the most significant areas of interest on advanced robotics and biomechanical studies.The principal interest on the development of this kind of robots lies on its ability to sort and navigate on unstructured terrains using stability functions. In this paper, stability in the system is considered as keeping the equilibrium of a standing position on the robot.

Maintaining a state of standing equilibrium on biped robots is a crucial task which can be achieved by introducing equilibrium criteria in the control law. The most appropriated criterion relays on Center of Mass (CoM) and Zero Moment Point (ZMP), this criterion takes into consideration the dynamic and static forces.

The analysis of passive dynamic walkers and the introduction to control method for powered bipeds such as (Ozawa *et al.* , 2010) and the reflex control implementation on walking bipeds by (H. Kimura and S. Shimoda , 2010); the need to develop a model for the analysis of stability control on a parametric plant becomes evident. The dynamic equations of biped robots are nonlinear and difficult to control; hence, researchers are confronted with heavy nonlinearity in the dynamic equation that describes the behavior of the robots.

New designs and methods to develop these robots have emerged around the world, having as a common goal to achieve a robust walking pattern in (Kajita *et al.* , 2003) and (Kherici *et al.* , 2014) ; these prototypes vary in both control strategies and structure design. In order to analyze and compare these different prototypes and eventually develop new and better systems, a method of dynamic mechanical analysis must be able to assess the behavior of this structures and its stability.

To maintain stability the biped must ensure some dynamic conditions controlling its joints to reach an specific pose where all internal and external perturbances are counteracted to assure walking, as in recent works (Kajita *et al.* , 2004) and (Kamogawa *et al.* , 2013), running or even standing positions. The whole body coordination (WBC) solution for this problem is provided by the control of the center of mass (CoM) of the robot through the kinematic solution of its Jacobian. (Choi *et al.* , 2007)

2. MODELING

A biped robot model its proposed considering only its lower limbs; waist, left leg and right leg. Seven bodies compose the biped structure. The robot's physical data matching a common robot configurations (Table 1) was taken from the literature reviewed (Kim *et al.* , 2009) . Each body is described as a rigid link with its own inertia moments and CoM configuration in order to obtain a single assembly as shown on Figure. 1.

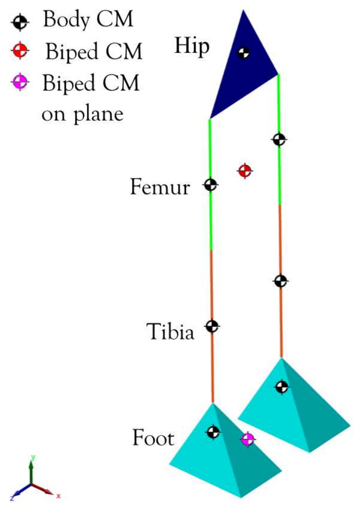

Figure 1. Biped model with links and CoM points.

Body	Length	Mass
Foot	45.4 mm	0.13 kg
Tibia	116.1 mm	0.42 kg
Femur	99.7 mm	0.75 kg
Waist	66.75 mm	1.36 kg

Table 1. Physical properties of the biped assembly

Mobility is an important factor in the robot development. A robot with many DOF can move smoothly but this implies more complexity in modeling and control. Some works on the search of walking parameters on active biped robots propose a 12-DOF model capable of sagital and coronal movements (Kim *et al.* , 2009).

A real model has parts like motors, cables, stability structures and other kinds of elements that affect the dynamics of the system; in the constructed model, such parts were joined to the principal links taking in to account their weigh, position and mass distribution. In actual operation these elements have an effect in the total inertia, perturbations and torque each joint needs to deal with in order to maintain the angles of stable stances and gait instances.

A virtual model was constructed using SimMechanics block design method and the physical information of each body, articulation and join actuator as shown on Figure. 2. This modeling method is proven to be useful on the design of mechanisms and the implementation of robust control laws, it allows the implementation of sensors, actuators, and control inputs to the model as presented on recent works (Hernández-Santos, C. and Soto, R and Rodríguez, E. , 2011) (Yuan *et al.* , 2008). This design method allows to speed-up modifications and parametrization of the robot characteristics to test the model under various conditions. The model was controlled by the force input of a virtual motor on each rotative joint, where a sensor constantly obtain the angular position and the torque reaction for each articulation.

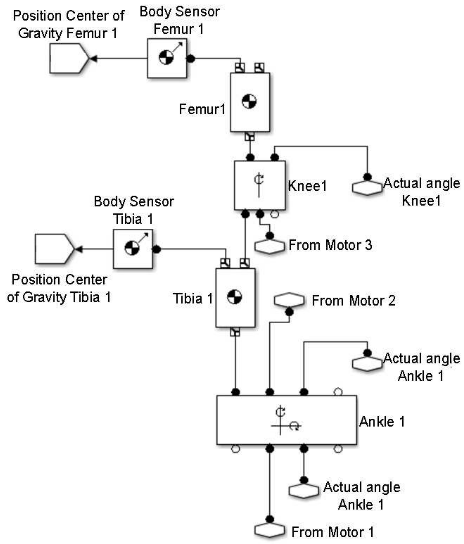

Figure 2. Modeling of a leg assembly using SimMechanics.

2.1 Contact Restriction

In recent works on biped walking stability (Sugihar *et al.* , 2002) , the contact interface between the robot and the environment is essential to define the support regions correctly and characterize obstacles along the path. Contact for the feet points is implemented as a viscoelastic elastic contact model in which the reaction force on the body depends on the relative position to the floor.

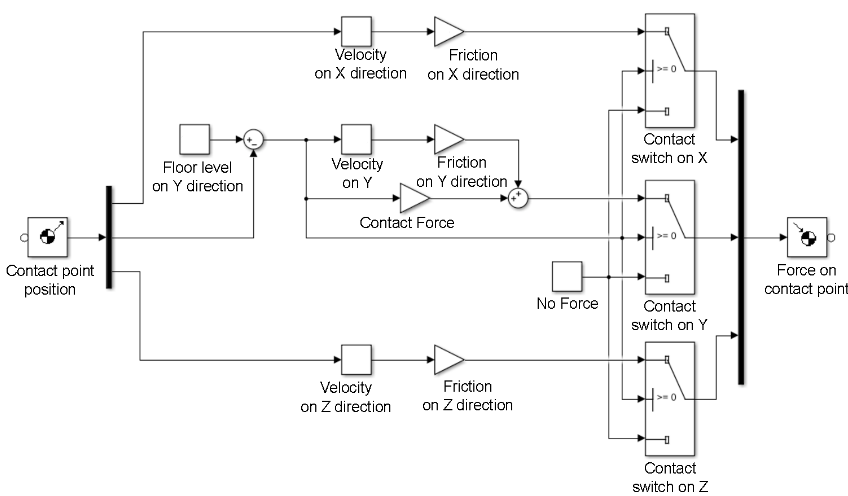

Figure 3. Contact model for a foot point.

Using body sensors on each link of the assembly, the exact position of the feet contact points can be acceded to calculate the force reacting in the point when it passes the floor physical restriction as shown on Figure 3. The reaction force, which exists only in the Y direction, is calculated with the amount of overlapping between the floor surface and the contact point. The reaction force on X and Z direction when the point is in a Y negative coordinate depends on the sliding velocity on each direction. The dynamic contact reaction to the velocity on each direction acts as an energy dissipation element in the model. The parametric model makes possible the configuration of different contact interfaces to simulate materials reaction and its effects on stability control.

3. STABILITY CONTROL

The virtual model was made using mechanical information about the robot such as weight, link dimensions and set position and analyzing it as a physical assembly. The mechanical characteristics of the 7 links on the mechanism are defined by its connection points coordinates, mass, center of gravity and inertia moment. The ground was modeled as a single horizontal $Y = 0$ surface where the foots react to a contact condition. The CoM is calculated according to the position and dynamic properties of the links in the assembly.

$$Mx_{cm} = \sum_{i=1}^{n} m_i x_i \quad \text{where} \quad M = \sum_{i=1}^{n} m_i \tag{1}$$

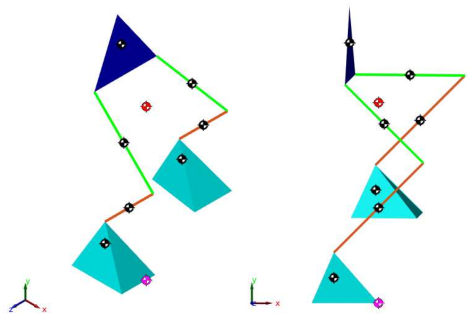

Figure 4. Biped robot in single leg stand.

The standing stability is reached trough the positioning of the CoM projection on the ground, that must be maintained under the support polygon formed by the bodies in contact with the ground. In Figure. 4 the robot is arranged in a single leg support pose where only its right leg is supporting the robot posture and the other leg acts as an active internal perturbation while its independent movement change the mass distribution of the assembly.

The desired motion of the CoM point of the robot is reached through the modification of the pose by rearranging the articulations, the relation between this articulation and the outcome on the desired pose of the robot is described by the Jacobian (J) analysis of the structure. Considering each limb of the robot as an independent parameter, both linear and angular velocity $\frac{\nu_p}{\omega_p}$ of the i-th element ($^0\dot{x}_i$) in the structure are defined by:

$$^0\dot{\boldsymbol{x}}_i =^0 J_i \dot{\boldsymbol{q}}_i \quad \text{where} \quad ^0\dot{\boldsymbol{x}}_i = \begin{bmatrix} \frac{\nu_p}{\omega_p} \end{bmatrix} \tag{2}$$

The Jacobian matrix (J) for the biped robot must be calculated on each position since the velocity relations between the articulations and final points depend on the actual pose of the robot, the Jacobian is constructed as in Eq. (3). Each articulation Jacobian is described by a z_{i-1} unit vector describing the direction of the i-th axis and $^{i-1}p_n$ a vector going from the $i-1$ link origin to the frame on the final x point.

$$J = [J_1, J_2, ..., J_n] \quad \text{where} \quad J_i = \begin{bmatrix} \boldsymbol{Z_{i-1}} \times^{i-1} \boldsymbol{p_n} \\ \boldsymbol{Z_{i-1}} \end{bmatrix} \tag{3}$$

As the robot pose changes the CoM projection ($CoM_{current}$) moves on the floor ideally to the desire position ($CoM_{desired}$), on any time this relation on actual and desire position is checked to calculate the error (CoM_{error}) on the x and z direction as shown on Figure. 5.

$$CoM_{error} = CoM_{desired} - CoM_{current} \tag{4}$$

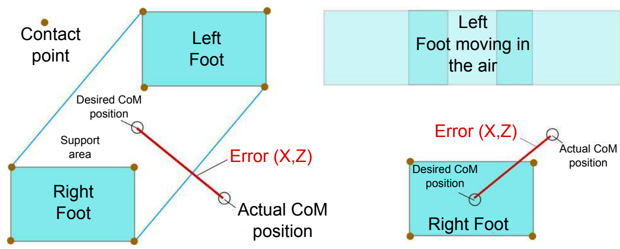

Figure 5. Error on the CoM ground projection over a double support and single stand pose.

The implemented control scheme continuously calculates the position of the CoM using the articular sensors on the robot, which is later compared to determine the error distance to the desired position. The error distance is computed with the Jacobian matrix to determine the kinematic control on each angle to move the final point x in the desired direction. Since the Jacobian matrix J is a function of the θ values of the articulations, the relation:

$$J(\theta) = \left(\frac{\partial x}{\partial \theta_j}\right)_{i,j} \quad \text{where} \quad {}^0\dot{\boldsymbol{x}}_i = {}^0 J_i \dot{\boldsymbol{q}}_i \tag{5}$$

An iterative method for solving equation Eq. (8) is used to determine the inverse kinematic relation between $\boldsymbol{x}$ and $\boldsymbol{\theta}$. Starting from a initial pose $\boldsymbol{\Theta}$ the Jacobian is computed and then an uptade $\triangle\boldsymbol{\theta}$ increments the n joint angles θ to a new robot pose.

$$\Theta_i = \Theta_i + \triangle\Theta_i \quad \text{with} \quad i = 1, n \tag{6}$$

The change on the final point position x caused by the Θ update can be estimated as

$$\triangle \boldsymbol{X} = J \triangle \boldsymbol{\Theta} \tag{7}$$

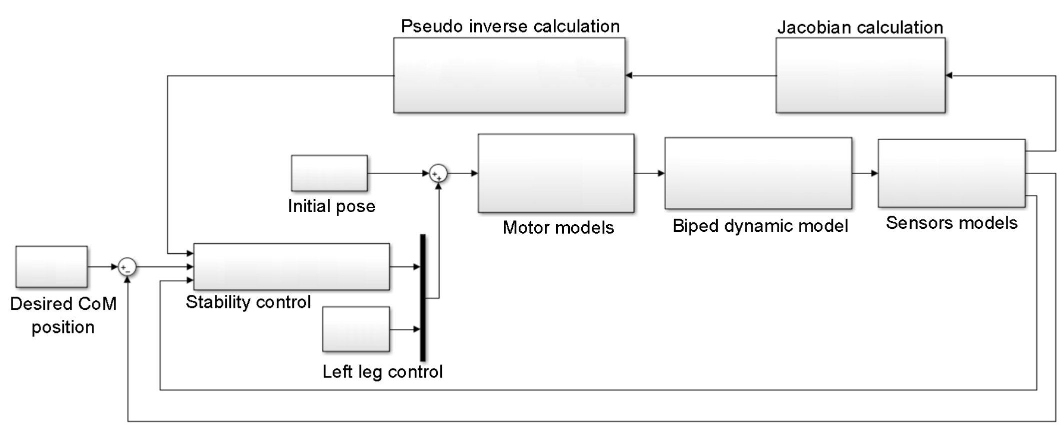

Figure 6. General control model for the biped robot.

The model presented on Figure. 6 aims to find the $\triangle\theta$ value for a desired $\triangle x$ movement of the CoM point by discretizing the error calculated on Eq. (5), this gradual process modifies the position of the CoM in the correct direction in order to minimize the error vector. This control method has been successful as shown on many works as on biped motion control as (Yan *et al.* , 2007) , (Wollherr, D. and Buss, M. , 2004) and (Kajita *et al.* , 2008) in the rejection of disturbances and accounting modeling error in trajectory precalculations.

4. RESULTS AND DISCUSSION

First set of simulations were conducted (driven) to find the correct control parameters to reach the desired pose beginning at a pose shown on Figure . 4.The robot is maintained in single leg standing position to calculate the responses of the model to an internal perturbation generated by the movement of the free leg on the air. The sequence on Figure. 7 shows the pose transitions of the robot while controlling the CoM position above of the support area with no internal or external disturbances applied (Fig. 7).

The results indicate that the model maintain the robot on a standing postion equilibrium for extended periods of time.

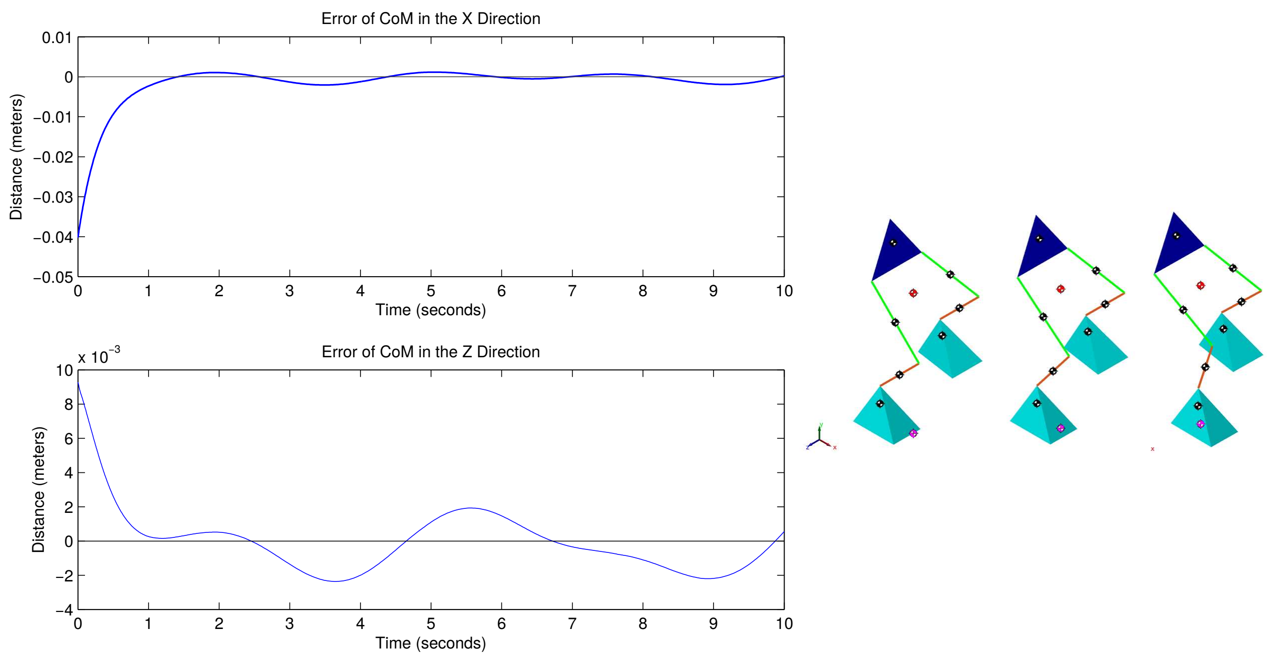

Figure 7. Position error of the projected CoM for the biped robot on single leg support position with no additional disturbances.

Another experiment carried out was to introduce an internal disturbance by extending the left leg, this movement is modeled as a second order function to reduce any potential jerk reaction to an abrupt change in the pose of the robot (Fig. 8). Even though the change in the mass distribution of the assembly alters the CoM, the control reject this disturbance by correcting the pose with its support leg and moving back the hip body in order to affect the CoM position to an optimal stable point Fig. 9. The sequence on Figure. 9 shows the pose transitions of the robot while correcting the position of the CoM above of the support area formed under the right foot.

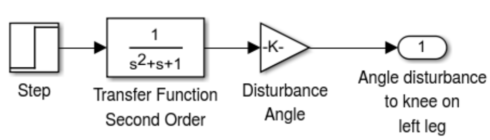

Figure 8. Second order block model for internal disturbance at left leg.

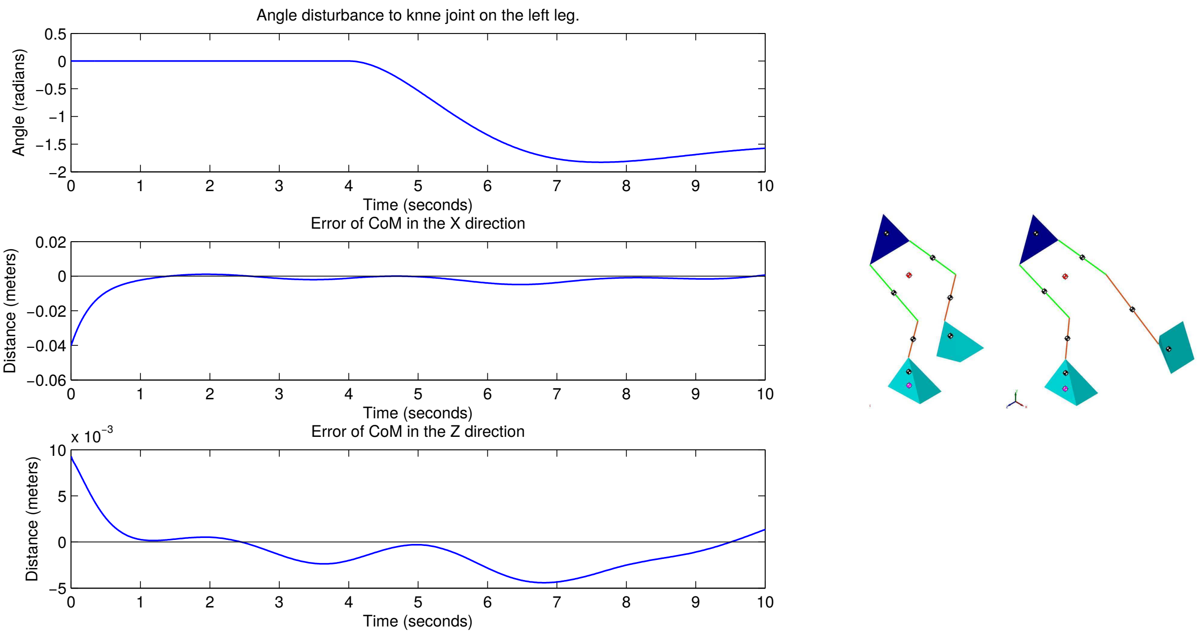

Figure 9. Position error of the projected CoM and sequence of movement for the biped robot on single leg support position with internal disturbance.

The contact condition defined by the elastic reaction force on the foot vertexes to the floor surfaces allows the evaluation of the model under external disturbances. A force is applied on the center of gravity of the hip body on the X direction. As the support foot is not fixed to the floor, some contact points act like pivots as other rise from the surface Fig. 10. The external force is a Gaussian symmetric function given by:

$$F_{external} = 1 \times \exp^{\frac{-0.5(x-C)^2}{\sigma^2}} \tag{8}$$

with variance $\sigma = 1$ and mean $C = 4$ acting at 4 seconds after the CoM have reached the center of the support foot.

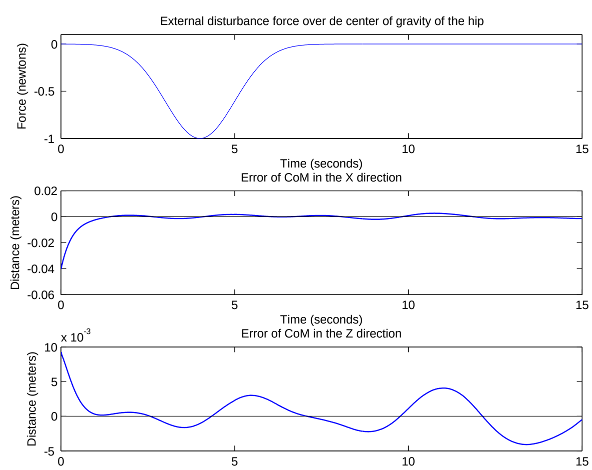

Figure 10. Position error of the projected CoM for the biped robot on single leg support position with external disturbance.

5. CONCLUSIONS

This modeling method offers fast and highly customizable procedure to create systems, which can be suitable for the stability evaluation of new or existing robotics platforms and the implementation of better control approaches.

Just as a real life implementation the robot modeled allows the acquisition of actual joint torques and reaction forces which can be used to improve the design, material selection and capabilities delimitation of any real prototype.

Improving the performance on the controllers and their combined action is important to ensure robustness of operation and the optimization of motion on fully actuated biped robots.

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