Modeling a Biped Robot on Matlab/SimMechanics

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***Abstract* — This paper presents a methodology for modeling a biped robot on Matlab/SimMechanics, which supports mathematical model development with time and effort savings. The model used for the biped robot simulation consists of 5-links which are connected through revolute joins. The identical legs have knee joints between the shank and thigh parts, and a rigid body forms the torso. Furthermore, modeling of ground contact forces is described. A PD controller is used on a linear model in state variable form in order to simulate the dynamic of the system. Results obtained from the dynamic simulation are presented.**

***Keywords*—Biped robot, SimMechanics, modeling, torque.**

I. INTRODUCTION

In the last decades there has been a growing interest in the research community with the ultimate goal to come up with walking biped robots emulating human displacement. The interest is motivated by a number of reasons based on the ability of biped robots to navigate in rugged terrains or irregular environments where wheeled robots cannot move [1,2]. A number of possible applications in diverse fields are continuously emerging: replacement of humans in hazardous works such as rescue operations [3], military operations, disaster scenarios [4], or restoration movement in people with disabilities such as dynamically controlled prosthetics [5] and rehabilitation robotics [6]. The research progress, however, has been relatively limited because of the complexity of legged robot dynamics, which grows with the number of links and degrees of freedom (DoF) [7,8]. Generally the dynamic model of biped robots is obtained through the Lagrange energy model, however, it must be noted that the computational complexity of the Lagrange equations is $O(n_q^3)$, where n_q represents the number of DoF of the mechanical system [9]. Lengthy formulations are therefore to be expected, so that they can define a three-dimensional system where the number of DoF is greater than twelve [10].

Usually, a Simulink model is represented by algebraic and differential equations that predict the future state of a system with the current state [11]. A SimMechanics-based tool is described in this paper as a design aid during the system modeling process.

A SimMechanics model is a representation of the physical structure of a machine, specified through some variables such as mass, geometry and kinematic relations between its components. SimMechanics converts this representation into an equivalent mathematical model [12], which saves time and effort during the development of the mathematical model. This paper presents a methodology for creating a model of a 5-link biped robot, with a proportional-integral-derivative (PID) control performed to track a desired trajectory.

II. MODEL OF BIPED ROBOT USING SIMMECHANICS

SimMechanics is a block diagram modeling environment for modeling and simulating mechanical systems using the standard Newtonian dynamics of forces and torques [12]. SimMechanics simulates translational and rotational motion in three dimensions, and includes a suite of tools to specify bodies, mass properties, possible motions, kinematic constraints, coordinate systems, and the means of initiating and measuring motions. The steps involved in SimMechanics in order to build and run a model representation of a machine are listed as follows:

- Specify body inertial properties, degrees of freedom, and constraints, along with coordinate systems attached to bodies to measure positions and velocities.
- Set up sensors and actuators to record and initiate body motions, as well as apply forces/torques.
- Start the simulation, calling the Simulink solvers to find the motions of the system, while maintaining any imposed constraints.
- Visualize the machine while building the model and animate the simulation while running, using the Handle Graphics or virtual reality-based visualization tool.

Modeling a biped robot can be divided into three parts: the links, the actuator or servo and modeling of the ground contact forces. In this work, the biped robot consists of 5-links which are connected through revolute joins (one rotational DoF). The identical legs have knee joint between the shank and thigh parts, and one rigid body forms the torso. Fig. 1 shows the model structure. Fig. 2 shows the block diagram of the biped robot. Three subsystems can be identified, both legs and torso, and the reference signal for each joint. These subsystems are described in the following section

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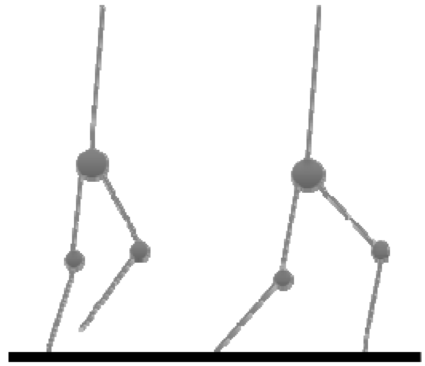

Figure 1. Structure of the biped robot

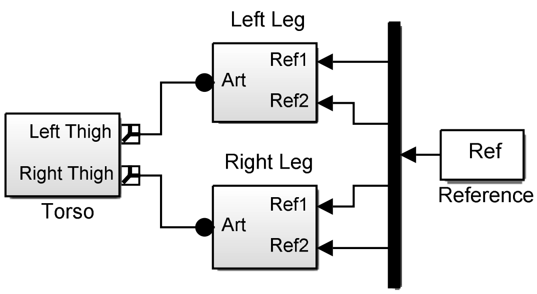

Figure 2. Simulink block diagram of biped robot

A. Modeling of the torso

The torso model of the robot is composed of a rigid body with connections to both legs. Fig. 3 shows the SimMechanics block diagram. The '*Ground'* block is a reference frame of the whole system, which is represented by a body of infinite mass and size. The "*In-plane*" block represents two translational DoF. The torso model of the robot is considered as a rectangular parallelepiped of sides a, b and c aligned along x, y, z axes, respectively. Table I. gives the torso parameters to configure the "*Torso*" block represented in Fig. 3. Equation (1) shows the moments of inertia.

$$I = \begin{bmatrix} \frac{m(b^2+c^2)}{12} & 0 & 0 \\ 0 & \frac{m(a^2+c^2)}{12} & 0 \\ 0 & 0 & \frac{m(a^2+b^2)}{12} \end{bmatrix} \quad (1)$$

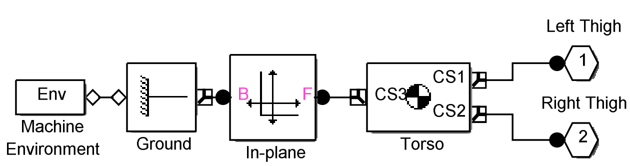

Figure 3. SimMechanics block diagram for the torso.

TABLE I. TORSO PARAMETERS

Torso Parameters	Torso
$a(m)$	0.15
$b(m)$	0.7
$c(m)$	0.4
Mass (Kg)	35

B. Modeling of the leg

The leg model is composed of two elements, thigh link and shank link. Fig. 4 shows the block diagram corresponding to the leg, where the '*Ground Contact Forces'* block simulates the reaction force of the biped robot with the floor. The thigh and shank model of the robot is represented as a cylinder of radius R and height h aligned along y axe. Table II describes the thigh and shank parameters used to configure the '*Left Thigh'* and '*Left Shank'* blocks depicted in Fig. 4. Equation (2) shows the moments of inertia tensor for a cylinder representing the robot body.

$$I = \begin{bmatrix} (\frac{m}{4})(\frac{3R^2}{5}+h^2) & 0 & 0 \\ 0 & (\frac{3mR^2}{10}) & 0 \\ 0 & 0 & (\frac{m}{4})(\frac{3R^2}{5}+h^2) \end{bmatrix} \quad (2)$$

C. Modeling of the servomotor

The servomotors are characterized by a position control located at an angular position inside a working range. Fig. 5 shows the SimMechanics block diagram corresponding to the servomotor. The error between the reference and angular position of the joint (sensor block) is used as the input signal to the PID which generates the necessary torque to the actuator; this signal is limited to a range empirically determined for the DC motor. The angular velocity is measured through the sensor1 block, and a torque loss of torque for friction in the joint is determined. The '*IC'* block sets the initial position of the join, and the *'Actuator'* block allows application of the torque to the joint.

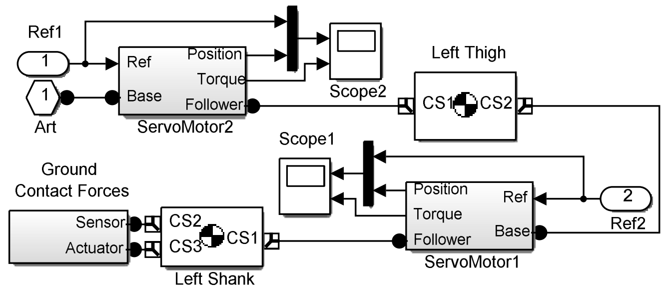

Figure 4. SimMechanics block diagram for the leg.

TABLE II. THIGH AND SHANK PARAMETERS

Parameters	Thigh and Shank
$R(m)$	0.01
$h(m)$	0.5
Mass (Kg)	8.75

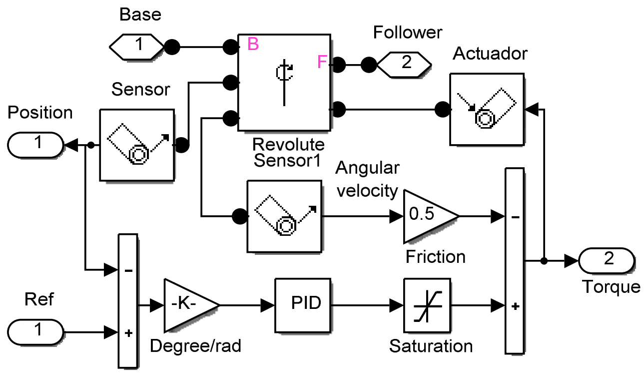

Figure 5. SimMechanics block diagram for servomotor.

D. Modeling of ground contact forces

Characterization of ground contact forces is a very important issue during the simulation process of the biped robot. The robot is supported by ground reaction forces but not attracted to ground [13]. When the leg tip touches the ground, normal and tangential forces are applied to it. The normal force, aligned to y axis, is modeled as a spring and damper [14]. Equation (3) represents the dynamic forces involved in the operation, where y is the current leg tip coordinate, k_y is the ground normal elastic constant, and b_y is the normal damping ratio. The normal force is limited to positive values in order to prevent the leg sticking system.

$$F_n = -k_y y - b_y \dot{y} \tag{3}$$

The tangential forces, aligned to x axis, includes the system friction and is represented by equation (4), where x is the current leg tip coordinate and μ_x the friction constant.

$$F_t = -\mu_x \dot{x} \tag{4}$$

Fig. 6 shows the Simulink block diagram for the ground contact forces; the position in the y axis is compared to the ground level. This signal selects the value of the normal and tangential forces, which is zero if the position foot is greater than the floor level. It is worth noting that the reaction force in the coordinate z is zero because in the described experiment, only movements in the sagittal plane are considered.

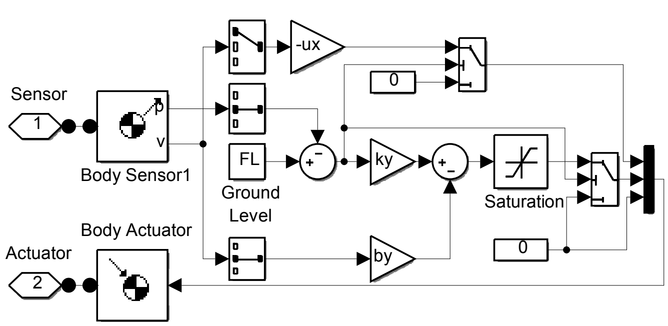

Figure 6. Simulink block diagram for ground contact forces.

III. CONTROL ALGORITHM

A PID controller was included in the model of the servomotor to verify the operation of the biped robot. For that purpose, a first linear model included in the MATLAB control toolbox 'linmod' was configured. For the described biped robot model, eight state variables corresponding to the position and velocity of each joint, and four input torques were defined. The '*linmod'* function gets the linear model of state variables, and the 8th order characteristic polynomial is then obtained. The '*pidtool*' function was used for tuning the PID control, with a settling time of 0.15 seconds, Kp=2000, and Kd = 55.

IV. SIMULATION RESULTS

In the previous section, we showed the process of modeling biped robot using SimMechanics tool. In this section all simulations are based on the Dormand-Prince 45th order method to solve nonlinear equations. Fig. 7 and 8 show the simulation of the biped robot using the Handle Graphics visualization tool. Fig. 8 shows a sequence of the biped robot frames at different times during a step movement. Fig. 9 shows the joint torques and Fig. 10 shows the position of each joint and its respective reference signal. The tracking obtained with the designed controller is within acceptable limits, allowing a continuous and smooth simulated walking.

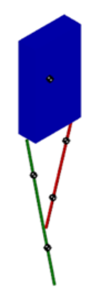
Figure 7. Simulation of biped robot in SimMechanics.

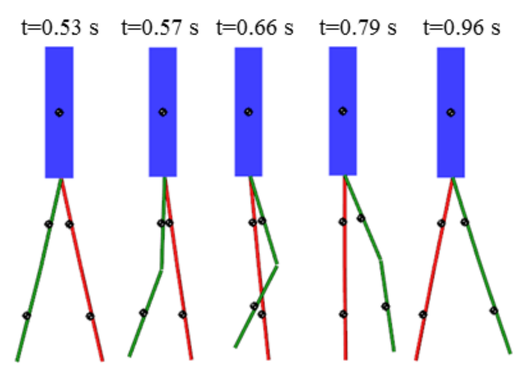

Figure 8. Frames for the simulation of biped robot

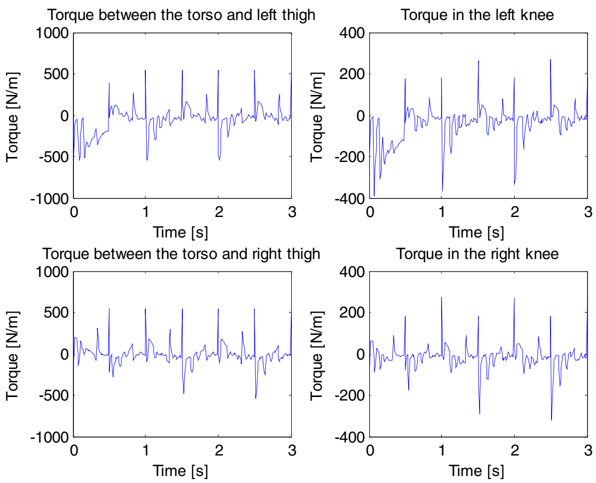

Figure. 9 Obtained torques in knee joints

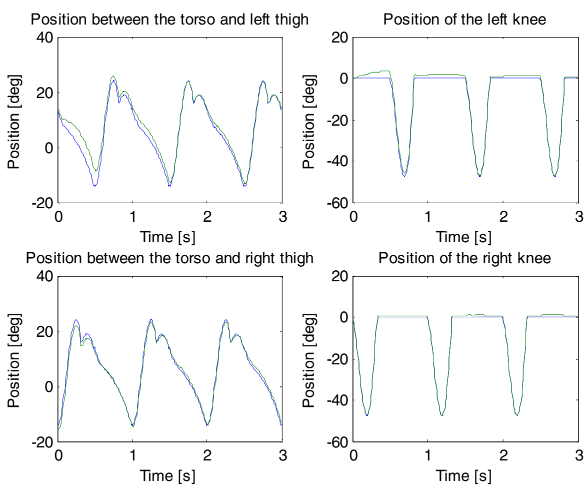

Figure 10. Position in knee joints. Position is shown in green and the reference signal is shown in blue

V. CONCLUSIONS

This paper presented an easy way to create a model of a 5-link biped robot using SimMechanics, which constitutes a support tool during the development and design of the associated complex mathematical models, with time and effort saving in the process. A PID controller was designed from the linear model, taking advantages of MATLAB functions from the control toolbox. Modular design allows the system model to easily incorporate variants in the control scheme.

ACKNOWLEDGMENT

First author acknowledges the financial support from the Mexican National Council of Science and Technology (CONACYT).

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