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MODELING AND SIMULATION OF WALKING ROBOTS WITH 3 DOF LEGS

Manuel F. Silva, J. A. Tenreiro Machado and Isabel S. Jesus
Department of Electrical Engineering, Institute of Engineering of Porto,
Rua Dr. António Bernardino de Almeida, 4200-072 Porto
Portugal
Email: {mss,jtm,isj}@isep.ipp.pt

ABSTRACT
This paper describes a simulation model for a multi-legged locomotion system with 3 dof legs and leg joint actuators having saturation. For that objective the robot prescribed motion is characterized in terms of several locomotion variables. Moreover, the robot body is divided into several segments in order to emulate the behavior of an animal spine. A non-linear spring-dashpot system models the foot-ground interaction, being its parameters computed from studies on soil mechanics. To conclude, the performance of the developed model is evaluated through a set of experiments while the robot leg joints are controlled using a proportional and derivative algorithm.

KEY WORDS
Modeling, Simulation, Kinematics, Dynamics, Robotics, Locomotion

1. Introduction

Walking machines allow locomotion in terrain inaccessible to other type of vehicles, since they do not need a continuous support surface, but the requirements for leg coordination and control impose difficulties beyond those encountered in wheeled robots. These aspects deserve great interest and, in order to study them, different approaches may be adopted. One possibility is to design and build a walking robot and to develop study based on the prototype. An alternative perspective consists on the development of walking machines simulation models that serve as the basis for the research. This last approach has several advantages, namely lower development costs and a smaller time for implementing the modifications. Due to these reasons, several different simulation models were developed, and are used, for the study, design, optimization, gait analysis and testing of control algorithms for artificial locomotion systems.
The gait analysis and selection requires an appreciable modeling effort for the improvement of mobility with legs in unstructured environments. Several articles addressed the structure and selection of locomotion modes but there are different optimization criteria, such as energy efficiency, stability, velocity and mobility, and its relative importance has not yet been clearly defined.
With respect to the control of legged robots, there exists a class of walking machines for which locomotion is a natural dynamic mode. Once started on a shallow slope, a machine of this class will settle into a steady gait, without active control or energy input [1]. However, the capabilities of these machines are quite limited. Previous studies focused mainly in the control at the leg level and leg coordination using neural networks, fuzzy logic, central pattern generators and subsumption architecture. In spite of the diversity of approaches, for multi-legged robots the control at the joint level is usually implemented through a simple PID like scheme with position/velocity feedback. Other approaches include sliding mode control, computed torque control, hybrid force/position control and fractional order control [2,3].
In this line of thought, this paper presents a simulation model for multi-legged locomotion systems, with 3 dof legs, and several periodic gaits. This tool is the basis for the study of the best system configuration and the type of movements that lead to a better mechanical implementation. Moreover, the model is also used to study the control, at the leg joint level, in the presence of joints with saturation [3].
Bearing these facts in mind, the paper is organized as follows. Section two introduces the robot kinematic model and the motion planning scheme. Sections three and four present the robot dynamic model and the foot-ground interaction model. Section five develops a set of experiments to evaluate the system performance under Proportional and Derivative (PD) leg joint control. Finally, section six outlines the main conclusions.

2. Robot Kinematic Model

We consider a walking system (Fig. 1) with n legs, equally distributed along both sides of the robot body, having each three degrees of freedom (dof) corresponding to three rotational joints (*i.e.*, $j = \{1, 2, 3\} \equiv$ {hip, knee, ankle}). The adoption of three dof legs stems from the fact that, as can be seen in Figure 2, irrespectively of the way how they place the foot on the ground during the locomotion, mammals have legs with three dof (three segments). Besides this aspect, the feet seem to have a great importance in human and animal locomotion [4].

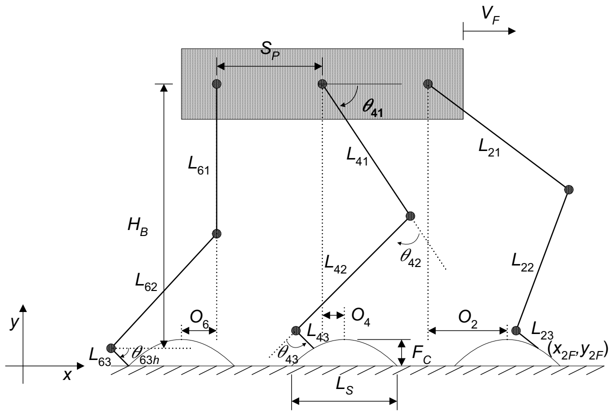

Figure 1. Coordinate system and variables that characterize the motion of the multi-legged robot.

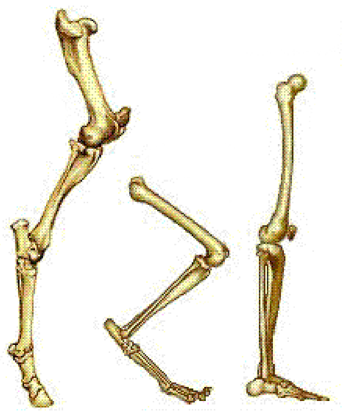

Figure 2. Different ways to place the foot on the ground (from left to right): skeleton of the rear leg of the horse (unguligrade), cat (digitigrade) and human (plantigrade).

The kinematic model comprises: the cycle time T, the duty factor β, the transference time $t_T = (1-\beta)T$, the support time $t_S = \beta T$, the step length L_S, the stroke pitch S_P, the body height H_B, the maximum foot clearance F_C, the i^{th} leg lengths L_{i1} and L_{i2}, the i^{th} foot length L_{i3} and the foot trajectory offset O_i ($i = 1, \ldots, n$). When the robot leg is equipped with a foot (*i.e.*, the robot has three dof legs), there is the need to consider an additional variable, namely the value of the desired angle between the foot and the ground (assumed horizontal) θ_{i3hd}. According to the planed value for this angle, the robot can walk on its toe tips ($\theta_{i3hd} < 0°$), can place the foot plant simultaneous on the ground ($\theta_{i3hd} = 0°$) or can walk over its heels ($\theta_{i3hd} > 0°$). Moreover, we consider a periodic trajectory for each foot, with constant body velocity $V_F = L_S / T$. Motion is described by means of a world coordinate system.

Gaits describe discontinuous sequences of leg movements, alternating between transfer and support phases. In the simulation model, we consider the Wave, Equal Phase Half Cycle, Equal Phase Full Cycle, Backward Wave, Backward Equal Phase Half Cycle and Backward Equal Phase Full Cycle gaits [5]. Given a particular gait and duty factor β, it is possible to calculate, for leg i, the corresponding phase ϕ_i, the time instant where each leg leaves and returns to contact with the ground and the cartesian trajectories of the tip of the feet (that must be completed during t_T) [5]. Based on this data, the trajectory generator produces a motion that synchronizes and coordinates the legs.

The robot body, and by consequence the legs hips, is assumed to have a desired horizontal movement with a constant forward speed V_F. However, according to the planed value for θ_{i3hd} it is necessary to adjust the height of the body to the ground. Therefore, if it is considered that the robot walks on its toe tips ($\theta_{i3hd} < 0°$), for leg i the cartesian coordinates of the hip of the legs are given by $\mathbf{p_{Hd}}(t) = [x_{iHd}(t), y_{iHd}(t)]^T$:

$$\mathbf{p_{Hd}}(t) = \left[V_F t \quad H_B + L_{i3}\,\mathrm{sen}\left(\theta_{i3hd}\right)\right]^T \tag{1}$$

Concerning the movement of the tip of the feet during the transfer phase, the trajectories must be performed in such a way to avoid collisions with ground or any obstacles that may be in the vicinity of the robot. To solve this problem several different strategies have been proposed.

When the robot design is a mimic of an animal, one approach frequently adopted consists on copying the animal feet trajectories. These animals are often filmed with special techniques, while walking on a treadmill, and the resulting film is analyzed to extract their feet trajectories in order to implement similar ones in the walking machines [6]. Another strategy, often adopted, considers that the robot feet trajectories, in the Cartesian space, are mathematical functions based on the sine and cosine functions, or combinations of these, circle arcs, ovals, ellipsis and cycloidal functions.

Motivated by the above described methods, on a previous work we evaluated two alternative space-time foot trajectories, namely a cycloidal function (2), where the feet lift-off and return to contact with the ground is vertical, and a sinusoidal function, where the trajectory is horizontal at those locations [7]. It was demonstrated that the cycloid is superior to the sinusoidal function, since it improves the hip and foot trajectory tracking, while minimising the corresponding joint torques. These results do not present significant changes for different acceleration profiles of the foot trajectory.

From the studies in biomechanics, Hodgins [8] concludes that the disturbances that occur at the instants of feet impact with the ground can be diminished by lowering the relative speed of the feet and the ground at the contact instants. This technique, often called ground speed matching, appears to justify the reason why the feet cycloidal trajectory is superior to the sinusoidal one.

Considering the above conclusions, the desired trajectory of the foot of the swing leg is computed through a cycloid function (2), for each cycle. For example, considering that the transfer phase starts at $t = 0$ s for leg $i = 1$ we have for $\mathbf{p_{Fd}}(t) = [x_{iFd}(t), y_{iFd}(t)]^T$:

- during the transfer phase:

$$\mathbf{p_{Fd}}(t)=\left[V_F\left[t-\frac{1}{2\pi f}\sin\left(\frac{2\pi t}{T}\right)\right]\quad\frac{F_C}{2}\left[1-\cos\left(\frac{2\pi t}{T}\right)\right]\right]^{\mathrm{T}} \tag{2}$$

- during the stance phase:

$$\mathbf{p_{Fd}}(t)=\left[V_F T \quad 0\right]^{\mathrm{T}} \tag{3}$$

Once defined the coordinates of the hips and feet of the robot, it is possible to obtain the leg joint positions and velocities using the inverse kinematics $\boldsymbol{\psi}^{-1}$ and the Jacobian $\mathbf{J} = \partial\boldsymbol{\psi}/\partial\boldsymbol{\theta}$.

The algorithm for the forward motion planning accepts the desired cartesian trajectories of the leg hips $\mathbf{p_{Hd}}(t)$ and feet $\mathbf{p_{Fd}}(t)$ as inputs and, by means of an inverse kinematics algorithm $\boldsymbol{\psi}^{-1}$, generates the related joint trajectories $\boldsymbol{\Theta}_\mathbf{d}(t) = [\theta_{i1d}(t), \theta_{i2d}(t), \theta_{i3d}(t)]^{\mathrm{T}}$, selecting the solution corresponding to a forward knee and a backward ankle:

$$\mathbf{p_d}(t)=\left[x_{id}(t)\quad y_{id}(t)\right]^{\mathrm{T}}=\mathbf{p_{Hd}}(t)-\mathbf{p_{Fd}}(t) \tag{4a}$$

$$\mathbf{p_d}(t)=\boldsymbol{\psi}\left[\boldsymbol{\Theta}_\mathbf{d}(t)\right]\Rightarrow\boldsymbol{\Theta}_\mathbf{d}(t)=\boldsymbol{\psi}^{-1}\left[\mathbf{p_d}(t)\right] \tag{4b}$$

$$\dot{\boldsymbol{\Theta}}_\mathbf{d}(t)=\mathbf{J}^{-1}\left[\dot{\mathbf{p}}_\mathbf{d}(t)\right],\ \mathbf{J}=\frac{\partial\boldsymbol{\psi}}{\partial\boldsymbol{\Theta}} \tag{4c}$$

In order to avoid the impact and friction effects, at the planning phase we impose null velocities of the feet in the instants of landing and taking off, assuring also the velocity continuity.

3. Robot Dynamical Model

3.1 Inverse Dynamics Computation

In order to derive the inverse dynamic equations of the multi-legged locomotion robot we adopt the Lagrange method (5):

$$\boldsymbol{\Gamma}=\frac{d}{dt}\left[\frac{\partial(\mathbf{K}-\mathbf{U})}{\partial\dot{\boldsymbol{\Theta}}}\right]-\frac{\partial(\mathbf{K}-\mathbf{U})}{\partial\boldsymbol{\Theta}} \tag{5}$$

This formalism requires the calculation of the kinetic (**K**) and potential (**U**) energies, both for the body, the links and the feet of all robot legs. The model for the robot inverse dynamics is formulated as:

$$\boldsymbol{\Gamma}=\mathbf{H}(\boldsymbol{\Theta})\ddot{\boldsymbol{\Theta}}+\mathbf{c}(\boldsymbol{\Theta},\dot{\boldsymbol{\Theta}})+\mathbf{g}(\boldsymbol{\Theta})-\mathbf{F_{RH}}-\mathbf{J}_\mathbf{F}^{\mathrm{T}}(\boldsymbol{\Theta})\mathbf{F_{RF}} \tag{6}$$

where $\boldsymbol{\Gamma} = [f_{ix}, f_{iy}, \tau_{i1}, \tau_{i2}, \tau_{i3}]^{\mathrm{T}}$ ($i = 1, \ldots, n$) is the vector of forces/torques, $\boldsymbol{\Theta} = [x_{iH}, y_{iH}, \theta_{i1}, \theta_{i2}, \theta_{i3}]^{\mathrm{T}}$ is the vector of position coordinates, $\mathbf{H}(\boldsymbol{\Theta})$ is the inertia matrix and $\mathbf{c}(\boldsymbol{\Theta},\dot{\boldsymbol{\Theta}})$ and $\mathbf{g}(\boldsymbol{\Theta})$ are the vectors of centrifugal/Coriolis and gravitational forces/torques, respectively. The $n \times m$ ($m = 3$) matrix $\mathbf{J}_\mathbf{F}^{\mathrm{T}}(\boldsymbol{\Theta})$ is the transpose of the robot Jacobian matrix, $\mathbf{F_{RH}}$ is the $m \times 1$ vector of the body inter-segment forces and $\mathbf{F_{RF}}$ is the $m \times 1$ vector of the reaction forces that the ground exerts on the robot feet. These forces are null during the foot transfer phase. During the system simulation, (6) is integrated through the Runge-Kutta method. Furthermore, we consider that the joint actuators are not ideal, exhibiting a saturation given by:

$$\tau_{ijm}=\begin{cases}\tau_{ijC}, & \left|\tau_{ijm}\right|\le\tau_{ijMax}\\ \operatorname{sgn}\left(\tau_{ijC}\right)\cdot\tau_{ijMax}, & \left|\tau_{ijm}\right|>\tau_{ijMax}\end{cases} \tag{7}$$

where, for leg i and joint j, τ_{ijC} is the controller demanded torque, τ_{ijMax} is the maximum torque that the actuator can supply and τ_{ijm} is the motor effective torque.

3.2 Joint $j = 3$ Implementation

Bearing in mind the fact that most walking animals have compliant feet and ankles, in order to lower the impact forces with the ground and prevent the occurrence of chattering (in which the foot repeatedly abandons and returns to contact with the ground before the contact stabilizes) [9], in this work it is considered that leg joint $j = 3$ can be either mechanical actuated or motor actuated. For the mechanical actuated case, we suppose that there is a rotational spring-dashpot system connecting leg links L_{i2} and L_{i3}. This mechanical impedance maintains the angle between the two links and imposes a joint torque given by (for leg i):

$$\tau_{i3m}=K_3\left[\theta_{i3d}(t)-\theta_{i3}(t)\right]+B_3\left[\dot{\theta}_{i3d}(t)-\dot{\theta}_{i3}(t)\right] \tag{8}$$

where, τ_{i3m} is the joint effective torque, K_3 and B_3 are the coefficients of stiffness and viscous friction and θ_{i3d} and θ_{i3} are the planned and real joint 3 trajectories.

3.3 Robot Body Model

Figure 3 presents the dynamic model for the hexapod body and foot-ground interaction.

It was considered robot body compliance because most walking animals have a spine that allows supporting the locomotion with improved stability [10]. This model is inspired on studies that point out this structure. For example, the hedgehog presents muscles in the omoplata that apparently actuate as spring-dashpot systems. This biomechanical structure absorbs part of the energy generated during the feet contact with the ground and returns that energy a little before the feet lift-off the ground [11]. In the present study, the robot body is divided into n identical segments (each with mass $M_b n^{-1}$) and a linear spring-dashpot system is adopted to implement the intra-body compliance:

$$f_{i\eta H} = \sum_{i'=1}^{u}\left[-K_{\eta H}\left(\eta_{iH} - \eta_{i'H}\right) - B_{\eta H}\left(\dot{\eta}_{iH} - \dot{\eta}_{i'H}\right)\right] \quad (9)$$

where ($x_{i'H}$, $y_{i'H}$) are the hip coordinates and u is the total number of segments adjacent to leg i, respectively. Concerning the definition of the numerical values for the parameters of (9) different methods have been proposed [12]. In this study, the parameters $B_{\eta H}$ and $K_{\eta H}$ ($\eta = \{x, y\}$) in the {horizontal, vertical} directions, respectively, are defined so that the body behavior is similar to the one expected to occur on an animal (Table 1).

4. Foot-Ground Interaction Model

The contact of the robot feet with the ground can be analyzed through different viewpoints leading to distinct models [12]. One method is to use the exact force-deflection relationships. Another method, and under specific restrictions, is to use approximate models of the ground deformation based on the studies of soil mechanics.

This second approach models the foot-ground interaction through a linear system with damping $B_{\eta F}$ and stiffness $K_{\eta F}$ ($\eta = \{x, y\}$) in the {horizontal, vertical} directions, respectively. The values for the parameters $B_{\eta F}$ and $K_{\eta F}$ are based on the studies of soil mechanics [12].

Although computationally simple, the linear foot-ground interaction model presents several weaknesses [12]. A solution to the shortcomings presented by this model, proposed by Hunt and Crossley [13], is to replace the linear spring/damper parallel combination through a non-linear one. While Hunt and Crossley make use of non-linear stiffness and friction elements, we adopt a mixed strategy, that is, we model the contact of the i^{th} robot feet with the ground through a linear stiffness $K_{\eta F}$ and a non-linear damping $B'_{\eta F}$ ($\eta = \{x, y\}$) in the {horizontal, vertical} directions, respectively (see Fig. 3), yielding:

$$f_{ixF} = -K_{xF}\left(x_{iF} - x_{iF0}\right) - B'_{xF}\left[-\left(y_{iF} - y_{iF0}\right)\right]\left(\dot{x}_{iF} - \dot{x}_{iF0}\right) \quad (10a)$$

$$f_{iyF} = -K_{yF}\left(y_{iF} - y_{iF0}\right) - B'_{yF}\left[-\left(y_{iF} - y_{iF0}\right)\right]^{v}\left(\dot{y}_{iF} - \dot{y}_{iF0}\right) \quad (10b)$$

where x_{iF0} and y_{iF0} are the coordinates of foot i touchdown and $v \approx 1.0$ is a parameter dependent on the ground characteristics [12].

In order to convert the parameters of this non-linear foot-ground interaction model (B'_{xF}, B'_{yF}) to the parameters of the linear model (B_{xF}, B_{yF}), we use the following relations:

$$-B'_{\eta F}\left(-\Delta_{iyFMax}\right)^{v_\eta} = -B_{\eta F}\ ,\ v_x = 1.0,\ v_y = 0.9 \quad (11)$$

where Δ_{iyFMax} if the maximum depth that the robot feet penetrates the ground.

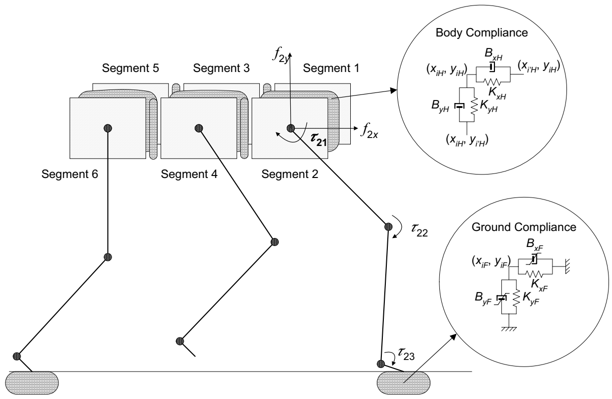

Figure 3. Robot body and foot-ground interaction model.

Table 1. System parameters

Robot model parameters		**Locomotion parameters**	
S_P	1 m	β	50%
L_{ij}, j=1,2	0.5 m	L_S	1 m
L_{i3}	0.1 m	H_B	0.9 m
O_i	0 m	F_C	0.1 m
M_b	88.0 kg	V_F	1 ms^{-1}
M_{ij}, j=1,2	1 kg	**Ground parameters**	
M_{i3}	0.1 kg	K_{xF}	1302152.0 Nm^{-1}
K_{xH}	10^5 Nm^{-1}	K_{yF}	1705199.0 Nm^{-1}
K_{yH}	10^4 Nm^{-1}	B_{xF}	2364932.0 Nsm^{-1}
B_{xH}	10^3 Nsm^{-1}	B_{yF}	2706233.0 Nsm^{-1}
B_{yH}	10^2 Nsm^{-1}	v	0.9

5. Model Test

In this section we present a set of experiments to evaluate the system model during the locomotion of a hexapod adopting a periodic gait. For simulation purposes we consider the locomotion, the robot and the ground parameters (supposing that the robot is walking on a ground of compact clay) presented in Table 1.

The simulation system includes a Graphical User Interface (GUI). This GUI, implemented in MATLAB, depicts the values of several robot and locomotion parameters, the gait diagram, the robot locomotion and the trajectories of the robot body, knee and feet (Fig. 4). However, the numerical algorithms of the simulation model are implemented in the C programming language to speed-up its computational burden. The results of the simulation are saved in text files that are read by the GUI application in order to generate the graphical reports.

The system performance is analyzed for two situations: two leg joints are motor actuated and the ankle joint is actuated through a passive mechanical system and the three leg joints are totally actuated through motors. These experiments show the superior performance of the locomotion system when all leg joints are motor actuated.

The control algorithm adopted at the robot leg joints is introduced in the next sub-section. This controller is the basis for the stable robot locomotion. In sub-section 5.2 the results of several simulations are presented in order to demonstrate the correct performance of the robot model implemented both in terms of trajectory planning, dynamics and control.

5.1 Control Architecture

The general control architecture of the hexapod robot is presented in Fig. 5.

The trajectory planning is held at the cartesian space but the control is performed in the joint space, which requires the integration of the inverse kinematic model in the forward path. This algorithm considers an external position feedback and a second internal feedback loop with information of the foot-ground interaction force. Therefore, $G_{c1}(s)$ and G_{c2} form a cascade structure in the forward control path. The superior performance of this control architecture was previously highlighted when applied to the joint control of hexapod robots, having two dof legs, and non-ideal actuators with saturation or variable ground characteristics [7]. Based on these results, in this study we adopt a PD controller for $G_{c1}(s)$ and a simple P controller for G_{c2}, with gain $Kp_j = 0.9$ ($j = 1, 2, 3$). The PD algorithm consists on:

$$G_{C1j}(s) = Kp_j + Kd_j s, \quad j = 1,2,3 \tag{12}$$

being Kp_j and Kd_j the proportional and derivative gains.

To tune the controller we adopt a systematic method, testing and evaluating several possible combinations of controller parameters. Moreover, it is assumed high performance joint actuators with a maximum actuator torque in (7) of $\tau_{ijMax} = 400$ Nm. The adopted controller parameters are presented in Table 2.

5.2 Simulation Results

With the system and controller parameters established previously, in this section we analyze the simulation model, namely in what concerns the values to adopt for the ankle joint system actuation parameters ($j = 3$).

In a first phase it is considered that leg joints 1 and 2 are motor actuated and joint 3 is mechanical passive actuated. For this case the hexapod locomotion is analyzed while varying the parameters K_3 and B_3. Following, it is considered that joint 3 is motor actuated, and the above procedure is repeated for the parameters Kp_3 and Kd_3.

When the ankle joint is mechanical passive actuated, it is verified that for values of $K_3 \approx 0.0$ Nm the foot jumps when touches the ground. Increasing the value for this parameter, namely to $K_3 \approx 0.1$ Nm, there is no foot oscillation but, on the other hand, at the end of the leg transfer phase the foot plant touches the ground after the heel. For higher values of K_3 (*e.g.*, $K_3 \approx 3.0$ Nm) the foot presents little oscillation and, at the end of the leg transfer phase, the front of the feet touches the ground after the heel. For high values of K_3 (*e.g.*, $K_3 \approx 1000.0$ Nm) the

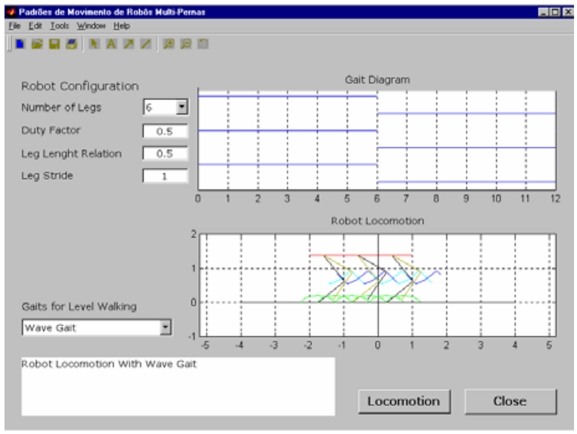

Figure 4. GUI of the simulation system for periodic gaits of hexapod walking robots.

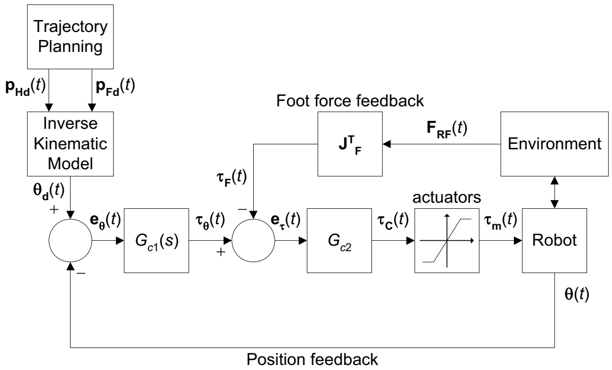

Figure 5. Robot control architecture.

Table 2. Controller parameters

Joint $j = 3$ actuation			
Passive actuation		**Active actuation**	
Kp_1	8000.0	Kp_1	8000.0
Kd_1	60.0	Kd_1	60.0
Kp_2	500.0	Kp_2	500.0
Kd_2	40.0	Kd_2	40.0
K_3	5.0	Kp_3	100.0
B_3	2.5	Kd_3	2.5

robot walks on its “toe tips” (the heel never touches the ground) but the heel and front feet trajectories present substantial oscillations. In each of the previous situations, the described behaviors are relatively independent of the values found for B_3. The value for this parameter is chosen considering only the damping optimization of the feet oscillations. Irrespectively of the chosen values for the joint 3 actuation system parameters, it is possible to conclude that the solution with the three leg joints motor actuated is superior, presenting lower values for the mean average power consumption, for the hip trajectory tracking errors and for the joint actuation torques (Fig. 6).

From the result analysis of the previous experiments, we conclude that the robot simulation model, described in this paper, implements correctly the planning, kinematic, dynamic and control schemes, for the locomotion of the hexapod, with 3 dof legs, allowing the simulation of different walking gaits. Moreover, the observed behavior seems to faithfully represent the real system.

6. Conclusion

In this paper we have presented a simulation model for multi-legged locomotion systems with segmented body and three dof legs. This tool is the basis for the study of the best system configuration and the type of movements that lead to a better mechanical implementation and for joint leg control algorithm testing.

The walking robot model includes the trajectory planning, for several different periodic walking gaits, the kinematics and the dynamics. By implementing joint leg actuator models that incorporate saturation, we are able to estimate how the robot controllers respond to a degradation of the actuators characteristics. Furthermore, the robot foot-ground interactions are also considered.

For implementing the robot locomotion simulation the C programming language is adopted due to its computational efficiency. Nevertheless, the user interface makes use of a GUI implemented in MATLAB, being the data interchange between the two modules accomplished through text files.

In this paper, for the model simulation and evaluation it is adopted a PD joint controller algorithm, with position/ force feedback. The simulation results demonstrate the correctness of the algorithms and parameters adopted in the modeling and simulation.

Future work in this area will address the refinement of our models to incorporate in the robot legs mechanisms that allow the storage of energy during the feet impact with the ground and its return before the leg starts the transfer phase. There are also plans to change the leg joint actuation, namely through the inclusion of linear actuators mimicking the muscle behavior when actuating the joints of living creatures.

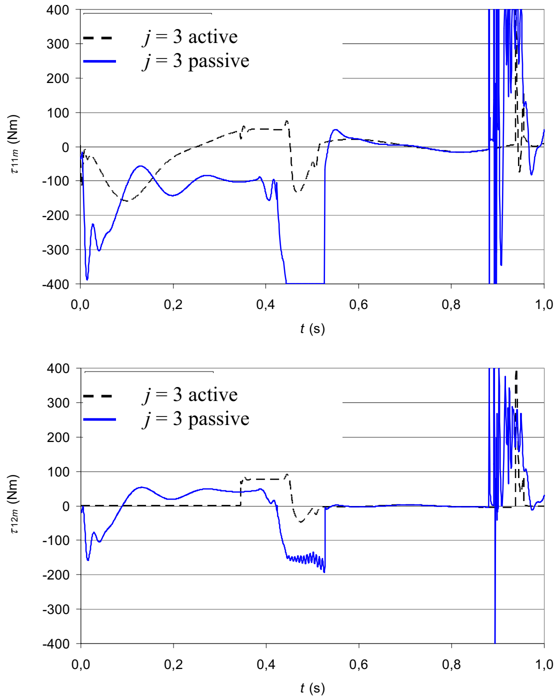

Figure 6. Joint actuator torques τ_{11m} and τ_{12m} *vs. t*, with the ankle joint actively and passively actuated, for the PD control architecture and τ_{ijMax} = 400 Nm.

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