ONLINE HIERACHICAL CONTROL FOR LEGGED SYSTEMS BASED ON THE INTERACTION FORCES

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Abstract: This paper presents a motion planning and control method with application in the field of legged robots. The general aim is to explore a set of simple underlying principles that govern balance of posture and gait of biped robots, and to develop control methodologies for such a highly unstable and non linear plants. The proposed controller reflects a hierarchical structure based on the interaction forces between the foot and ground and simple feedback rules used online. The algorithms are applied to a simulated 3-D leg model with five degrees of freedom (DOF). The simulation analyses demonstrate the capability of the control system to keep balance when the leg executes different tasks. To validate the proposed method several aspects are investigated, such as the posture robustness on the level ground when subject to external perturbations, the adaptation when standing in a moving platform and the improvements introduced by the compensation of the tangential reaction forces.

1 INTRODUCTION

Biped locomotion, the core technology for a humanoid robot, has attracted an enormous interest around the world, both from the industry and the academic communities. The major problems associated with human-like walking results from the high centre of gravity (COG) with a small contact area to the ground. With other words, balance maintenance is a central concern in order to engage useful tasks, from standing upright posture to motion goals. In what concerns control, the difficulty lies in the uncertainty of the environment and the limitations of the contact between the robot and the environment. On the one hand, the advantages of biped locomotion are well-known for irregular terrains described by deterministic, but a priori unknown models. On the other hand, the degree of freedom formed between the foot and the ground is unilateral and under-actuated, affecting the postural stability (Goswami, 2004). The most prominent stability measure to enhance trajectory-tracking controllers and to analyse their stability is the so-called zero moment point (ZMP) criterion (Vukobratovic, 1990).

Current works in motion generation fall largely into two categories: trajectory replaying and online generation. The former is mainly characterised by pre-planned trajectories that are then played back during walking and modified online through feedback (Hirai, 1998; Yamaguchi, 1999; Park, 2000). By contrast, the later generates a trajectory online, feeding back the present state of the system in accordance with the pre-provided goal of the motion (Sugihara, 2002; Kajita, 2003). Planning and control are executed in a unified way, although requiring a larger amount of computation power.

Bearing these facts in mind, this paper aims to explore a set of simple underlying principles that

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govern balance and to develop online control methods for such a highly unstable and non-linear plant. The approach followed in this paper consists of studying a simple model but keeping enough complexity to allow a clearly evaluation of the control method. The algorithms are then applied to a simulated 3-D robot model with a total of 5-DOF. The main features of the proposed scheme are the consideration of the interaction forces as the primary control variable and the minimal dependency on pre-programmed references.

The tasks to be performed include a variety of motion goals specified in the intuitive Cartesian space (e.g., hip coordinates, Centre of Gravity COG), as well as in the joint space. The discussion includes the choice of control principles, the selection and grouping of control variables and measurements. The scope of the paper covers the sagittal and lateral planes for a robot model that stands itself on a platform. The analysis will be carried out in a dynamic simulation environment.

This paper is organised as follows. Section 2 describes the robot model, the sensorial requirements and the tasks' description. Section 3 presents the online motion-control algorithm on which the walking tasks are formulated. Section 4 discusses the computer simulations used to illustrate the different characteristics of the control algorithm. Section 5 concludes the paper and outlines the perspectives towards future research.

2 SYSTEM AND TASK DESCRIPTION

The control algorithms presented in this paper are applied to a simulated 3-D robot model with 5-DOF and 4-links (foot, shank, thigh and trunk). The Open Dynamics Engine simulation library (Russell, 2004), based on the Newtonian mechanics for articulated rigid bodies, is used along with an interactive graphical user interface. Figure 1 illustrates the articulated system with a total weight of 5 kg and a maximum height of 66 cm. The detailed parameters of this model are summarised in Table 1.

Table 1: Robot and environment parameters.

$Link_i$	Mass (*kg*)	Dimensions (*m*)			Spring-damper model	
		lx_i	ly_i	lz_i	K_z (*N/m*)	B_z (*Ns/m*)
Trunk	4,00	0.06	0.15	0.330	50.0×10^3	1000.0
Thigh	0,70	0.04	0.04	0.165	Friction model	
Shank	0,23	0.03	0.03	0.142	MU_K	mu_f
Foot	0,07	0.12	0.08	0.023	1.20	2.50

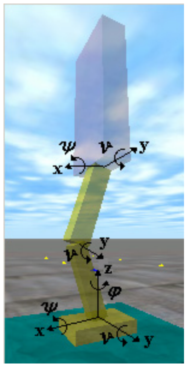


Figure 1: Three-dimensional 4-link model.

2.1 Actuators and Sensors

The leg proportions and the structure were selected as a result of the desired similarity with the human body. In order to provide adequate mobility the model considers five rotary joints: two joints at the ankle whose axes are orthogonal (pitch ν, roll ψ), one at the knee (pitch ν) and two at the hip (pitch ν, roll ψ). The contact of the foot with the constraint surface is modelled through linear spring-damper systems in the horizontal and vertical directions.

The specification of the actuators was obtained, given the desired goals, by adjusting the values of the maximum power, maximum torque and electrical time-constant. These actuation constraints are considered to evaluate the system's ability when performing a desired task. At the same time, a walking robot can not afford to move on without sensor feedback for even a smallest time segment. While in motion or just standing still the robot must continuously check the balance of the body. To this purpose, it is considered feedback control from several sensors, including angular position in each joint, a three-axis inclinometer attached to the trunk section and four force sensors inserted in the foot corners. The sensors in the foot corners provide information about the ground reaction forces and the location of the centre of pressure (COP), as well as about the full contact of the foot with the ground. The inclinometer, the angular position in the joints and the detention of full contact between the foot and the ground provides the system with the ability to detect the ground slope.

2.2 Task Description

A complete classification of possible tasks to be performed is not feasible in view of the large variety of cases that may occur, nor would such a classification be really useful to find a general strategy of control. On the other hand, systems capable of general legged locomotion are often redundantly actuated. The immediate question is how to exploit and coordinate the multiple degrees of freedom. In general, it is observed that the joints nearest to the ground (ankle and knee) are closely related to the mobility and stability of the system, and the more distant from the ground (hip) has a compensation mechanism purpose.

The tasks to be performed include a variety of motion goals specified in the intuitive Cartesian space, both for the hip coordinates and the COG. A generic robot task requires the execution of specific motions prescribed in the joint space, as well. In the present study, we will exploit mainly voluntary movements such as the trunk inclination, either sideways or front-backward. Accordingly, the task description (refer to Figure 2) is provided with a first block ensuring the fundamental motion directives and a second block concerning individual joint motions. However, it must be pointed out that all five actuators will contribute to attain the motion directives specified in the Cartesian space.

In this paper, it is assumed that the goal of the articulated system (support-leg and trunk) is to achieve a stable behaviour for a variety of motion goals specified for the hip section, the centre of gravity and other points, while it adapts to discrete disturbances. More concretely, the desired task to be performed consists of movements of crouch from standing and then thrusts the body upwards to assume an upright position again. Moreover, the robot foot is assumed to be on two different support surfaces: level ground and inclined ground. The main goals are to investigate the posture robustness on the level ground when subject to external perturbations, the system's adaptation when standing in a moving platform and the improvements introduced by the compensation of tangential forces.

A useful means to assess balance skill and gain insight into postural control is by applying external perturbations and recording reactions. One typical disturbance experienced by a service robot is a change in body mass. To demonstrate the capability of adaptation to changes in mass, the system is submitted to both loading and unloading of an external load. There are other perturbations due to external forces applied while the system is moving.

3 CONTROLLER BASED ON THE INTERACTION FORCES

3.1 Highlight of the Method

Biped robots exhibit complex dynamic phenomena that make difficult their analysis and control. A major problem is the difficult relation between planning and stability, namely the robot cannot follow arbitrary motion commands. This difficulty has justified a different line of thought where the skill of locomotion emerges from the physical interaction between the machine and the environment itself (Fujimoto, 1998; Park, 2001).

In this line of thought, one approach based on the interaction forces between the foot and the ground is investigated. We emphasize the main role of these forces as the key element through which new control strategies are proposed to provide the required level of compliance, adaptation and dynamic stability. The proposed controller reflects a hierarchical structure using force as the primary control variable and simple feedback rules (Figure 2).

A block diagram of the resulting controller is sketched in Figure 2, revealing the parallel operation of a force control loop and a position control loop. Hence, the control signal to the actuators is composed of a force control action and a motion control action integrated in a hierarchical way, as follows:

$$\tau = K_f \tau_f + K_p \tau_p \qquad (1)$$

where K_f and K_p are positive activation constants (unitary sum) that define the dominance in the contribution to the output. This parallel composition of control actions aims at exploit the redundancy of the system: a given actuator can be utilized to meet more than one task requirement (thus providing redundancy resolution).

A relevant feature of the proposed method is the possibility of performing both indirect and direct force control. The former is obtained via motion control and without explicit closure of a force feedback loop (solid line). The later, instead, offer the possibility of controlling the contact force to a desired value, thanks to the closure of a force feedback loop (dashed line).

The position controller uses a time-dependent algorithm that involves the tracking of pre-computed trajectories using a PID control law. The following subsection is aimed at presenting the implementation

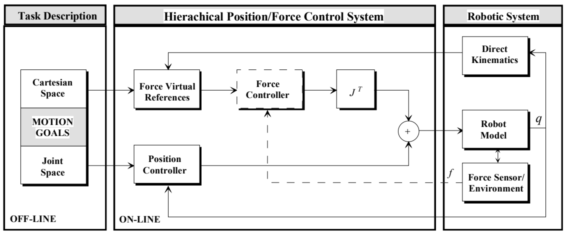


Figure 2: Blocks diagram of the hierarchical control scheme.

of the force interaction control with reference to their properties.

3.2 Force Interaction Control

As far as the force control is concerned, the tasks to be performed depend on motion goals defined in the Cartesian space. On the other hand, the variables to be controlled are the reaction forces distributed along the foot's corners. In order to ensure the proper behaviour through the execution of an interaction task, the reference variables must be generated online in result of the demands imposed to the system. These are the variables that some force control law must follow.

For the present purposes, the reference forces are calculated through suitable actions on the position errors in both horizontal and vertical directions. The resultant normal reaction force is calculated from the errors measured in the vertical coordinate (*z*-axis) using a linear control law:

$$f_n^{ref} = K_P^f ez + K_i^f \int_0^t ezdt + K_d^f \frac{d}{dt} ez \tag{2}$$

Here, ez is the vertical position error given by $(z^{ref} - z)$ where z^{ref} and z are the desired and real vertical coordinates, f_n^{ref} is the reference normal force, and K_p^f, K_i^f and K_d^f are the proportional, the integral and the derivative appropriated constant feedback gains, respectively.

On the other hand, the desired location of the centre of pressure (COP) is calculated from the errors measured in the horizontal coordinates (*x* and *y* axis), as follows:

$$COP^{ref} = K_P^{COP} ex + K_i^{COP} \int_0^t exdt + K_d^{COP} \frac{d}{dt} ex \tag{3}$$

where COP^{ref} is the reference centre of pressure, ex is the horizontal position error of the COP given by $(x^{ref} - x)$, where x^{ref} and x are the desired and real horizontal coordinates, K_p^{COP}, K_i^{COP} and K_d^{COP} are the proportional, integral and derivative feedback gains, respectively. All the feedback gains in equations 2 and 3 were tuned with a standard method. Finally, the reference COP is actively used to calculate the distribution of the total reaction force along the extremities of the support foot.

Having defined the reference forces, there are many different ways to implement the compliance control. This paper contributes with one strategy that considers only the indirect force control. In spite of the enhanced disturbance rejection provided by an inner force control loop, a compliant behaviour can be successfully achieved with the proposed solution.

In this line of thought, the signal forces obtained for each corner of the foot are directly transformed into joint torques by using the transpose of the Jacobian matrix:

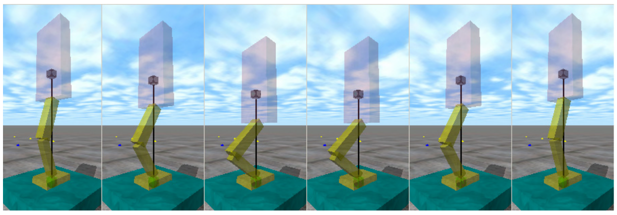
$$\tau_f = \sum_{i=1}^{4} J_i^T f_i \tag{4}$$

Here, J_i is the Jacobian matrix which transforms the differential variation in the joint space into the differential variation of the end-effector's frame *i* (each foot corner) with respect to the reference frame (located at the hip). The subscript ^{T} denotes the transpose of a matrix. In the above treatment, it has been implicitly assumed that the friction is large enough to avoid any foot's slippage. Nevertheless, the general form of f_i used in (4) may contain a tangential force term. Further, the equation requires lower computation than inverse kinematics or dynamics equations and it is well-behaved since, for a given force vector, a corresponding torque vector can always be obtained even if the robot is in a singular configuration.

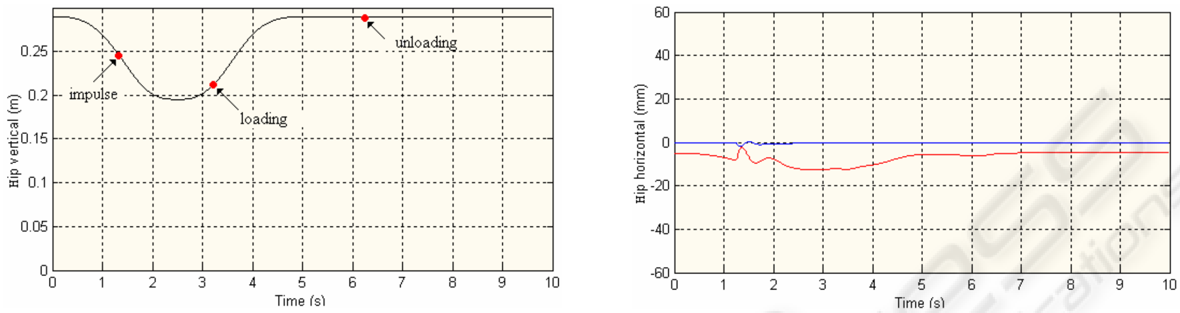
In other words, the support leg "feels" the forces, while the controller distributes them as driving torques in order to regulate the desired high-level directives. This strategy was generalised to all degrees of freedom, from the ankle until the hip joints. It is worth noting that, after some analytical simplifications, a computationally simpler control law can be derived as function of the desired normal forces, tangential forces and COP. For example, the output torque for the ankle joints can be written as:

$$\begin{aligned} \tau_a^{\upsilon} &= -x_P^{ref} \cdot f_z^{ref} - l_h \cdot f_x^{ref} \\ \tau_a^{\psi} &= \left[y_P^{ref} f_z^{ref} + l_h f_Y^d \right] \cos\left(\theta_a^{\upsilon}\right) - f_z^{ref} \cdot \sin\left(\theta_a^{\psi}\right) \end{aligned} \tag{5}$$

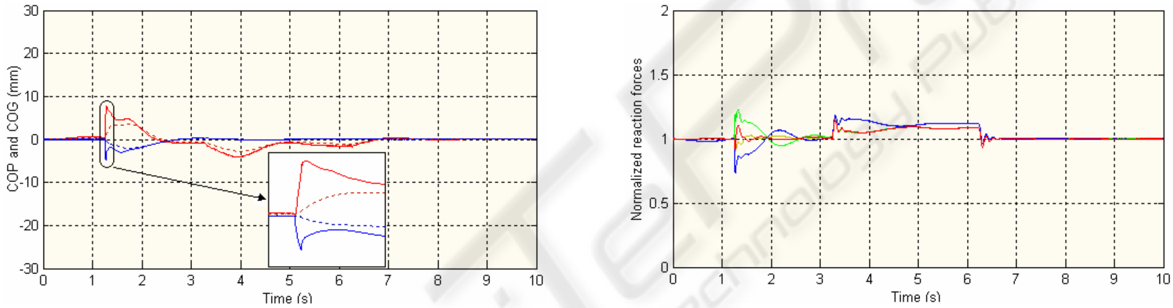
where x_P^{ref} and y_P^{ref} are the reference COP, f_x^{ref}, f_y^{ref} and f_z^{ref} are the reference interaction forces, θ_a^{υ} and θ_a^{ψ} are the pitch and roll ankle angles respectively,



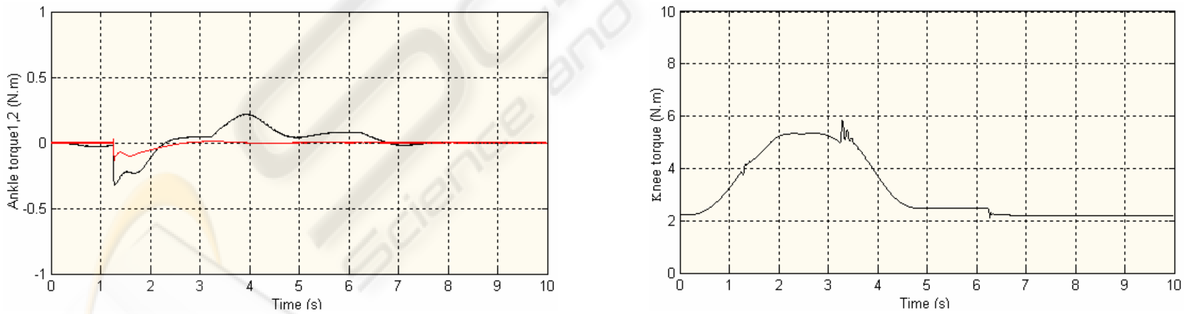
(*a*) Movement sequences with the hierarchical integration.



(*b*) Hip's vertical position under disturbances (left) and hip's horizontal position (right): along the x-axis (in red) and along the y-axis (in blue).



(*c*) Location of the COP (solid line) and projected COG (dotted line) along the x-axis (in red) and along y-axis (in blue). Normalized normal reaction forces at the corners of the foot: back right (in yellow), back left (in blue), front right (in green) and front left (in red).



(*d*) Temporal evolution of the torques at the ankle joints (left) and knee joint (left).

Figure 3: Simulation results for the robot standing on level ground when subject to external perturbations.

and l_h is the foot's height. This expression can be useful whenever is necessary to sacrifice mobility goals to ensure postural stability.

3.3 Hip Control

The trunk section has a particular role both in the mobility and the stability of the overall system. On the one hand, it has a great influence on the location of the COG, what can be helpful to achieve a given task. On the other hand, the postural stability imposes limitations to the trunk motion: its inclination must remain within a limited range of the angular space and, when operating in steady state, it must converge to a limit cycle. The idea of the parallel control is to conciliate two imperatives –

mobility and stability – that in many circumstances are contradictories.

In this regard, the control structure of the trunk section integrates also the control actions designed on the basis of the position controller, as described before. It is the sum of both components that actuate over the hip joints, while providing some sort of redundancy resolution. For certain motion tasks, it can be necessary to adopt the same strategy with any other joint.

4 SIMULATION RESULTS

In order to verify the effectiveness of the proposed controllers several simulations are carried out. Motivated by applications in biped locomotion, this section focuses on the posture robustness of the simplified model on the level ground when subject to external perturbations, on the system's adaptation when standing in a moving platform and on the improvements introduced by slip compensation.

4.1 Robustness to Perturbations

The first analysis illustrates the properties of the proposed control scheme when the system is on the level ground subjected to unpredictable perturbations.

The results displayed below are based on the following path: the system is standing, moves down and up again to the initial posture in 5 seconds. The initial state is set to $z_{hip} = 0.29m$ and the desired (x_G, y_G) should be zero along the motion. The motion planning is accomplished by prescribing the desired trajectories using sinusoidal-based functions. The controller's performance is evaluated by applying two unpredicted perturbations. The first perturbation corresponds to a horizontal force of $(F_x, F_y) = (+10, -5)\,N$ applied to the hip section at a pre-defined instant of time (1.25 *s*) and sustained for 20 *ms*. At the same time, an external virtual load of 10% of the body mass is added instantaneously on the hip at a pre-defined instant of time (3.25 *s*) and removed when standing (6.25 *s*). The simulation results are shown in Figure 3. It is observed that the actual hip height profile was well-achieved, and the system makes the necessary postural adjustments. The system is only displaced by a few millimetres and it has stabilised shortly after the push. The results also demonstrate that mass adaptation is feasible, for both loading and unloading of an external load. The control method is able to minimise the sway by generating a shear force quickly at the ground to counteract the perturbation. It depends on the latency at which it starts to resist the push and the rate at which this force can be increased. The last graphs show the temporal evolution of the computed joint torques. Given the proposed task, it is required a knee torque value that is significantly greater than the others, while the lateral joints require almost no torque.

4.2 Adaptation to Inclined Ground

The second analysis illustrates the emergence of an appropriate behaviour when the system stands on an inclined ground. The task performed is the same as before, while the control system relies on the inclinometer data to estimate slope changes. The complete information data is depicted in Figure 4 (the top graph illustrates the movement sequence).

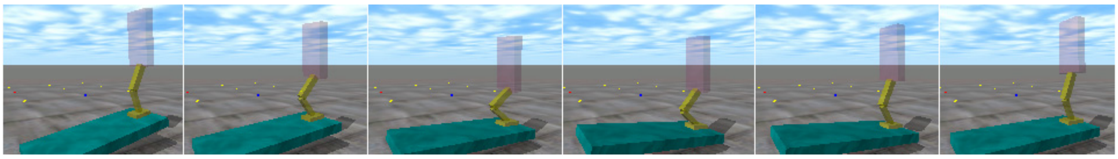
The task performed comprises forty cycles for the robot's motion (period of 3 s) and sixty cycles for the platform's motion (period of 2 s). The robot is placed at a distance of 30 cm from the platform's rotational axis. Further, sinusoidal movements are specified to the hip joints both in the sagittal and lateral planes. For the roll axis, the amplitude is 0.15 *rad* and the period 3.5 s. For the pitch axis, the amplitude is 0.1 *rad* and the period 5 s. The phase planes represented in Figure 4-(*e*) show the limited amplitude of the trajectories in each joint.

In summary, the proposed control scheme demonstrates self-adaptation and robustness against external forces and load changes. The automatic adaptation of the proposed controller to inclined grounds represents another relevant property.

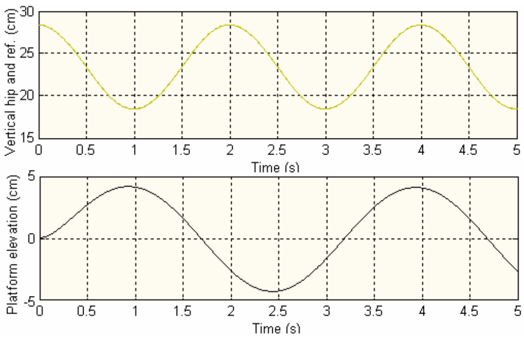
4.3 Tangential Forces Compensation

In the third analysis, we study the influence of the tangential forces and how they are regulated in the proposed control scheme. Therefore, contact force measurements are fully exploited hereafter to design the indirect force control.

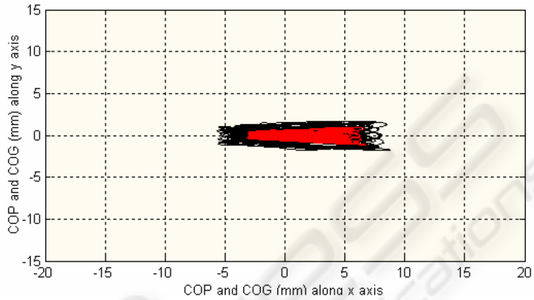
The objective is to thrust the body upwards to assume an upright position, while regulating the tangential reaction forces (zero tangential force) for a short period of time (160 ms). The simulation results are shown in Figure 5. The graphs show the improvements induced on the tangential component that, whereas the normal component remains unchanged. In view of the previous results, the introduction of these control variables could help to avoid the foot's slippage.



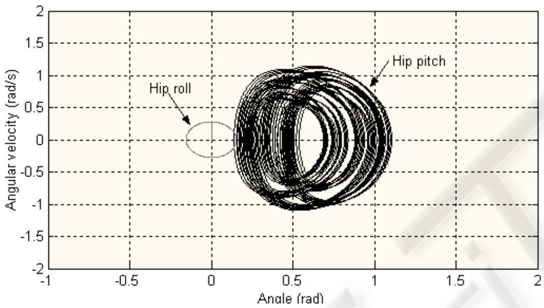
(*a*) Movement sequence during two seconds (the complete motion rounds 120 seconds).



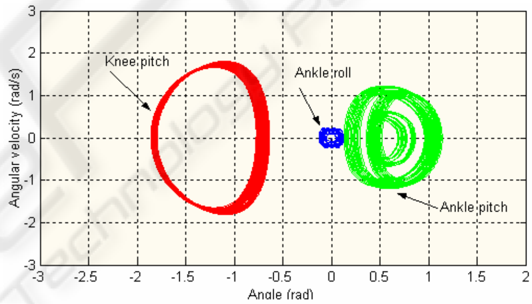
(*b*) Hip and platform (point of support) positions for a complete cycle.



(*c*) Trajectory of the COP (in black) and COG (in red).



(*d*) Limit cycles observed in the hip joints.



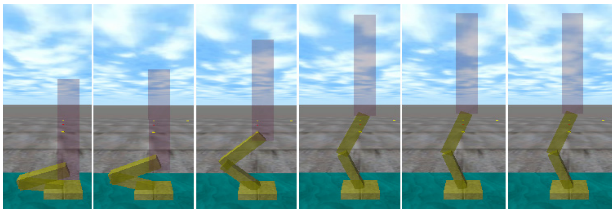
(*e*) Limit cycles observed in the knee and ankle joints.

Figure 4: Simulation results obtained for the robot standing on inclined ground with variable slope.

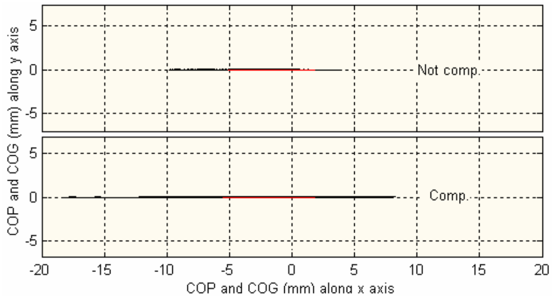
5 CONCLUSIONS

This paper investigated motion-control algorithms with application in the field of biped locomotion. Topics such as the algorithm robustness and postural stability were discussed through several experiments. From the results achieved a few remarks ought to be made. First, the Force Interaction Control is effective to generate the desired leg motion, while assuring the desired postural balance. The combination of position and force control algorithms is essential to exploit the system's redundancy. Second, the results illustrate the capability of the system to adapt to external forces and to changes in the body mass. Third, the results obtained provide an intuitive understanding of the postural adaptation when the system stands on an inclined ground with variable slope.

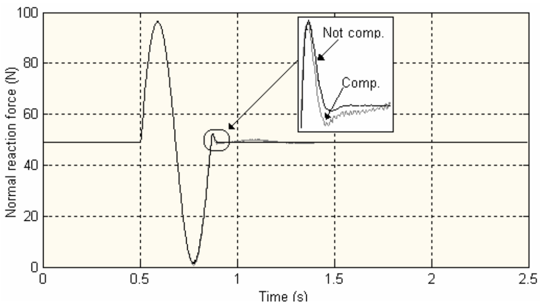
Ongoing research focuses in two main directions: *i*) to extend this study to a biped locomotion system; *ii*) to apply the proposed schemes to different walking tasks. Therefore, issues like active postural recovery, inner force control loop, advanced algorithms such as adaptive and learning strategies are currently being challenged.



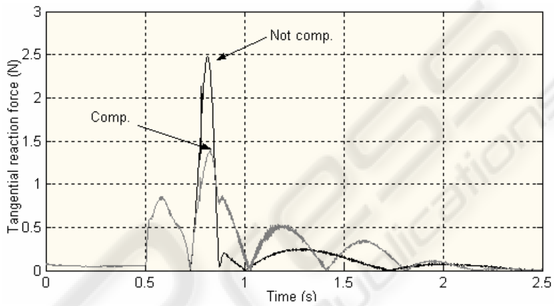
(*a*) Movement sequence for a fast (400 ms) thrusting the body upwards to assume an upright position.



(*b*) Trajectory of COP (in black) and COG (in red).



(*c*) Time evolution of the normal reaction forces.



(*d*) Time evolution of the tangential reaction forces.

Figure 5: Simulation results obtained for the robot standing on level ground with the regulation of the tangential forces.

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