Interactive Dynamic Simulator for Humanoid Robots with Deformable Soles

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Abstract— We present an interactive dynamic simulator for poly-articulated bodies. We use constraint-based methods to compute contact forces with non-discretized friction, allowing fast simulation. The user can interact with the virtual environment while sensing force feedback through a haptic device. We integrated in our simulator the possibility to design and model an external passive system that allows to absorb shocks generated by impacts. Especially we fixed in simulation a compliant sole under HRP-2 humanoid robot feet. We illustrate our talk by giving a simulation example.

Key Words: Dynamic simulation, constraint-based method, haptic interaction, deformable bodies

1. Introduction

Most of the robots we can see in medias like Honda's Asimo or Toyota's robots are mostly presented for entertainment. These humanoid robots are however designed to cooperate with human beings in factories or in everyday life. Several issues are therefore to be considered. The first issue is to be well operated, meaning physical models that are developed must be validated through simulation. Consequently, developments of simulators increase with the developments of robots. Since a few years, some simulators were proposed, especially for planification or control. We can cite SAI [1] working in the operational space, or OpenHRP [2, 3] which is however not interactive. Duriez et al. [4] show interactive simulation of deformable objects using constraint-based methods with non-discretized friction.

Many proposed simulators use penalty-based methods to compute contact forces [5]. Even if these methods are fast and easy to implement, they however need parameters tuning which is a critical issue.

In our simulator we implemented constraint-based methods based on Ruspini and Khatib's work [1]. We allowed a user to interact with the virtual environment and feel force feedback through a haptic device. This simulator is integrated in a general framework designed for virtual prototyping, AMELIF [6].

The second issue is security and safety matters. Robots are aimed to move in unknown environments or uneven floors. Especially, fast displacements of the robot involves hard interactions between the robot and the environment, creating thus impacts and vibrations on the robot structure. The movements of the robot can become more or less jerky as these interactions can excite the structure's own frequencies. In order to protect the robot's structure and to ensure the persons' security and safety while cooperating, we must consider two systems that absorb shocks: internal and external passive systems. Internal pas-
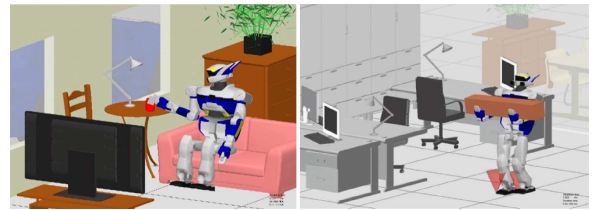

Fig.1 Examples of multi-contact simulation with HRP-2.

sive systems are typically mechanisms implemented on HRP-2 feet [7] consisting in rubber bushes inside the feet. External passive systems are typically skins or deformable mechanisms such as in [8]. We chose to integrate in our simulator compliant soles fixed under HRP-2 feet. Unlike [8], these soles are modeled analytically and do not have internal sensors. Thanks to our simulator's architecture's modularity, this can be easily and quickly implemented.

2. Constraint-based method for computing contact forces

This method, more common nowadays, explicitly includes non-penetration constraints in dynamic equations and is generally written in a complementarity form:

$$0 \leq a_c \perp f_c \geq 0 \qquad (1)$$

From the dynamic equations, we can show that contact forces and contact accelerations are linked by a linear equation:

$$a_c = \Lambda^{-1} f_c + a_{free} \qquad (2)$$

where Λ^{-1} is the well-known Delassus operator expressing the system's inertia in the contact space, a_{free} is the free acceleration of contact points computed with Featherstone's algorithm [9]. These two equations form a Linear Complementarity Problem (LCP) that can be easily solved with for example Lemke's solver.
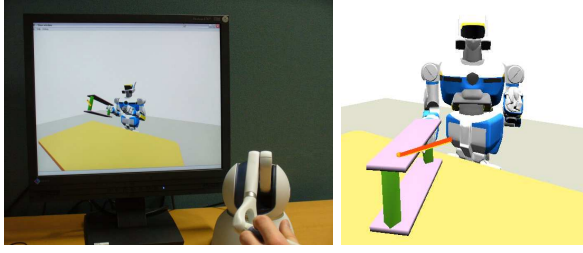
Fig.2 Interactive collaborative task with HRP-2.

Fig.3 Mesh of the sole

Considering Coulomb's friction ($\|f_t\| \leq \mu f_n$) introduces a non-linearity. An LCP form can be kept unless discretizing friction cones, involving bigger matrix for Λ^{-1} and thus time-consuming computation with a compromised accuracy. We prefered using iterative methods, more specifically Gauss-Seidel like methods, that allow to keep exact friction cones. Compared to LCP formulation, Gauss-Seidel like methods are faster and more precise [4]. We obtain a general algorithm in $\mathcal{O}(nm + m^2)$ with n the number of bodies and m the number of contact points. Implementation details can be found in [10, 11].

3. Haptic interaction

The user may want to interact with the virtual environment to perform for example collaborative tasks while sensing force feedback. It is then necessary to interface a haptic device. We chose the Phantom[1] device which has 6 dof of movements and 3 dof of force feedback. There are mainly two ways of interactivity:

- Touching: the force applied by the user is given by the device;
- Dragging: the dragged object must follow the user's movements while returning force sensing. The common way is to model a spring-damper between the haptic probe and the dragged object.

This interaction force is then added to the free dynamics of objects.

4. Compliant soles

We use a Finite Element Model to integrate the compliant soles in our analytical model. This approach is based on [4]. We designed and meshed our soles using GMesh[2]. The sole is composed of one material with a linear elasticity and an isotropic behavior, and the mesh is composed of linear field tetrahedras (Fig. 3). We use a small displacement model as we choose a material that presents a small deformation compared with the size of the sole. In this case, the nodes displacement vector U is a linear function of the external force F applied on all the nodes ($KU = F$ with K the stiffness matrix computed from Young's modulus and Poisson's coefficient).

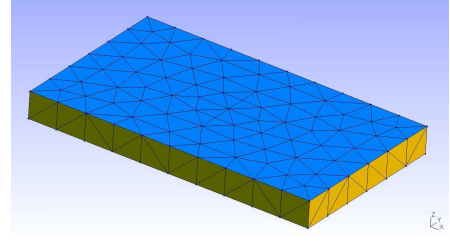[1]PHANToM©Omni[TM] is a SensAble Technologies product (http://www.sensable.com).

[2]http://www.geuz.org/gmsh/

In order to take into account the compliant soles in the dynamics, the contact force model (2) is upgraded. Writing (2) in a velocity form, this equation is enhanced with the deformation velocity vector of the contacting surface nodes $\dot{U}_c$:

$$v = W f_c + v_{free} + \dot{U}_c \qquad (3)$$

with $W = dt\Lambda^{-1}$ et dt is the time step. $\dot{U}_c$ can be approximated using an explicit Euler integration scheme:

$$\dot{U}_c = \frac{U_c - U_c^{t+dt}}{dt} = \frac{K_c^{-1} f_c - U_c^{t+dt}}{dt} \qquad (4)$$

with K_c the stiffness matrix of the contacting surface nodes. U_c and K_c are obtained by a condensation operation on the equation $KU = F$:

$$\begin{bmatrix} K_{cc} & K_{cn} \\ K_{nc} & K_{nn} \end{bmatrix} \begin{bmatrix} U_c \\ U_n \end{bmatrix} = \begin{bmatrix} f_c \\ f_n \end{bmatrix} \qquad (5)$$

where the index c represents the contacting nodes and n the other nodes. In order to obtain a linear relation between U_c and f_c while taking into account the influence of other nodes, we express U_n from the previous equation and, using the first line of the previous equation and assuming that the nodes that are not in contact do not generate contact forces ($f_n = 0$) we obtain:

$$f_c = \left[K_{cc} - K_{cn} K_{nn}^{-1} K_{nc} \right] U_c = K_c U_c \qquad (6)$$

Mixing this equation with (3) we obtain:

$$\begin{aligned} v_c &= \left(W + \frac{K_c^{-1}}{dt} \right) f_c + \left(v_{free} - \frac{U_c^{t+dt}}{dt} \right) \\ &= W^c f_c + v_{free}^c \end{aligned} \qquad (7)$$

which is a similar equation to the rigid case. Therefore it can be solved as in the rigid case.

5. Simulation example

We performed several tests in simulation on HRP-2 robot with compliant soles under its feet. Our simulation were made on a 2Ghz CPU PC running on Windows. The soles are simple pads covering the surface under the feet. We used the reference trajectory given by the robot pattern generator [12] and played with a simple PD controller (Fig. 4). In order to choose
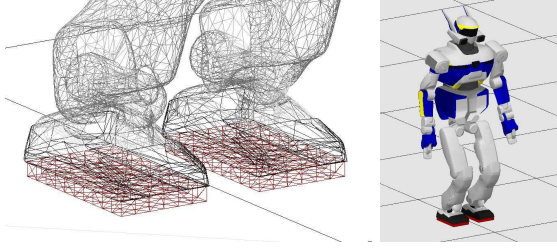
Fig.4 Compliant sole under HRP-2 feet
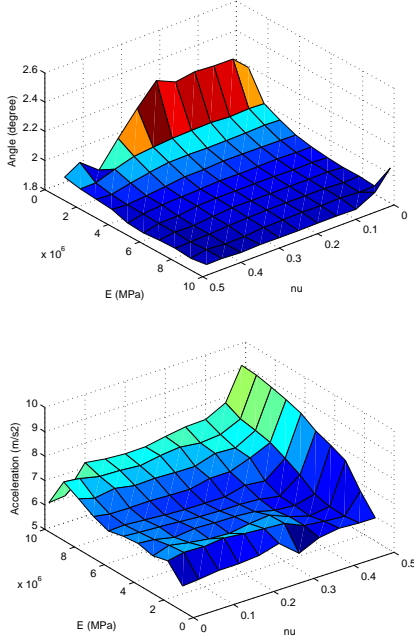
Fig.5 Evolution of acceleration peaks (left) and of the waist inclination (right)

the best material that absorbs shocks during walking, we ran several simulations changing the values of Young's modulus E and Poisson's coefficient ν and we measured the evolution of acceleration peaks during impacts with these parameters and the evolution of the waist inclination (Fig. 5). These graphs show an antagonism between the acceleration and the waist inclination. Indeed, the more compliant is the sole, the smaller are the acceleration peaks but the larger is the waist inclination. The velocity of the rigid part of the robot will decrease as the sole is compliant but if the waist inclination is too large, the robot may loose balance and so fall down. Therefore we choose values for E and ν that balance this antagonist effect and best absorb shocks.

6. Conclusion

This work is a preliminary step for the development of a complex multi-layer compliant sole for humanoid robots. We successfully implemented a simple sole on the robot in simulation. The next step will consist in including directly the analytical model of our compliant soles in the dynamic equations of the robot.

This will allow to use the control law based on the dynamic equations with the compliant soles. In the same time, we will work on the design of a new sole with a more complex shape. In particular, it will be interesting to compose with more than one material in order to have the best shock absorption and less residual deformation of the sole.

We are also working on reducing the computational cost of our contact force model as it is a major limitation for having interactivity, especially we are working on reducing the problem by computing contact forces per contacting bodies rather than per contact points.

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