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Experimental Evaluation of the Dynamic Simulation of Biped Walking of Humanoid Robots

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Abstract

We have been developing a software platform, called OpenHRP, for humanoid robotics which consists of a dynamic simulator and motion control library for humanoid robots. This paper tries to answer a frequently asked question "do the dynamic simulations and the experiments of biped walking of humanoid robots correspond?". Using OpenHRP and humanoid robots HRP-1S and HRP-2P, the comparisons between the simulations and experiments are shown at various aspects.

1 Introduction

The Ministry of Economy, Trade and Industries of Japan has run Humanoid Robotics Project (HRP for short) since 1998 for five years [5]. Humanoid robot HRP-1 has been used as a platform in HRP, and new humanoid robot HRP-2 is under development. Software platform for humanoid robotics, called OpenHRP[12], has also been developed that consists of a dynamic simulator and motion control library for humanoid robots. The controllers developed on the simulator can be used for the robot hardware as it is[12]. This is a distinguished feature of OpenHRP.

A crucial point in the dynamics simulation is how to compute the contact force and torque between the feet of humanoid robots and the floor, since the ZMP of a humanoid robot plays an important role in the control of its biped locomotion. Analytical methods can give consistent results by reducing the problem into a linear complementarity problem (LCP)[1, 9, 14]. An impulse-based method has also been proposed for the purpose[11]. The methods are more stable numerically and efficient than the penalty method in which the collision forces are computed explicitly based on a physical model like the virtual spring-damper[10]. But some humanoid robot including HRP-1 has very soft spring-damper mechanism on its feet whose dynamic simulation by the analytical methods is very difficult, since the simulation must cause vibrations of the feet whose mass is relatively small when the spring-damper element is embedded between a foot and a leg. The penalty method is rather appropriate for the case [13, 15]. An explicit spring-damper model is employed in this paper from the observation.

A frequently asked question here is "do the dynamic simulation and experiments of biped walk of humanoid robots correspond?". This paper tries to answer the question by comparing the results of the simulations and the experiments at various aspects, including the contact force and torque, the stability of the feedback control and the macro behavior of the robot.

This paper is organized as follows. Section 2 overviews the platforms. Section 3 presents the comparisons between the simulations and the experiments. Section 4 concludes the paper.

2 Humanoid robotics platforms

2.1 OpenHRP

2.1.1 Overview of OpenHRP

The configuration of OpenHRP is shown in Fig.1. OpenHRP can simulate the dynamics of structure-varying kinematic chains between open chains and closed ones like humanoid robots[16]. OpenHRP is implemented as a distributed object system on CORBA (Common Object Request Broker Architecture) [18].

The dynamics simulator of OpenHRP consists of five kinds of CORBA servers (see Fig.1) each of which can be replaced with another implementation if it has the same interface defined by IDL. Using the language independence feature of CORBA, ModelParser

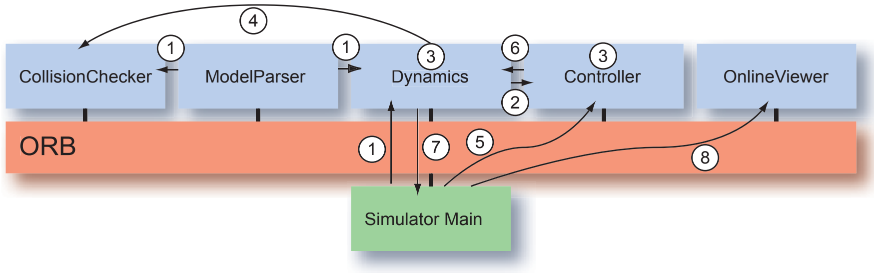


Figure 1: Configuration of OpenHRP

and OnlineViewer are implemented using Java and Java3D, other servers are implemented using C++. Using the servers, the forward dynamics of the robots is computed in the sequence shown by the numbers in Fig.1.

2.1.2 Finding the contact force

The spring-damper model used in the dynamics simulator of OpenHRP assumes that the infinitesimal translation $\Delta X : 3 \times 1$ and rotation $\Omega : 3 \times 1$ which make two objects penetrated can be found when the penetrating objects are given. This can be done efficiently and robustly using the Oriented Bounding Box trees [2] and extending the concept of the separating plane[3], but it is not described here since it is out of the scope of this paper. From the infinitesimal translation and rotation, the contact force and torque are computed based on a nonlinear spring-damper model as follows.

The spring element of the contact force is found by

$$\begin{pmatrix} F \\ \tau \end{pmatrix} = -K \begin{pmatrix} \Delta X \\ \Omega \end{pmatrix}, \qquad (1)$$

where F and τ are the force and torque respectively, $K : 6 \times 6$ a spring constant matrix.

The next mission is how to find the damper element. Let V_0 and ω_0 be the relative translational velocity and the angular velocity between the objects in contact respectively. V_0 and ω_0 must satisfy inequalities

$$\begin{pmatrix} n_1^T & (p_1 \times n_1)^T \\ n_2^T & (p_2 \times n_2)^T \\ \vdots & \vdots \\ n_M^T & (p_M \times n_M)^T \end{pmatrix} \begin{pmatrix} V \\ \omega \end{pmatrix} \geq 0, \qquad (2)$$

where n_i is the penetrating direction of the i-th intersection point p_i the position vector of the point, and M the number of the points. The solution set of inequalities (2) is a polyhedral convex cone, and we can not have the unique solution in general[9]. The proposed algorithm choose the orthogonal projection $(\tilde{V}, \tilde{\omega})$ of (V_0, ω_0) onto the polyhedral convex cone from the set of the feasible solutions, since the projection can be computed only in $O(M)$.

The damper force along the normal vector at the penetrating points is computed from $(\tilde{V}, \tilde{\omega})$ based on a nonlinear damper model [4, 10] by

$$\begin{pmatrix} F \\ \tau \end{pmatrix} = -\lambda \begin{pmatrix} \Delta X^n \, \tilde{V} \\ \Omega^n \, \tilde{\Omega} \end{pmatrix}, \qquad (3)$$

where $\lambda = \frac{3}{2}\alpha K$, α is a constant defining the linear dependence of the coefficient of restitution on the impact velocity, and the n-th power of a vector is defined by the vector whose elements are the n-th power of the original elements respectively. In the nonlinear model, the damping is dependent on the penetration depth, and then the damping increases with the depth of the penetration continuously as the objects is coming into contact[4, 10]. This feature is essential to simulate the biped walking in which a foot of the robot collides the floor at a finite velocity.

Then the normal force and torque from the spring and the damper are given by

$$\begin{pmatrix} F \\ \tau \end{pmatrix} = -K \begin{pmatrix} \Delta \hat{X} \\ \hat{\Omega} \end{pmatrix} - \lambda \begin{pmatrix} \Delta \hat{X}^n \, \tilde{V} \\ \hat{\Omega}^n \, \tilde{\omega} \end{pmatrix}. \qquad (4)$$

It is not straightforward to determine the damper wrench caused by Coulomb friction. A possible way is solving the LCP[1, 9, 14] which is bit expensive to compute. Instead, the proposed algorithm estimates the wrench from the projection $(\bar{V}, \bar{\omega})$ of (V_0, ω_0) to be orthogonal to the direction of the normal wrench in Eq.(4) by

$$\begin{pmatrix} F \\ \tau \end{pmatrix} = -C \begin{pmatrix} \bar{V} \\ \bar{\Omega} \end{pmatrix}, \qquad (5)$$

where $C : 6 \times 6$ is the damper coefficient matrix to simulate the tangent force generated by the friction. Though the force found by Eq.(5) may pull a foot of the robot to the floor in the restitution phase, but it does not break the physical law since the passive damper mechanism in the foot can generate the damper force in that direction when the foot is leaving the floor.

In total, the contact force and torque by the spring-damper model is given by

$$\begin{pmatrix} F \\ \tau \end{pmatrix} = -K \begin{pmatrix} \Delta\hat{X} \\ \hat{\Omega} \end{pmatrix} - \lambda \begin{pmatrix} \Delta\hat{X}^n \tilde{V} \\ \hat{\Omega}^n \tilde{\omega} \end{pmatrix} - C \begin{pmatrix} \bar{V} \\ \bar{\Omega} \end{pmatrix}. \quad (6)$$

Note that the norm of the tangent wrench is clipped to make the overall force within the friction cone. The clipping implies that the tangent wrench becomes zero when two objects are leaving.

2.1.3 Walking pattern generator

A walking pattern generator is a part of the controller which manages a dynamically stable biped walking. During walking, the dynamics of a biped robot can be approximated by a single inverted pendulum which connects the supporting foot and the center of mass of the whole robot. However, even with this approximation, the inverted pendulum has the vast possibilities of moving pattern which are not good for walking. To pick up the suitable motion for walking we constrain the center of mass to move on a plane specified by equation,

$$z = k_x x + k_y y + z_c, \quad (7)$$

where (x, y, z) is the position of the mass with respect to the supporting point, $(k_x, k_y, -1)$ specifies the normal vector of the constraint plane and z_c is the z intersection. In the case of the walk on a flat floor, the constraint plane is horizontal and the height of the center of mass is kept constant.

We obtain the following dynamics of the pendulum under the constraints

$$\ddot{x} = \frac{g}{z_c}x + \frac{1}{mz_c}u_p, , \quad (8)$$

$$\ddot{y} = \frac{g}{z_c}y - \frac{1}{mz_c}u_r.. \quad (9)$$

We call this dynamics as the 3D Linear Inverted Pendulum Mode (3D-LIPM)[6]. The only parameter which governs 3D-LIPM is z_c, i.e., the z intersection of the constraint plane and the inclination of the plane never affects the horizontal motion. Since equations (8) and (9) are linear and independent, we can easily obtain the closed form solutions which can be directly used for a dynamic biped walking. Particularly, when the input torques of the supporting point are zero ($u_r = u_p = 0$), we obtain hyperbolic trajectories on the constraint plane.

The reference joint angles and speeds are calculated by the inverse kinematics so that the position and the velocity of the feet with respect to the center of mass follow the 3D-LIPM.

2.1.4 Stabilizer for walking

The walking pattern generator can give walking motions that should be dynamically stable, but a feedback stabilizer for the biped walking is still necessary to realize the walking to cope with possible disturbances. Especially, the stabilizer is essential for the robot that has a soft spring-damper mechanism on its feet like HRP-1S and HRP-2P. We have developed a stabilizer that consists of a body inclination control, ZMP dumping control and foot adjusting control for the purpose[17].

2.2 Humanoid robots HRP-1S and HRP-2P

Humanoid robots HRP-1S[17] (1600mm height, 120kg weight) and HRP-2P (1540mm height, 58kg weight)[8] are used to compare the simulations and experiments. Figure 2 shows the front views of HRP-1S and HRP-2P.

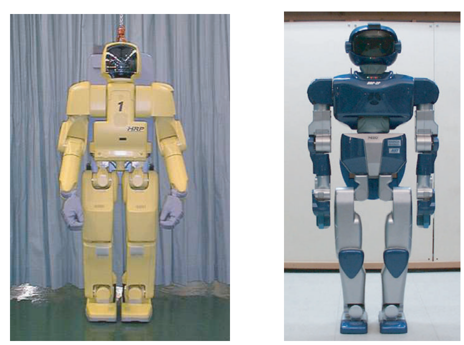


Figure 2: Humanoid robot HRP-1S and HRP-2P

3 Comparisons between the simulations and experiments

Now we are ready to describe the comparisons, in which the simulations start from a simple one and more elements are taken into account in turn.

3.1 Impulse-based method

The first example is a biped walking of HRP-1S in which a stable walking pattern is made by the above generator and no feedback stabilizer is applied to the robot. The contact forces between the feet of the robot and the floor are simulated using an impulse-based method[16]. HRP-1S can walk stably in the simulation, but it falls down to the floor in the experiment. Figure 3 shows the snapshots of the experiment. The

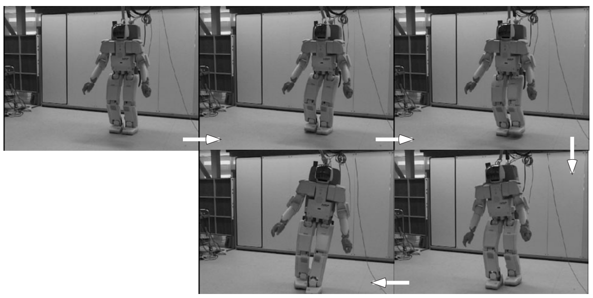


Figure 3: Real HRP-1S walking without the stabilizer

walking in the simulation is stable mainly because the soft spring-damper elements on the feet of HRP-1S lack in the simulation.

3.2 Spring-damper model

3.2.1 Identifications of the spring-damper parameters

The spring-damper parameters K and C must be identified before staring the simulations. The initial estimates of K and C are computed from the physical parameters of the mechanism on the feet, and they are adjusted by the following experiment. That is, a robot is inclined slightly at the standing position, and the external force to incline the robot is removed. Then the robot shows a damped oscillation along the pitch axis, when no feedback control is applied. Figure 4 shows an example of the torque curve along the pitch axis of a foot of HRP-1S. The curve with the higher first peak is the result of the simulation, and the other is that of the experiment. K is adjusted by the magnitude of the oscillation, and C by its frequency.

3.2.2 Walking without the stabilizer

Figure 5 shows the snapshots of the walking in the simulation using the spring-damper model, and the

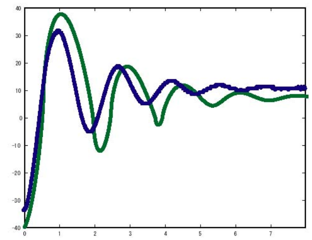


Figure 4: Damped oscillation of HRP-1S

robot falls down to the floor that matches the experimental result. The sequence of the snapshots is same as Fig.3. Though the macro behavior of the robot in

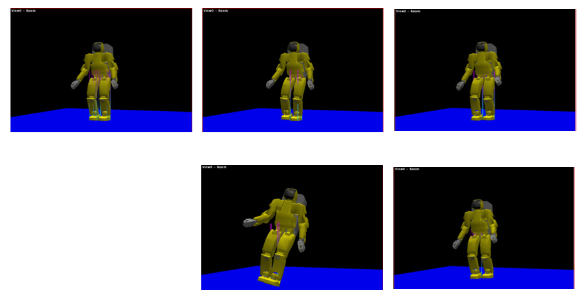


Figure 5: Virtual HRP-1S walking without the stabilizer

the simulation is not identical to that in the experiment, but at least the robot becomes to fall down in the simulation as well.

3.2.3 Walking with the stabilizer

Then we proceed to the walking with the feedback stabilizer. HRP-1S can walk in the simulation as well as the experiment. However, the feedback controller seems to be unstable in the simulation from the observation of the contact force from the floor to a foot of HRP-1S shown in Fig.6, while the controller seems to be stable in the corresponding experiment with the identical feedback gain.

3.3 Simulation of the lower feedback loop

The result of the simulation shown in Fig.6 is done under the assumption that each joint angle should follow the desired trajectory, which may cause the above mismatch. Then the feedback control at each joint is also been taken into account considering the inertia of the rotors of the motors at the joints. Figure 7 shows the contact force in the simulation under the

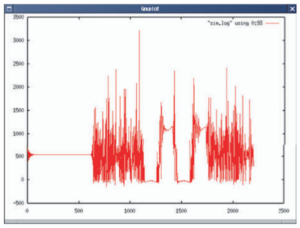


Figure 6: Vertical contact force from the floot to a foot of HRP-1S

new setting and the corresponding experiment. Now

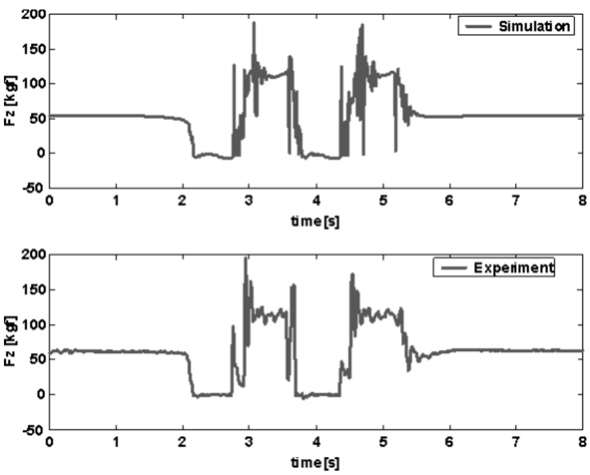


Figure 7: Normal contact force from the floor

the oscillations in the curve has disappeared in the simulation, and we can see that the curve stays in the middle when two feet are on the floor, at zero when the foot is that of the swinging leg and around the high value when the foot supports the whole body. The result of the simulation seems to correspond to that of the experiment.

Figure 8 shows the snapshots of a walking of HRP-2P in the simulation, and Fig.9 that in the experiment. HRP-2P falls down in the simulation without the stabilizer as well as the experiment, and it can walk stably in both the cases.

Figure 10(a) shows the torque curve about the roll axis sensed at the force/torque sensor at an ankle in the simulation and (b) that in the experiment. The torque is essential to compute the ZMP of the robot, and very important to realize the stabilizer. The curves in Fig.10 shows that the robot rolls inward both in the simulation and experiment, and the magnitudes of the curves also seems to correspond. The vibrations in the curve of the simulation is caused by the relatively long integration interval, i.e. 1 milli-second.

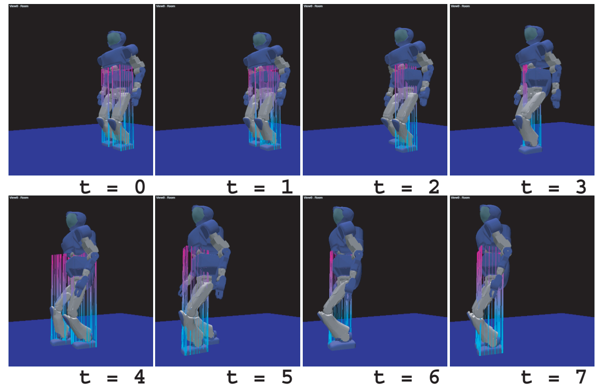


Figure 8: HRP-2P walking in the simulation

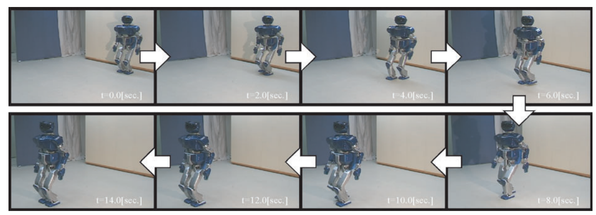


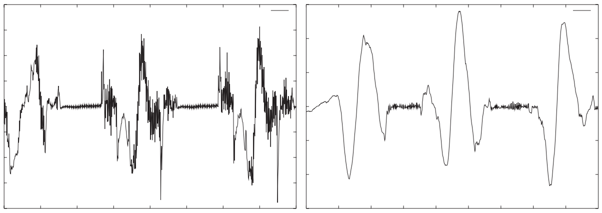
Figure 9: HRP-2P walking in the experiment

The impact force is exerted to the foot when it hits the floor, which is simulated by the nonlinear damper model in Eq.(3). Figure 11(a) shows the impact force in the simulation, and (b) that in the experiment. The impact force goes up to about 500[N] in the simulation as well as the experiment, down to about 100[N] with the bound after the collision, and up to 550[N] when the whole weight is put on the foot. This process happens during about 250 milli-seconds. The nonlinear model can be considered to be reasonable from the results.

4 Conclusions

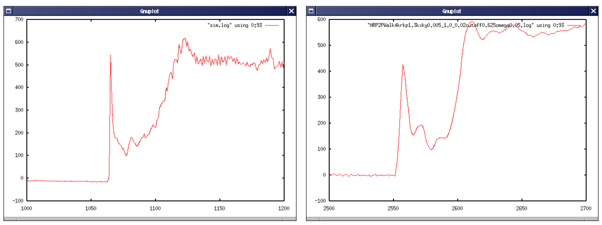
This paper has evaluated the dynamic simulations of biped walking of humanoid robots by the experiments using HRP-1S and HRP-2P. The results are summarized as follows.

- The experiments have confirmed that the proposed spring-damper model can simulate the contact force and torque between the feet and the floor with the sufficient accuracy when the lower feedback loop is also simulated properly.



(a) (b)

Figure 10: Torque about the roll axis



(a) (b)

Figure 11: Impact force when a foot hits the floor

- The experiments have also proved that the nonlinear damper model should work well to simulate the impact force at the collision between the foot and the floor.

We believe that such detailed evaluation has not been published using a humanoid robot that has a same size as a human so far and that this paper could answer the frequently asked question positively. The future study includes the development of a more accurate simulator which enables us to say that “we can know whether a robot can walk or not by a new controller before the controller is applied to the robot”.

Acknowledgments

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