Control Architecture and Algorithms of the Anthropomorphic Biped Robot Bip2000

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ABSTRACT

INRIA [1] and *LMS* [2] have designed and realized an anthropomorphic legged robot, *BIP2000* (fig.1). A planar version achieves walking, and the whole robot is able to keep its balance on one foot while moving. The purpose of this paper is to present the principles and the architecture of the robot control we have used. After having presented the robotic system, and the software architecture, we will detail the principles of the robot control. We will finally present implementation issues and experimental results.

Keywords: Robot Control, Biped Robots, Walking Machines.

1. DESCRIPTION OF THE SYSTEM

The design of the robot was inspired from the human anthropometric data and his dynamic capabilities. We recall here only the main characteristics of *BIP2000*, the reader being referred to [5] and [9] for more details.

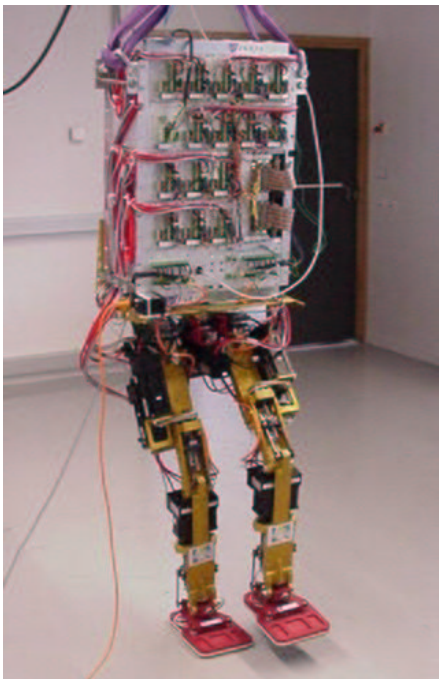

Fig1. The Biped Robot *BIP2000*

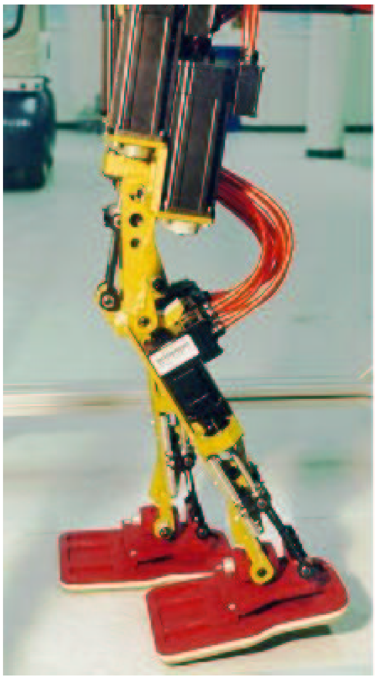

Fig2. *BIP* without Pelvis

1.1 Mechanical Structure of *Bip2000*

Designed by the *Laboratoire de Mécanique des Solides of Poitiers* [2], the robot has 15 active joints (fig.3). It is able to walk forward thanks to the rotation of the ankles, knees and hips allowing the flexion/extension of the biped in the sagittal plane (fig.4). The ability of changing direction is given by the trunk, the pelvis and the 2 hips internal/external rotations. For the lateral equilibrium, the rotation of the ankles, hips, and lumbar vertebra allow the robot abduction/adduction in the coronal plane. One more degree of freedom between the pelvis and the trunk makes the systems of locomotion and equilibrium independent. *Bip2000* is 180 cm height and 105 kg weight. The segments length, weight, position of mass, and inertia momentum are close to human ones.

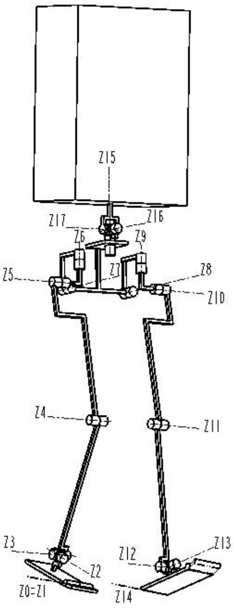

Fig3. Robot Kinematics

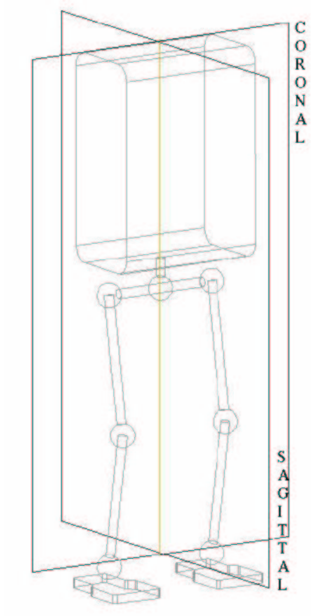

Fig4. Sagittal and Coronal Planes

1.2 Actuation and Transmission

The actuators are brushless DC motors. Five joints are equipped with classical harmonic-drive gears (rotations z6,z7,z8,z9,z15 in fig.3). The other joints transmitters are screw-nuts with satellite rollers combined with rod-crank systems (fig.5). The use of this system gives high reversibility and variable mechanical advantage (ex. reduction ratio varies from 0.6 to 1 at the knee). These transmissions are arranged in parallel at the ankles and at the trunk/pelvis linkage (fig.6).

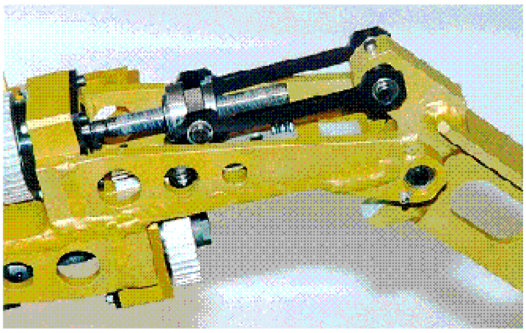

Fig5. Knee Transmission System

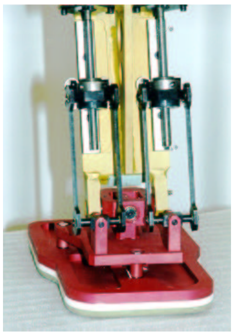

Fig6. Ankle Parallel Mechanism

1.3 Sensors

Synchro-resolvers provide with the relative angular positions of the motor axes. In order to recover absolute angular position, potentiometers are mounted on every joint.

The 3 strain gage-based force sensors located on each foot allow to recover the vertical component of the ground reaction force, two moments and the XY position of the center of pressure. We also use a two-axis inclinometer in order to know the direction of the gravity vector, and ultrasonic sensors on the legs for reconstructing the ground profile.

1.4 Computer Architecture

The computer architecture and control algorithms were designed by *INRIA*.

The payload in the trunk includes parts of commercial power units and control boards (VME/68040 25Mhz-based CPU). The real-time operating system is VxWorks and the control development is achieved under the *ORCCAD* environment [10] running on a Unix workstation (fig.7).

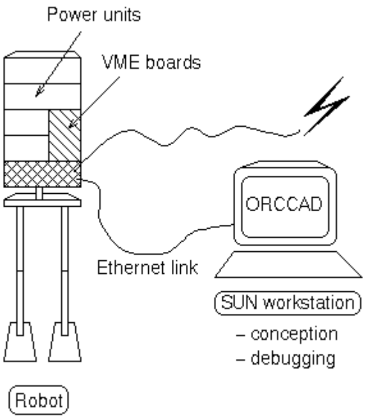

Fig7. System Architecture

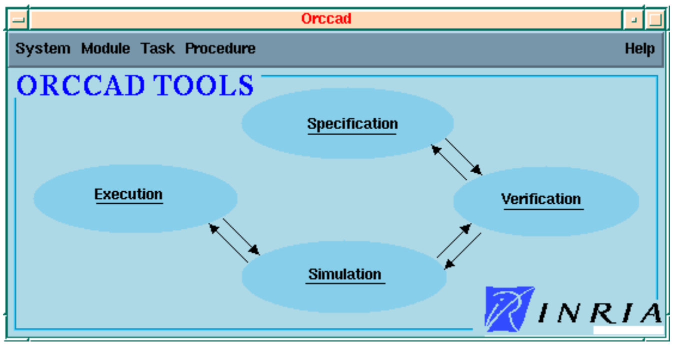

Fig8. The Robot Controller ORCCAD

2. SOFTWARE CONTROL ARCHITECTURE

The effectiveness of our control technique is based on the accurate modeling of the robot, the generation of adapted trajectories and the implementation via a dedicated robot controller.

2.1 Model

We consider the robot with rigid links and 15 joints. The reference frame is attached to the foot which is in contact with the ground. Its dynamics can always be written under the Lagrangian form:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \Gamma \tag{1}$$

where q is the set of joint variables (15 angular positions), M is the matrix of kinetic energy, C is the vector of Coriolis/centrifugal forces, G is the vector of potential-based forces, and Γ is the 15-dimensional actuation vector. In order to determinate each term of equation (1), we use an automatic generation tool [8] of the Lagrange dynamics of free-flying rigid tree robots with variable references. The robot is described in terms of Khalil Kleinfinger representation parameters. We compute three models, in case the robot is supported by its right foot, by its left foot or hung up. During the double support phase, we compute an intermediary model based on the 2 single support models (equ.3).

2.2 Reference trajectories generation

A gait is generated by defining several positions of the robot in the space (postures) and interpolating between them to get the desired motion. Different elements are taken into account: the aesthetic of the position, the cost in terms of energy consumption, and the stability (right location of the center of mass). The robot's walking patterns vary depending on the stretchiness of the legs, the height and the length of the steps, the speed of the execution and the pelvis movements. The robot's postural patterns vary depending mainly on the movements of the center of mass, the opening of the leg and the bendness of the trunk. Bounds on the actuators limit the available torques.

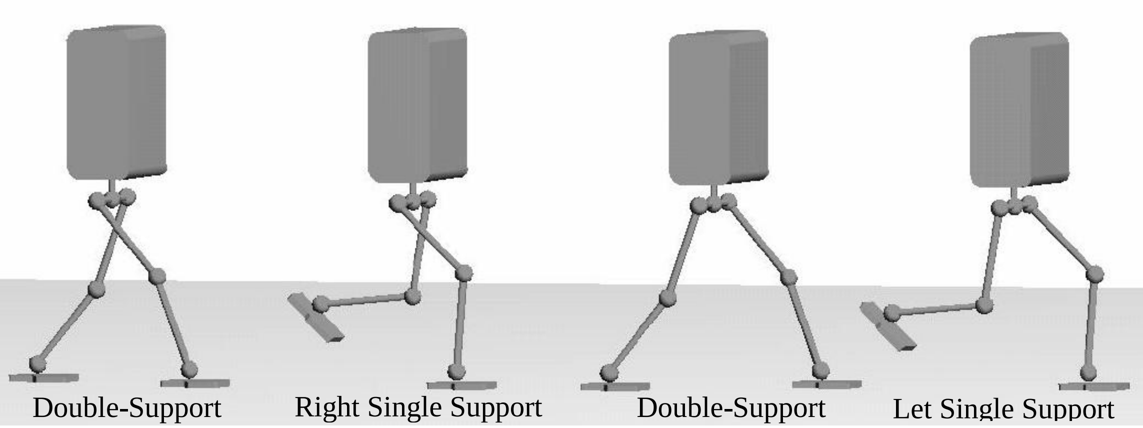

Fig9. Walking gait

The generation is based on task-function [7] and nonlinear constrained optimization approaches that allow to parameterize the postures. The trajectories are translated in terms of angular coordinates.

2.3 Robot controller : *ORCCAD*

Since dynamical issues were strongly involved and because of the existence of different phases in the walk, the system is an hybrid one with specific real-time requirements. This led us to take special care to the control implementation. The design and analysis of the whole system are handled using the generic robot controller *ORCCAD* (fig. 8). This allows the specification, the simulation and the implementation of robotic elementary actions *(Robot-Tasks*) integrating discrete events and continuous-time aspects. The overall robotic mission (*Robot Procedure*) is described by composing the *Robot-Tasks* through a synchronous language.

3. CONTROL PRINCIPLES

The objective of the control is to track optimal joint trajectories q_d that have been computed off-line. With the first prototype of *BIP2000* the available computing power was limited in order to preserve a low sampling period of 8ms (fig.10). We therefore use a simple control law belonging to the class of passive controls: Proportional Derivative associated with gravity and friction compensation:

$$\Gamma = K_p(q_d - q) + K_v(\dot{q}_d - \dot{q}) + \hat{G}(q) \qquad (2)$$

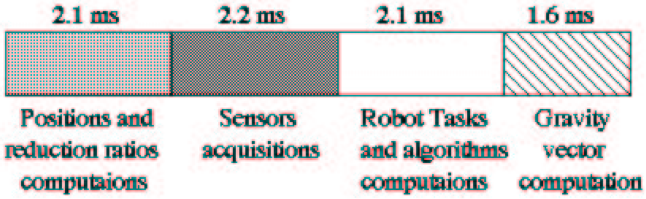

Fig10. Relative computations duration

We use the force sensors to determinate which foot is in contact with the ground in order to select the corresponding model and the gravity vector to be used in the control law. We have computed the gravity vector for 3 configurations, left and right single support phases and no support phase. During the double support phase, we use an intermediary gravity vector, function of the weight on each foot:

$$\begin{cases} \text{Robot Hung Up} & \rightarrow \hat{G} = G_{NS} \\ \text{Right Single Support} & \rightarrow \hat{G} = G_{RSS} \\ \text{Left Single Support} & \rightarrow \hat{G} = G_{LSS} \\ \text{Double Support} & \rightarrow \hat{G} = \lambda G_{RSS} + (1-\lambda) G_{LSS} \end{cases} \quad (3)$$

With λ the rate between the weight supported by the right foot and the total weight of the robot. This torque Γ is translated in terms of current motors *U'*. The friction coefficients *F* are experimentally estimated, using Armstrong model [12] and introduced in the control at the motor level. Finally, the current sent to the motor is therefore, with $\dot{\theta}_m$ the motor velocity:

$$U = U' + F.\mathrm{sign}(\dot{\theta}_m) \quad (4)$$

The difficulty comes here from the transmissions which reduction ratio is not constant and from the parallel arrangement at the ankles and the trunk. We have computed the cinematic model of the transmissions:

$$J\dot{\theta}_m = \dot{q} \quad (5)$$

with *J* the associated Jacobian containing the reduction ratios.

4. IMPLEMENTATION

Two elementary robotic actions (*Robot-Tasks*) are used:

1- The robot is hung up, its position is estimated with the potentiometers. A polynomial trajectory is computed for the system to reach the starting posture from the initial position. A specific set of gains is available for this configuration, the corresponding model is available with the right gravity vector to use in the control law. When the starting conditions are satisfied, the robot is put down and starts the moving stage.

2- The robot has to realize a desired motion pattern. The control law uses the gravity vector corresponding to the actual situation and computes the right currents to send to the motors. A specific set of gains is available for this configuration.

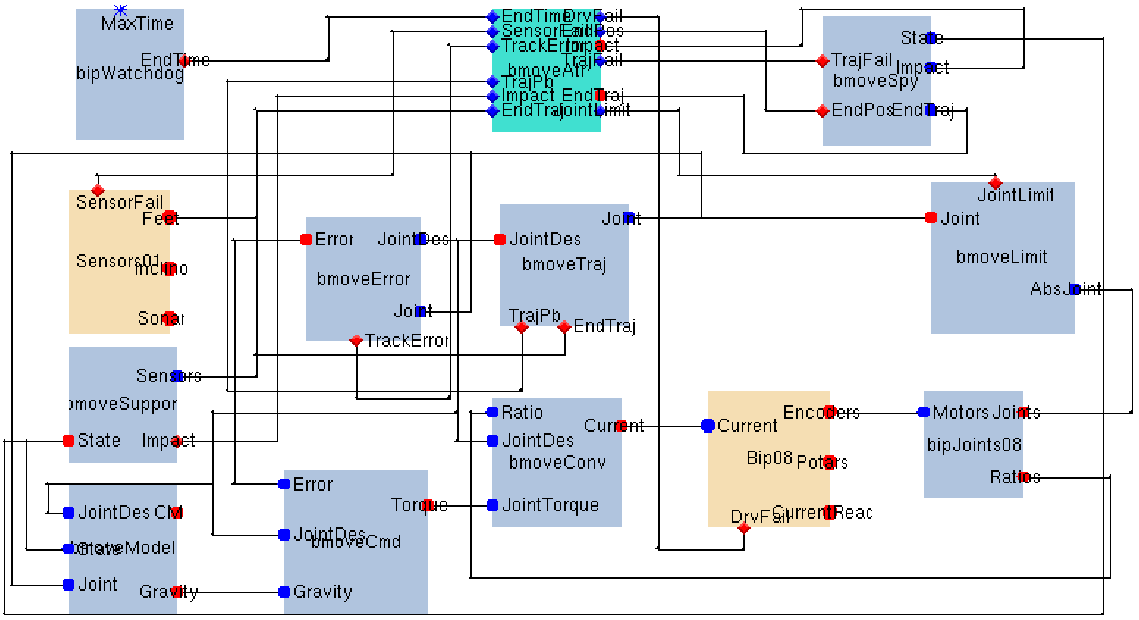

Fig11. ORCCAD Robot-task : bipMove

The Robot-Task *bipMove* (fig.11) is constructed around the *Physical-Resource Bip15* that represents the robot. The encoders positions are translated in terms of joint positions which are used by different *Modules* in order to compute the correct torque that has to be sent to the robot. The *Module bmoveCmd* receives information like the *Error* and the right *Gravity* vector and computes the corresponding articular *Torque*. The real-time events are managed in the *Module bmoveAtr*. We use several types of events, for instance, *T3 exception*, like the *TrackError* event which is generated if the error $(q_d - q)$ becomes too big, and stops immediately the whole process. We also use the *Post-Condition* event *TrajEnd*, on the occurrence of which the task ends.

5. RESULTS

Up to now, control laws allowing plane walking and postural control are running. These experiments are shown at the *Hanover Universal Exposition 2000* [3], video movies are also available.

5.1 Static plane walking

Walking is a cyclic pattern of body movements that is repeated step after step. One foot or the other is always on the ground, there is a brief period when both feet are on the ground (9). The walking experimentation were done with the planar robot. The two legs were associated with a wheeled trolley that maintains the robot in the sagittal plane (8 d.o.f restricted to 6). We are able to achieve different static walking gaits, forward and backward, with different speeds, and step lengths. During our experiments we have stored the values of different variables. The next plots correspond to the data of 4 steps (32 seconds) of a given walking gait. Figure 12 represents the phase diagram of the right knee joint. Figure 13 shows the evolution of the interaction forces on each foot. The total weight of the robot is 46kg. During the double-support phase the weight passes linearly from one foot to the other. The corresponding input (fig.14) and trajectory tracking (fig.15) are also plotted.

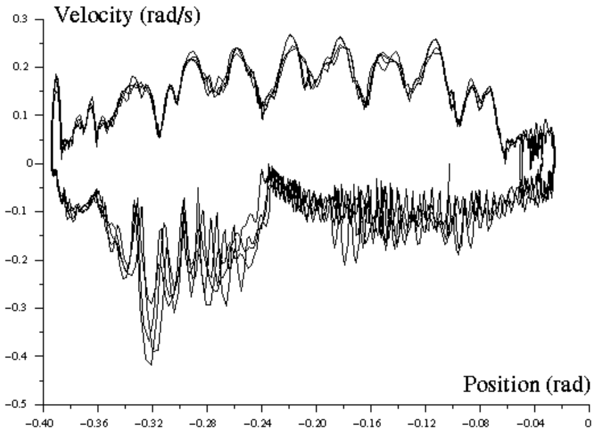

Fig12. Phase Diagram of the knee joint

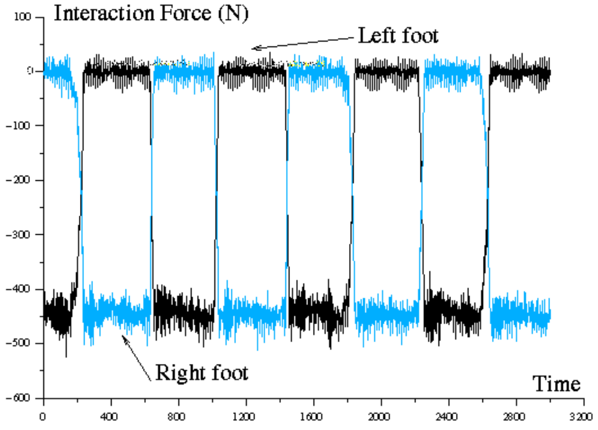

Fig13. Interaction Forces on the Feet

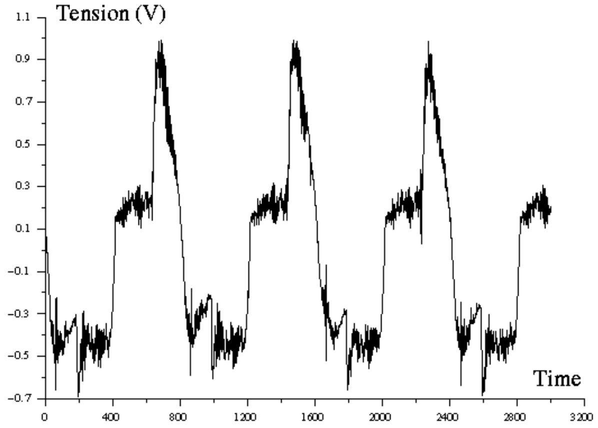

Fig14. Knee Input Voltage

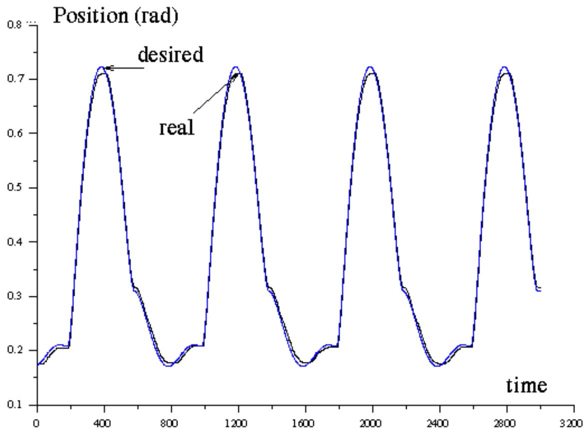

Fig15. Knee Desired and Real position

Here, we present simulation plots of the trajectories we are able to realize with the real robot.

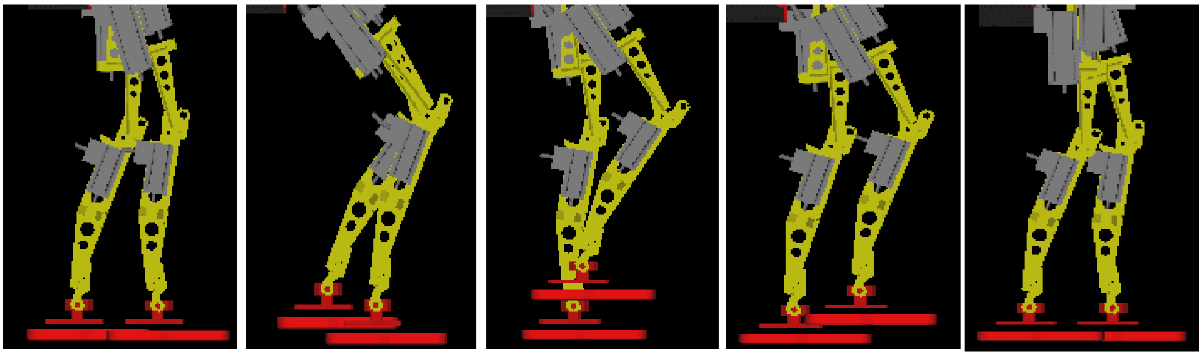

Fig16. Walking Gait

5.2 Postural moving

The 15 d.o.f robot is able to perform large amplitude motions while standing on one foot. In this movements the articulated trunk/pelvis is especially helpful to keep equilibrium. We have achieved several postural patterns, for different opening amplitudes of the free leg and associated trunk bending to maintain the center of mass inside the support foot. During our experiments we have saved the values of different elements. The next plots correspond to the data of the postural movement corresponding to lateral movements of the left leg. Figure 17 represents the input on the right knee, the torque peak is 3 times lower than the maximum allowed one. Figure 18 shows the positions of the center of mass on the support foot.

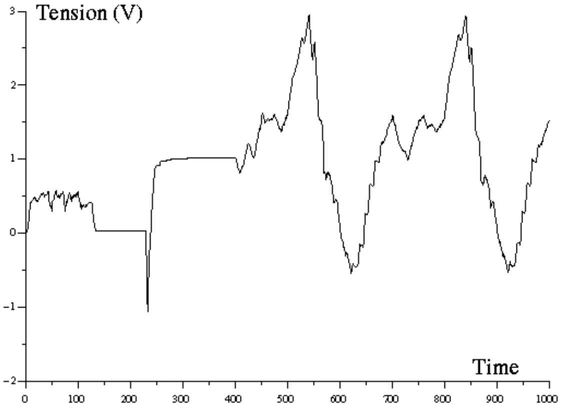

Fig17. Knee Input Voltage

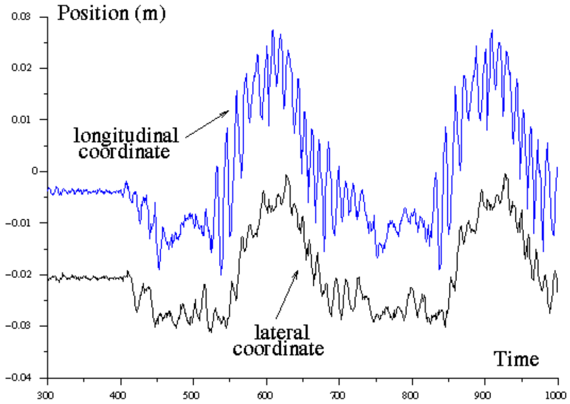

Fig18. Center of Mass Movements

Here, we present simulation plots of the trajectories we are able to realize with the real robot.

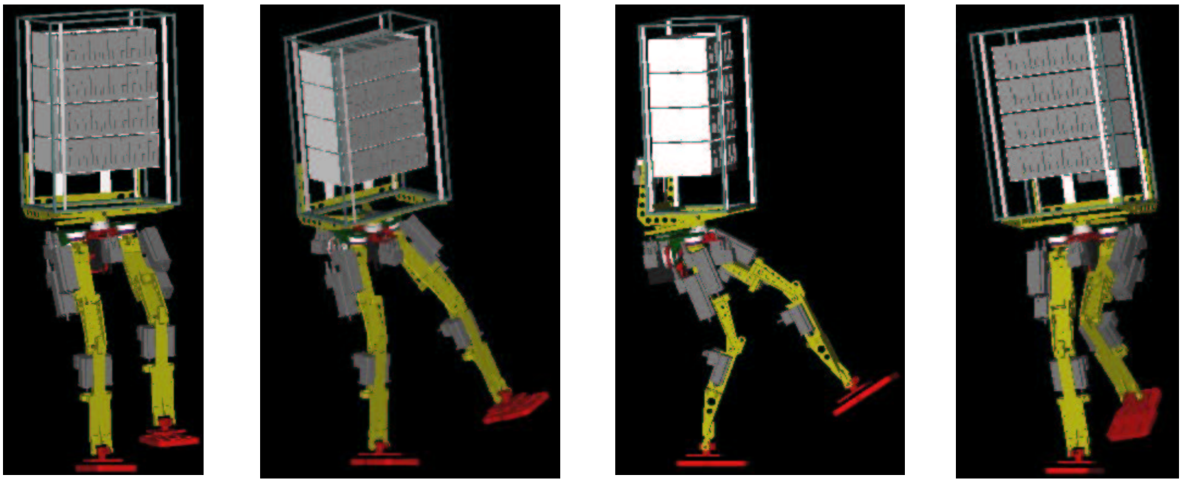

Fig19. Postural Movements

6. FUTURE WORK

A second prototype of Bip2000 will be available in October 2000. We will improve the computation rates adding a second processor, we will deal with the complete dynamical model using multiclock computations. We are working on the implementation of new control laws ensuring that three dimensional dynamical walking can be realized. In the walk it is not the accurate trajectory tracking which is really important, the problem is to achieve an objective (reaching a geographical point) while respecting different constraints (stability). Investigations on impact and contact are carried out. We are analyzing two approaches, the generation of a parameterized set of walking trajectories [11] and the techniques of optimization under constraints and Model Predictive Control of NonLinear systems.

7. ACKNOWLEDGEMENTS

The reported work is the result of the contributions from several researchers and engineers. The Bip team members are presently : Nicolas Andreff, Gérard Baille, Guy Bessonnet, Nathalie Cislo, Pascal Di-Giacomo, Bernard Espiau, Alain Girault, Hervé Mathieu, Roger Pissard-Gibollet, Philippe Sardain, Pierre-Brice Wieber.

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