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Path-Planning and Tracking in a 3D Complex Environment for an Anthropomorphic Biped Robot

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Abstract

Biped robots have specific dynamical constraints and stability problems which reduce significantly their motion range. In these conditions, motion planning used for mobile robots cannot be applied to biped robots. In this paper, the path planning problem is seen as finding a sequence of footholds in a 3D environment, keeping robot stability, motion continuity and working within the structural constraints of the biped.

The designed path planner contains two parts : The first one determines a reference path which maximises success rate in view of biped capabilities. This reference track is computed by the well know $A^\star$ search in the graphs algorithm.

The second part of the path planner is a path tracking algorithm which makes the robot follow the reference track.

Simulation results concern the anthropomorphic 15 degrees of freedom robot BIP2000.

1 Introduction

Biped machines have the potential to emulate the human superior capacities of crossing obstacles. The need for a biped robot is obvious in application requiring locomotion in hazardous human environment. Biped robots are superior to wheeled mobile robots when it is necessary to run up/down stairs or to cross over a hole. Moreover biped machines can pass through a narrow corridor where a large multipod walking robot cannot.

Since many years, research in biped locomotion has traditionally been focused on generating smooth walking trajectories which preserve the robot stability. Unfortunately, only a few researches have been achieved on the biped navigation problem [2] [7], although a significant amount of work has been done for wheeled mobile robots [6] [3, chapter 10,11]. With biped robots, motion planning for walking on an unstructured terrain primarily involves :

- the determination of the trajectory of the vehicle,
- the selection of the footholds in space,
- the sequencing of the footsteps in space.

Lorch *et al* [7] show an example of planner which adapts an offline pre-calculated trajectory on a vision-based biped robot. Barry's and Zheng's [2] path planner uses a geometric transformation to translate the 3D space problem into a 2D plane; in this 2D plane the biped path can be planned using the same algorithms as the ones developed for wheeled robots. In [5], Cislo and Espiau developed a navigator for BIP2000 in a 3D partially structured environment divided into hexagonal stairs. Despite the efficiency of the method, in this environment the restrictions on the foot placement were too strong for the biped abilities. The aim of the work presented in this paper is to develop a method with fewer restrictions on the foot placement of the robot.

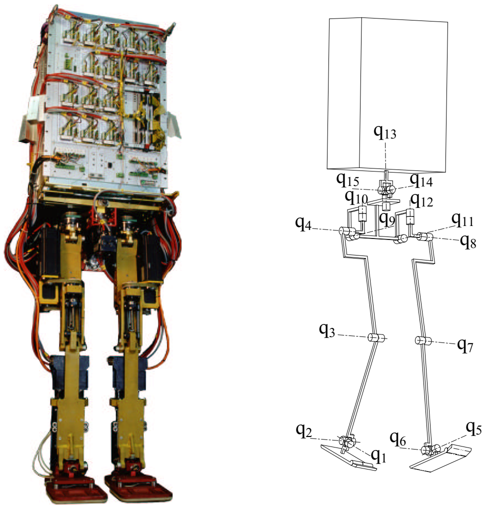

Figure 1: *The anthropomorphic biped robot BIP2000*

In this paper, we present a path planner for a biped robot. The path planner has two parts : a first algorithm determines a *reference path* and the second part is a path tracking which makes the biped follow the reference track. In the next section, we first present the BIP2000 robot, and the problem formulation. A classification of the different ground types is given in third section. The path planning algorithm is discussed in the fourth section, which is followed by the section of results obtained by simulation on the BIP2000 robot.

2 Motivation & problem formulation

This section presents the BIP2000 biped robot, and exposes the problem of finding feasible steps according to mechanical and energetical limits, and following environmental constraints. Then the 3D environment where the biped will evolve is described.

2.1 The BIP2000 project

BIP2000 (figure 1) is a French 15 degrees of freedom (dof) anthropomorphic robot jointly designed by the Laboratoire de Mécanique des Solides and INRIA Rhône-Alpes with the aim to realize a reliable evolutive testbed for studies in locomotion and posture. The characteristics of BIP2000, from the point of view of locomotion, are as follows:

- the robot has two legs (4 dof each), a pelvis (4 dof) and a trunk with 3 more dof, which is very interesting for postural control;
- the leg structure is closely inspired from the human one, in geometry and mass and inertia values and distribution (the global mass is about 105 kg, for a total height of 1.80 m, each leg has a weight of about 17 kg);
- the range of possible joint motions is rather large, since the robot is supposed not only to walk steadily but also to adopt various postures;
- the transmissions are original and contribute to BIP2000's anthropomorphic character: screw-nuts with satellite rollers combined with rod-crank systems, sometimes arranged in parallel.

2.2 Path generation for a biped robot

The path generation on rough terrain for a biped robot can be seen as finding a sequence of suitable footholds keeping robot stability and motion continuity. Each step is a trajectory, a sequence of statically stable postures, that follows environmental constraints and fulfills the mechanical and energetical limits of the robot.

Constraints. It is considered that the robot is almost always in a single support phase. A reference frame is attached to the support foot. In this frame, the robot dynamics has the wellknown form :

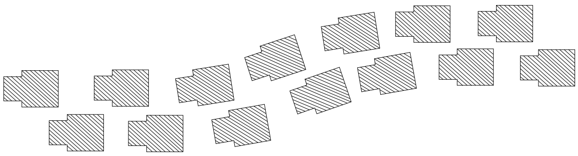

Figure 2: *Sequence of footholds*

$$\Gamma = M(q)\ddot{q} + W(q,\dot{q}) + G(q)$$

where q is the n-set of joint variables and $G(q)$ is the gravity vector. Considering static stability only, velocity and acceleration are assumed small. Therefore the above expression is reduced to:

$$\Gamma = G(q)$$

A first technical limitation is that

$$q \in \{q, \{\Gamma(q)\} \in \{\Gamma_{min}; \Gamma_{max}\}\} \qquad (1)$$

The second constraint is due to the kinematics limitation of the articulations.

$$\{q\} \in \{q_{min}; q_{max}\} \qquad (2)$$

If we consider an environment where slopes are not too steep (less than 30°), and such that the friction coefficient between foot and ground is high enough so that the foot does not slip, the static stability condition is reduced to:

$$X_g(q) \in convex\ hull\ of\ contact\ points \qquad (3)$$

where $X_g(q)$ are the coordinates of the projection of the centre of mass expressed in the reference frame.

Feasible step. A feasible step can now be defined as:

1 It is possible to move from a static posture P_I to a final posture P_F satisfying (1) and (2), keeping the same support foot, and such that the final position of the free foot is infinitely close to a possible foothold.

∘ Note: It is assumed that, given P_I and P_F, there exists a trajectory from P_I to P_F satisfying (1) and (2).

2 The transfer of support foot leads to a new initial position preserving (1) and (2), keeping the same posture with a new reference frame.

Nonlinear optimization method. The problem of finding postures satisfying (1), (2) and (3), with given location and evolution of the free foot is solved by a nonlinear optimization method. This nonlinear optimization method is encapsulated into a software (implemented in Scilab [9]) we called "Jacadi" (French equivalent for "Simon says"). This "Jacadi" function is used in the path tracking part of the path planner to determine if a step is feasible or not. In case of unsuccessful attempts, the path tracking will try another shorter step (see section 4.2).

2.3 The 3D environment

In this paper, we study the motion of the biped robot in a 3D environment which is made only with triangles. In the horizontal plane, each triangle vertex are placed on a regular grid, this means that each triangle surface are about $0.5m^2$ and that stairs cannot be modeled in this environment. These triangles are sufficient to model complex environment (except stairs), and the number of primitives is not too high to be computed quickly. Figure 3 shows an example of this environment.

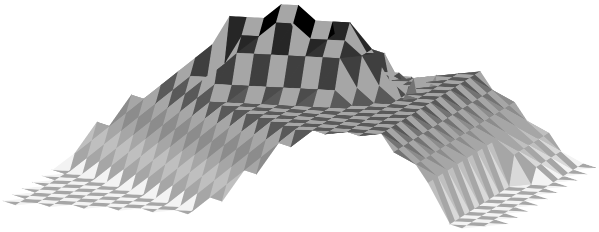

Figure 3: *The 3D environment (the vertical scale is expanded).*

3 Ground classification

Before designing a path-planner algorithm, it is needed to know how the biped performs in a 3D environment. The types of grounds are splitted into three classes. The abilities of the biped robot to cross these classes of terrain are then studied.

3.1 Flat ground class

On flat ground, the biped has no difficulties to walk; this class was already studied in [5]. The major result is that the biped foot can reach almost every position within a $40cm$ radius. On horizontal ground the maximum step is about $60cm$ long. But at this extreme, the biped posture is not anthropomorphic, indeed to maintain static stability the biped needs to lean over its chest excessively. In this paper we consider a maximal step length of 40cm.

3.2 Tilt ground class

The second class concerns sloping plot. The evolution of the step length is studied according to the incline, and to the influence of pitch and roll. The contact between ground and feet is high enough to consider that the foot cannot slip.

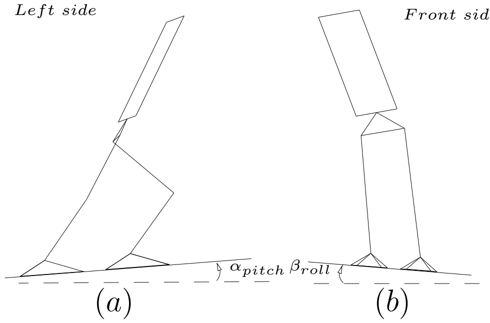

Figure 4: *pitch & roll angles*

Pitch study. The pitch angle is defined as the angle made by the ground with the horizontal in the sagittal plane (see figure 4.a). The BIP2000 behavior is very good in pitching, the max step length declines steadily (see figure 5). The limit is due to the ankle links : when the ground incline rises, the ankle bends until it hits its joint limit.

Roll study. The roll angle is defined as the angle made by the ground with the horizontal in the frontal plane (see figure 4.b) The same tests are made on the roll angle, and the biped behavior is much poorer here. Figure 5 shows that the robot cannot make steps with roll angle greater than 12°. It can be explained by the technical limitation of the BIP robot: indeed ankle joints limits are three times lower in the frontal plane than in the sagittal plane.

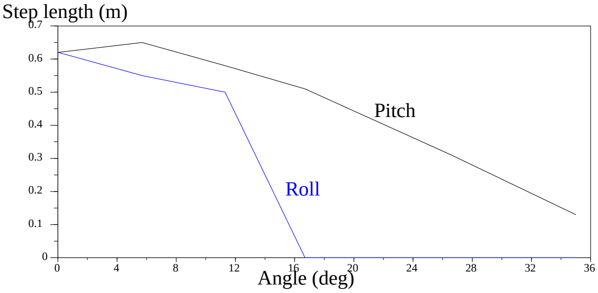

Figure 5: *Steps length evolution*

3.3 Stair class

The third class is devoted to stairs that are not yet modeled in the environment developed for this work. Some simulations have shown [1] that the biped is able to climb up stairs very well, but it has difficulties to go down. This is partially explained by the fact that Humans use dynamic walking when they go down, although the biped is studied here during static walking (and it is more difficult to go down than to go up in static walking).

3.4 Hole class

To list all the terrain classes, it is needed to introduce the class of holes. This class can be used to design more complex path planning strategies which take into account the holes in the ground. We can wonder how the biped reacts when encountering a hole. Has it to jump over it ? Or, should it skirt around the hole ? This class is not used in this work.

4 Path-planning algorithm

In the following, the results of the previous section about the biped stability over rough terrain are used to design a path-planning algorithm.

4.1 Reference path

Section 3 shows that the biped performances are better over flat ground than tilt ground. And they are better over pitching than rolling. To obtain the best success rate, the path-planning algorithm needs to make the robot walk over a path which avoids tilt ground and which prefers pitching than rolling when slope is not avoidable. In a first time, a *reference path* is computed according to these constraints.

Shortest path. This first step determines the shortest path between the start and final points. The path is computed by the well known search in the graphs $A^\star$ algorithm.

The heuristics used by the $A^\star$ algorithm are :

$$h_{n\to f} = dist(n,f)$$
$$g_{n-1\to n} = dist(n-1,n)$$

The path chosen with these heuristics is the straight line between the start and the final point (see figure 6), it is the shortest path but it does not take into account the type of terrain involved. It is impossible for the biped to track this path. The heuristics must incorporate a term which contains information about the terrain.

Shortest and tiltless path. To choose a path which avoids tilt grounds, the $A^\star$ algorithm heuristic is changed to penalize paths which cross over slope.

The heuristics used by the $A^\star$ algorithm are :

$$h_{n\to f} = dist(n,f)$$
$$g_{n-1\to n} = dist(n-1,n) + k_i . \mid \alpha_{incline} \mid$$

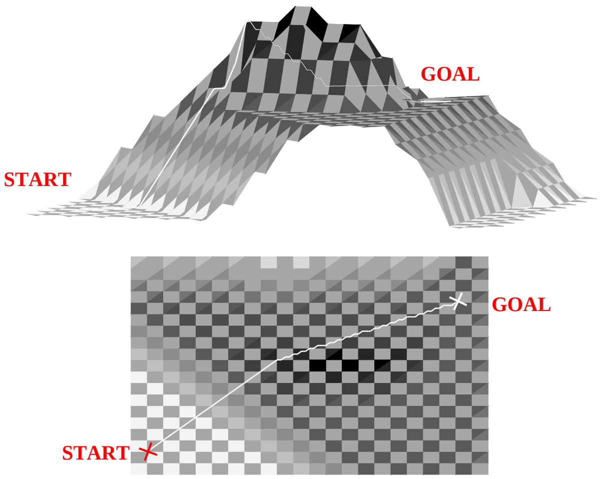

Figure 6: *The shortest path*

where $\alpha_{incline}$ represents the incline angle of the slope, and k_i is a fixed gain. Figure 7 shows the path computed by this algorithm. The path gets around the central obstacle, but it cannot avoid the first slope, the path crosses the slope at an angle. It may produce difficulties because the biped capabilities are lower when it must lean laterally.

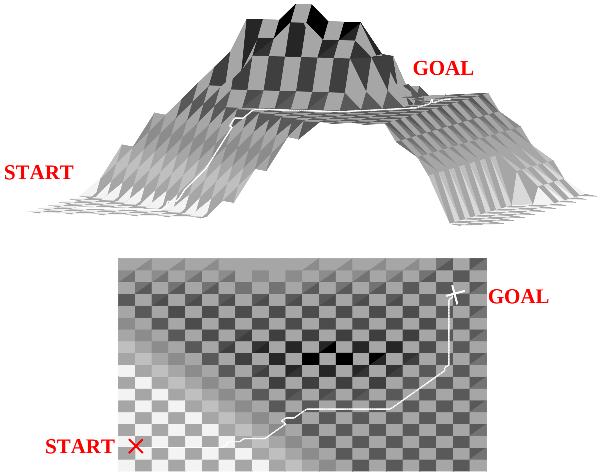

Figure 7: *The shortest and tiltless path*

Shortest path without rolling. Finally, the path chosen must take into account the lateral incline of the ground, the new heuristics are :

$$h_{n\to f} = dist(n,f)$$
$$g_{n-1\to n} = dist(n-1,n) + k_p . \mid \alpha_{pitch} \mid + k_r \mid \beta_{roll} \mid$$

With $k_r > k_p > 0$ to penalize rolling. The path in figure 8 gets around the central obstacle as before, but the first slope is crossed by the path where there is less rolling.

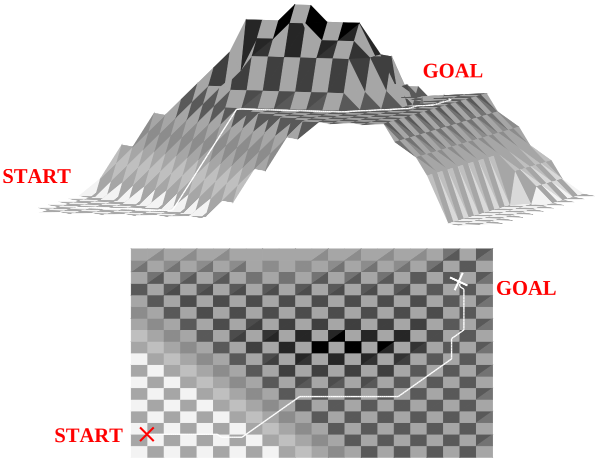

Figure 8: *The shortest path without rolling*

4.2 Path-tracking strategy

Now, the path determined above needs to be tracked. The path-tracking algorithm is given on figure 10. The accuracy with which the vehicle motion complies with the path-tracking assignment may be measured in terms of heading (θ_{os}) and lateral (l_{os}) offsets. These offsets are defined as follows : (see figure 9)

- l_{os} : distance between the biped and the path,
- θ_{os} : angle between the biped direction and the path tangent.

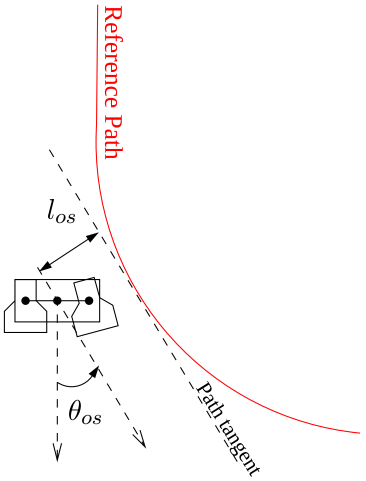

Figure 9: *lateral & orientation offsets*

The strategy must make the path tracking offsets (l_{os} and θ_{os}) tend to vanish. If the algorithm does not find a new step which makes the biped progress, the strategy is to put the robot in an *escape posture*. In "go straight" mode the planner tries first a step of $40cm$, and if it is not a feasible step, the planner tries a shorter one. After n_{max} tries, the planner switches into *escape posture*. The same tactic is used for the turning mode. The entire strategy is shown in figure 10.

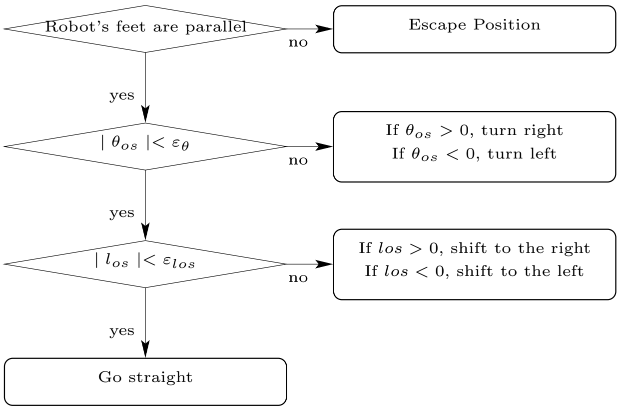

Figure 10: *Path-tracking strategy*

The *escape posture* is defined as a position that is always reachable. In the escape position the feet are parallel and spaced at hip width.

5 Results

This path-planning algorithm was applied to the BIP2000 biped robot. The path is planned in a 3D environment as shown in subsection 2.3. Two situations were precisely studied during the path : when the biped follows the track on horizontal flat ground and when the biped encounters a slope.

5.1 Results on horizontal flat ground

Figure 11 shows that the proposed path tracking strategy is feasible for a biped on flat ground. The biped follows the track and spins around when necessary. In *zone* 1 the robot turns too large and it catches up with the path by making small lateral steps.

The nominal step length is fixed at $40cm$, and when the biped needs to change direction, it spins around itself by increment of $10°$ (or less if necessary) in this example.

5.2 Crossing a slope

Figure 12 presents the biped crossing a slope of about $20°$, *zone* 2 shows that the *reference path* makes a detour before beginning to climb. With this detour, the robot faces the slope, and then it avoids ascent with a rolling angle. The nominal step length and

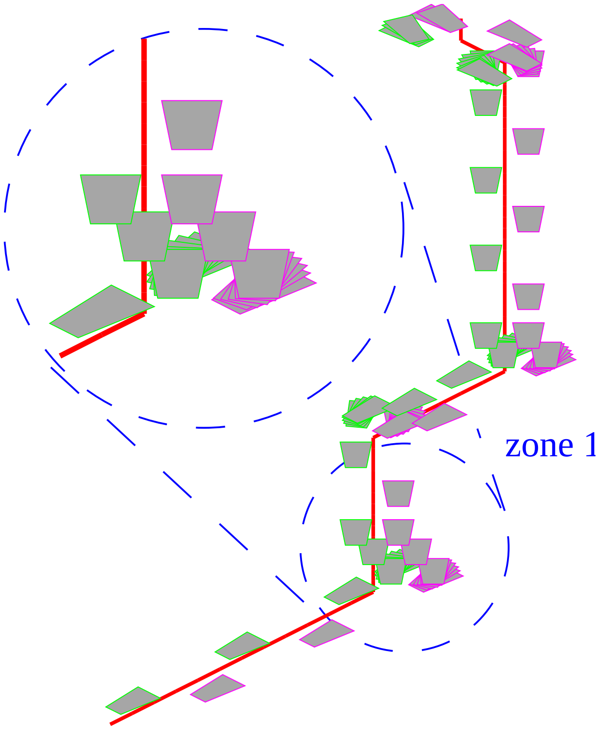

Figure 11: *Path-tracking on a flat ground*

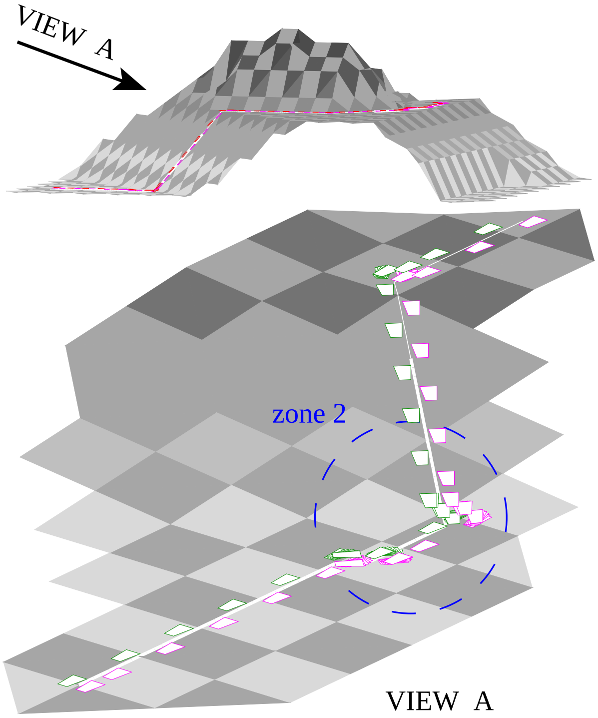

Figure 12: *Path-tracking over a slope*

turn increment are the same as above (40cm and 10°).

6 Conclusions

A 3D path planning method has been developed for biped robots to walk on uneven terrain. This planning process ranges from high-level environment navigator (or *reference path* generator) to a low-level path tracking algorithm. The high level environment navigator uses the well-known $A^\star$ algorithm to find the easiest track for the biped robot, then the low-level path tracking follows this path.

These simulations show the feasibility of a path tracking for a biped robot preserving static stability on rough terrain.

A challenging goal is now to incorporate stair and hole classes obstacles into our environment. The environment description made with triangle can quickly model holes and stairs, but the path planning method needs to be modified to incorporate these altitude discontinuities.

References

[1] B. El Ali. *Contribution à la commande du centre de masse d'un robot bipède.* PhD thesis, Institut National Polytechnique de Grenoble, December 1999.

[2] J.D. Barry and Y.F. Zheng. A 3-d navigation mechanism for autonomous biped robots to travel in the obstacle-filled world. *Automation in Construction,* Elsevier, 1992, vol. 1, pp. 175–188.

[3] S. Cameron and P. Probert. *Advanced guided vehicles, aspects of the Oxford AGV Project.* World Scientific, 1994.

[4] C.H. Chen and V. Kumar. Motion planning of walking robots in environment with uncertainty. In *Proc of the Int. Conf. on Robotics and Automation*, Minneapolis, April 1996, pp. 3277–3282.

[5] N. Cislo and B. Espiau. Path-planning for biped locomotion in a 3d partially structured environment. In *Proc. of the 32nd International Symposium on Robotics*, Seoul, April 2001, pp. 1539–1544.

[6] J-C. Latombe. *Robot Motion Planning.* Kluwer Academic Publishers, 1991.

[7] O. Lorch, J. Denk, J. Fernandez Seara, M. Buss, and G. Schmidt. Co-ordination of perception and locomotion planning for goal-oriented walking. In *CLAWAR*, Spain, October 2000, pp. 183–192.

[8] R. McGhee and G. Iswandhi. Adaptive locomotion of a multilegged robot over rough terrain. In *1979 IEEE Trans. Systems Man and Cybernetics*, volume 9, 1979.

[9] `http://www-rocq.inria.fr/scilab/`. Scilab Home Page.