Neuro-Fuzzy ZMP Control of a Biped Robot

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Abstract - This paper describes the control of a biped robot that possesses innovative characteristics, namely regarding its autonomy, becoming important the existence of a wireless transmission that binds software running in a PC to the robot in an efficient way and without physical links. It is used a radio transmission link and a power battery is carried by the robot.

In this work a 1st order Takagi-Sugeno-Kang type neuro fuzzy net is proposed, based on experimental and simulation data. This net uses the ZMP position and its variation as input and the longitudinal correction of the robot's body is obtained as the output. The ZMP is obtained making use of the force distribution on four force sensors placed under each robot foot.

Keywords: biped robot, robotics, stability, ZMP, neuro-fuzzy control.

1 Introduction

This paper describes the control of a biped robot that uses an inverted pendulum like structure for its balance.

Research in biped robotics have had a great increment recently, due to the challenges of the subject and the media impact of famous biped robots like Honda's.

Vukobratovic [1], a well known researcher in the biped robotics area, has developed a mathematical model of a biped robot and its method of control. Zarrugh [2] investigated the gait of biped robots based on the data of the human kinematics. Mcgeer [3] presented a pattern of locomotion for a passive use of the gravity and inertia in a descending slope.

With the objective of extending the application of the "Energy-Optimal Walking" method to the ascending locomotion in slopes, Rostami [4] and Roussel [5] proposed methods of gaits generation through the minimization of the energy consumption. However, the research developed does not consider the stability of the robot.

Because a biped robot is easily knocked down, it is necessary to take into account its stability in its gait calculation. Zheng [6] proposed a method of gait synthesis taking into account the static stability. Chevallereau [7] raised the discussion concerning the dynamic stability through the analysis of the reaction force between the base of the foot and the ground. Unfortunately the defined reference trajectory does not assure that the stability restriction is satisfied.

To assure the dynamic stability of a biped robot, Shin [8], Hirose [9] and Vukobratovic [10] proposed standard methods for gaits synthesis based on the zero moment point (ZMP). Basically this method consists of two stages:

1 – design of a desired ZMP trajectory;

2 - correction of the movement of the torso and pendulum to materialize the defined trajectory in balance.

However, because the change of the ZMP due to the movement of the torso and pendulum is limited, not all desired ZMP trajectories are possible [11]. Moreover, to materialize the trajectory of the desired ZMP, the movement of the torso and pendulum can vary radically. As the torso of the biped robot is relatively voluminous, the energy consumption will increase. Then, both the robot stability and the smoothness of the movement of the torso are two aspects to have in consideration.

The ZMP position can be obtained computationally using a mathematical model of the robot. But it is possible that there is a significant error between the real ZMP and the calculated one, due to the difference between the real robot physical parameters and its approximated mathematical model. Thus, the real ZMP should be measured in order to obtain a steady stable gait. Being the ZMP control non-linear, a fuzzy controller is appropriate, once fuzzy logic is widely used in many non-linear applications [13-15]. Some researchers propose neuro-fuzzy nets for the control of biped robots [16-18].

This work considers a 1st order Takagi-Sugeno-Kang (TSK) type neuro-fuzzy net trained with data obtained by simulation of the mathematical model of the robot and by observation of the real system.

2 Implemented Robot and Software

A biped robot was designed and built at the Institute of System and Robotics of the Department of Electrical and Computer Engineering of the University of Coimbra, in Portugal.

The mechanical structure of the robot is quite simple since it has only the main joints of hip, knee, and ankle, for each leg. There is another joint, an active inverted pendulum that is used to balance the structure in the lateral way. The robot carries, at this inverted pendulum, its own batteries, both for the motorization and the electronics. The robot is actuated by seven servo motors and the structure is made of acrylic and aluminium, with 2.3 kg of weight and 0.5 m height. Figure 1 presents the implemented robot.

The robot was designed to move both in horizontal and inclined planes, to go up and to go down stairs, having a speed of approximately 0.05 m/s. The project possess innovative characteristics, namely the autonomy, becoming important the wireless transmission link that binds the control software that runs on a PC to the robot without physical connections. Figure 2 shows the three main components of the system.

An integrated software platform was developed which allows both the simulation and the real time control of the biped robot. The software screen layout is illustrated in figure 3.

Fig. 1–Implemented robot.

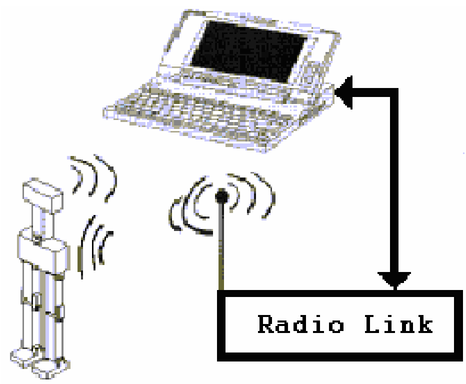


Fig. 2 – Main components of the system.

3 Kinematics

In the area of robotics, kinematics study the problem of the position, speed and acceleration of a body, applied to manipulators, legs and, more generically, robots. We can say that kinematics allows the description of the movement of a robot in terms of its position, speed and acceleration. The kinematics ignores the concepts of force, mass and inertia. The most used formalism for this problem is the method of Denavit-Hartenberg. The coordinate systems adopted to model our biped robot are shown in figure 4, together with the robot 3D model.

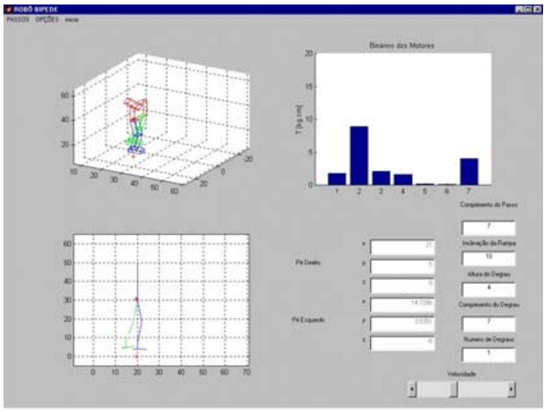


Fig. 3 – Simulation and control software window.

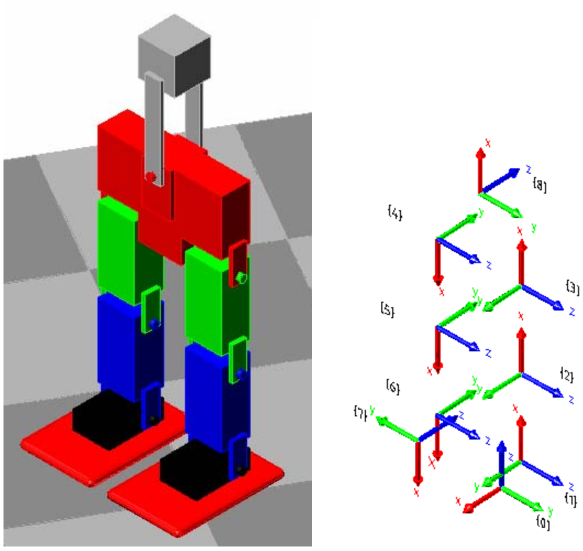


Fig. 4 – 3D model and the respective coordinate systems.

4 Dynamics

The dynamics is the field of physics that studies the application of systems of forces and moments to a rigid body. In the case of the biped robot the ZMP formulation can be used [12], based on a dynamic calculation.

4.1 Zero Moment Point – ZMP

Consider an anthropomorphic biped robot with torso and pendulum, where each leg is constituted by hip, ankle and foot. For a robot with four or more legs it is possible to consider the static stability that uses the gravity center, but for a biped robot it might be necessary to have in account the dynamic stability, and the calculation of the ZMP allows to enter this aspect. The ZMP is defined as the point in the ground where the sum of all the active moments of force is null. In figure 5, the minimum distance between the ZMP and the border of the stable region (foot border) is called the stability margin and can be considered as an indicator of the quality of the stability.

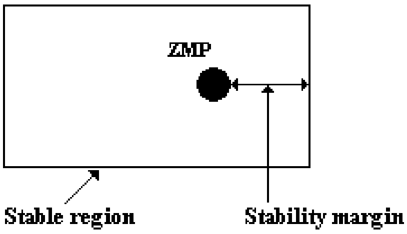


Fig. 5 – Definition of the stability margin.

If the ZMP is inside the polygon of contact (stable region of the foot) between the foot and the ground, it can be said that the biped robot is stable. When the distance between the ZMP and the border of the stable region of the foot is maximum, that is when the coordinates of the ZMP are next to the ones of the center of the steady region, it can be affirmed that the biped robot presents a high stability.

For the robot model of figure 6, with the physical characteristics presented in table I, the ZMP location is calculated by the following expressions:

$$x_{zmp} = \frac{\sum_{i=0}^{7} m_i\left(\ddot{z}_i + g\right)x_i - \sum_{i=0}^{7} m_i \ddot{x}_i z_i - \sum_{i=0}^{7} I_{iy}\alpha_{iy}}{\sum_{i=0}^{7} m_i\left(\ddot{z}_i + g\right)} \quad (1)$$

$$y_{zmp} = \frac{\sum_{i=0}^{7} m_i\left(\ddot{z}_i + g\right)y_i - \sum_{i=0}^{7} m_i \ddot{y}_i z_i + \sum_{i=0}^{7} I_{ix}\alpha_{ix}}{\sum_{i=0}^{7} m_i\left(\ddot{z}_i + g\right)} \quad (2)$$

where: $\ddot{x}$, $\ddot{y}$ e $\ddot{z}$ are linear accelerations, I_{ix}, I_{iy} , are inertia coefficients, α_{ix} α_{iy} are angular accelerations, m_i is the mass of the link i and g is the gravity acceleration

5 Designed Gaits

In this work, a gait similar to the human locomotion in horizontal planes was conceived.

To design the gait, a trajectory for the moving foot was defined, considering the following conditions:

- the robot's walking must be like a human being;
- at the beginning and at the end of the trajectory, the height of the foot is null, relative to the ground;
- at 50% of the trajectory the height of the foot is maximum (figure 7).

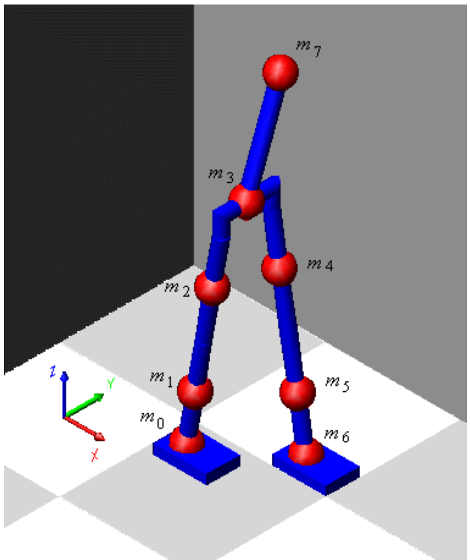


Fig. 6 –Biped model.

Table I – Physical characteristics of the biped robot.

Biped	Mass (kg)	Length (m)	I_x ($\times 10^{-4}$ kg.m^2)	I_y ($\times 10^{-4}$ kg.m^2)
Foot	0.16	0.025	0.813	1.413
Shank	0.17	0.115	8.188	7.721
Thigh	0.17	0.115	8.188	7.721
Haunches	0.40	0.065	14.167	6.467
Pendulum	0.30	0.065	50.725	51.050

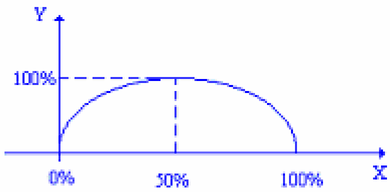


Fig. 7 – Normalized trajectory.

With these conditions the following normalized equation for the trajectory of the foot was considered:

$$y = \sin(x) \quad 0 \le x \le \pi \quad (3)$$

In order to obtain the real trajectory, the height, A, and the length, C, of the gait, must be defined, resulting in

$$X = \frac{C \cdot x}{\pi} \quad (4)$$

$$Y = A \cdot y \quad (5)$$

6 Trajectory Planning Algorithm

The control method used in this work to achieve the equilibrium of the gait consists in correcting the hip's and the pendulum's angles.

First, having into account the gait's characteristics, several via points of the trajectory are obtained, and the trajectory of the foot is generated using a cubic spline. After that, the trajectories of the joints are calculated, using the direct and the inverse kinematics; finally, the ZMP is calculated and the stability margin determined. This stability margin is then used to make corrections to the hip's and the pendulum's angles, using the desired ZMP as reference.

It must be noticed that not all gaits can be stable due to the fact that the working range of the used servomotors is limited.

Figure 8 shows the algorithm explained before.

This algorithm is used with static and dynamic models, but in the static model the spline is not needed, leading to a great reduction of the computational effort. In the dynamics case, four splines are needed for each link, resulting in a great computational effort, making the real-time computation difficult.

Figure 9 shows the obtained ZMP trajectory, with the previous algorithm, for the "walk in horizontal planes" gait with a step of 0.11 m. The figure shows ZMP points marked with crosses. In each foot 4 of them belong to single support phase, where the stability is very critical.

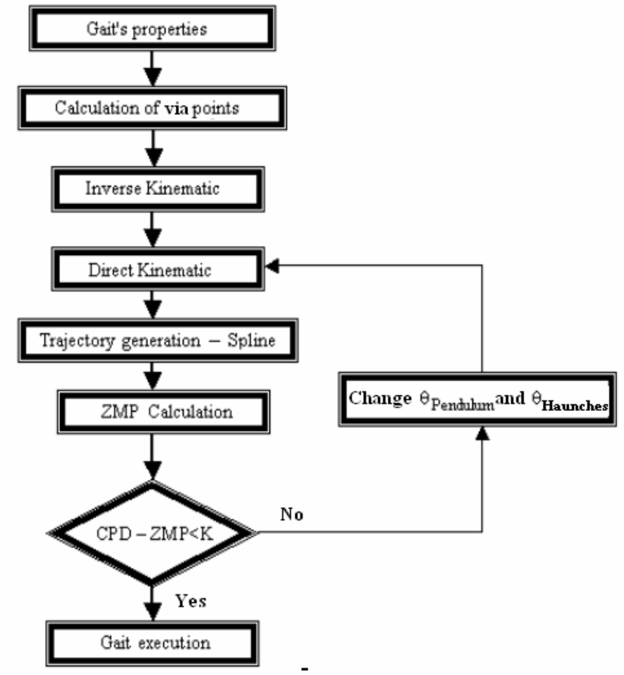


Fig. 8 – Trajectory planning algorithm.

In the double support phase, 2 ZMP points are located inside the foot and 1 is outside, between the feet, when the ZMP is transferred to the other foot.

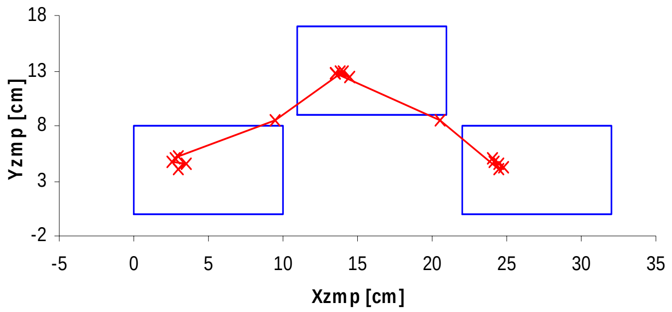


Fig. 9 – ZMP trajectory.

In the annex, gaits executed by the implemented and by the virtual biped robot are presented.
From the simulation of the trajectory planning algorithm, with a gait period of 2 s, it was obtained the relation between the X_{ZMP} and the longitudinal angle correction necessary to maximize the biped robot stability margin, that is to keep X_{ZMP} as low as possible (see figure 10).

7 Control Strategy

In order to allow a real time control, the actual (real) value of the ZMP (ZMP_R) is needed. To determine the ZMP_R, four force sensors are used in each foot of the robot as figure 11 illustrates. These sensors are used to detect the force intensity and where the force is exerted, which is determined by equation 6, thus allowing the control in closed loop with a neuro-fuzzy controller.

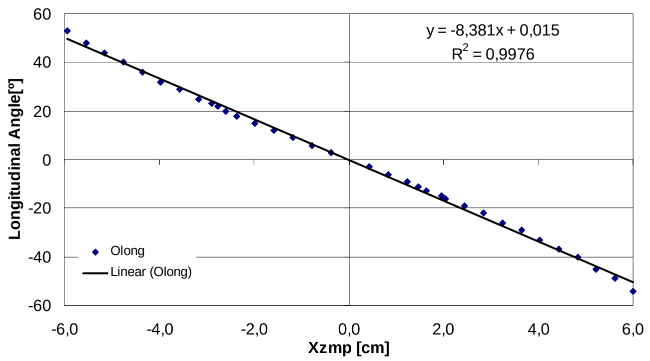
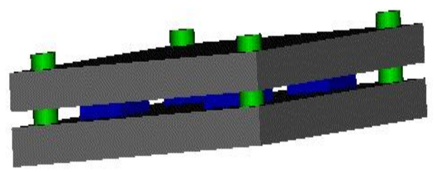
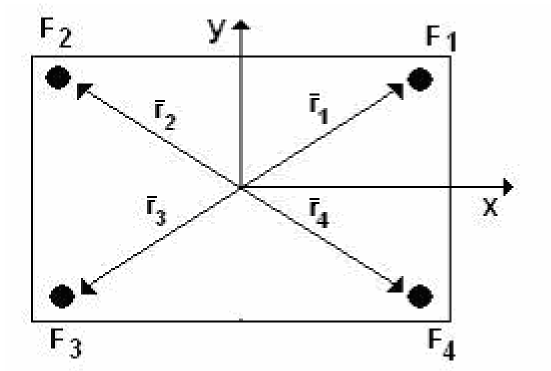


Fig. 10 – ZMP trajectory.



a)



b)

Fig. 11 – Localization of the force sensors a) in the physical model and b) in the top view diagram of the foot.

$$ZMP_R = \frac{\sum_{i=1}^{4} F_i \cdot \bar{r}_i}{\sum_{i=1}^{4} F_i} \qquad (6)$$

where:

F_i – force measured in sensor i

$\bar{r}_i$ – position vector

The proposed control model is presented in figure 12. From the trajectory planning, the internal coordinates of the robot are calculated. These are corrected in real time with the neuro-fuzzy controller, which has also into account the ZMP_R, determined with the sensors placed under the feet of the robot.

It is intended with this control to assure the stability of the robot, even in the event of external disturbances.

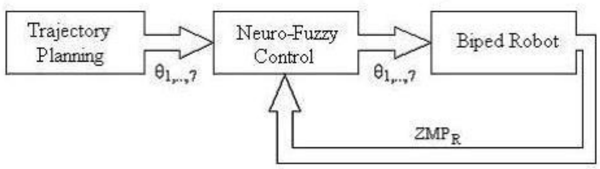


Fig. 12 – Neuro-fuzzy control of the biped robot.

8 Neuro-Fuzzy Control

Neuro-fuzzy control allows excellent performances in controlling complex systems. The control of the biped robot is achieved with the use of simulation data, with the manipulation of the real system and with intuitive biped balancing expert knowledge. The proposed neuro-fuzzy net, illustrated in figure 13, is of the type Takagi-Sugeno-Kang, 1st order TSK, with two antecedents, one consequent and seven membership functions.

The antecedents have seven linguistic terms: negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive big (PB), positive medium (PM) and positive small (PS). Table II presents the fuzzy rule table used in the generation of the training numerical data. The training data are the X_{ZMP} and its variation, DX_{ZMP}. The net output, θ_{long}, is the hip's angular correction.

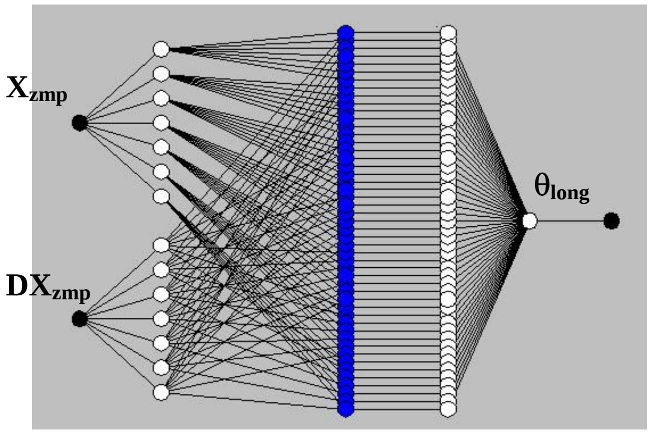


Fig. 13 – The proposed neuro-fuzzy net.

Table II – Rules of the fuzzy system.

X_{ZMP} \ DX_{ZMP}	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PM	PM	PM	PS
NM	PM	PM	PM	PM	PM	PS	PS
NS	PS	PS	PS	PS	PS	ZE	ZE
ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PS	ZE	ZE	NS	NS	NS	NS	NS
PM	NS	NS	NM	NM	NM	NM	NM
PB	NS	NM	NM	NM	NB	NB	NB

The data used in the neuro-fuzzy net training were obtained through the simulation module. These data are normalized, using scale factors K_1, K_2 and K_3, as it can be seen in figure 14, in order to allow a more efficient optimization method.

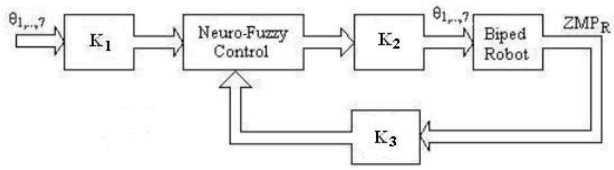


Fig. 14 – Normalization of the antecedents.

In order to define the type of the membership functions to use, triangular, gaussian and sigmoidal functions were simulated in this net, using the ANFIS of Matlab. The quadratic error and the behaviour of the net in the permissible range of values were compared. These results are presented in table III and in figures 15 through 17.

Table III – Quadratic error of the neuro-fuzzy system.

Type of membership function	Error
Triangular	0.2438
Gaussian	0.2287
Sigmoid	0.1952

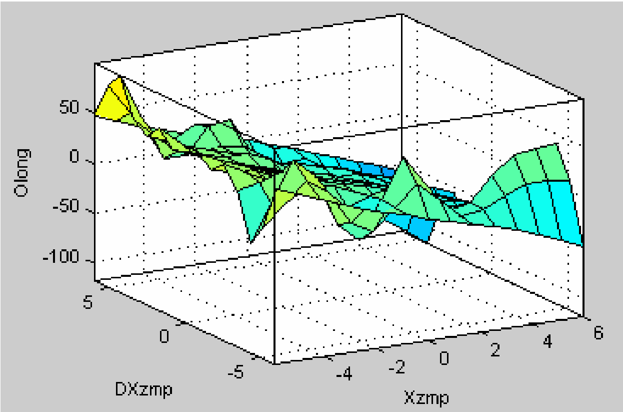


Fig. 15 – Variation of the longitudinal angle obtained with the neuro-fuzzy net using triangular membership functions.

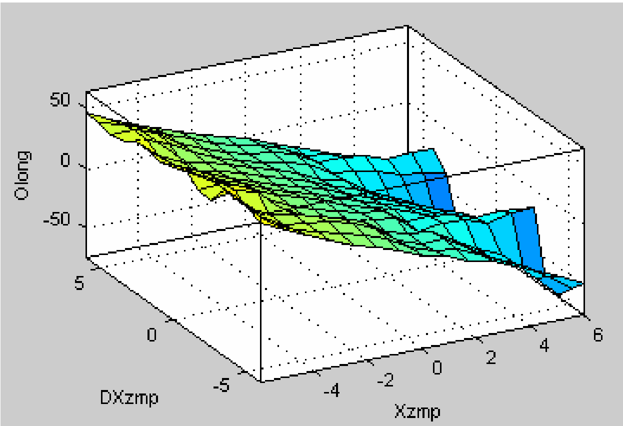


Fig. 16 – Variation of the longitudinal angle obtained with the neuro-fuzzy net using Gaussian membership functions.

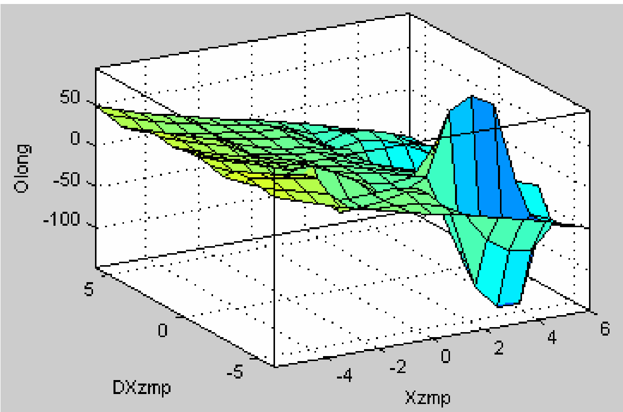


Fig. 17 – Variation of the longitudinal angle obtained with the neuro-fuzzy net using sigmoid membership functions.

After the simulation and analysis of the obtained figures, we arrived to the conclusion that the membership function that is more adequate for this system is the Gaussian. Although it does not present the least quadratic error, its behaviour is more smooth. The membership functions of the antecedents, after the optimization, are those that figure 18 and figure 19 present.

Being the execution time of the neuro-fuzzy net less than 10 ms, the real time control of the biped robot is possible.

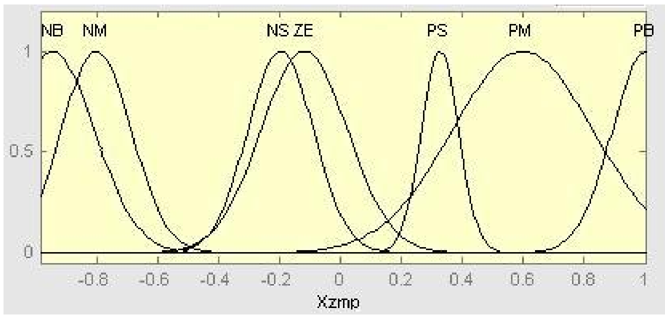


Fig. 18 – Membership functions of the variable Xzmp.

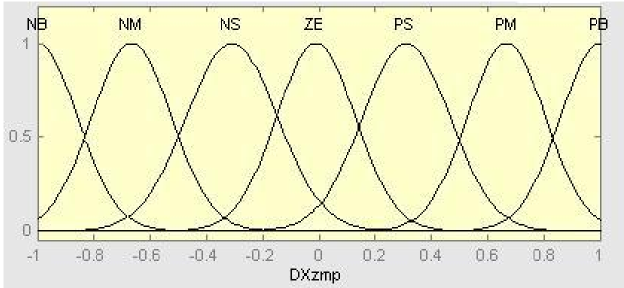


Fig. 19 – Membership functions of the variable DXzmp.

9 Conclusions

The real time control of the biped robot using the dynamic model of the ZMP is not possible, due to the processing time of the corresponding equations. The use of the neuro-fuzzy net allows the real time control of the robot. This net is based on the real ZMP control, acquired through the force sensors placed on the feet. The net was tested and satisfactory results have been obtained. In the annex the resultant gait is visualized by a series of snap shots.

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A. Annex