Supervisory Fuzzy walking for a Humanoid Robot

P.E. Mendez-Monroy, I. Sanchez Dominguez

IIMAS - Universidad Nacional Autonoma de Mexico
Parque Cientifico y Tecnologico de Yucatan. Km. 5.5 Carretera Sierra Papacal - Chuburna C.P. 97302 Sierra Papacal, Yucatan
erick.mendez@iimas.unam.mx
israel.dominguez@iimas.unam.mx

Abstract: A Humanoid robot must be able to perform their tasks in an unknown environment, this requires a dynamic locomotion with high performance. The main problem of locomotion is to keep the balance and modify their trajectories using environment information. The zero moment point (ZMP) is a concept related with dynamics and control widely used to get the stability of legged locomotion but it can not reject disturbances without other methods. In this work, a new method is presented to compensate the ZMP trajectory to improve the stability of biped walking, which is subjected to disturbances using a supervisory fuzzy control (SFC). We applied a walking pattern to generate the footsteps, the ZMP position and the center of mass (COM). The ZMP trajectory is compensated based on the trunk's position and acceleration using an inertial measurement unit. The effectiveness of our method was confirmed by experiment on an actual humanoid robot, Darwin-op.

Keywords: fuzzy control, humanoid locomotion, zero moment point, preview control.

1. INTRODUCTION

A humanoid robot aims to move in an environment through legged locomotion, such movements must have the ability to change its speed and direction to perform a task in a dynamic environment where the humanoid robot is usually subjected to external disturbances during walking. It is very important for a humanoid robot to overcome disturbances during walking.

Several methods were proposed to ensure stable walking with disturbances based on ZMP(Zero Moment Point) concept (Kajita et al., 2003). Kamogawa et al. (Kamogawa et al., 2013) proposed a stability control method using ZMP compensation control and inverted pendulum control. A ZMP compensation method was proposed to improve the stability of locomotion while a robot suffered from disturbance (Prahlad et al. , 2008). These methods estimate the desired ZMP rather than acceleration measurement. This may lead to appreciable ZMP error to decrease the stability.

In other hand, foot placements control was proposed to maintain stable walking in front of large disturbances. Pratt et al. (Pratt et al. , 2012) and Fu (Fu , 2014) modified the step location using the capture region. Urata et al. (Urata et al., 2011) computed online the foot placement by using singular LQ preview regulation of an inverted pendulum model. These algorithms needed large amount of calculation.

In this paper, we introduce a new method to reject disturbances in the humanoid locomotion. The external disturbances are detected joint trajectories From desired speed path, the path of the foot to move is planned, generating the paths ZMP and COM, and applying inverse kinematics to establish the position of each joint of the robot. The foot path is generated from the desired direction and position. the ZMP reference trajectory is calculated by establishing the center of the support into an area at each step. The COM reference trajectory is obtained using a fuzzy controller of the ZMP reference trajectory, which adapts the ZMP trajectory according to the inclination of the trunk, and modifies the position of the foot to keep the robot stable during walked to external disturbances. The angles of the joints of the swing leg are calculated based on the position of the foot in motion, while the position of the trunk and support leg with COM reference are calculated based on inverse kinematics.

The remaining paper is organised as follows. The next section sets a view of the walking strategy, it shows the footprint algorithm, which plans the next position of the feet. Also, ZMP and COM path generator are presented. Section 3 explains the fuzzy controller applied to ZMP walking to generate the joint trajectories. Section 4 presents experimental results of the method implemented in a humanoid robot. General conclusions and future work are discussed in the last section.

2. ZMP AND COM TRAJECTORY

This section presents the design of footstep planner, COM and ZMP generators, which give the robot a walking path. Developing a walking consists of several complex components. Figure 1 shows the strategy and its components and how they interact with each other to maintain a stable walking.

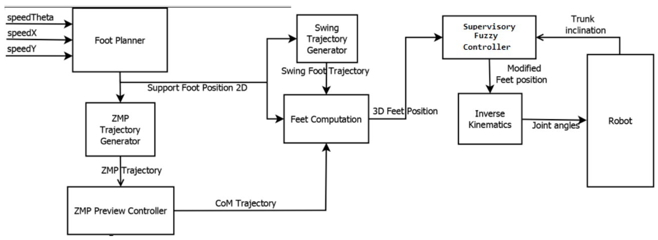

Fig. 1. Walking strategy

2.1 Foot planner

The footstep planner generates the future positions of the supporting foot. During the walking process, we need to plan steps based on current state of feet, desired walk vector and the preview controller. At the initial state, the robot is in double support and CoM is located at the center of the line that connects the feet centers. After changing the CoM to the area of the support foot, the robot lifts its swing foot and moves it to next footprint. The CoM moves from its initial location to a new position. The next position and orientation of right (swing) foot based on velocity vector (V_x, V_y, θ) in XY plane.

We first calculate the next position of CoM by multiplying the time duration of one step by the input velocity. This gives the linear position and orientation change that can be used to determine the next position and orientation of CoM $(V_x, V_y, \theta$. Then, we calculate a reference point, which is used to compute the next swing foot position. The reference point has a d distance (the half distance of two legs in the robot), at 90 degrees, from the support foot. From the previous reference point and the CoM position, the next reference point can be determined, from which the next support position can be derived. In order to rotate CoM θ degrees, we rotate the target footstep θ degrees relative to the CoM frame.

2.2 COM Generator

Biped walking can be modeled through the movement of ZMP and CoM. Biped walking trajectories can be derived from the desired ZMP by computing the feasible CoM. The possible body swing can be approximated using the dynamic model of a Cart on a table.

The cart-table model has some assumptions and simplifications in its model (Kajita et al., 2003). First, it assumes that all masses are concentrated on the cart. Second, it assumes that the support leg does not have any mass and represents it as a mass-less table. Although these assumptions seem to be far from reality, modern walking robots usually have heavy trunks with electronics circuits and batteries inside. Therefore, the effect of leg mass is relatively small. Figure 2 shows a schematic in how robot dynamics is modeled by a cart-table.

Two cart-table models are used to model 3D walking. for sagittal and coronal axis respectively. The Equation 1 provides the moment or torque around p

$$\tau_p = Mg(x - P_x) - M\ddot{x}z_c \tag{1}$$

If the robot is dynamically balanced, ZMP and center of pressure (CoP) (the point where the resultant of all

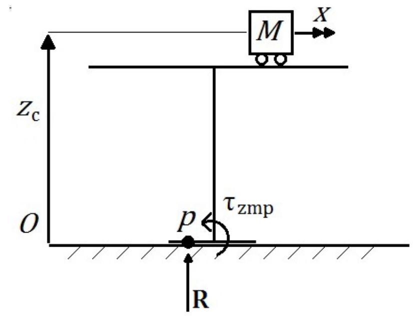

Fig. 2. Cart-table schematic

ground reaction forces act) are identical, therefore the amount of moment in the CoP point must be zero, $\tau_p = 0$. By assuming the left-hand side of Eq 1 to be zero, equation 2 provides the position of the ZMP. In order to generate proper walking, the CoM must also move in the coronal plane, hence another cart-table must be used in y direction. Using the same assumption and reasoning equation 3 can be obtained. Here, y denotes the coronal movement

$$P_x = x_{zmp} = x_{com} - \frac{z_c}{g}\ddot{x}_{com} \tag{2}$$

$$P_y = y_{zmp} = y_{com} - \frac{z_c}{g}\ddot{y}_{com} \tag{3}$$

The aforementioned equations present the relationship between the ZMP and the sagittal and coronal COM motions of the cart-table model. The solutions of (2) and (3) are obtained by applying the inverse Laplace transform as follows.

1) Sagittal COM motion:

$$\begin{bmatrix} x_f \\ v_f T_c \end{bmatrix} = \begin{bmatrix} C_T & S_T \\ S_T & C_T \end{bmatrix} \begin{bmatrix} x_i \\ v_i T_c \end{bmatrix} - \frac{1}{T_c} \begin{bmatrix} \int_0^T S_T \overline{p}_x dt \\ \int_0^T C_T \overline{p}_x dt \end{bmatrix} \tag{4}$$

1) coronal COM motion:

$$\begin{bmatrix} y_f \\ w_f T_c \end{bmatrix} = \begin{bmatrix} C_T & S_T \\ S_T & C_T \end{bmatrix} \begin{bmatrix} y_i \\ w_i T_c \end{bmatrix} - \frac{1}{T_c} \begin{bmatrix} \int_0^T S_T \overline{p}_y dt \\ \int_0^T C_T \overline{p}_y dt \end{bmatrix} \tag{5}$$

where $(x_i, v_i)/(x_f, v_f)$ and $(y_i, w_i)/(y_f, w_f)$ denote the initial/final COM position and velocity in sagittal and coronal plans, respectively. S_T and C_T are defined as $sinh(T/T_c)$ and $cosh(T/T_c)$, respectively, where $T_c = \sqrt{Z_c/g}$. T is the remaining single-support time and $\overline{p}_x = p_x(T - t)$ and $\overline{p}_y = p_y(T - t)$.

The first and second terms on the right-hand side of (4) and (5) are the homogeneous and particular solutions of (2) and (3), respectively. The particular solutions make the sagittal and coronal COM motions more extensive by varying the ZMP trajectory with p_x and p_y.

In the conventional 3-D LIPM (Kajita et al., 2006), the particular solutions were not considered because of the assumption that the ZMP is fixed at the contact point. Consequently, in the single-support phase, the robot is unable to independently modify the elements of the walking pattern, i.e., the single- and double-support times, the sagittal and coronal step lengths, and the direction of the swing leg.

However, in this method the COM position and velocity can be changed independently at any time during the single-support phase by the ZMP functions p_x and p_y, the method enables the biped robot to change the elements of the walking pattern independently without any extra footstep for adjusting the COM motion.

As an input of the method, a vector state c is defined as follows.

$$c \equiv \left[T^{ss}, T^{ds}, S, \theta\right]$$

where

T^{ss} single support time
T^{ds} double support time
S step length
θ direction angle for swing leg

The states of the cart-table model, defined as the COM position and velocity is obtained for c.

The next step is to calculate the trajectory using COM (Eq. 2) and (eq.3). Finally, inverse kinematics must be used to obtain the angular trajectories of each joint based on the desired position of the foot and the COM calculation. The main objective of implementing the cart-table model is to solve the differential equations. Kajita et.al. [(Kajita et al., 2003)] present a method to calculate the position of the COM from the cart-table model. The method is based on the preview control of the reference ZMP.

2.3 Reference Generator

The most important trajectories for the walking development are the foot reference trajectory **C** and the ZMP reference trajectory **p** those are very similar. The foot trajectory defines the ankle and footprint locations where steps the swing foot, also from this the support polygon is defined. ZMP reference determines the desired position of the ZMP, but not the support polygon because the reference ZMP must be within the support polygon.

Establishing a sequence of m steps $\Phi = [\mathbf{S}_0, \mathbf{S}_1, ..., \mathbf{S}_m]$ starting from a standing up position. the vector $\mathbf{S}_0$ is defined to shift body mass toward the first stance foot in the double support phase with an initialization period, and depending on whether it is the left or right foot is the development algorithm. A variable compensation δ is defined to change the ZMP reference to the outside or inside of the foot depending depended on of stance foot, the following update equations can be used to define the reference values after the initialization period:

$$\begin{aligned} \mathbf{C}_i &= -\left(\mathbf{C}_{i-1} + \mathbf{S}_{i-1}\right) \; i > 0 \\ \mathbf{p}_i &= \mathbf{p}_{i-1} - \mathbf{C}_i - \epsilon\delta\,\hat{\mathbf{j}} \; i > 0 \end{aligned} \quad (6)$$

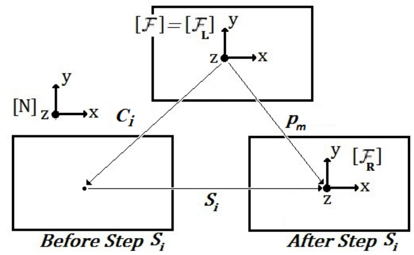

Fig. 3. F and N Frames of humanoid feet

where $\epsilon = -1$ if the stance foot is right and $\epsilon = 1$ if the stance foot is left. This allows an easy switch between left and right step method. It is also implemented with $\mathbf{C_0}$ to start in the middle of both feet.

From a position with both feet parallel to the ground,the position of the ZMP is $\mathbf{p}_0 = [0 \;\; -0.5w \;\; 0]^T$ and foot position $\mathbf{C}_0 = \mathbf{C}_1 = [0 \;\; w \;\; 0]^T$, where w is the amplitude y of the stance foot. These values are used to update the trajectories.

With only a set of steps and a predefined initialization period, foot and ZMP reference values can be calculated from equations (6). Using these trajectories the inverse kinematics is used to obtain for joint and obtained the angles for both legs.

For walking, the stance foot strategy is to use the COM trajectory and other constraints to determine the angles of ankle joints, the knee to determine the height of the body, and the two hip joint angles to orient the body, but the swing leg needs to establish its trajectory to define its angles. This trajectory P_m tracks the location of the swing foot on the local frame F . F frame is aligned with the N frame, but it is located at the ankle joints of the stance foot as shown in Figure 3.

This cycle is repeated each stride, such that the trajectories change according to swing foot. Each trajectory P_m is defined with respect to the F frame, this requires two vectors. The stride vector S_i with components (x, y), those are the length and amplitude stride respectively. The reference vector C_i locate the swing foot before the single support phase. So the vector stride is defined:

$$s_i = \{C_i, C_i + S_i\} \quad (7)$$

Defining a function for s_i at different times, this movement is a translational displacement and the swing leg trajectory has two objectives:

- the stance feet remain on the ground during the double support phase before swinging.
- Set a trajectory for the swing foot with a length s_x and amplitude S_y within a time T_{ss}

So, the trajectory P_m is defined by the direction vector of foot that starts at C_i and ends at $C_i + S_i$. With those two objectives, the swing foot trajectory is divided into the double support and single support phase.

The single support phase is divided into three parts: initial, medial and terminal. As the initial and terminal a percentage of stride time αT_{ss} and the rest of the time is for the middle. A major parameter to define this path is that the foot must reach a certain height above the surface Z_g to prevent foot drag.

In the double support phase, it is imposed that the foot remains in contact on the ground $P_m = C_i$, and is defined as the initial point for the single support phase.

3. FUZZY ZMP PREVIEW CONTROLLER

In each step, the robot's trunk must be fitted in the desired posture. The real angle of the robot's posture is measured by the accelerometer. If the robot is affected by any irregular external force or the robot's trunk is not the expected posture, the accelerometer will detect the incline angle and send a control signal. The robot will then adjust the hip or ankle motors immediately to avoid the robot falling down. We design a preview fuzzy controller, to realize the mechanism of auto-balance. The input data of the controller comes from the output of the two-axis accelerometer. The gains of the controller are adjustable and determined by the inclined condition and sensor feedback signals.

In this section, fuzzy ZMP preview controller is presented as a modification of controller by Kajita (Kajita et al., 2006). The jerk of the COM was chosen as the input because the acceleration terms must appear as the state to define the position ZMP p_x

$$\frac{d}{dt}\begin{pmatrix} x \\ \dot{x} \\ \ddot{x} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} x \\ \dot{x} \\ \ddot{x} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} u$$
$$P = \begin{pmatrix} 1 & 0 & -\frac{z_h}{g} \end{pmatrix}\begin{pmatrix} x \\ \dot{x} \\ \ddot{x} \end{pmatrix} \quad (8)$$

Using this model, a digital controller is designed with a sampling period T

$$X(k+1) = AX(k) + Bu(k)$$
$$P(k) = CX(k) \quad (9)$$

where

$$A = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix}$$
$$B = \begin{bmatrix} T^3/6 \\ T^2/2 \\ T \end{bmatrix} \quad (10)$$
$$C = [\, 1 \;\; 0 \;\; -z_h/g \,]$$

Assume that the actual ZMP needs to track the reference ZMP, P_x^{ref}. With N preview time steps into the future, the discrete control law proposed is

$$u(k) = -Fe(k) - GX(k) - \sum_{l=1}^{N} H_l P_x^{ref}(k+l) - u_s \quad (11)$$

where $e(k) = P_x(k) - P_x^{ref}(k)$. With this control law the ZMP can sufficiently track the reference with the preview gain H_l and is robust to disturbance with the fuzzy feedback term u_s, G the feedback and F_i is the integral term.

The gain H_l could be calculated by using the linear quadratic regulator for discrete time systems (Figure 5).

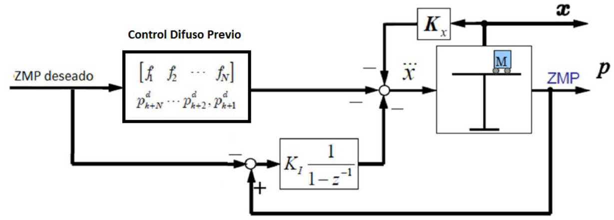

Fig. 4. ZMP supervisory fuzzy control

The preview gain becomes negligible towards the end of the preview period.

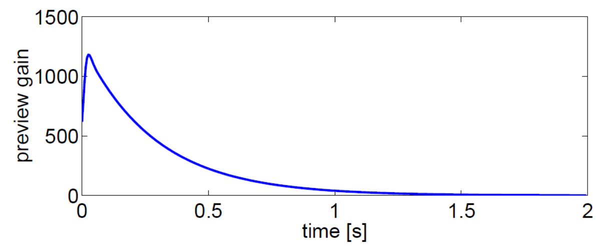

Fig. 5. Preview gain

The ZMP can be controlled to follow the reference trajectory (eq.6). In an ideal condition without disturbances, the ZMP response does not have a considerable error (Figure 6).

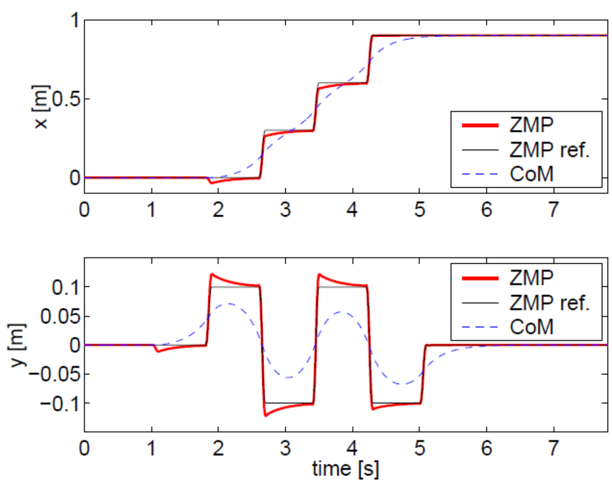

Fig. 6. ZMP and COM without disturbances (simulation).

But in the case of disturbance, the preview controller can not be controlled so a supervisory control is necessary. In this case, a supervisory fuzzy controller is used. The 2 axis accelerometer signals are the fuzzy inputs and the COM compensation is the fuzzy output.

So, we define some fuzzy rules like:

If a_x is μ_{1j} and a_y is μ_{2j} then $u_s = G_j X$

The overall controller is:

$$u_s = \sum_{j=1}^{r} G_j X \quad (12)$$

where

$$G_j = \frac{\phi_j}{\sum_{i=1}^{r} \phi_i}$$

$$\phi_j = \prod_{i=1}^{2} \mu_{ij}$$

$$\mu_{ij} = exp\left(-\frac{(a_i - c_{ij})^2}{\sigma_{ij}^2}\right)$$

For r fuzzy rules and gaussian membership functions μ.

4. RESULTS

A DARwIn-OP humanoid robot developed by the RoMeLa lab was used to implement the supervisory fuzzy control experimentally. It is 45 cm tall, weighs 2.8kg, and has 20 degrees of freedom. It has a web camera for visual feedback, and 3-axis accelerometer and 3-axis gyroscope for inertial sensing. Position-controlled Dynamixel servos are used for actuators, which are controlled by a CM730 microcontroller connected by an Intel Atom-based embedded PC at a control frequency of 100hz. (Figure 7).

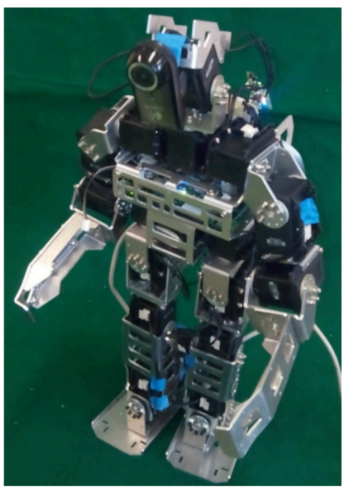

Fig. 7. humanoid robot from PCC-UNAM robotic lab

Define three fuzzy memberships for a_x and a_y a fuzzy surface is obtained with nine rules (Figure 8). the gains for the fuzzy output are obtained using LQR i.e. $F = 257.7$ and $G = [1085.4,\ 1648.3,\ 1648.3]^T$ (Figure 5).

In Figure (9) is shown the ZMP and COM trajectories for the robot in normal conditions using a preview controller (11) with $u_s = 0$ and in Figure (10) is used the supervisory fuzzy control. Here the main difference is that the desired ZMP for x axis with the preview controller does not update to correct the jerk and it has a visible tracking error.

The advantage of this method is shown in the Figures 11 and 12. Here the walking robot is disturbed for a coronal force at 1.5 s. The preview controller can not vanish the high jerk and has an error in p_x tracking. Using the supervisory fuzzy controller the jerk is minimized and has a better tracking performance.

5. CONCLUSION

Here a supervisory fuzzy controller is presented, to compensate disturbances in the walking action. It uses the

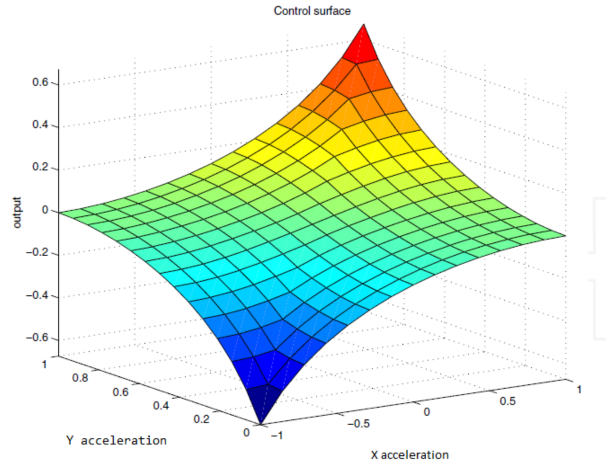

Fig. 8. fuzzy surface with x, y acceleration inputs

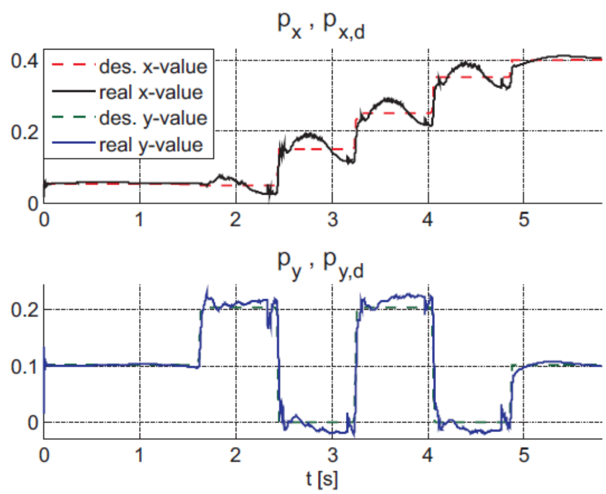

Fig. 9. preview ZMP controller in normal operation

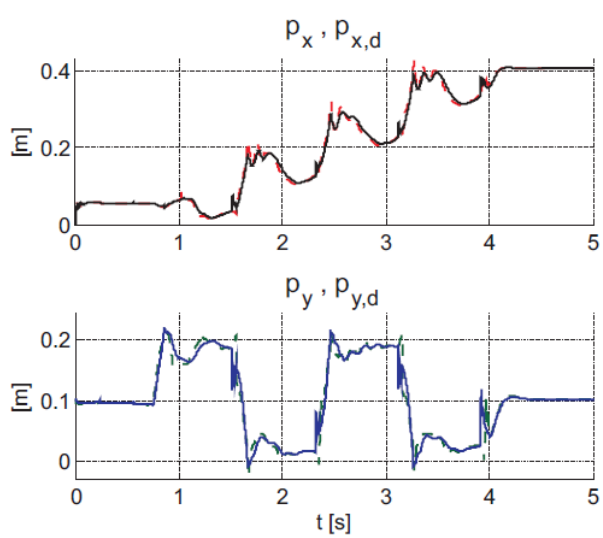

Fig. 10. fuzzy ZMP controller in normal operation

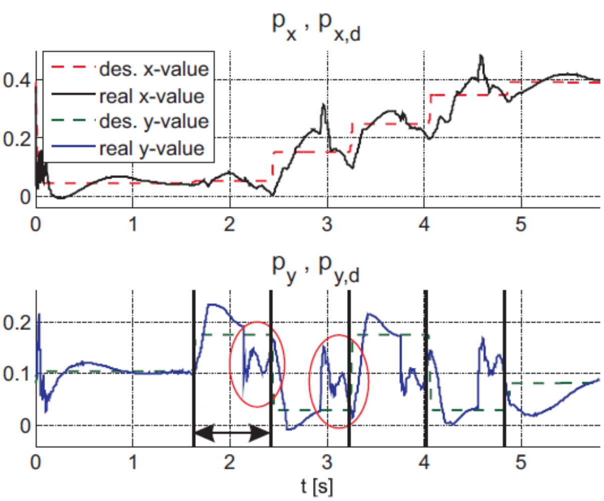

Fig. 11. preview ZMP controller with disturbance in 1.5 s

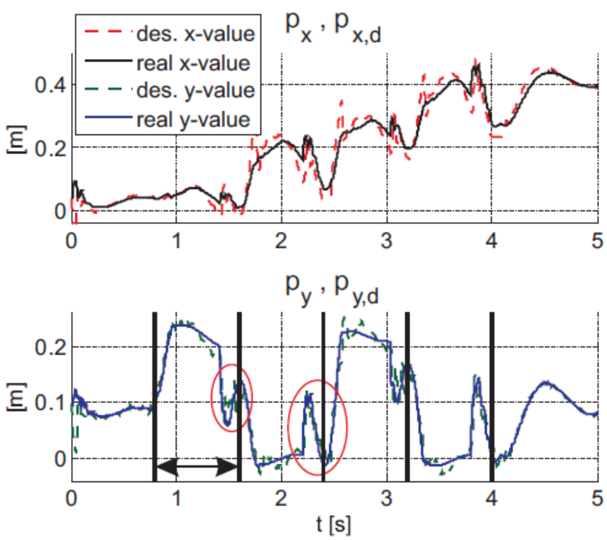

Fig. 12. fuzzy ZMP controller with distubance in 1.5 s

acceleration sensor to know about the robot stability. The acceleration is used to correct the hip and ankle angles. Using this method the jerk is minimized and the robot is robust to downfall. The method is compared with a preview controller implemented in a humanoid robot with a better performance.

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