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ZMP trajectory reference for the sagittal plane control of a biped robot based on a human CoP and gait

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Abstract − **This paper introduces two new important issues to be considered in the design of the zero moment point (ZMP) trajectory reference for the sagittal plane balance control of an autonomous walking biped robot with an human-like gait.**

ZMP trajectory reference generation is very important in the design and balance control of the walking of a biped robot.

ZMP reference generation algorithms based on the Linear Inverted Pendulum Model (LIPM) and moving ZMP references in the swing phase have already been proposed with the ZMP trajectory during the swing phase being designed moving along a symmetric trajectory relative to the center of the foot. It was verified experimentally that in the human gait the ZMP trajectory moves along the foot in a way that it is shifted forward relative to its center. To take this into account a shift parameter is then proposed to move forward the X_{ZMP} trajectory reference during the swing phase. It was also verified experimentally that in the human gait the ZMP trajectory amplitude depends on the swing time. Its variation law has been determined experimentally and it was verified that this range decreases as the swing time increases, reducing to zero for a static gait. It is then proposed a parameter H to take into account this variation with the swing time of the gait.

Six experiments were carried out for three different X_{ZMP} trajectory references. In order to evaluate and compare the performance of the biped robot using the three X_{ZMP} trajectory references two performance indexes are proposed.

Index terms − **biped robot, balance, ZMP trajectory reference, static gait, dynamic gait, human-like biped gait.**

I. INTRODUCTION

Biped robots have link structures similar to the human's anatomy. To be able to maintain its stability under dynamic situations such robotic systems require good mechanical designs and force sensors to acquire the zero moment point (ZMP). Many such robots have been developed like ASIMO by Honda [1], WABIAN 2R by Waseda University [2], HUBO KHR-3 by KAIST [3] and QRIO by Sony [4].

Vukobratović has developed a mathematical model of a biped robot and its method of control [5]. A number of researchers [6-9] have investigated the gait of biped robots based on human kinematics data, and a very good study of the kinematics of a human body was done by Winter [10].

Because a biped robot is easily knocked down its stability must be taken into account in its gait design. Zheng *et. al* [11] proposed a method of gait synthesis taking into account the static stability. To assure the dynamic stability of a biped robot, Hirai *et. al* [12] proposed a standard method for gait synthesis based on the ZMP. Basically this method consists of designing a desired ZMP trajectory, duly correcting the movement of the torso and pendulum to maintain the ZMP trajectory as designed.

For humanoid robotics, static walking is when the projection of the center of mass (CoM) on the floor is always within the support polygon, during the walking motion. The supporting polygon corresponds to the support foot in the single support phase, if a flat contact with the ground is verified. In the double support phase the support polygon is the convex polygon inscribing the two feet. In static walking the robot is always in a static equilibrium, so it can stop its motion at any moment and does not fall down. Note that fast motions are not possible, since the dynamic couplings of the body parts could affect the static equilibrium. In stable dynamic walking the projection of the CoM on the floor is outside of the supporting polygon during some phases of the gait. The ZMP, however, is always inside the support polygon. The equilibrium of the robot depends on the dynamics, and in general, the motions performed are faster and smoother than with static walking. Vukobratović *et. al* states that theoretical work on the difference between static and dynamic biped motion is still to be done [13].

To apply the necessary torque for the robot balance, some authors compute the ZMP using an inverted pendulum centered in the ankle [23-25] or centered in the hip [26]. To control biped robots some researchers have developed controllers with artificial intelligent systems, such as neuro-fuzzy nets, support vector regression (SVR), and fuzzy systems [14-21], [27]. These techniques have been surveyed by Katić *et. al* [22].

ZMP trajectory reference generation is crucial to control the balance of a biped robot walking. An indicator for a good ZMP reference generation is the need of minimal control action during a stable walking.

Improved versions of the linear inverted pendulum model (LIPM) based reference generation, obtained by applying the ZMP criterion in the design process, have been reported [28]. In this approach, during a stepping motion the ZMP is kept fixed in the middle of the supporting foot sole, while the robot's CoM is following the linear inverted pendulum path. Although reference generation with the LIPM and fixed ZMP reference positions is the technique employed for the most successful biped robots today, this kind of reference generation lacks naturalness.

A good option would be to have a human-like ZMP trajectory reference, suitable to be followed by the robot. Investigations revealed that the ZMP in the human walk does not stay fixed under the supporting foot. Rather, it moves forward from the heel to the toe direction [29-31] and back again. Zhu *et. al* [31] proposed the idea of having a moving ZMP reference to generate a dynamically stable gait. The ZMP reference moves from the heel to the toe of the foot following first order functions, in the single support phase. They have used LIPM. Kurt takes a similar approach and proposes a reference generation technique based on the LIPM and moving support foot ZMP reference [34]. He used Fourier series approximations to the solutions of the linear inverted pendulum dynamic equations simplifying the solution as in [32]. He also generates a smooth ZMP trajectory reference for the double support phase.

These proposed ZMP trajectory references are symmetric relative to the center of the foot. However, analyzing the human gait using devises as in [33], the ZMP trajectory moves along the foot in a way that it is shifted forward relative to its center. To take into account this asymmetry it is proposed a change in the start and in the end of X_{ZMP} trajectory reference, using a shift parameter α.

It was also verified that in a human gait the ZMP trajectory range varies with the swing time, decreasing as the swing time increases, and reducing to zero for a static gait. Its variation law has been determined experimentally and to take it into account a reduction parameter H is proposed in the X_{ZMP} trajectory reference equation.

To determine the performance of the robot's balance control system based on an SVR using three different X_{ZMP} trajectory references, some experiments were performed and two performance indexes are proposed.

II. USED BIPED ROBOT

Our experiments were performed with a biped robot that was designed and built at our Institute. The robot, shown in Fig. 1, has the main joints of hip, knee, and ankle, for each leg (Fig. 2). There is another joint, an active inverted pendulum that is used for the lateral balance of the structure. The robot carries, at this inverted pendulum, its own motorization batteries. The robot is actuated by seven servo motors and the structure is made of acrylic and aluminum. It weighs 2.3 kg and is 0.5 m tall [14].

The robot was designed to move both in horizontal and inclined planes, to go up and down small stairs, and has a speed of approximately 0.05 m/s. A wireless transmission link binds the control software that runs on a PC to the robot. The board in the robot includes two microcontrollers, one to acquire the digital value of the force sensors and the other to command the servo motors. This board is connected to PC via wireless RS232 communication link. This PC runs the control software The robot has implanted a set of four force sensors under each foot, which are used to calculate the real ZMP, enabling the use of a closed loop SVR controller.

To obtain a good stable step it is very important to design the trajectories of the legs very well.

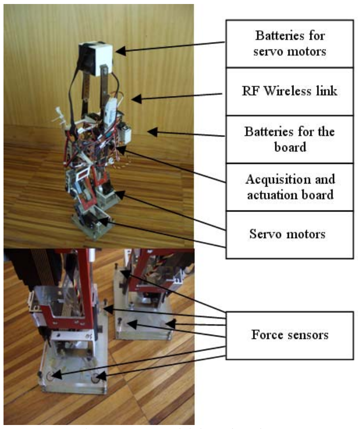

Fig. 1. Used biped robot.

Humans are among the best biped walkers, which is a good reason for obtaining their joint trajectories when they walk, and then apply this information to a biped robot, even though its physical characteristics differ from those of a human being. Human trajectories were obtained [9], [33] and scaled to our biped. The used biped gait is then similar to a human locomotion in horizontal planes.

The method used to obtain the equilibrium of the robot in the sagittal plane consists of correcting the hip (torso) angle based on the difference of the X_{ZMP} actual position and the designed one. The balance in the lateral plane is done by alternately positioning the pendulum ($\theta_{lateral}$) in its two extreme positions. This way Y_{zmp} is neglected. The ground projection of the X component of the centre of mass (CoM) can be calculated in real time as

$$X_{CoM} = \frac{\sum_{i=0}^{7} m_i \cdot g \cdot x_i}{\sum_{i=0}^{7} m_i \cdot g} \quad (1)$$

where x_i is the X coordinate position of the link, m_i is the mass of the link i and g is the gravity acceleration.

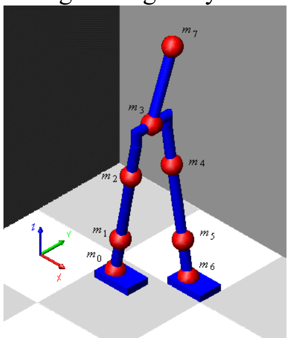

Fig. 2. Biped model.

III. ZMP TRAJECTORY REFERENCE GENERATION

Some researchers initially used fixed ZMP trajectory references, but this trajectory references provides an unnatural biped movement, comparing to the human's walking. To provide a natural movement different ZMP trajectory references can be chosen.

a. Human-like ZMP Trajectories by Kurt

The use of a natural (human-like) ZMP trajectory reference for gait generation will result in a more natural and energy-efficient CoM trajectory [31].

To produce a natural ZMP trajectory reference Kurt uses the next equations to calculate X_{CoM_old} and X_{ZMP_old}

$$X_{CoM\_old}(t)=\frac{B}{T_0}\left(t-\frac{T_0}{2}\right)+\sum_{n=1}^{\infty}\left[(B-2b)\frac{T_0^2\omega_n^2(1+\cos(n\pi))}{n\pi(T_0^2\omega_n^2+n^2\pi^2)}\operatorname{sinc}\left(\frac{n\pi}{DSP}\right)\sin\left(\frac{n\pi}{T_0}t\right)\right] \quad (2)$$

$$X_{ZMP\_old}(t)=\frac{B}{T_0}\left(t-\frac{T_0}{2}\right)+\sum_{n=1}^{\infty}\left[(B-2b)\frac{(1+\cos(n\pi))}{n\pi}\operatorname{sinc}\left(\frac{n\pi}{DSP}\right)\sin\left(\frac{n\pi}{T_0}t\right)\right] \quad (3)$$

where B is the step length, b is the half foot length, T_0 is the step time, w_n is the natural angular frequency and DSP is the double support parameter [34]. The suffix "old" is used to distinguish from a "new" definition, proposed next.

b. Proposed Human-like ZMP Trajectories

The gait designed for our biped robot is based on a human gait. Its CoM (X_{CoM_sim}) trajectory was obtained by simulation. This trajectory was then compared with Kurt's trajectory (X_{CoM_old}, (2)) and it was verified that it is shifted forward relative to Kurt's one. So, it is proposed in this paper to shift forward X_{CoM} (becoming X_{CoM_New}) and X_{ZMP} (X_{ZMP_New}) trajectory references as described by

$$X_{CoM\_New}(t)=X_{CoM\_old}(t)+\alpha\cdot B \quad (4)$$

$$X_{ZMP\_New}(t)=X_{ZMP\_old}(t)+\alpha\cdot B \quad (5)$$

α is the proposed shift parameter.

The above four equations were calculated for B = 7 cm, b = 5.5 cm, ω_n = 6.02 rad/s, T_0 = 1 s, DSP = 20 and α = 0.1, and the results are presented in Fig. 3, together with the X_{CoM} simulated trajectory.

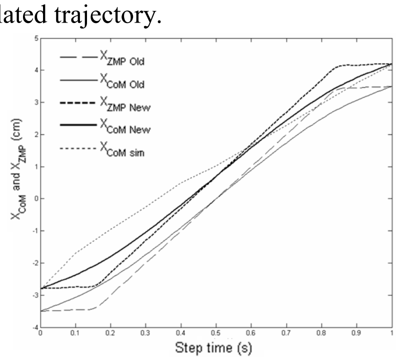

Fig. 3. X_{ZMP} and X_{CoM} trajectory behavior.

With the introduction of the α parameter it is verified in the Fig. 3 that the $X_{CoM\ New}$ is closer to $X_{CoM\ sim}$ than to $X_{CoM\ old}$. The α parameter value was determined using

$$\alpha=\frac{X_{CoM\_sim}(0)-X_{CoM\_old}(0)}{B} \quad (6)$$

Another problem arose: how to know what is the better and more natural X_{ZMP} reference for different swing times. For a pure static gait the X_{ZMP} reference should be zero, and for a pure dynamic gait the X_{ZMP} trajectory reference can be given by (5). What happens in the middle? To solve this problem we analyzed the X_{ZMP} behavior of a human being walking with different swing times and the results are presented in Fig. 4.

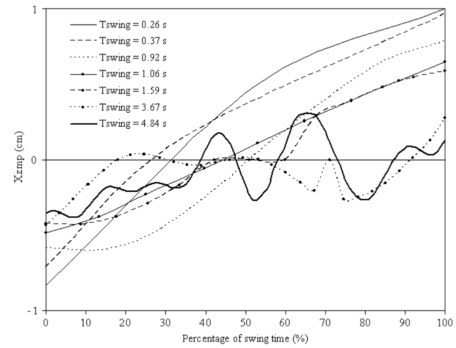

Fig. 4. X_{ZMP} behavior of a human being for several swing times.

Fig. 4 shows X_{ZMP} human trajectories for several swing times (T_S). It can be seen that the range (amplitude) of these X_{ZMP} trajectories decreases with the increase of the swing time. When the gait is considered a static gait (T_S = 3.67 s and T_S = 4.84 s) X_{ZMP} oscillates around zero (the oscillations are due to the human difficulty to perform a very slow step).

Using the information above we propose a parameter $H(T_S)$ to quantify the variation of the normalized X_{ZMP} trajectory range with the swing time. This parameter is plotted in Fig. 5 with the human data from Fig. 4 and data from other 2 persons, and it is verified that the parameter changes approximately linearly with the swing time. The data of this parameter is valid for the person in the experiment; for the biped robot a linear relation will be determined in the next section.

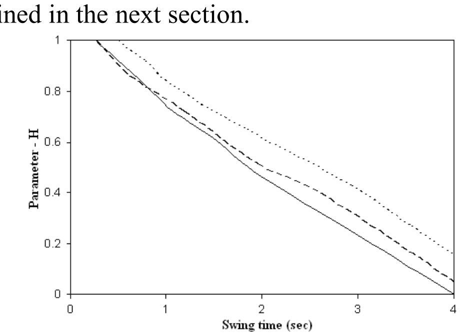

Fig. 5. Parameter $H(T_S)$, describing the variation of human X_{ZMP} trajectory range with the swing time for 3 different persons.

The parameter $H(T_S)$ is used to correct (4) and (5) resulting in

$$X_{CoM\_New\_Final}(t)=B\cdot\alpha\cdot H(T_S)+\frac{B}{T_0}\left(t-\frac{T_0}{2}\right)+\sum_{n=1}^{\infty}\left[(B-2b\cdot H(T_S))\frac{T_0^2\omega_n^2(1+\cos(n\pi))}{n\pi(T_0^2\omega_n^2+n^2\pi^2)}\operatorname{sinc}\left(\frac{n\pi}{DSP}\right)\sin\left(\frac{n\pi}{T_0}t\right)\right] \quad (7)$$

$$X_{ZMP\_New\_Final}(t)=B\cdot\alpha\cdot H(T_S)+\frac{B}{T_0}\left(t-\frac{T_0}{2}\right)+\sum_{n=1}^{\infty}\left[(B-2b\cdot H(T_S))\frac{(1+\cos(n\pi))}{n\pi}\operatorname{sinc}\left(\frac{n\pi}{DSP}\right)\sin\left(\frac{n\pi}{T_0}t\right)\right] \quad (8)$$

The result of the use of parameter H, using the behavior presented in Fig. 5 by the solid line, over (7) and (8) is plotted in Fig. 6 ($X_{ZMP\_New\_Final}$ and $X_{CoM\_New\_Final}$). X_{ZMP_Old}, X_{CoM_Old}, X_{ZMP_New} and X_{CoM_New} are plotted for comparison (they do not vary with the swing time). It should be noticed that X_{ZMP_New} and X_{CoM_New} are equal to $X_{ZMP\_New\_Final}$ and $X_{CoM\_New\_Final}$ for a swing time of 0.26 s, where the parameter $H(T_S)$ is 1 (a pure dynamic step).

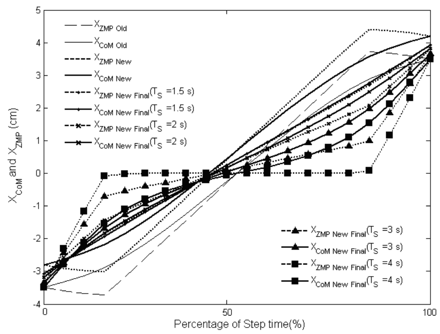

Fig. 6. X_{ZMP} and X_{CoM} trajectory behavior for different swing times (T_S).

IV. Experimental Determination of Proposed Parametres

To validate the above proposed $H(T_S)$ and α parameters some experiments were performed with our robot using a human-based gait. When the X_{ZMP} is within the stable area, the X_{ZMP} is equal to the center of pressure (CoP). To determine the CoP, four force sensors are used under each foot of the robot. The force measurements are noisy because the force sensors are very sensitive to vibrations dues to the motion. This high frequency noise is removed with a second order Butterworth low pass filter.

Two experiments were performed to determine the proposed parameters. In the experiments the biped robot walked, during four steps with swing times of 1.8 s (Fig. 7) and 2.4 s (Fig. 8), using the trajectories of the human gait. The step length was 0.07 m. The values presented in the next two figures were normalized such that the unit values correspond to 55 degrees for $\theta_{Lateral}$ and 0.047 m for X_{zmp}.

These experiments show the same behavior of the proposed change of the X_{ZMP} reference. For a non static gait (T_s = 1.8 s and T_S = 2.4 s) the range of the X_{ZMP} trajectories increases with the velocity of the walk (decreases with the step time) and their absolute minimum (negative) values are smaller than the corresponding maximum (positive) values (i.e. the trajectory is not symmetrically distributed relatively to the center of the foot, being shifted forward). For a given robot (with sensors for ZMP determination) the values of α and H parameters can be determined experimentally, during the swing phase, for n steps, using

$$\alpha_e = \frac{\sum_{i=1}^{n} \left(\max(X_{ZMPi}) + \min(X_{ZMPi})\right)}{2 \cdot \sum_{i=1}^{n} \left(\max(X_{ZMPi}) - \min(X_{ZMPi})\right)} \quad (9)$$

$$H_e = \frac{\sum_{i=1}^{n} \left(\max(X_{ZMPi}) - \min(X_{ZMPi})\right) / n}{2} \quad (10)$$

The X_{ZMPi} in (10) must be normalized in the range -1 to 1.

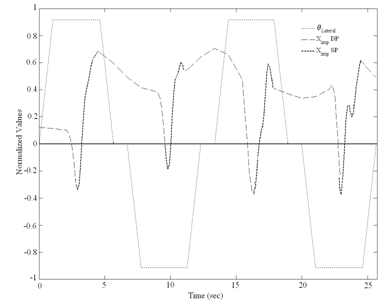

Fig. 7. Lateral angle ($\theta_{lateral}$) and X_{ZMP} in the double (DP) and single (SP) phases, obtained for T_{swing} = 1.8 s.

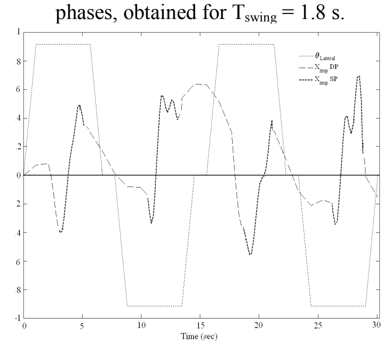

Fig. 8. Lateral angle ($\theta_{lateral}$) and X_{ZMP} in the double (DP) and single (SP) phases, obtained for T_{swing} = 2.4 s.

With the performed experiments, it is obtained the values of the parameters α_e and H_e presented in table 1.

TABLE 1 - α_e AND H_e FOR THE USED BIPED ROBOT WITH THE DESIGN.

T_S (sec)	α_e	H_e
1.8	0.13	0.48
2.4	0.12	0.40

To design the X_{ZMP} reference trajectory, it is considered α_e=0.125 and considering that H_e changes linearly with the swing time, like the human, and based in table 1 the H_e is given by

$$H_e(T_S) = -0.13 \cdot T_S + 0.71 \quad (11)$$

Due communications time and hardware response limitations of our biped robot, T_S must be higher than 1.5 s, and for T_S higher than 5.46 s the value of H_e is zero.

V. Real Time Control Strategy

The real time control strategy that uses an SVR [14] [19] controller is shown in figure 9. From the initial gait design and trajectory planning results in the internal coordinates of the robot. These gaits are corrected in real time with an SVR controller, which has into account the calculated CoP. A Butterworth filter is necessary to remove high frequency noise from the force sensors measurements. The output of the SVR is separated into the ankle and torso angles corrections, 50% for each. The value of the ankle's angle correction is divided by the constant 2.76. The value of 2.76 is calculated based on the two link planar robot [1].

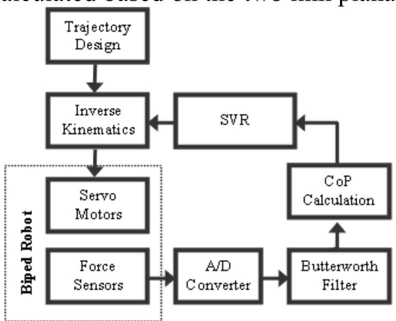

Fig. 9 – SVR control of the biped robot.

With this control strategy, the stability of the robot is assured, even in the event of external disturbances.

VI. Experimental Results

To compare the performance of the three different X_{ZMP} trajectory references some experiments were performed. The values presented in the next figures were normalized such that unit values correspond to 25 degrees for θ_{torso}, 10 degrees for θ_{ankle}, 55 degrees for the pendulum lateral angle ($\theta_{lateral}$) and 0.047 m for X_{ZMP}.

In the next three experiments the robot was walking with a 0.07 m step length (X_l) and 2 s of swing time (T_{swing}), on a horizontal flat surface, using the trajectories of the human gait, with three different X_{ZMP} references: fixed X_{ZMP} (Fig. 10), X_{ZMP} from Kurt (Fig. 11) and X_{ZMP} proposed (Fig. 12). A video that shows the different performances is included, where it is possible to see that the walk with the proposed X_{ZMP} trajectory reference the robot oscillates a little less than with the other references. Similar experiments were also performed for a 0.12 m step length and 2.9 s of swing time.

To conclude which trajectory reference is the best, and because the result plots are inconclusive, two performance indexes are proposed. The first are is the root of the mean squared of the normalised X_{ZMP} - X_{ZMP_ref} (XN_{RMS}); and the second one is the root of the mean squared of θ_{torso} (NM_{RMS}). The normalization is with the X coordinate of the force sensor (approximately half of the foot length). The first index quantifies the X_{ZMP} trajectory error controller. The second one quantifies the natural movement of the walking. These indexes were calculated during 4 walking steps and are described by

$$XN_{RMS} = \frac{\frac{1}{k}\sum_{i=1}^{k}\sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(X_{ZMP}(i,j) - X_{ZMP\_ref}(j)\right)^2}}{X_S} \tag{12}$$

$$NM_{RMS} = \frac{1}{k}\sum_{i=1}^{k}\sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(\theta_{torso}(i,j)^2\right)} \tag{13}$$

where k is the number of steps (4 in our case), n is the number of the X_{ZMP} samples and X_S is the X absolute coordinate of the force sensors location which corresponds to the maximum possible value of X_{ZMP} (in our robot equals to 0.047 m). The optimal values for XN_{RMS} and NM_{RMS} are zero.

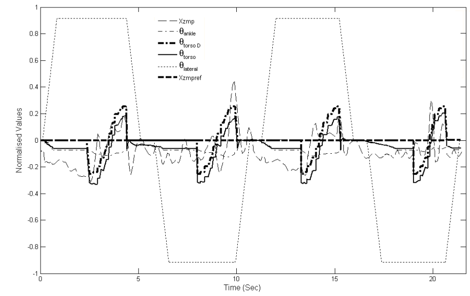

Fig. 10 – X_{ZMP}, X_{ZMPref}, ankle, designed torso (θ_{torsoD}), torso and lateral angles X_{ZMP} equal to zero as reference.

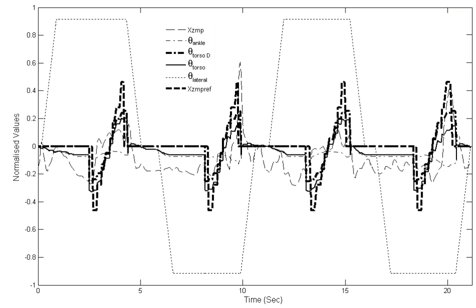

Fig. 11 – X_{ZMP}, X_{ZMPref}, ankle, designed torso (θ_{torsoD}), torso and lateral angles with X_{ZMP_Old} as reference.

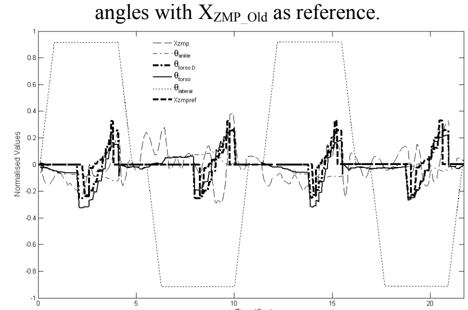

Fig. 12 – X_{ZMP}, X_{ZMPref}, ankle, designed torso (θ_{torsoD}), torso and lateral angles with $X_{ZMP\_New\_Final}$ as reference.

The results of these two performance indexes are presented in the next table.

TABLE 2 - Performance indexes for walking.

X_{ZMP} Reference	X_l=0.07 m and T_{swing}=2 s		X_l=0.12 m and T_{swing}=2.9 s	
	XN_{RMS}	NM_{RMS}	XN_{RMS}	NM_{RMS}
Fixed	0.203	4.652	0.167	22.739
Kurt	0.239	4.351	0.240	21.853
Proposed	**0.187**	**4.035**	**0.162**	**21.843**

It is visible from the performed experimental results that the proposed trajectory reference improves the natural movement (lower NM_{RMS}) and the tracking of the X_{ZMP} trajectory reference (lower XN_{RMS}). The reference defined by Kurt for steps with low dynamics, presents lower performance in the tracking of the X_{ZMP} trajectory reference than the fixed reference and a little improvement in the natural movement.

It should be noticed that in the 0.12 m step length experiments the XN_{RMS} of the fixed trajectory reference is closer to the proposed trajectory reference XN_{RMS}. This happens due to the higher swing time, as expected.

VII. Conclusions

It is clear from the experiments with the human being (and with the biped robot with a human-adapted gait) that the X_{ZMP} trajectory reference amplitude changes with the swing time, so it is proposed the inclusion of a parameter $H(T_S)$ in the X_{ZMP} trajectory reference in order to quantify that change.

The human gait ZMP trajectory moves along the foot in a way that it is shifted forward relative to its center. To take into account this asymmetry it is proposed the shift parameter (α).

From the experiments carried out it is possible to conclude that the X_{ZMP} trajectory reference proposed develops a more natural movement of the robot.

We believe that for each pattern walking gait a different X_{ZMP} trajectory reference (with different α and $H(T_S)$ parameters) is needed to perform a natural movement.

To obtain a good stable step it is very important to design the trajectories of the legs very well and to have small corrections of the torso angle in the balance control. A good option is to have a human-like ZMP trajectory reference. An exhaustive study of the human being locomotion can produce much information that can be used in biped robotics and particularly in humanoid robots, to improve their behavior and stability.

Acknowledgments

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