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A Method for the calculation of the effective Center of Mass of Humanoid robots*,**

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***Abstract*—In this paper we present a general strategy for the calculation of the effective Center of Mass (CoM) of humanoid robots, allowing the reduction of the error between the virtual robot model and the real platform. The method is based on an algorithm that calculates the real position of the CoM of a biped humanoid robot using only 2 force/torque sensors located on the feet of the robot. By means of this algorithm, it is possible to reduce the gap between the real and the virtual posture of the robot and consequently the errors between the ZMP trajectory calculated by the offline pattern generator and the ZMP trajectory calculated by the real-time pattern generator of the humanoid robot. Thus, the influence of the real-time control in the static and dynamic balance of a humanoid platform is minimized. Experimental results using SABIAN platform are provided to validate the proposed method. The results support the applicability of the method to more complex systems.**

Keywords - Humanoid robot; Center of Mass; Biped walking robot; Posture Control; Dynamic Balance; Zero Moment Point.

I. INTRODUCTION

Humanoid robots are complex machines studied with the main purpose of recreating some peculiar tasks of humans, the perfect machines. By now, researches on humanoid robotics are focused on many different areas like grasping, manipulation, locomotion, vision, skin sensors, etc. In this paper a method to solve an issue in the field of robotic locomotion is described.

The main problematic in the walking control of a biped humanoid robot is the stabilization. Since controlling the robot's Center of Mass (CoM) provides significant aid in maintaining static balance and given the complexity of the problem, many studies were already conducted in this area. In [1] Kwon and Oh propose a method to estimate the Center of Mass of Humanoid Robot using two force/torque load cells (from which ZMP is obtained) and data from joint encoders fused in a Kalman filtering framework. Still, with this method the CoM is just estimated, not exactly determined. In [2] Kim et al. propose an adjustment method of home posture for a humanoid robot using incremental encoders, an inertial sensor and force/torque sensors. The authors show that many joints and links errors are accumulated between any humanoid robot and its virtual model. The adjustment of the real-time offset posture is performed by means of four kinds of controllers [2]. In this way the offline error between the humanoid robot and its virtual model is still present. Another approach, oriented to the definition of an inertial force posture controller is shown in [3], while Suleiman et al. describe a dynamic algorithm allowing the real-time calculation of the gradient function of joint torques with respect of joint position, velocity and acceleration [4, 5].

The authors of this paper propose a different method focused on the determination of an algorithm finding the real position of the Center of Mass (CoM) of a biped humanoid robotic platform using only 2 force/torque sensors located on the feet of the robot. This method allows to minimize the error between a humanoid robotic platform and its virtual model without any change to the control system and any realization of new kinds of posture controllers. Applying the algorithm, it is possible to reconstruct the virtual humanoid model for the simulation in a way that guarantees the highest similarity to the real humanoid robot. The procedure that will be explained for the correct calibration is only necessary the first time the platform is used; so, if no changes are applied to the platform (e.g.: wires, links, motors, etc…), the iteration of the procedure is not necessary. Calculating the effective CoM by means of this method has several advantages: a reduction of the gap error among ideal and real ZMP trajectory [6, 7] and consequently a reduction of the imbalance of the robot; a reduction of the gap error between virtual and real position, velocity and acceleration of the robot joints. In order to prove the effectiveness of our approach, we tested the method on the biped humanoid platform SABIAN.

This paper is organized as follows: in section II the humanoid platform used for testing is briefly introduced; section III describes the proposed algorithm; section IV shows

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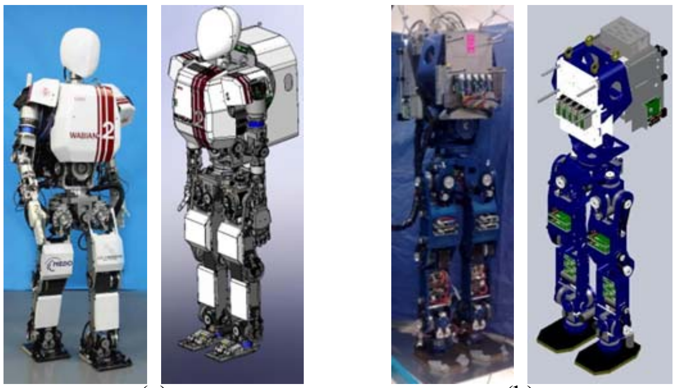
the experimental setup; finally, section V consists in a discussion about tests results and future works.

II. HUMANOID ROBOTIC PLATFORMS

A. *SABIAN (*Sant'Anna BIped humANoid)



(a) (b)

Figure 1. a) WABIAN (real picture and CAD model); b) SABIAN (real picture and CAD model).

The humanoid robot SABIAN (fig. 1) is a partial copy of the WABIAN 2 (WAseda BIped humANoid) [8, 9, 10, 11, 12], designed and developed by Waseda University of Tokyo.

SABIAN was developed in 2004 in Robotan Lab., a joint laboratory between Waseda University (Tokyo-Japan) and Scuola Superiore Sant'Anna (Pisa-Italy) to perform researches in the fields of humanoid and biomedical robotics. Compared to most bipedal humanoid robots walking with bent knees, SABIAN is able to perform a human-like walking, with stretched knees and to get the pelvis motion raising the hip (table 1).

The electronic hardware dedicated to the motion control of SABIAN is mounted on the trunk and consists of a PCI CPU board and two PCI I/O boards. As I/O boards, a HRP interface board (16ch D/As, 16ch counters, 16ch PIOs) and a 6-axis force/torque sensor receiver board are mounted (fig. 2). The operating system is QNX Neutrino ver. 6.3. The drive system consists of a DC servo motor with an incremental encoder attached to the motor shaft and a photo sensor to detect the basing angle. Furthermore, each ankle has a 6-axis force/torque sensor, used to measure Ground Reaction Force (GRF) and Zero Moment Point (ZMP).

B. *WABIAN/SABIAN Control System*

The walking control system of the WABIAN/SABIAN has two execution phases. The first phase uses a pattern generator that calculates the trajectory of the end-effectors (represented by the hands and feet). In the second phase, the trajectories to be executed are sent to the robot. The SABIAN Pattern Generator uses the feet positions file in order to create the motion pattern of the lower limbs. Additionally, for the dynamic balance of the humanoid robot during the walking stages, legs and waist motions are corrected by a walking stabilization control (Torso Position Control) that is based on the ZMP position [6, 7] [9, 10, 11, 12]. In this way we have an ideal motion pattern, and a real one with the online corrections due to the control.

TABLE 1: WABIAN & SABIAN CHARACTERISTICS.

CHARACTERISTICS	WABIAN	SABIAN
Height [mm]	1487	1300
Weight [kg]	64,5	40,75
DOF	Leg 6x2 / Foot 1x2 (passive) / Waist 2 / Trunk 2 / Arm 7x2 / Hand 3x2 / Neck 3. Total: 41.	Leg 7x2 / Foot 0 / Waist 2 / Trunk 2 (not working) / Arm 0 / Hand 0 / Neck 0. Total: 16.
6 axis Force sensors	4 (2 on the hands and 2 on the feet)	2 on the feet

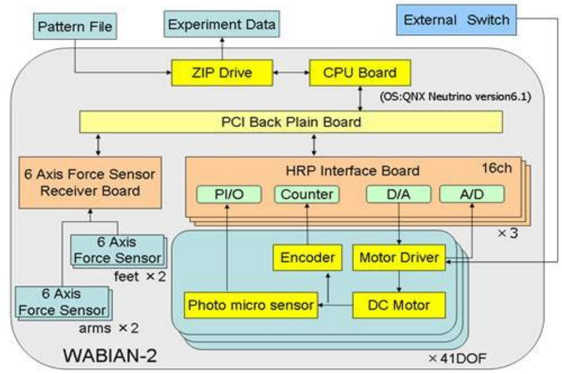


Figure 2. Control System.

III. THE MODEL DESCRIPTION

A. *Error Mass*

In order to compensate all errors between the humanoid robot and its virtual model an error mass is usually added to the ideal model. Since the real position of the CoM of the robotic platform is not known, it is necessary to find the position of the error mass in order to obtain a virtual position of the CoM as close as possible to the real one.

The value of the error mass is determined by a simple subtraction between the real weight and the CAD model weight of the robot. In fig. 3 the sketch of WABIAN with the links masses is shown. The virtual model of the robot, including the masses of the links and their spatial position is defined by the user in the offline pattern generator. By now, the spatial position of the error mass in the WABIAN ideal model was usually determined by experience.

The Z position was fixed by the user and the X and Y positions were determined by minimizing the gap error between the position of the ZMP of the robot and the position of the ZMP of its virtual model with a manual and iterative methodology. However, this procedure requires a big amount of time and the user must define the Z position. Thus, the calculation of the position of the error mass is not accurate. Furthermore it is necessary to repeat periodically the whole procedure because of the imprecision of the methodology.

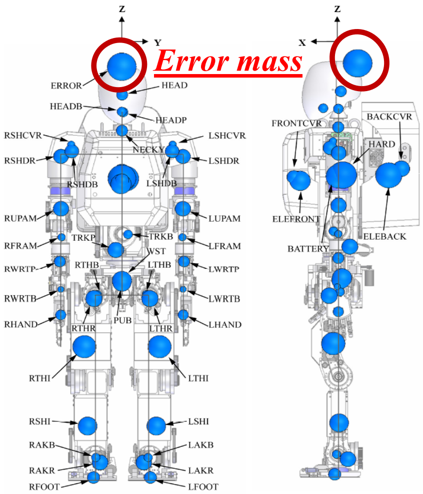


Figure 3. WABIAN masses.

B. *Methods and Formulas*

The authors of this paper propose an analytic formula and a new methodology to determine the spatial position (X, Y and Z) of the CoM of biped humanoid robots. The calculation needs just the data from the 2 force-torque sensors on the feet of the robot.

In fig. 4 a), points 0 and 1 can be seen as two points of a rigid body in space, while the CoM of the rigid body is set at point 2. The rigid body can be compared to a humanoid robot with his feet at points 0 and 1 and his CoM at point 2. Considering the equilibrium $\left(\sum \vec{F} = 0; \sum \widehat{M} = 0\right)$ of the humanoid robot, (1) was determined. (2), directly derived from (1), is constituted by six variables F_{X2}, F_{Y2}, F_{Z2}, X_2, Y_2, Z_2, in five equations. The other parameters in (2) are known by means of the force/torque sensors, by computing the current consumptions and from geometrical conditions of the humanoid robot. m_2 is the real weight of the humanoid robot without feet.

Assumption 1: a=b; c=d=e=f=0. The assumption 1 is geometrical. With this premise (3) is derived, representing two equilibrium positions of the humanoid robot using *i=A* or *i=B* (schemes A ($\theta = 0$) and B ($\theta \neq 0$) in fig. 4 b) or schemes A ($\theta_t = \theta_s = \theta_w = 0$) and B ($\theta_t \neq 0; \theta_s \neq 0; \theta_w \neq 0$) in fig. 4 c)). By means of fig. 4 b) and (3), (4) is given. It is constituted by six equations in six variables X_{2A}, Z_{2A}, X_{2B}, Z_{2B}, r_w, l_w, while U, r_u, l_u, m_u are determined by means of the CAD model of the robot and θ is fixed by the user. In fig. 4 c) an alternative equilibrium condition with respect to fig. 4 b) is shown. In this case the equations system is alternative to (4) and it is constituted by six variables in six equations too. The parameters U, L_1, L_2, L_3, r_u, l_u, r_t, l_t, r_s, l_s, m_u, m_t, m_s, are determined by means of the CAD model. θ_t, θ_s θ_w are defined by the user.

Solving (4) (or the alternative system obtained by fig. 4 c)) (5) is given and thus the correct spatial position of the real CoM (X_2, Y_2, Z_2) on the biped platform without the feet is obtained . In (6) the mass position of the feet of the humanoid robot (X_F, Y_F, Z_F) is calculated with respect to the mass position of the biped CAD model with (m_V, X_V, Y_V, Z_V) and without (m_C, X_C, Y_C, Z_C) the feet. By using (6), the real position of the total CoM (X_R, Y_R, Z_R) of the humanoid robot with feet can be calculated.

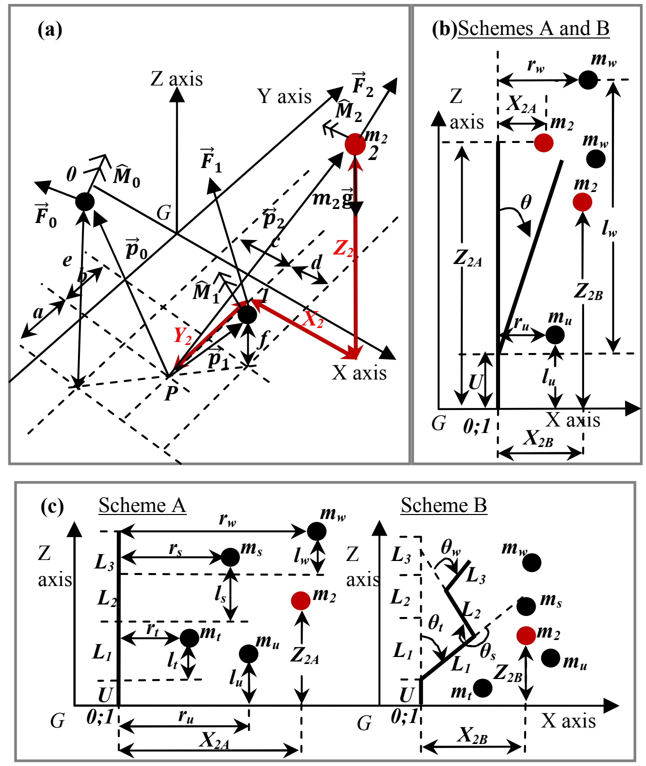


Figure 4. Schemes used for the definition of the method: a) Points 0, 1 and 2 in the space; b) Two configurations of equilibrium (schemes A ($\theta = 0$) and B ($\theta \neq 0$)); c) Two alternatives configurations of equilibrium (schemes A ($\theta_t = \theta_s = \theta_w = 0$) and B ($\theta_t \neq 0; \theta_s \neq 0; \theta_w \neq 0$)).

$$\begin{cases} m_2 * \vec{a}_2 = m_2 * \vec{g} + \vec{F}_0 + \vec{F}_1 + \vec{F}_2 = 0; \\ \widehat{M}_P = \widehat{M}_0 + \widehat{M}_2 + \widehat{M}_1 + \vec{p}_0 \times \vec{F}_0 + \\ \quad + \vec{p}_1 \times \vec{F}_1 + \vec{p}_2 \times \vec{F}_2 = 0; \end{cases} \tag{1}$$

$$\begin{cases} F_{X0} + F_{X1} + F_{X2} = 0; \\ F_{Y0} + F_{Y1} + F_{Y2} = 0; \\ F_{Z0} + F_{Z1} + F_{Z2} - m_2 g = 0; \\ M_{X0} + M_{X1} + M_{X2} - aF_{Z0} + bF_{Z1} + Y_2 F_{Z2} + \\ \quad - Y_2 m_2 g - eF_{Y0} - fF_{Y1} - Z_2 F_{Y2} = 0; \\ M_{Y0} + M_{Y1} + M_{Y2} + cF_{Z0} - dF_{Z1} - X_2 F_{Z2} + \\ \quad + X_2 m_2 g + eF_{X0} + fF_{X1} + Z_2 F_{X2} = 0; \\ M_{Z0} + M_{Z1} + M_{Z2} - cF_{Y0} + dF_{Y1} + X_2 F_{Y2} + \\ \quad + aF_{X0} - bF_{X1} - Y_2 F_{X2} = 0; \end{cases} \tag{2}$$

The formula proposed in (5) is applicable to any humanoid robot with 2 force/torque sensors on the feet. The values: α_A, β_A, α_B, β_B, γ_A and δ_A, in (5) are derived from (3) with *i=A* or *i=B*.

$$\begin{cases} F_{X2i} = -F_{X0i} - F_{X1i}; \\ F_{Y2i} = -F_{Y0i} - F_{Y1i}; \\ F_{Z2i} = m_2 g - F_{Z0i} - F_{Z1i}; \\ X_{2i} = \{-[(M_{Y0i} + M_{Y1i} + M_{Y2i})/(F_{Z0i} + F_{Z1i})]\} + \\ +[(F_{X0i} + F_{X1i})/(F_{Z0i} + F_{Z1i})] * Z_{2i} = \alpha_i + \beta_i * Z_{2i}; \\ Y_{2i} = \{[(M_{X0i} + M_{X1i} + M_{X2i})/(F_{Z0i} + F_{Z1i})] + \\ +[a * (F_{Z1i} - F_{Z0i})/(F_{Z0i} + F_{Z1i})]\} + \\ +[(F_{Y0i} + F_{Y1i})/(F_{Z0i} + F_{Z1i})] * Z_{2i} = \gamma_i + \delta_i * Z_{2i}; \end{cases} \quad (3)$$

$$\begin{cases} X_{2A} = [m_u r_u + m_w r_w]/m_2 ; \\ Z_{2A} = [m_u l_u + m_w * (U + l_w)]/m_2 ; \\ X_{2B} = [m_u r_u + m_w * (l_w \sin\theta + r_w \cos\theta)]/m_2 ; \\ Z_{2B} = [m_u l_u + m_w * (U + l_w \cos\theta - r_w \sin\theta)]/m_2 ; \\ X_{2A} = \alpha_A + \beta_A Z_{2A}; m_w = m_2 - m_u; X_{2B} = \alpha_B + \beta_B Z_{2B}; \end{cases} \quad (4)$$

$$\begin{cases} X_2 = (\beta_A * \alpha_B - \alpha_A * \beta_B)/(\beta_A - \beta_B) ; \\ Y_2 = [\gamma_A * (\beta_A - \beta_B) + \delta_A * (\alpha_B - \alpha_A)]/(\beta_A - \beta_B) ; \\ Z_2 = (\alpha_B - \alpha_A)/(\beta_A - \beta_B) ; \end{cases} \quad (5)$$

$$\begin{cases} X_F = \dfrac{X_V m_V - X_C m_C}{m_V - m_C}; \\ Y_F = \dfrac{Y_V m_V - Y_C m_C}{m_V - m_C}; \\ Z_F = \dfrac{Z_V m_V - Z_C m_C}{m_V - m_C}; \end{cases} \begin{cases} X_R = \dfrac{X_2 m_2 + X_F * (m_V - m_C)}{m_2 + m_V - m_C}; \\ Y_R = \dfrac{Y_2 m_2 + Y_F * (m_V - m_C)}{m_2 + m_V - m_C}; \\ Z_R = \dfrac{Z_2 m_2 + Z_F * (m_V - m_C)}{m_2 + m_V - m_C}; \end{cases} \quad (6)$$

C. *Implementation*

The practical implementation of (5) and then (6) was conducted in the following way: first the robot was kept in an upright position (after the calibration and activating the motors) and all values from the load cells (all forces and momentums) were extracted; then, the same operation was conducted with the robot inclined at an angle of 1 degree to the vertical (these two positions correspond to positions A and B in fig. 4 b)). So, by using (5), X_2, Y_2 and Z_2 (and consequently X_R, Y_R, Z_R from (6)) were calculated. In order to verify our method the schemes A and B in fig. 4 c) were also implemented and all values from the load cells were extracted. In this case the robot was kept in knee stretched and knee bended position. The final solution is similar in both cases. The value of M_{X2}, M_{Y2}, M_{Z2} were determined by:

$$\begin{cases} M_{X2} = \sum M_{joint\_roll} ; \ M_{Y2} = \sum M_{joint\_pitch} ; \\ M_{Z2} = \sum M_{joint\_yaw} ; M_{joint}[Nm] = K[Nm/A] * I[A]; \end{cases} \quad (7)$$

where K is a fixed parameter related to every motor and I is the value of the current.

D. *Virtual Models*

The authors created four different virtual models of the biped robot by changing the position of the error mass in the virtual robot model. The four models are:

- Model n: without any mass error.
- Model r: the mass error was located in the position of the total real CoM of the robot (X_R, Y_R, Z_R) calculated with (6).
- Model s: the mass error was located in the same position used for the WABIAN.
- Model v: the mass error was located in the total virtual CoM generated by the CAD model (X_V, Y_V, Z_V).

A simple gait trajectory (stretched forward) equal for all four models was simulated and implemented by means of the SABIAN platform. Data and discussions are presented in the sections below.

IV. EXPERIMENTAL METHODOLOGY AND RESULTS

A. *Experimental Setup*

To demonstrate the effectiveness of our approach, a simple gait was implemented in order to test the behaviour of the robot with the four different models. The gait was first designed and simulated with the offline Pattern Generator software [10] to obtain the feet positions files necessary to perform the walk. The walking process consists of three stages: 128 phases for the start still stage; 256 phases for the actual movement: eight walking steps (right and left alternated) of 40 cm along X (forward) direction of the global referent system (only the first and the last steps are of 20 cm); 128 phases for the end still stage. Every phase lasts 0.03 seconds, so the experiments were done with a step cycle of 0.96 s/step. Walking experiments were carried out on a horizontal flat plane and five runs were performed with each of the four models. In this walking process the tip of the toe and the heel of the biped robot contact the ground at the same time.

B. *Results*

During the motion, data related to the effective joints and ZMP positions were collected, stored and compared to the virtual (target) ones. As mentioned in section II, the online Torso Position Control [9, 10, 11, 12] is necessary to correct any error arising from differences between the ideal modelling and reality. The more ideal and real values are close and correlated to each other, the less the online control must take action and the more the walking process is stable. The correlation between ideal and effective ZMP and the Root Mean Square of the difference of these signals were calculated for both axes. The temporal traces of the ZMP Y position for each of the four models are shown in fig. 5, where the target position and the real ones are overlapped. A mean value among the five runs was considered. In the XY Plane, the distance from the origin was calculated:

$$\rho = \sqrt{((ZMPx)^2 + (ZMPy)^2)} \quad (8)$$

Same considerations about correlation values and RMS error were assessed for the ideal and real ZMP in the XY

Plane (correlation between ideal and real ρ and RMS of the difference signal). Fig. 6, 7 and 8 show the ZMP position in XY plane and the error between ideal and real value. Furthermore, data were calculated for the whole duration of the walking process (512 phases) and also just for the effective duration of the motion (256 phases). Since data are quite similar, just the first ones (512 phases) are shown. In addition to the simple position, also velocity and acceleration data (ideal values in relation with the real values) were considered by differentiating collected and target position data. Finally, the errors and the correlations between the ideal and the effective positions, velocity and accelerations of the 16 joints were assessed. As an example, data related to the roll joints (2 for each leg) are shown. All results are summarized in tables 2, 3 and 4. Best data for every line are highlighted in bold.

V. Conclusion and Discussions

In this paper, a new approach that calculates the effective CoM using just 2 force/torque sensors on the feet of a humanoid robotic platform was proposed. By means of this method, a manual methodology to determine the position of the error mass (to make the virtual model closer to the real one) is not necessary, but the error mass can be directly set in the CoM. The shown methodology can be applied to any humanoid robot. Next works will be oriented to improve the calculation of the error mass position.

The formulation was first theoretically explained and then tested with a simple walking pattern of eight walking steps using the biped humanoid platform SABIAN, in relation with other reasonable configuration of masses. The aim of the experiment is to demonstrate that the mass configuration resulting from (5) and (6) gives the better results in terms of correlation and RMS error between the planned ZMP and the real one; in other words, that the real implementation of the motion pattern is closer to the theoretical one. The table 2 shows the correlation data related to the ZMP position and velocity trajectories.

In table 3 and in table 4 the RMS data related to position, velocity and acceleration of the ZMP and of the roll joints of the robot are shown. As can be seen, using model r the correlation between target and real value is higher than with other models. Furthermore, the RMS values of the model r are the lowest in most cases. Also figures 5, 6, 7 and 8, shown in this paper confirm that using model r is the best choice. In particular in fig. 8 the zoom of the contact point between foot and ground shows that, compared with other models, the model r is closer to the ideal signal.

Another interesting point is that in most of the analyzed data, the second best mass configuration was *n*, which has the theoretical structure without any error mass. So, it could be underlined as, for a simple forward walk, the absence of any error mass can give better results than with using a wrong error mass. The good results shown in this paper create the bases for future works: more analysis with other control systems and different kinds of gaits are planned.

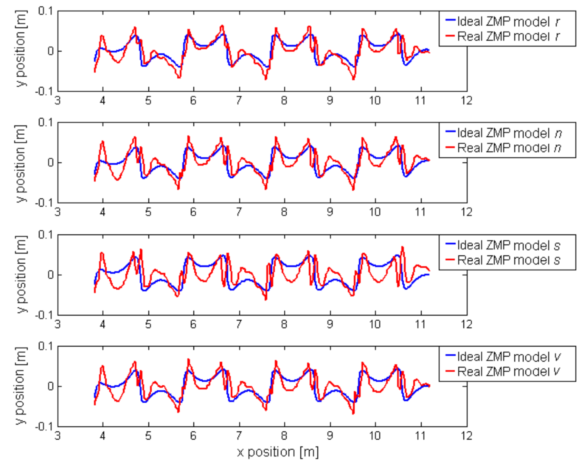


Figure 5. Ideal and Real ZMP Y position obtained with the models r, n, s, v.

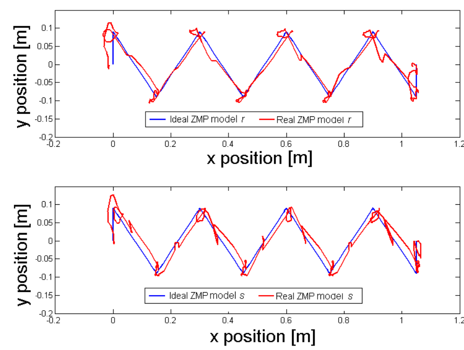


Figure 6. Ideal and Real ZMP XY position obtained with the models r and s.

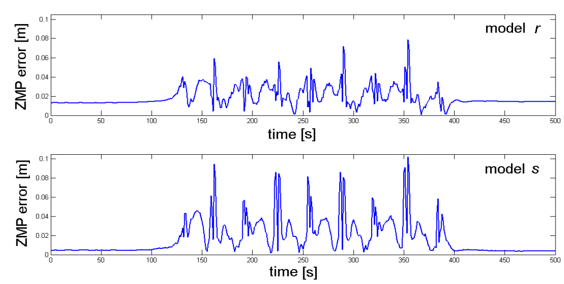


Figure 7. Error between ideal and real ZMP XY position of the virtual models r and s.

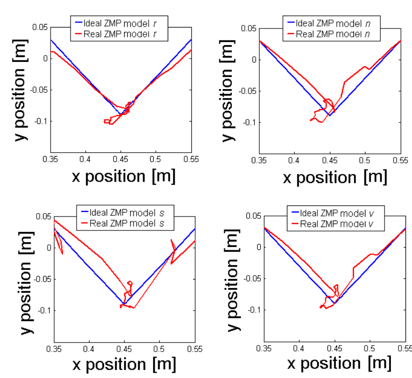


Figure 8. Ideal and Real ZMP XY position obtained with the models r, n, s, v, around a ground-foot contact point.

TABLE 2: CORRELATION DATA (ZMP TRAJECTORY).

Type of data	*Model n*	*Model r*	*Model s*	*Model v*
X pos. [m]	0.8418	**0.8709**	0.7370	0.8357
Y pos. [m]	0.6959	**0.7799**	0.4432	0.6710
XY pos. [m]	0.7073	**0.7337**	0.5748	0.6768
X vel. [m/s]	0.4389	**0.5212**	0.2401	0.4293
Y vel. [m/s]	0.3069	**0.4118**	0.1306	0.2992
XY vel. [m/s]	0.4950	**0.5232**	0.4639	0.4910

TABLE 3: RMS DATA (ZMP TRAJECTORY).

Type of data	*Model n*	*Model r*	*Model s*	*Model v*
X pos. [m]	0.0164	0.0179	**0.0142**	0.0171
Y pos. [m]	0.0161	**0.0142**	0.0224	0.0169
XY pos. [m]	0.0230	**0.0229**	0.0265	0.0240
X vel. [m/s]	0.2885	**0.2611**	0.3369	0.2866
Y vel. [m/s]	0.4228	**0.3651**	0.5070	0.4181
XY vel. [m/s]	0.5199	**0.4492**	0.6088	0.5071
X acc. [m/s^2]	12.5505	**11.2278**	14.0172	12.4586
Y acc. [m/s^2]	17.8598	**15.7074**	19.8534	17.8414
XY acc. [m/s^2]	21.8301	**19.3339**	24.3073	21.7749

TABLE 4: RMS DATA (ROLL JOINTS OF THE SABIAN).

Type of data	*Model n*	*Model r*	*Model s*	*Model v*
Left Ankle pos. [m]	0.2513	**0.2443**	0.3708	0.2877
Left Ankle vel. [m/s]	2.2847	**1.8386**	2.7547	2.2713
Left Ankle acc. [m/s^2]	61.322	**48.665**	66.7449	60.417
Left Hip pos. [m]	0.8048	**0.7636**	0.8849	0.8170
Left Hip vel. [m/s]	4.2046	**3.5794**	4.9478	4.1973
Left Hip acc. [m/s^2]	102.33	**82.286**	114.668	101.31
Right Ankle pos. [m]	0.2475	**0.2385**	0.3711	0.2835
Right Ankle vel. [m/s]	2.2640	**1.8252**	2.7682	2.2466
Right Ankle acc. [m/s^2]	60.817	**48.334**	67.5456	59.624
Right Hip pos. [m]	0.7464	**0.7364**	0.9155	0.7611
Right Hip vel. [m/s]	4.0059	**3.4111**	4.7636	3.9885
Right Hip acc. [m/s^2]	99.672	**80.903**	111.693	98.377

Additionally, other tests will be performed by means of the WABIAN platform and they will be oriented to achieve a better resolution of the CoM. However, from the analysis of the shown data, it seems clear that the position of the error mass plays a very important role in the implementation of a stable and repeatable walk. Even though the stability control tries to correct any error arising from differences between the ideal modelling and reality, working with a configuration of masses closer to reality can achieve better results, preventing unwanted oscillations and deviation from the equilibrium position. Thus, this paper offers the possibility to use an analytic formula giving to the final user a very accurate position of the CoM of any humanoid platform using just 2 force-torque sensors and without any iterative and manual procedure. This paper is confidential. Patent pending.

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