Optimum Walking of the Bioloid Humanoid Robot on a Rectilinear Path

G. Reyes[1] , J.A. Pamanes[1], J.E. Fierro[1] and V. Nunez[2]

[1] *Division of Postgraduate Studies and Research, Institute of Technology of La Laguna (ITLag) / National Institute of Technology, Blvd. Revoloucion y Cuauhtemoc, Torreon, Coah. Mexico C.P 27000, e-mail: japamanesg@correo.itlalaguna.edu.mx*

[2] *Polytechnic University of Sinaloa (UPSIN), Mazatlan, Sin. Mexico C.P. 82199, e-mail: jnunez@upsin.edu.mx*

Abstract. A method is presented in this paper to determine optimal values of the parameters for the gait of a humanoid robot. These parameters are relevant for a stable walking of the robot when this one follows a rectilinear path. By applying such optimal parameters the set of zero moment points of the support foot, corresponding to a step in the walking, is located as close as possible to the center of the footprint of the support foot. The computation of the optimal parameters is accomplished by minimization of a nonlinear objective function that describe the distance from the center of the footprint to a typical remote zero moment point (ZMP) estimated from a sample of such points generated during a step. A study case is presented to illustrate the efficacy of the proposed method. This one provide some advantages compared with other approaches in the literature.

Key words: Bioloid robot, biped robots, optimum walking, humanoid walking.

1 Introduction

High instability during the walking is characteristic in humanoid biped robots. Relatively slow perturbations may cause that the robot falls during the walking. Thus, great challenges exists in designing, motion planning and control of humanoids in order to reduce the instability as much as possible. The main goal of studies developed on biped locomotion is to get a stable walking. The criterion of stability of biped robots applied in most of research works is based on the notion of the Zero Moment Point (ZMP), proposed by Vukobratovic [1]. Indeed, Shi et al. [2], for instance, proposed to minimize the deviation between the center of the stable region and the ZMP by defining the optimum trajectory of the hip of a biped. The authors studied a 12 degree of freedom (DOF) robot and they specified the pelvis motion by using sinusoidal functions. These kind of functions, however, produces impact forces during the landing of the free foot. In other work [3] the maximization of the stability margin of a biped was proposed by using optimum values of two parameters. The gait of the robot is based on third order spline functions. In this case the impact forces aren't neither avoided. Other authors [4], based on a human walking, specify an *ideal* trajectory of the ZMP and then the pelvis motion of the robot is determined such that the real trajectory of the ZMP is near to the ideal one.

In more recent works, others criteria were applied in synthesizing walking patterns. To reduce the instability, in [5] the motion planning was oriented to compensate the yaw moment of the robot during the walking. On the other hand, a method was proposed in [6] to generate walking patterns that require the lowest friction forces.

In the present paper an approach is introduced to establish the optimum values of walking parameters that maximize the stability margin of the robot during the simple support phase of the walking. The proposed method is applied to the Bioloid humanoid robot with 12 DOF in legs. The gait of the humanoid is based on the cycloidal functions proposed in [7].

The next section describes the main features of the gait applied for the robot. The formulation of the optimization problem and the process to solve it are presented in third section. Then, this method is applied for walking optimization of the Bioloid robot for a rectilinear path. Finally the conclusion of the work is presented.

2 Specification of a walking

In the walking pattern of a biped robot, the desired poses for both the pelvis and the oscilating (or *free)* foot are specified with respect to a world's frame ($\boldsymbol{x_W}$-$\boldsymbol{y_W}$-$\boldsymbol{z_W}$) as time functions. The points for position specification of these bodies are O_p (***pelvis***) and O_f (*free **f**oot*), showed in Fig. 1. The positions are given in Cartesian coordinates. For orientation with respect to the world's frame, the Bryant angles λ, μ and ν are applied to frames $\boldsymbol{x_p}$-$\boldsymbol{y_p}$-$\boldsymbol{z_p}$ and $\boldsymbol{x_f}$-$\boldsymbol{y_f}$-$\boldsymbol{z_f}$ attached to the pelvis and the free foot, respectively. Both frames and the world's frame are shown in Fig. 1. The Bryant angles correspond to successive rotations applied in the order $\boldsymbol{x}$ - $\boldsymbol{y}$ - $\boldsymbol{z}$ to a frame whose orientation initially matches the world's frame in order to obtain the desired orientations. The equations that define all the coordinates as time functions are those proposed in [7]. Some of the main walking parameters are appreciated in Fig. 2.

The cycle of a step is composed by two phases: single support phase (SSP) and double support phase (DSP). The first one is achieved during a period T_S, when only one foot is in contact with the floor while the other foot is moving forwards. DSP is accomplished in a period T_D and starts when the moving foot lands and both feet keep the contact with the floor. DSP finishes when the rear foot leaves the floor to start the next step. In SSP both the hip and the free foot move. In DSP only the hip moves. Each step period is $T=T_S+T_D$. The SSP is the most instable one during the walking and requires of a suitable motion planning.

The walking process is achieved in 3 stages: stage 1 or *starting* (completed in one step), stage 2 or *cruising* (completed in n_p steps) and stage 3 or *stopping* (completed

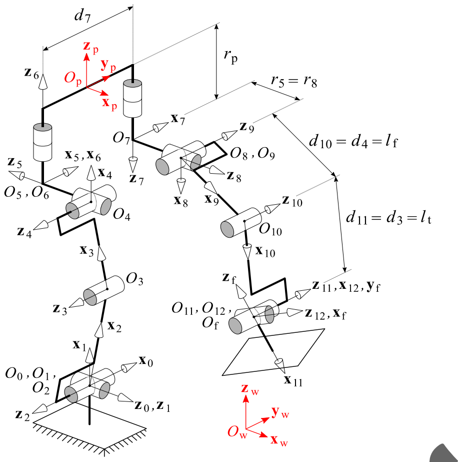
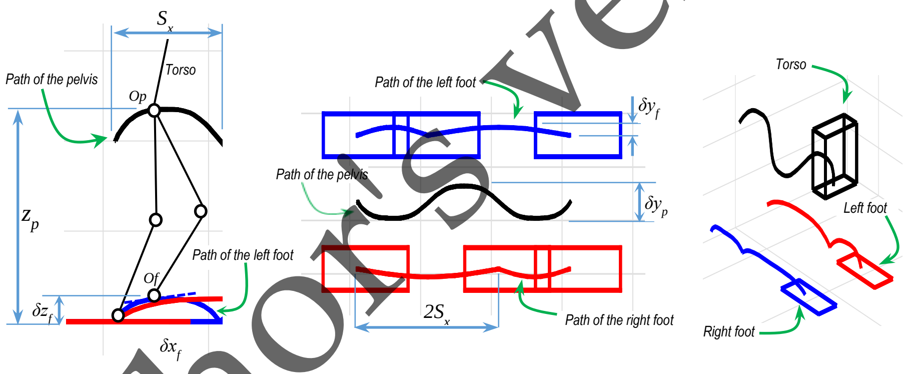


Fig. 1 Kinematic scheme of legs of the Bioloid humanoid



(a) Lateral view (b) Top view (c) Isometric view

Fig. 2 Paths and main parameters for motion of pelvis and feet

in one step). In stage 1, the pelvis accelerates on direction $\mathbf{x}_W$ from zero velocity by using a starting semi-cycloidal motion until cruising speed (*Vmax*). This stage occurs in the period T_1 of the first step. The *x* coordinates of position for both feet when the walking begins ($t=0$) are zero. The period of each step in cruising stage is T_2 with the pelvis moving in direction $\mathbf{x}_W$ with speed *Vmax*. In stage 3 the speed of the pelvis decreases by using a stopping semi-cycloidal motion, from *Vmax* to zero, in the time T_3 of the last step. A step at each stage has one single support phase (SSP) and one double support phase (DSP). In rectilinear walking in direction $\mathbf{x}_W$, both feet finish their motion having the same *x* coordinate. The total time is $T_T = T_1 + n_p T_2 + T_3$ for the walking The main parameters of the walking equations are shown in Fig. 2.

3 Optimization problem

The geometry of a path of the ZMP that is generated on a footprint during the walking of a humanoid robot is determined by the dynamics of the robot's motion. The features of such a motion depends on the parameters of equations that define the walking. Thus, the coordinates of the ZMP are implicit functions of the parameters of the walking pattern. Consequently, the optimal values of such parameters must be computed for the best behavior of the ZMP.

The criterion used in this work for optimization of walking consists in the location of the set of ZMP associated to a step in SSP as close as possible to the center of the sole of the support foot. The following procedure is proposed to solve this problem.

For an arbitrary set of walking parameters, the coordinates corresponding to a sample of n_{pm} zero moment points P_i are taken ($i=1, 2..., n_{pm}$), which correspond to a single step in SSP during the walking. Such coordinates are obtained in a simulation process by using the *Webots©* software. Then, the distances d_i are computed between each one of the P_i of the sample and the centroid C_0 of the sole of the support foot. The zero moment points of the set and C_0 are schematized for the sole of the humanoid in Fig. 3, and a distance d_i is also indicated. We compute the average $\bar{d}$ and the standard deviation d_σ of the set of distances and replace them in the following objective function:

$$f = \bar{d} + d_\sigma \tag{1}$$

where

$$\bar{d} = \frac{1}{n_{pm}} \sum_{i=1}^{n_{pm}} d_i \tag{2}$$

$$d_\sigma = \sqrt{\frac{1}{n_{pm}} \sum_{i=1}^{n_{pm}} (d_i - \bar{d})^2} \tag{3}$$

It can be observed that f represents a typical large distance of the set of distances d_i. Therefore, a set of distances as close as possible to the centroid C_0 corresponds to the minimum value of f. Such a set can be obtained by using optimum values of some significant parameters of the walking pattern. When f is minimized, then the stability margin of the robot will be maximized.

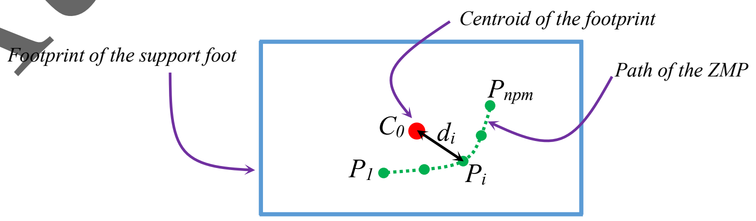


Fig. 3 Sample of zero moment points P_i for a step of a walking.

Because of f is not an explicit function of parameters of the walking pattern, the optimal values of such parameters cannot be computed in a conventional way. Thus, we use a regression model to obtain an approximative function f^* whose independent variables are the parameters of the walking pattern. In a first assessment of our approach we use only two parameters of walking as optimization variables, and propose the following quadratic function as a regression model:

$$f^* = b_0 + (w_1 - b_1)^2 + (w_2 - b_2)^2 \tag{4}$$

The coefficients b_0, b_1, b_2 are the parameters of the function (4), and w_1, w_2 are the independent variables of walking. Thus, the values of the coefficients b_0, b_1 and b_2 must be determined in such a way that f^* approaches to f as much as possible for a sample of sets of the independent variables. Such values of coefficients will be optimal.

To compute the optimal values of coefficients of function (4), the method starts with an arbitrary set of values of b_0, b_1 and b_2. Then the function f^* is evaluated by Eq. (4) for six different sets of values of parameters w_1 and w_2 chosen by the user. The greater the number of sets is, the better optimum coefficients we obtain. In this work we chose six sets of values of w_1 and w_2 and suitable results were obtained.

On the other hand, for the same sets of variables w_1 and w_2 used in evaluation of the approximative function f^*, we additionally evaluate the exact function f of Eq. (1). The specific values of f evaluated for the set of variables w_1 and w_2 will be termed f_w. Clearly, for each set of w_1 and w_2, there will exists an error of f^* with respect to f_w, which is defined as

$$e = |f^* - f_w| \tag{5}$$

When this error is evaluated for the six sets of values of w_1 and w_2, we have six errors that must be globally minimized in the process of optimization of coefficients b_0, b_1 and b_2. For this optimization we propose the following objective function:

$$f_e = \bar{e} + e_\sigma \tag{6}$$

where $\bar{e}$ is the average error, and e_σ the standard deviation, of the set of errors evaluated by Eq. (5).

To evaluate the functions f_w that are employed in Eq. (5) during the process of minimization of (6), numeric experiments must be achieved by using the sets of variables w_1 and w_2. Such experiments consists in simulations of walking of the robot by using the current values of w_1 and w_2 and the other walking parameters that are constant. In Table 1 the values given for these parameters are displayed. The values of those parameters not included in this Table are zero.

On the other hand, the two walking parameters that will be considered as independent variables w_1 and w_2 must be choosen for computation of b_0, b_1 and b_2. In previous experimental studies on the walking of the Bioloid robot [9] it was observed that the balancing of the robot was more sensitive to changes in values of the lateral displacements δy_p of the pelvis. Consequently, in this work we use the displacements δy_{ps}

and δy_{pd} of point *Op* of the pelvis in direction $\boldsymbol{y}_W$, associated to the single support phase and double support phase, respectively. Thus, we define:

$$w_1 \equiv \delta y_{ps} \tag{7}$$

$$w_2 \equiv \delta y_{pd} \tag{8}$$

The meaning of these independent variables in the motion of the biped can be appreciated in Fig. 4. The six sets of δy_{ps} and δy_{pd} considered are given in Table 2. Thus, minimizing function (6) by using the function *fmincon* of *Matlab*© for these sets of parameters we obtain $b_0 = 0.020, b_1 = 0.015$ and $b_2 = 0.085$. The function *fmincon* is based on the *Interior Point* algorithm [10]. Such a function minimize constrained non-linear functions.

The plot of function (4) with the obtained values of b_0, b_1, b_2 is shown in Fig. 5. The optimal values of w_1 and w_2 are gotten by using the partial derivatives of (4) with respect to w_1 and w_2. Making equal to zero such derivatives we obtain:

$$w_{1\,opt} = b_1 = 0.015\ m$$

$$w_{2\,opt} = b_2 = 0.085\ m$$

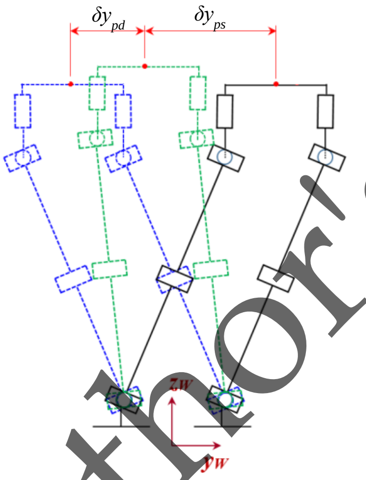


Fig. 4 Independent variables of functions (1) and (4)

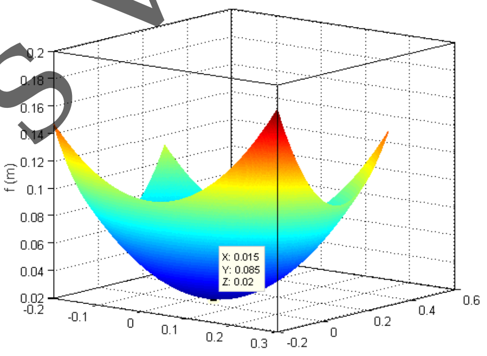


Fig. 5 Plot of function (4) with optimal values of b_0, b_1 and b_2

Table 1. Parameters specified for the numerical experiments

Parameter	*Units*	*Value*
n_p	*steps*	6
T_{SS}	*sec*	1
T_{DS}	*sec*	1
z_{pini}	*m*	0.125
δx_p	*m*	0.030
δz_p	*m*	0.005
δx_f	*m*	0.030
δy_f	*m*	0.010
δz_f	*m*	0.015
$\mu_{p\ in}$	*deg*	15

Table 2. Sets of independent variables considered for the numerical experiments

Experiment	δy_{ps} (m)	δy_{pd} (m)	f (m)
1	0.010	0.025	0.0241
2	0.010	0.030	0.0238
3	0.012	0.026	0.0208
4	0.013	0.028	0.0202
5	0.015	0.025	0.0229
6	0.015	0.030	0.0209

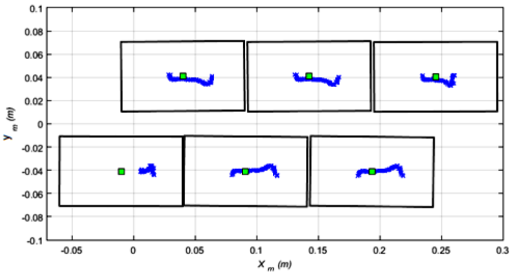


Fig. 6 Paths of the ZMP obtained by using optimum parameters of walking

Therefore, we have $\delta y_{ps\ Opt} = 0.015\ m$ and $\delta y_{pd\ Opt} = 0.085\ m$ as the values of the independent variables which minimize the objective function. Finally we achieve a simulation by using these values for displacements of the pelvis, in single and double support phases, in order to obtain the optimum path of the ZMP on the footprint of the support foot during the walking. The obtained optimum paths are shown in Fig. 6 for 6 steps of walking, and a sample of postures of the robot during the walking is presented in Fig. 7.

4 Conclusion

A method was proposed in this paper to obtain the values of parameters that optimize the gait of the Bioloid humanoid robot during a rectilinear walking. The set of zero moment points of the support foot, corresponding to a step in the walking, is located as close as possible to the center of the footprint of the support foot. Consequently, the stability margin of the robot is maximized during the walking.

The considered walking pattern is based on cycloidal motions of the pelvis and free foot, as proposed in [7]. The equations of this pattern are explicitly expressed in function of geometric parameters such as the lateral and vertical displacements of the

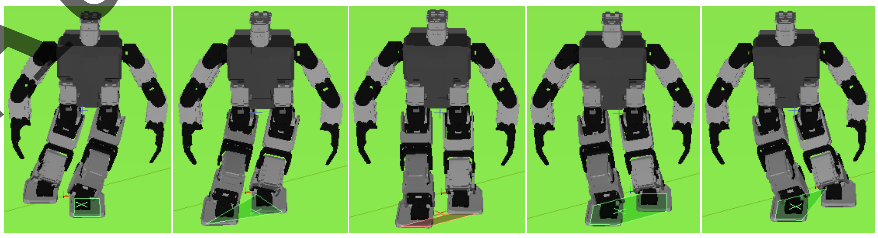


Fig. 7 Simulation of one step for the optimum walking in Webots©

pelvis, size of the steps, amount of rotations of the torso and the free foot, etc. This feature of the walking pattern allows to identify the relevant parameters for optimization of the gait. The study case presented in the paper shows the efficacy of the proposed method. Indeed, by applying the obtained optimal parameters the greatest stability margin is obtained compared with those corresponding to sets of parameters in Table 2.

In future work, an experimental validation of the results in this study will be accomplished. Besides, curvilinear paths and more parameters will be considered for optimization. In following curvilinear paths, and taking into account centrifugal forces, different optimal parameters will be required for lateral displacements of the pelvis in motions from the right to the left than those required from the left to the right, as previously observed in a preliminar study [8].

Acknowledgments This work was supported by the CONACyT (National Council of Research and Technology) and the DGTN (General Direction of the National Institute of Technology) of the Ministry of Public Education of Mexico.

References

1. Vukobratović, M. and Juricić, D.: Contribution to the Synthesis of Biped Gait. IEEE Transactions on Bio-Medical Engineering, Vol. 16, No. 1 (1969)
2. Shih, C. and Zhu, Y. and Gruver, W.: Optimization of the Biped Robot Trajectory. Proceedings of the 1991 IEEE International Conference on Robotics and Automation, pp. 899-903 (1991)
3. Huang, Q. and Yokoi, K. and Kajita, S. and Kaneko, K. and Arai, H. and Koyachi, N. and Tanie, K.: Planning Walking Patterns for a Biped Robot. IEEE Trans. on Robotics and Automation, Vol. 17, No. 3, pp. 280-289, June (2001)
4. Shi, J. and Li, Y., and Chung, S. and Lee, T., and Gruver, W.: Trajectory Synthesis and Physical Admissibility for a Biped Robot During the Single Support Phase. Proc. of the IEEE International Conference on Robotics and Automation, pp. 1646-1652 (1990)
5. Hirabayashi, T. and Ugurlu, B. and Kawamura, A. and Zhu, C.: Yaw Moment Compensation of Biped FastWalking using 3D Inverted Pendulum. Proc. of the *AMC'08. 10th IEEE International Workshop on. Advanced Motion Control,* pp. 296–300 (2008)
6. Khadiv, M. and Moosavian, S.A.A. and Yousefi-Koma, A., and Sadedel, M. and Mansouri, S.: Optimal gait planning for humanoids with 3D structure walking on slippery surfaces. Robotica, pp. 1-19, Cambridge University Press, (2015)
7. Arias, L. and Olvera L., and Pamanes, J.A. and Nunez, J.V,: Patrón de marcha 3D de tipo cicloidal para humanoides y su aplicación al robot Bioloid. Revista Iberoamericana de Ingeniería Mecánica (RIBIM), pp. 03-22 (2014)
8. Reyes, G. and Pamanes, J.A. and Nunez, V.: Análisis de la Marcha del Robot Humanoide Bioloid en una Ruta Circular con Parámetros Óptimos. Memorias del XIII Congreso Mexicano de Robotica (COMRob 2011) de la AMRob. Articulo A25, Matehuala, Mexico (2011)
9. Nunez, V. and Olvera, L. and Pamanes, J.A.: Simulation and Experimentation of Walking of the Bioloid Humanoid Robot. Proc. of the 13th IFToMM World Congress on Theory of Machines and Mechanisms, pp. 1644-1650, Guanajuato, México (2011).
10. Byrd, R.H. and Gilbert J.C. and Nocedal J.: A Trust Region Method Based on Interior Point Techniques for Nonlinear Programming, Mathematical Programming, Vol 89, No. 1, pp. 149–185, 2000.