# A Dynamic Walking Strategy for the Nao Robot Considering Path Planning, CoM and ZMP

Fredy H. Martínez S.#1, Fernando Martínez S.#2 and Edwar Jacinto G.#3
# FacultadTecnológica, Universidad Distrital Francisco José de Caldas
Carrera 13 #40-53, Bogotá D.C., Colombia
1 fhmartinezs@udistrital.edu.co
2fmartinezs@udistrital.edu.co
3ejacintog@udistrital.edu.co

*Abstract*—**This paper deals with the problem of the locomotion of robots with two legs with a design inspired by human locomotion (anthropomorphic bipedal robots). The future intention of the research group is to consolidate a robotic platform capable of interacting side by side with the human being, in particular by providing services to people. We propose a dynamic bipedal walking scheme based on a simulated model of inverted pendulum and using the Zero Moment Point (ZMP) as a control strategy. To solve the problem of closed-loop control, the strategy estimates the robot's Center of Mass (CoM) continuously. The formulation, analysis, solution and implementation is done on the Nao robot from Aldebaran Robotics. The strategy was encoded in a NAOqi module in Python, and executed in a Nao V5. The behavior of the robot during the walk demonstrated the success of the strategy.**

**Keyword -** Bipedal robot, Center of mass, Dynamic walking, Locomotion, Zero moment point

## I. INTRODUCTION

Despite the great progress made in recent years in robot control, and in particular in the area of bipedal walking schemes, many problems remain open to solution in this area [1]. The inherent complexity of these robots makes their control a difficult task, even with the most advanced hardware. This paper focuses on the predictive control of the model of a bipedal robot, which, following the previous experiences of other research projects of the group, uses an approximation of the behaviour of the leg to an inverted pendulum [2]. The proposed model is estimated in real time, using a simplified method with an approximation of the robot's Centre of Mass (CoM). The formulation, analysis, solution and implementation is done on the Nao robot from Aldebaran Robotics [3]. We selected the Nao robot for its great versatility, its wide range of movements that allows it to perform various tasks [4], which can be controlled through a simple programming algorithm [5].

The path planning for autonomous robots in human environments is one of the areas of greater research in robotics. In the case of robots with legs the possibilities of movement are greater, and therefore the problem is more complex [6]. Thanks to this type of displacement robots have the possibility to navigate rough terrain, unlike the flat floors used by robots with wheels. To do this, legged robots should support their legs in the surrounding environment regions that meet a certain number of characteristics, generally similar to those in flat environments. The rest of the environment does not require these characteristics, reason why they have in general a greater capacity of displacement.

The problem of walking robots with legs can be divided into two: the problem of route planning in the environment, and the problem of robot movement along this route [7]. In the first case, a global path planning scheme is usually proposed. These planning schemes consider the placement of the foot in the environment, the configurations of the contact with the terrain, and the connectivity of these configurations. According to these criteria, a route is defined that guarantees safety and stability during the movement.

In the case of dynamic environments in which obstacles do not have a fixed position in the environment, it is normal to use reactive navigation strategies [8]. Under this principle, each new movement of the robot depends on the analysis of its current state through local readings. These local readings provide the required environmental information for the next step. Although this strategy is used by the man in conscious walking, this generates stability problems by forcing the robot into a position during information processing.

In the second case (second problem) the coordinated movement of the robot (not only its legs, but the whole body) is considered, allowing its movement along the planned path [9]. With bipedal robots, the forced model is the human walk, basically due to its high energy efficiency, stability and performance [10]. From the studies of human biomechanics, patterns of walking with continuous and differentiable functions have been defined [11]. Most of these patterns are supported in the ZMP (Zero Moment Point) criterion [12, 13, 14].

The classic definition is that it's a point on the ground where the inertial and gravity moments cancel out resulting in a net zero moment [15]. A more practical definition is that it's the center of pressure in a process of mechanical support. The claim that ZMP is equivalent to COP (Center Of Pressure) has had much controversy over the years. This concept is important because it allows to estimate the stability of the leg (and of the robot). If the ZMP moves towards the edge of the leg, then the leg starts tipping over. Uncontrolled tipping is not good and often times leads the robot to fall over.

An alternative strategy to the ZMP is the CPG (Central Pattern Generator). The CPG models the walk with a nonlinear function derived from neuronal activity [16]. Although more complex, this scheme has the advantage that it does not depend on the constructive structure of the robot, however, as is always the case with neural networks, the weights of the solution have no relation to the parameters of motion. Another strategy independent of the topology of the robot is PFS (Partial Fourier Series or Truncation Fourier Series, TFS). In contrast to CPG, the parameters of the TFS can relate to the physical movements of joints, this allows the adjustment of the model. Also, the parameters of the Fourier series can be determined by means of an uninformed search algorithm [17].

An additional problem of these robots, not existing in robots with wheels, is the time of support on their feet. When the robot spends a lot of time leaning on a single leg, the contact of the foot with the ground becomes a very important variable for its stability.

This research focuses specifically on the problem of autonomous locomotion of a robot with two legs [18]. In this type of problem, the complexity of its solution stands out particularly due to the high non-linearity of the models developed for bipedal platforms. This is why many developments in control schemes assume simplified models of the robot with limited success [19, 20, 21].

In addition to the non-linear model of the bipedal structure, there are other problems in designing a walking strategy for robots. For example, many strategies take into account the position of the torso to establish robot balance. However, this criterion does not always work correctly, as it is affected by many factors, such as the movement of the arms. In our proposed bipedal walking scheme we use the center of mass of the robotic platform instead of the torso position, so we achieve greater stability in walking. Given the complexity of the robot's center of gravity calculation, we use a simplified method for its estimation and calculation. The walking strategy is also based on the inverted pendulum [22], a strategy that has been researched by our research group for the last ten years [2].

The following part of the paper is arranged in this way. Section 2 presents preliminary concepts and problem formulation. Section 3 illustrates the design profile and development methodology. Section 4 we present the preliminary results. And finally, in Section 5, we present our conclusions.

## II. PROBLEM FORMULATION

T When talking about bipedal robots, reference is made to robotic platforms whose displacement capacity is mainly centered on the movement of two legs. Although the movement can be carried out in different ways (for example, by dragging, levering, walking, etc.), in principle the design of the robots seeks to imitate human walking. Human walking is a system of locomotion made up of a sequence of multiple contacts of the legs with the ground. During the sequence, contacts and gaps are made between the legs and the floor, but gaps are never made simultaneously. A typical walking cycle is shown in Fig. 1.

The walking cycle of a biped is divided into two phases of swinging of the left and right leg (single support, SS), and two phases of double support (DS) when the two legs are on the ground. Within the swinging phases there are three stages: the detachment of the leg from the ground, the swinging itself and the impact of the leg on the ground. The convex edge in contact with the ground (ground plane) is called the support area. In the technical literature this area is represented by a polygon, which is why it is denoted as a polygon of support (PoS).

A step is defined as half of the walking cycle, which includes an SS and a DS. The term *gait* is used to indicate the pattern of movement during the walk. Finally, the term *balance* defines a state in which the bipedal system maintains its upright (vertical) position, and the terms static balance and dynamic balance are used to indicate situations in which the bipedal system is balanced while still, and while in motion. The objective is to achieve the displacement of the bipedal platform by implementing a walking cycle, and maintaining balance at all times.

Two strategies to ensure the dynamic balance of a bipedal system are currently being investigated with particular interest: projection of the center of mass of the bipedal robot (CoM, Center of Mass), and adjustment of the Zero Moment Point (ZMP, Zero Moment Point) of the platform.

### *A. Center of Mass*

This strategy focuses on the position of the CoM projection on the ground plane, which should be kept within the support area. Robots that use the CoM projection are called static walkers to indicate that the static balance is always maintained. Therefore, they can stop safely at any time. Static walkers are quite limited in their abilities. In particular, they are very slow as they have to control their acceleration. Furthermore, this criterion is only valid when all ground contacts are in the same horizontal plane (does not work on ramps).

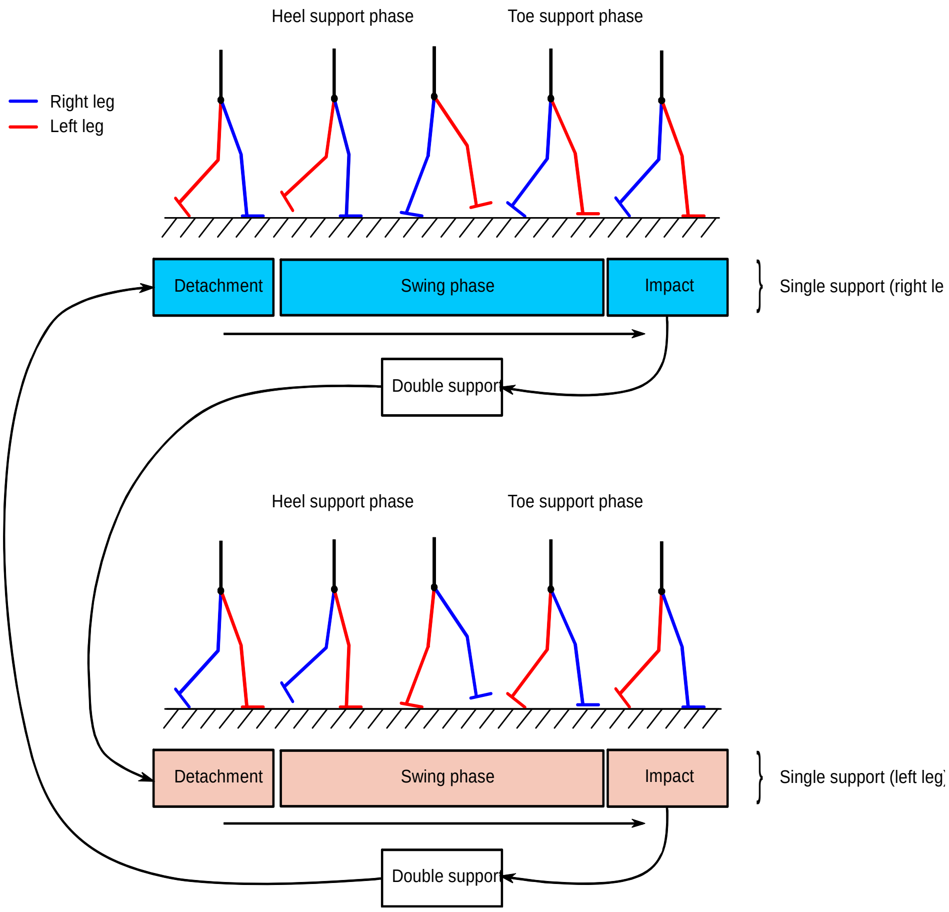

Fig. 1.Walking cycle of a biped

### *B. Zero Moment Point*

The ZMP is used to determine if a bipedal robot is in stable configuration. It corresponds to the point on the ground where the sum of all the moments of the active forces equals zero, i.e. the point where the reaction force at contact of the foot with the ground does not produce a horizontal momentum. In the simplified schematic inFig. 2, $m$ is the mass of the robot, $g$ is the gravity and $a$ is the acceleration of the CoM. The torque at any point $p$ is given by (Eq. 1):

$$M_p = p \cdot \vec{CoM} \times mg - p \cdot \vec{CoM} \times ma - H \qquad (1)$$

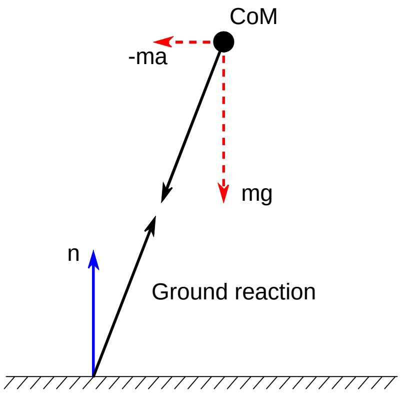

Fig. 2. Forces in the ZMP

Where $H$ is the rate of angular momentum in the CoM. The ZMP is the point on the ground that swings the robot. Therefore (Eq. 2):

$$P \cdot \overrightarrow{ZMP} = \frac{n \times M_p}{F \cdot n} (2)$$

where$P$ is the projection of the angle on the ground (normal projection of the CoM), and $n$ is the normal to the ground. This strategy assumes that the contact area is flat, and that it has enough friction to prevent the legs from slipping.

This research requires real-time operation. This is an important feature for a bipedal robot, since if the possible navigation routes are generated off-line, and then tried to adapt to the robot's movement, then there would be problems of movement and stability when forcing the movement. This is why the robot movement profile must be made in real time (on-line) from the current status of the robot. To achieve this requirement requires the use of a predictive control scheme. This predictive control is based on a simplified linearized model of the robotic platform in order to reduce the computational cost, and again, allow real-time operation.

The simplified linear model of robot dynamics used in the research corresponds to that of the inverted pendulum model. This model has been used by the research group for 10 years as a high performance strategy for the balance and walking process of different bipedal platforms [2, 23]. As stated in such works, the advantages of working with such a model include the possibility of ignoring the real structure of the robot by replacing it with a simplified model of inverted pendulum, and reducing the movements of the robot to a single plane. This plane is assumed without slope, parallel to the ground, and intercepts the $z$ axis at the height of the CoM. Since the system is controlled by applying torques, and the bipedal walk must be dynamic, the ZMP is selected as the movement and control strategy.

The implementation of the navigation strategy is done in the Nao robot of Aldebaran Robotics. Nao is a programmable humanoid robot with a height of 58 cm and 25 degrees of freedom (DoF). It has two cameras, four microphones, an ultrasonic distance sensor, an inertial sensor, nine tactile sensors and eight pressure sensors. We are working with a Nao Evolution V5 with NAOqi 2.0 operating system (Linux-based), Atom Z530 @ 1.6 GHz processor, 1 GB of RAM and 2 GB of Flash ROM memory. NAOqi is able to run modules written in C++ or Python, all our modules are developed in Python 2.7. These modules require the use of the Software Development Kit (SDK).

## III. METHODOLOGY

### A. Predictive Control Scheme

Under this principle it is assumed that the dynamics of the system is described by a system model, and that the immediate behaviour of the system can be predicted from this model. In this way, it is possible to select the control inputs in such a way that they behave as desired. The problem is solved continuously (iteratively) in order to keep the system within the desired behaviour. The objective of this research is to use the simplified model of the robot to estimate the CoM and ZMP in each iteration, and thus calculate the system response.

The predictive model compensates for the error in the ZMP caused by the difference between the model used for the robot (inverted pendulum) and a more accurate multibody model. This is a feedback control scheme that requires limited knowledge of the robot dynamics (e.g. the exact location of the CoM) or its structure, but compensates from this feedback.

The strategy produces a stable gait by changing the location of a leg from its original position. For this reason a flat floor without obstacles or ramps is required, this is a design constraint. Future research will adopt these problems in greater depth.

Let us suppose that the ZMP can be controlled by a linear system of form (this system is defined below in this Section)(Eq. 3):

$$\begin{aligned} \dot{\boldsymbol{X}}(t) &= \boldsymbol{A}\boldsymbol{X}(t) + \boldsymbol{b}u(t) \\ p(t) &= \boldsymbol{C}^T\boldsymbol{X}(t) \end{aligned} (3)$$

where$p$ are the ZMP coordinates in the plane $(x,y)$, and $p_{ref}$ is the ZMP reference. This system of equations can be written in discrete time, with $T$ sampling time, such as (Eq. 4):

$$\begin{aligned} \boldsymbol{X}[n+1] &= \boldsymbol{A}\boldsymbol{X}[n] + \boldsymbol{b}u[n] \\ p[n] &= \boldsymbol{C}^T\boldsymbol{X}[n] \end{aligned} (4)$$

where:

$$\boldsymbol{X}[n] \equiv \begin{bmatrix} X(nT) & \dot{X}(nT) & \ddot{X}(nT) \end{bmatrix}^T (5)$$

$$u[n] \equiv u_x(nT) (6)$$

$$p[n] \equiv p_x(nT) (7)$$

$$\boldsymbol{A} \equiv \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} (8)$$

$$\boldsymbol{b} \equiv \begin{bmatrix} \frac{T^3}{6} \\ \frac{T^2}{2} \\ T \end{bmatrix} (9)$$

$$\boldsymbol{C^T} \equiv \begin{bmatrix} 1 & 0 & -\frac{z_c}{g} \end{bmatrix} (10)$$

The performance index is given by:

$$J = \sum_{i=n}^{\infty} \{Q_e e(i)^2 + \triangle \boldsymbol{X}^T(i) \boldsymbol{Q}_x \triangle \boldsymbol{X}(i) + R \triangle u(i)^2\} (11)$$

where $e(i) = p(i) - p_{ref}(i)$ (Fig. 4), $Q_e$ and $R$ are greater than zero and $\boldsymbol{Q}_x$ is a non-negative symmetrical square matrix. $\triangle X[n] \equiv X[n] - X[n-1]$ is the incremental state vector and $\triangle u[n] \equiv u[n] - u[n-1]$ is the incremental control input.

The ZMP can be estimated $N$ future steps in each sampling interval minimizing the performance index.

### *B. Inverted Pendulum*

The dynamics of the robot's leg can be simplified by an inverted pendulum(Fig. 3). In addition, when the movement of this pendulum is restricted, for example, by making the mass move only on one plane (in our case parallel to the ground), then the pendulum model (and therefore the robot) is simplified to a linear system known as a three-dimensional linear inverted pendulum (3D-LIPM, Three-Dimensional Linear Inverted Pendulum Mode) [24]. In Fig. 3, the $x$ axis corresponds to the robot's forward direction.

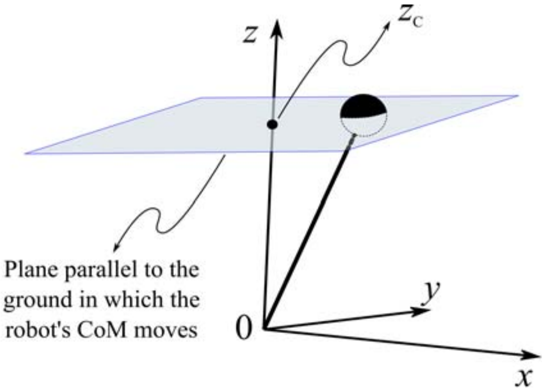

Fig. 3.Inverted pendulum with restricted movement

The plane parallel to the ground that restricts movement is represented by a normal vector ($k_x$,$k_y$,-1), and the intersection with the $z$ axis, $z_c$, is indicated as (Eq. 12):

$$z = k_x x + k_y y + z_c (12)$$

But since this plane is horizontal to the ground, that is, $k_x = k_y = 0$, then the dynamic model of the system is simplified to (Eq. 13):

$$\begin{aligned} \ddot{y}(t) &= \frac{g}{z_c} y(t) - \frac{1}{m z_c} \tau_x(t) \\ \ddot{x}(t) &= \frac{g}{z_c} x(t) + \frac{1}{m z_c} \tau_y(t) \end{aligned} (13)$$

where $m$ is the mass of the equivalent pendulum, $g$ is the acceleration of gravity and $\tau_x$, $\tau_y$ are the torques around the axes $x$ and $y$ respectively. The system of equations shown in Eq. 13 corresponds to a linear differential system. From this set of equations, it can also be seen that $z_c$ (the intersection of the plane with the $z$ axis) is the only parameter that affects the behaviour of the system.

From this system description, we can determine the ZMP of the 3D-LIPM model as (Eq. 14):

$$\begin{aligned} p_x(t) &= -\frac{\tau_y(t)}{mg} \\ p_y(t) &= \frac{\tau_x(t)}{mg} \end{aligned} \qquad (14)$$

where the coordinates ($p_x$,$p_y$) correspond to the location of the ZMP on the ground. Replacing the Eq. 14 in the Eq. 13 we obtain the dynamic model of the inverted pendulum (Eq. 15):

$$\begin{aligned} \ddot{y}(t) &= \frac{g}{z_c}\left(y(t) - p_y(t)\right) \\ \ddot{x}(t) &= \frac{g}{z_c}\left(x(t) - p_x(t)\right) \end{aligned} \qquad (15)$$

*C. Zero Moment Point (ZMP)*

For the calculation of the ZMP we rewrote the system of equations of the Eq. 15 (Eq. 16):

$$\begin{aligned} p_y(t) &= y(t) - \frac{z_c}{g}\ddot{y}(t) \\ p_x(t) &= x(t) - \frac{z_c}{g}\ddot{x}(t) \end{aligned} \qquad (16)$$

Now, since by definition the momentum around the ZMP must be zero, from the Eq. 1 we obtain (Eq. 17):

$$\tau_{ZMP}(t) = \left(x(t) - p_x(t)\right)mg - z_c m\ddot{x}(t) = 0 \qquad (17)$$

The latter equation (Eq. 17) actually coincides with the second equation in the system of equations of the Eq. 16. To calculate the sequence to follow during the walk, the movement variables of the equation Eq. 17 must be determined from a given ZMP.

In the equations Eq. 17and Eq. 16 (actually in the second equation of the system indicated in Eq. 16) the input variable is the horizontal acceleration of the CoM$\ddot{x}(t)$. If we take as control input the derivative of this acceleration, that is to say (Eq. 18):

$$\frac{d}{dt}\ddot{x}(t) = u_x(t)(18)$$

So the equation Eq. 16 of the ZMP (again the second equation of the system) can be rewritten as a dynamic system of form (Eq. 19):

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} x(t) \\ \dot{x}(t) \\ \ddot{x}(t) \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x(t) \\ \dot{x}(t) \\ \ddot{x}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u_x(t) \\ p_x(t) &= \begin{bmatrix} 1 & 0 & -\frac{z_c}{g} \end{bmatrix}\begin{bmatrix} x(t) \\ \dot{x}(t) \\ \ddot{x}(t) \end{bmatrix} \end{aligned} \qquad (19)$$

If we define similarly to $u_y(t)$ we obtain (Eq. 20):

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} y(t) \\ \dot{y}(t) \\ \ddot{y}(t) \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} y(t) \\ \dot{y}(t) \\ \ddot{y}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u_y(t) \\ p_y(t) &= \begin{bmatrix} 1 & 0 & -\frac{z_c}{g} \end{bmatrix}\begin{bmatrix} y(t) \\ \dot{y}(t) \\ \ddot{y}(t) \end{bmatrix} \end{aligned} \qquad (20)$$

Using the equations Eq. 19 and Eq. 20 we can build a closed-loop control block that tracks the ZMP from a reference, and in so doing produces the trajectory of the CoM (Fig. 4).

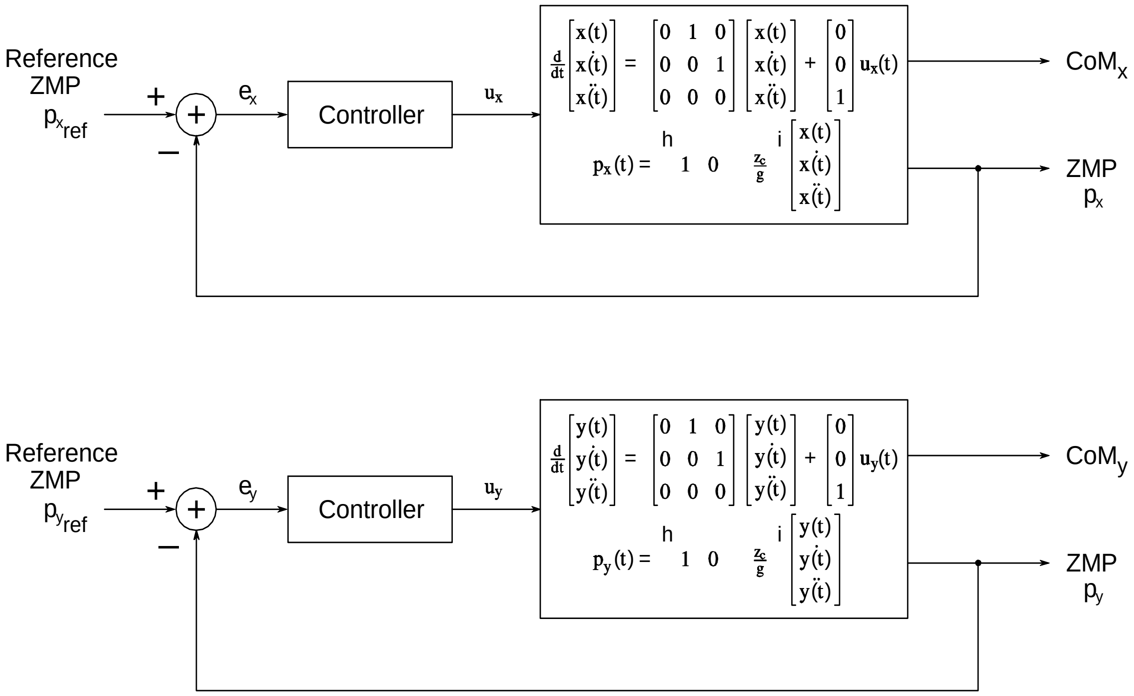

Fig. 4. ZMP tracking and CoM generation

## IV. RESULTS AND DISCUSSION

The proposed strategy was implemented in a module for the Nao robot written in Python 2.7. The module calculates the walking pattern and walking movements for the Nao by solving the inverse kinematics so that the robot's CoM follows the output of the predictive control. Fig. 5 shows a simulation of predictive control by estimating the robot position (ZMP and CoM) for a step. This module loads and runs in the NAOqi framework of the robot. Control commands are sent to the robot software via command line from a 64-bit Linux computer with kernel 4.13.0-46.

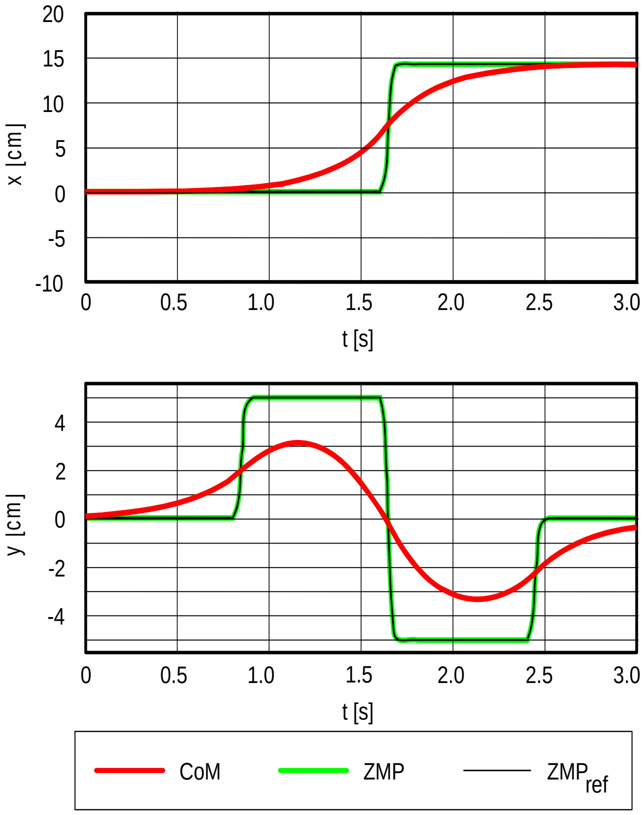

Fig. 5. Predictive control simulation by estimating the robot position (ZMP and CoM) for a single step

With respect to inverse kinematics, the angles required in each joint are determined according to the desired position, and the current position of the leg. The support leg of each step serves as the basis for the kinematic calculation, this base changes with each step. In addition, the angles of the upper joints remain fixed, and are not activated during walking (activation of the 12 lower joints is performed).

The height (1.5 cm) and length (5.5 cm) of the step were set in advance in such a way as to increase the stability of the robot without significantly affecting the walking speed. The SS phase has an approximate duration of 340 ms, and the DS phase has an approximate duration of 170 ms.

The strategy was evaluated on the robot by walking in a straight line. Unlike simulations, the actual operation of the robot did not precisely follow the path designed for the legs. In principle, the robot's oscillations and the roughness of the ground affected the behaviour away from the ideal. The final behaviour can be seen in the video of the following link: https://youtu.be/hbPzzWBevOE (Fig. 6).

Fig. 6. Nao robot walk in a straight line according to the proposed strategy

## V. CONCLUSION

In this paper we present a walking strategy for bipedal humanoid robots that allows the dynamic control of the robot in real time. The strategy uses a combination of ZMP-based strategies and inverted pendulum to calculate the new location of the leg at each step. The feedback of the global control scheme is carried out by means of a predictive model that allows the complex structure of the real robot to be taken into account, but making simple calculations in real time relative to an inverted pendulum. The strategy was implemented in a Python module for use in a Nao robot. The observed performance validates the design hypotheses, and makes it possible to verify that it is possible to implement the walking strategy in real time. Future research will focus on problems of obstacle avoidance (incorporating artificial vision) and ramp handling.

## ACKNOWLEDGMENT

This work was supported by the Universidad Distrital Francisco José de Caldas, in part through CIDC, and partly by the FacultadTecnológica. The views expressed in this paper are not necessarily endorsed by Universidad Distrital. The authors thank the research groups ARMOS and DIGITI for the evaluation carried out on prototypes of ideas and strategies.

## REFERENCES

[1] I. Lopez, Skill acquisition for industrial robots: From stand-alone to distributed learning, IEEE International Conference on Automatica (ICA-ACCA 2016), 2016, pp. 1–5.
[2] F. Martínez, D. Acero and M. Castiblanco, Hybrid fuzzy-sliding scheme for the balance control of a biped robot, Lecture Notes in Computer Science, vol. 5216, 2010: pp. 434–441.
[3] S. Shamsuddin, L. Ismail, H. Yussof, N. Zahari, S. Bahari, H. Hashim and A. Jaffar, Humanoid robot nao: Review of control and motion exploration, IEEE International Conference on Control System, Computing and Engineering, 2011, pp. 511–516.
[4] I. Ariffin, A. Hakam, M. Rasidi, H. Yussof, M. Miskam and A. Omar, Vision tracking application for mobile navigation using humanoid robot nao, International Symposium on Micro-NanoMechatronics and Human Science (MHS 2015), 2015, pp. 1–7.
[5] S. Michieletto, D. Zanin and E. Menegatti, Nao robot simulation for service robotics purposes, European Modelling Symposium, 2013, pp. 477–482.
[6] J. Chestnutt, J. Kuffner, K. Nishiwaki and S. Kagami, Planning biped navigation strategies in complex environments, International Conference on Humanoid Robots (Humanoids 2003), 2003, pp. 1–16.

[7] C. Ullrich, S. Dotenco and F. Gallwitz, A hybrid approach for simultaneous obstacle avoidance and stabilization of dynamic bipedal walking using the aldebarannao robot, 15th International Conference on Innovations for Community Services (I4CS 2015), 2015, pp. 1–6.

[8] A. Rendón, Evaluación de estrategia de navegaciónautónomabasada en comportamientoreactivo para plataformasrobóticasmóviles, Tekhnê, vol. 12(2), 2015: pp. 75–82, ISSN 1692-8407.

[9] J. Ning, C. Liu, H. Wang and Q. Chen, Self-balanced motion planning for humanoid robot based on dynamic multitasking mechanism, IEEE 13th International Conference on Networking, Sensing, and Control, 2016, pp. 1–6.

[10] K. Teachasrisaksakul, Z. Zhang, G. Yang and B. Lo, Imitation of dynamic walking with bsn for humanoid robot, IEEE Journal of Biomedical and Health Informatics, vol. 19(3), 2015: pp. 794–802.

[11] J. Liu, U. Schwiegelshohn and O. Urbann, Stable walking of a bipedal humanoid robot involving three-dimensional upper body motion, 14th IEEE-RAS International Conference on Humanoid Robots (Humanoids), 2014, pp. 80–85.

[12] H. Fadli, E. Hidayat and C. Machbub, Design and implementation of walking pattern and trajectory compensator of nao humanoid robot, IEEE 6th International Conference on System Engineering and Technology (ICSET 2016), 2016, pp. 184–188.

[13] H. Wang, C. Liu and Q. Chen, Omnidirectional walking based on preview control for biped robots, IEEE International Conference on Robotics and Biomimetics (ROBIO 2016), 2016, pp. 856–861.

[14] S. Piperakis, E. Orfanoudakis and M. Lagoudakis, Predictive control for dynamic locomotion of real humanoid robots, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014), 2014, pp. 4036–4043.

[15] Z. Sun and N. Roos, An energy efficient dynamic gait for a nao robot, IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC 2014), 2014, pp. 267–272.

[16] H. Farazi, F. Ahmadinejad, F. Maleki and M. Shiri, Evolutionary approach for developing fast and stable offline humanoid walk, 3rd Joint Conference of AI and Robotics and 5th RoboCup Iran Open International Symposium (RIOS 2013), 2013, pp. 1–6.

[17] S. Haider, S. Abidi and M. Williams, On evolving a dynamic bipedal walk using partial fourier series, IEEE International Conference on Robotics and Biomimetics (ROBIO 2012), 2012, pp. 8–13.

[18] D. Gouaillier, C. Collette and C. Kilner, Omni-directional closed-loop walk for nao, 10th IEEE-RAS International Conference on Humanoid Robots, 2010, pp. 448–454.

[19] J. Yeon and J. Park, A fast turning method for biped robots with foot slip during single-support phase, IEEE/ASME Transactions on Mechatronics, vol. 19(6), 2014: pp. 1847–1858.

[20] R. Khusainov, I. Shimchik, I. Afanasyev and E. Magid, Toward a human-like locomotion: Modelling dynamically stable locomotion of an anthropomorphic robot in simulink environment, 12th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2015), 2015, pp. 141–148.

[21] D. Galdeano, A. Chemori, S. Krut and P. Fraisse, Optimal pattern generator for dynamic walking in humanoid robotics, 10th International Multi-Conferences on Systems, Signals & Devices 2013 (SSD13), 2013, pp. 1–6.

[22] I. Motoc, K. Sirlantzis, S. Spurgeon and P. Lee, Zero moment point/inverted pendulum-based walking algorithm for the nao robot, Fifth International Conference on Emerging Security Technologies, 2014, pp. 63–66.

[23] J. Gordillo and F. Martínez, Fuzzy control for bipedal robot considering energy balance, Contemporary Engineering Sciences, vol. 11(39), 2018: pp. 1945–1952.

[24] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi and H. Hirukawa, Biped walking pattern generation by using preview control of zero-moment point, IEEE International Conference on Robotics and Automation, vol. 2, 2003, pp. 1620–1626.

## AUTHOR PROFILE

Fredy Hernán Martínez Sarmiento PhD in Engineering - Systems and Computation, Professor at the Universidad Distrital Francisco José de Caldas, Director and principal researcher of the ARMOS research group.

Fernando Martínez Santa MSc in Electronic and Computer Engineering, Professor at the Universidad Distrital Francisco José de Caldas, Researcher of the ARMOS research group.

Edwar Jacinto Gómez MSc inSciences of the Information and Communications, Professor at the Universidad Distrital Francisco José de Caldas, Researcher of the ARMOS research group.