World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:13, No:8, 2019

Combined Model Predictive Controller Technique for Enhancing NAO Gait Stabilization

Brahim Brahmi, Mohammed Hamza Laraki, Mohammad Habibur Rahman, Islam M. Rasedul, M. Assad Uz-Zaman

***Abstract*—**The humanoid robot, specifically the NAO robot must be able to provide a highly dynamic performance on the soccer field. Maintaining the balance of the humanoid robot during the required motion is considered as one of a challenging problems especially when the robot is subject to external disturbances, as contact with other robots. In this paper, a dynamic controller is proposed in order to ensure a robust walking (stabilization) and to improve the dynamic balance of the robot during its contact with the environment (external disturbances). The generation of the trajectory of the center of mass (CoM) is done by a model predictive controller (MPC) conjoined with zero moment point (ZMP) technique. Taking into account the properties of the rotational dynamics of the whole-body system, a modified previous control mixed with feedback control is employed to manage the angular momentum and the CoM's acceleration, respectively. This latter is dedicated to provide a robust gait of the robot in the presence of the external disturbances. Simulation results are presented to show the feasibility of the proposed strategy.

***Keywords*—**Preview control, walking, stabilization, humanoid robot.

I. Introduction

A qualified and practical robotics system has been developed to be used in human environments, known presently as humanoid robots or human-like robot [1]-[4]. Humanoid robot research field is still emerging and active. Over the past decade, many mechanical improvements have been proposed which permit to this class of robots to operate, collaborate, support and interact with humans. This improvement accommodates the cooperation with the human and appropriately adapts to his disorganized and large environment. Among the important challenges of this kind of robots are whole-robot motion modeling, movement coordination and dynamic control. For example, the desired activity for human-like robots is not restricted to the characterization of the position and/or orientation of a single effector. But the characterization of the desired activity may include incorporation of coordinates linked with the limbs, the legs, the head-camera, and/or the torso among others. Several criteria associated with the human-like posture and its internal and environmental constraints may be assigned to the residual freedom of motion. Consequently, the design complexity of the kinematics and dynamics of humanoid robot make the implementation of control techniques very challenging.

Latterly, NAO robot [5] has drawn significant attention from the scientific community due to its capability to participate in many areas even daily activity. Since 2008, NAO is the main robot used in the RoboCup Standard Platform League [6]. In this competition, the stabilization of the walk and the collaboration of the team play a significant role in the game results. RoboCup competition provides an excellent examination conference for balance control, formation control and many dynamic skills for humanoid robots [7]-[9]. The implementation of these controls in real robots still stays an open problem. In this paper, we concentrate on the dilemma of walking robustness and effect rejection of external disturbance for NAO robot. Various approaches dedicated to the biped walking pattern generation can be classified into two categories. The first group uses accurate knowledge of the dynamic behaviour of the robot, like the location of the centre of mass, inertia of each link and mass to provide walking pattern [10], [11]. Unlike the first group, the second one uses limited knowledge of the dynamics of the robot, such as the absences of the exact location of the centre of mass and total angular momentum to prepare the walking pattern [12]-[14]. This approach is known as the simplified dynamic models of the humanoid robot and stability criteria. So, the walking pattern developed in this paper is inspired from the second group.

The most frequent stability criterion is based on the ZMP idea [15]-[17]. The ZMP defines the point on the ground where the tipping moment acting on the robot equals zero because of gravitational and inertial forces [17]. This point always exists inside the limits of the support polygon or convex hull. Contrarily, gravitational and inertial forces would cause a moment around an axis located at the nearest side of the support polygon. Practically the accurate position of ZMP is not available due to the requirement of complex and heavy computation. In this case, the legged robot is modeled as inverted pendulum by focusing robot's all mass at the location of the CoM. Applying 3D linear inverted pendulum mode (3D-LIPM) [18] permits to linearize the nonlinear dynamic of CoM and present it by second order linear differential equation. This configuration allows for the ZMP's desired path to implement the preview approach to the design of CoM trajectory [17], [19]-[21].

Despite the exceptional success of the walking pattern generation strategies by incorporating 3D-LIPM and ZMP, they ignore the rotational inertia of the upper parts of the robot, which plays a significant role in walking balance [22]. So, the presence of even small external disturbances can negatively influence the stabilization of the robot. In such case, the control of angular momentum can be used to overcome the influence of external and unexpected disturbances [23], [24]. To solve the mentioned problem, a

Brahmi Brahim is with the Ecole Technologies Superieure, Canada (e-mail: brahim.brahmi.1@ens.etsmtl.ca).

resolved momentum control strategy [25] is developed to plan the trajectory of the robot's joints by associating both the CoM's linear momentum and angular momentum throughout the CoM. Additionally, ankle, hip and step approaches [26] are combined in order to reject the effect of the external unforeseen disturbances. In fact, the implementation of approaches that help to reduce or to reject the effect of external disturbances and unforeseen forces presents a challenge in the real environment and requires a sophisticated algorithm to reduce them. Note that there is a big difference between the real physical model of the robot and the simplified dynamic model that make it difficult to implement these approaches in the presence of limited computing resources, delays and noisy of the sensors.

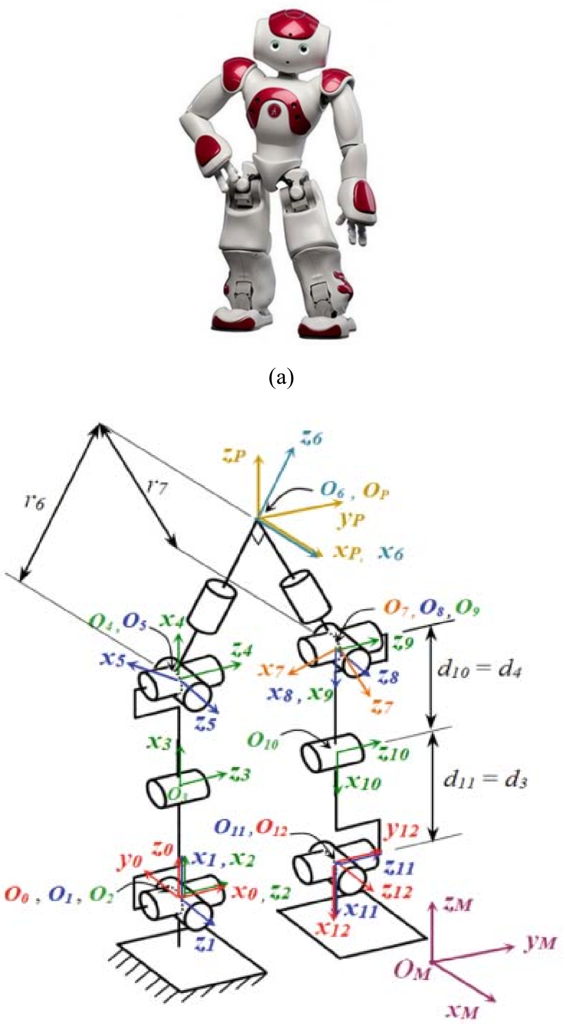
In this paper, a dynamic controller is proposed in order to ensure a robust walking (stabilization) and to improve the dynamic balance of the robot combined with a robust algorithm. It permits to reject the external disturbances and unexpected forces. An MPC is applied and combined with ZMP and 3D-LIPM in order to perform the CoM trajectory. Taking advantage of the availability of sensors in NAO robot, we use a feedback controller in order to improve the stability and disturbance reduction operation during walking. The first feedback control is adopted to control the angular momentum taking into consideration the characterization of the rotational dynamics of the whole-body system. The controller employs a proportional action (P) to manage the acceleration of CoM, which means that the 3D-LIPM is expanded by the angular momentum, taking advantage from its capability to increase the effect of the disturbances. This combination allows increasing the balance performance. Using this controller helps to avoid a large tracking error of ZMP caused by the trajectory of CoM generated by MPC. This control is a powerful technique which is used to reduce the disturbances and unexpected forces. The incorporation of these techniques helps us provide a robust control able to ensure a satisfactory walking pattern with very high stabilization and balancing algorithm against the external disturbances.

The rest of the paper is organized as follows: A kinematic description of NAO robot is presented in the next Section. A MPC is described in Section III. Angular momentum problem and control strategy are given in Section IV. In Section V, we present some simulation results. A conclusion and future work are discussed in the last section.

II. The Humanoid Robot NAO

NAO is a biped robot, made by Aldebaran Company. It has 0.57 m of height and 4.5 kg of weight with 25 degrees of freedom (DOFs): 5-DOFs for each arm, 1-DOFs for each hand, 2-DOFs for the head, and 12-DOFs for the legs (each leg has six rotational joints) see Fig. 1. The movement of the leg joints connected to the pelvis are constrained in such a way that one actuator performs symmetrical rotations which complicate the solution of inverse kinematics [27].

NAO robot is equipped with a set of sensors providing a state feedback of the robot that allows controlling it. Among them, two cameras are used to localize the objects and generate the walking trajectory of the robot. An accelerometer and gyrometer measurements are installed to provide a direction and orientation motion of the robot. In addition, sonar sensors and force-sensitive sensor are located under its feet to provide the feedback of the contact forces with the environment. All these feedbacks help improve the balancing of the walk.



(a)

(b)

Fig. 1 (a) The NAO humanoid robot designed by the Aldebaran Company [6], (b) Kinematic chain of NAO's legs

III. Generation Trajectory of COM

The motion of CoM plays an important role in maintaining the balance of NAO robot. The generation of the CoM's trajectory is still an emerging area. However, the ZMP stability criterion remains the most used to achieve a robust walking of the robot. The ZMP criterion usually neglects the rotational inertia of the NAO robot, which considered the main shortcoming of this criterion. Neglecting rotational inertia can be acceptable in the presence of limited disturbances. But, in the environment such as soccer game with unexpected disturbances, this assumption is invalid to complete a robust gait. For this purpose, we mixed the CoM's trajectory with feedback controller with the objective to adapt it to unexpected disturbances during interaction with environment or other robots.

It is important to know that the ZMP stability criterion forces the ZMP to stay in the support polygon of the NAO robot in order to keep it balanced. In this case, we used 3D-LIPM to compute the ZMP position. This approach is valid based on two assumptions: 1) the NAO robot acts as a single point located in CoM and 2) the movement of this point is limited to a horizontal plane. Now, let us plan the CoM's trajectory that allows precise tracking of the desired trajectory of ZMP. Based on the 3D-LIPM model, the relationship between the CoM's state and ZMP is given by [27]:

$$\ddot{x} = \frac{G}{Z}(x - p) \tag{1}$$

where x and Z are the CoM's positions, p is the ZMP's position in the sagittal plane and G is the gravitational force. There are many solutions for CoM's trajectory given a reference ZMP's trajectory. To solve the problem of CoM trajectory, we used MPC approach to obtain CoM's trajectory that minimizes both the tracking error of the trajectory ZMP's reference and control input. MPC has been shown to be an effective control strategy that is well suited to solve complex problems. Based on the optimal control theory, it is widely applied in the industry. The objective of MPC is to obtain predicted state trajectories using the current states and the predictive computed control signals. The main motivation of the use of MPC in the NAO robot is its ability to handle many limits and constraints. Indeed, MPC has the ability to handle the dynamic limits in an explicit way by including them in the optimization process which is used to obtain the predictive control laws. The MPC technique uses an explicit model of plant control to predict future output behavior. Employing this prediction, an optimal control solution can be ensured online, where a minimization solution of tracking error can be obtained between the expected output and the desired trajectory is over a future horizon [20].

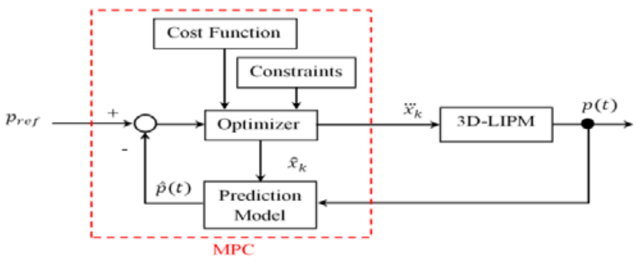


Fig. 2 The diagram of MPC scheme

Fig. 2 shows the overall scheme of the MPC solution. A LIPM prediction model is utilized to expect the current output variables. The error between the reference position and the estimated position is considered as input to the optimizer block as shown in Fig. 2. In this block, control computation is performed at each step time to compute expectation. Constraints on the input and output variables can be introduced in either type of computation. The calculations are based on current measurements and predictions of the future values of the outputs. The objective is to determine a sequence of control movements (i.e. manipulated input changes) so that the predicted response moves to the set-point in an optimal manner. The control is the jerk of CoM where the system contains the position, velocity and acceleration of CoM. Hence, the quantity of the jerk used to the CoM remains constant for the period of control sequence and the state equations turn into:

$$\begin{bmatrix} x_{k+1} \\ \dot{x}_{k+1} \\ \ddot{x}_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_k \\ \dot{x}_k \\ \ddot{x}_k \end{bmatrix} + \begin{bmatrix} \frac{T^3}{6} \\ \frac{T^2}{2} \\ T \end{bmatrix} \dddot{x}_k \tag{2}$$

Upon the preview period, the cost function is a composite of the squared ZMP tracking errors and the squared jerks motion [20]. So, the solution or control input $\dddot{x}_k$ is given in [20] such that:

$$\dddot{x}_k = -E\left(\left(M_u^T M_u + \frac{R}{Q} I\right)^{-1} M_u^T\left(M_x \hat{x} - p_k^{ref}\right)\right) \tag{3}$$

The state's estimation of the system with respects to the sample k is given by $\hat{x}_k$ is described by $\hat{x}_k = [x_k, \dot{x}_k, \ddot{x}_k]$ and the remainder matrix of function (3) is given such that:

$$E = [1,0 \ldots ,0]_{1\times N} \tag{4}$$

$$M_u = \begin{bmatrix} \frac{T^3}{6} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ (1+3N+3N^2)\frac{T^3}{6} & \cdots & (1+3N+3N^2)\frac{T^3}{6} \end{bmatrix}_{N\times N} \tag{5}$$

$$M_x = \begin{bmatrix} 1 & T & \frac{T^2}{2} - \frac{Z}{G} \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ 1 & NT & \frac{N^2T^2}{2} - \frac{Z}{G} \end{bmatrix}_{N\times 3} \tag{6}$$

$$p_k^{ref} = \left[p_k^{ref} \quad \ldots \quad p_{k+N-1}^{ref}\right]_{N\times 1}^T \tag{7}$$

where p_k^{ref} is the desired ZMP position. $N = 100$ presents the number of reference samples and $I_{N\times N}$ is $(N \times N)$ identify matrix. Also, R and Q are respectively, the weights for the tracking error of ZMP position and minimum jerk with the ratio $\frac{R}{Q} = 10^{-1}$. $T = 10ms$ is sampling time, and $CoM_z = 260mm$.

IV. Walking Balance Control

In the previous section, an approach is offered to perform a walking pattern in order to give an appropriate rule for the walk. A smooth trajectory of CoM is provided to keep the gravity and inertial force of the robot in the support polygon.

While examining this method, the walking robustness is questionable since it assumes that the feet are flat on the ground, the robot's motors skillfully follow the planned trajectory, fully neglect the rotational inertia of whole body of the robot and disregard any presences of external disturbances. In this section, two feedback controllers are developed with the goal to eliminate all the previous simplification of the model and to provide robust gait of the NAO robot.

A. The Angular Momentum Dilemma

As we discuss above, MPC approach uses a simplified model of the robot which permits to generate the CoM trajectories. However, the interaction of the robot with an unknown or external force, for example, when NAO robot kicks a ball, this action leads to inclination of the feet plane. In this case, the support polygon or convex hull decreases to a line or point which considers the borders of the sole touch with the ground, which causes a reaction force acting to be located outside the convex hull. In such situation, the ZMP is converted to an FZMP (fictitious zero moment point), where ZMP can only occur within the convex hull boundary. The slope of the sole support causes an offset between the CoM's state and the inner MPC's state. Thus, the position of the FZMP cannot meet the ZMP determined by the MPC because it uses an inexact CoM state.

For illustration, if the reference position of ZMP is established to a fixed point located between the NAO's ankles of the robot, the CoM's path acquired from the MPC approach will go to the perpendicular projection of the ZMP over the constant height level. Without feedback control, this reference will be preserved despite the external disturbance. In this case, the sole plane will incline and the FZMP will shift far from the location of the ZMP since the NAO robot experiences a disturbance. While the amplitude of perturbation is decreased, the torque produced by the FZMP on the boundary of the support polygon will decrease the rotational velocity of the NAO robot and will meet the flexion point. In this latter case, the rotational velocity of the sole plane will change its sign and will begin to retrieve the horizontal position while the length between the ZMP's reference position and the FZMP will be maximum. In such case, the amplitude of the rotational velocity has increased when the sole retrieves the horizontal position, which implies that the NAO robot has accumulated a certain angular momentum that will turn it in the opposite direction.

The purpose of the suggested angular momentum controller is to adjust the torque τ produced at the borders of the polygon support by modifying the CoM's trajectory acquired from the MPC approach. The torque is changed to decrease the angular velocity. As shown in Fig. 3, the angular momentum controller creates an additional acceleration that performs an inertial force f_I. The latter moves the FZMP's position based on rotational velocity. The performance of the proposed controller is shown in Fig. 4 in two distinct cases. If ($\dot{\theta} > 0$), it means that the perturbation is influenced the position of the sole plane by $\dot{\theta} > 0$ with respect to the horizontal coordination. The proposed controller produces a torque to slow the rotational velocity by moving the FZMP away from the rotation axis. If ($\dot{\theta} \leq 0$), it means that the sole plane returns to its initial position or opposite position with value of $\dot{\theta} \leq 0$. The proposed controller moves the FZMP in the opposite direction in order to decrease the performed torque which permits to keep a small rotation velocity.

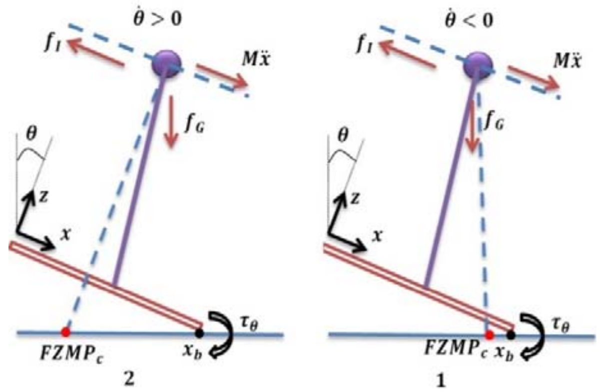


Fig. 3 The CoM's acceleration performed by the angular momentum controller

B. Angular Momentum Control

Let us assume a CoM point located at world frame $(O_M, x_M y_M z_M)$ (see Fig. 1), the torque is expressed such that:

$$\tau = l \times f \tag{8}$$

where l is the length from the CoM position to the rotation axis, f is the force applied on CoM point. Note that the rotation axis exists at the borders (one of its extremes) of the sole support (x_b). In this paper, we investigated the dynamics of the robot only on the sagittal plane since similar results can be obtained with dynamics obtained on the frontal plane. So, the forces that participate on the sagittal plane can be described as:

$$\begin{cases} f_x = f_{Ix} + f_{Gx} = -M\ddot{x} + MG\sin(\theta) \\ f_z = f_{Iz} + f_{Gz} = -MG\cos(\theta) \end{cases} \tag{9}$$

where θ is the angle of rotation of z-axis around y-axis with respect the world frame. M is the NAO's mass and G is the gravitational force. From the mentioned forces, we can define the torque around x_b such that:

$$\tau_\theta = M\big(G\big(z\sin(\theta) - x_b\cos(\theta) + x\cos(\theta)\big) - \ddot{x}z\big) \tag{10}$$

Based on the sign of θ, the position of the limit of the sole in contact with the world or with the floor, x_b will be between the toe and the ankle. In such case, the objective of the control is to manage the acceleration CoM ($\ddot{x}$) to reduce the NAO's angular momentum:

$$L = I\dot{\theta} \tag{11}$$

For the real physical parameters of NAO robot, the range of x is within $[-30\,mm, 40mm]$, the CoM's height is fixed to

260 mm, which helps to simplify the model. Thus, any change of the momentum (I) around the extremes of the sole support makes it possible to treat it as constant. Therefore one obtains:

$$\tau_\theta = I\frac{d(\dot{\theta})}{dt} = I\ddot{\theta} \quad (12)$$

We can conclude that the angular acceleration ($\ddot{\theta}$) is relatively proportional to the torque around the sole limit (x_b). We can also remark from (10) a direct participation of the acceleration of CoM ($\ddot{x}$) to the torque around the sole limit (x_b). Therefore, a suitable control for CoM's acceleration of the proposed controller (x_f) is:

$$\ddot{x}_f = K\dot{\theta} \quad (13)$$

where $K > 0$. Integration of both side of (13) and discretization with T period or sampling period time, we find:

$$x_{fk+1} = x_{fk} + K\theta_k T \quad (14)$$

Because of the angular momentum control, there is an increase in the CoM's position as:

$$x_{AMk} = K\theta_k T \quad (15)$$

Let us summarize the structure of the controller, (10) is used to find the torque around the sole limit, and (15) is employed to perform the control action. Via (12), we can define the angular acceleration and its double integral to obtain θ. Fig. 4 presents the schematic diagram of the proposed controller.

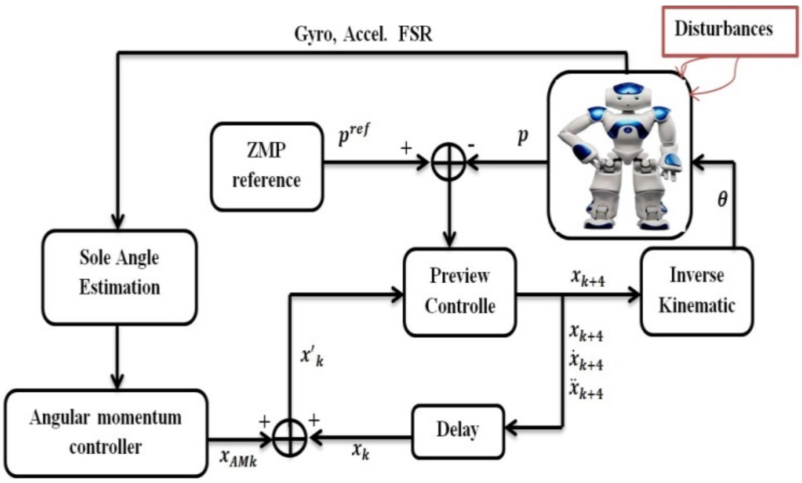


Fig. 4 The schematics of the whole proposed balanced walking controller

C. ZMP Preview Controller

In this section we will present the ZMP preview control and its extension proposed by [27]. Firstly, the ZMP equation can be written as:

$$p_x = x - \frac{Z}{G}\ddot{x} \quad (16)$$

$$p_y = y - \frac{Z}{G}\ddot{y} \quad (17)$$

where Z is defined in the world frame and it presents the distance between the CoM position and the sole. Supposing that $u = \ddot{x}$, the ZMP equation can be rewritten in the following state space representation or Cart table model*:*

$$\frac{d}{dt}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u$$
$$p = \begin{bmatrix} 1 & 0 & -\frac{Z}{G} \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} \quad (18)$$

where p is the CoM's state. To force the system to follow the input reference, a digital controller is proposed. Let us firstly discretize the system (18) using sampling time T as:

$$\begin{cases} x_{k+1} = Ax_k + Bu_k \\ p_k = Cx_k \end{cases} \quad (19)$$

with: $A = \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \\ 0 & 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} \frac{T^3}{6} \\ \frac{T^2}{2} \\ T \end{bmatrix}$, $C = \begin{bmatrix} 1 & 0 & -\frac{Z}{G} \end{bmatrix}$. Let us assume the incremental state by: $\Delta x_k = x_k - x_{k+1}$. The state is augmented as $\tilde{x} = \begin{bmatrix} p(k) \\ \Delta x_k \end{bmatrix}$, therefore (19) can be reformulated as:

$$\begin{cases} \tilde{x}_{k+1} = \tilde{A}\tilde{x}_k + \tilde{B}u_k \\ p_k = \tilde{C}\tilde{x}_k \end{cases} \quad (20)$$

where $\tilde{A} = \begin{bmatrix} 1 & CA \\ 0 & A \end{bmatrix}$, $\tilde{B} = \begin{bmatrix} CB \\ B \end{bmatrix}$, $\tilde{C} = [1 \quad 0 \quad 0 \quad 0]$. The proposed digital control is given as:

$$u_k = -g_i \sum_{i=1}^{k} e_i - g_x x_k \quad (21)$$

where $e_i = p - p^{ref}$ is the ZMP tracking error, and g_i, g_x are respectively the gain of ZMP tracking error and the gain of the feedback state. Due to the phase delay, the control (21) is not able to force the system to follow the reference ZMP perfectly. To resolve this problem, a new term has been added to the controller (21) as follows:

$$u_k = -g_i \sum_{i=1}^{k} e_i - g_x x_k - \sum_{j=1}^{N} g_p p^{ref}(k+j) \tag{22}$$

Note that the third term consists of the planned ZMP trajectory to N samples in the future. It is named preview controller since the control employs future information. The term g_p represents the preview gain. One second of future reference walking is adequate for this controller to perform a smooth motion. Based on incremental time step, the N can be easily obtained such that: $N = \frac{1}{T}$. A detail of the previous control strategy as an optimal controller approach can be found in [27]. The optimal g_i and g_x are obtained by solving the discrete algebraic Riccati equation as follows:

$$\tilde{p} = \tilde{A}^T \tilde{p} \tilde{A} - \tilde{A}^T \tilde{p} \tilde{B} \left(R + \tilde{B}^T \tilde{p} \tilde{B}\right)^{-1} \tilde{B}^T \tilde{p} \tilde{A} + \tilde{Q} \tag{23}$$

where $\tilde{Q}$ and R are positive weights. Hence, the optimal gain can obtained as:

$$\tilde{g} = [g_i \quad g_x] = \left(R + \tilde{B}^T \tilde{p} \tilde{B}\right)^{-1} \tilde{B}^T \tilde{p} \tilde{A} \tag{24}$$

So, the optimal preview gain is calculated recursively by considering $\tilde{A}_c = \tilde{A} - \tilde{B}\tilde{g}$ as:

$$\begin{gathered} g_p(i) = \left(R + \tilde{B}^T \tilde{p} \tilde{B}\right)^{-1} \tilde{B}^T \tilde{x}(i-1) \\ \tilde{x}(i-1) = \tilde{A}_c{}^T \tilde{x}(i-1) \end{gathered} \tag{25}$$

where $g = -g_i \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $\tilde{x}(1) = \tilde{A}_c{}^T \tilde{p} \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $Q = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ and $R = 1 \times 10^{-6}$.

V. Case Study

In this section, we present the simulation results of the suggested balancing strategy. This strategy was used with the model of the NAO robot given in [28]. The simulation process was done on Simulink under MATLAB (2018a) environment. The first trial (Fig. 5) presents the results of a generation of CoM using MPC approach, while in the second and third trials, we tested the robustness balance of the NAO robot against external disturbances using the proposed approach.

Fig. 5 shows the performance of MPC control in the sagittal plane. It is clear from the plot that the generated ZMP is overlapped with the desired ZMP position with acceptable control input as we remark in Fig. 5. Also, the MPC control keeps the trajectory of the CoM always within the ZMP position, which means that the NAO robot maintains always its balance.

Figs. 6 and 7 present the comparison results of the evaluation balance of the NAO robot with and without angular momentum control in presence of the external disturbances (at t = 5 s to 6 s). It is clear from Fig. 7 that the NAO robot keeps his balance without angular momentum control in the absence of the disturbances where the angle (θ) is relatively equal to zero and CoM's trajectory was within the generated ZMP position. However, in the presence of the disturbances, the robot lost his balance because the CoM trajectory exits from the support polygon of the robot as shown in Fig. 6. The efficiency of angular momentum control (τ_θ) appears clearly in results of Fig. 7. Where, even in the presence of the same disturbances, the proposed control drive the CoM trajectory to stays within support polygon and the angle (θ) remains always converging to zero.

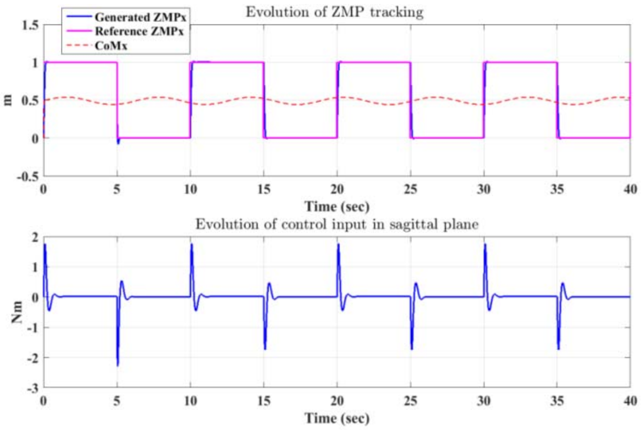


Fig. 5 The evolution of ZMP tracking and CoM by MPC control in sagittal plane

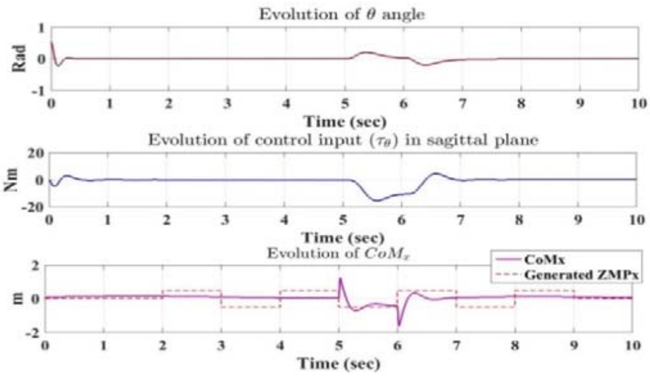


Fig. 6 Evaluation the balance of NAO robot in the presence of disturbances (at t=5s to 6s) without Angular Momentum control (τ_θ)

VI. Conclusion

In this paper, we investigated a dynamic controller to ensure the robustness of the balance system of the robot during the walking process under external disturbances. An MPC is applied and combined with ZMP strategy to perform the CoM trajectory. The feedback control is combined with preview control strategy to control the angular momentum and manage the CoM's acceleration taking into consideration the characterization of the rotational dynamics of the whole-body system. Simulation and comparison results are presented to confirm the feasibility of the proposed strategy. In future works, we are looking forward to implement this approach with NAO robot.

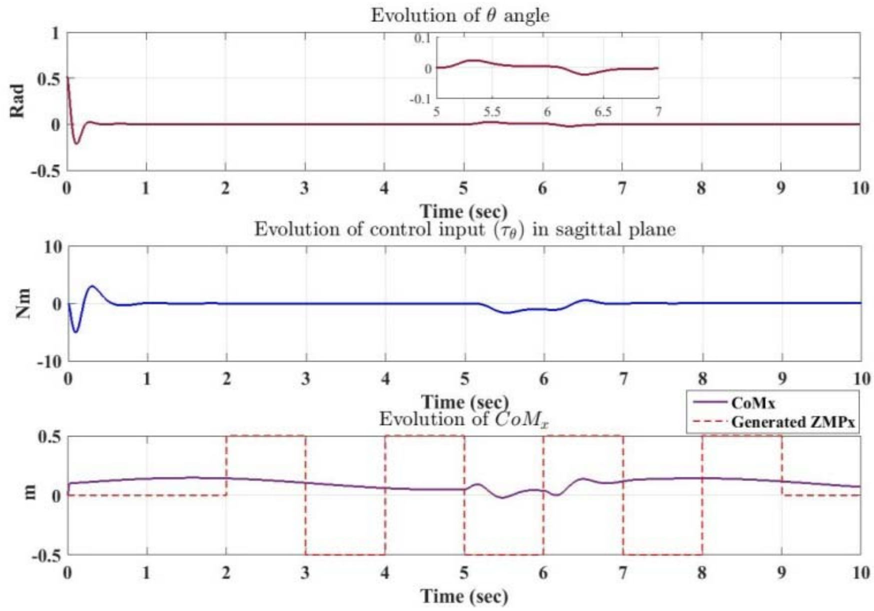


Fig. 7 Evaluation the balance of NAO robot in the presence of disturbances (at t=5s to 6s) with Angular momentum control (τ_θ)

REFERENCES

[1] M. A. Diftler, J. Mehling, M. E. Abdallah, N. A. Radford, L. B. Bridgwater, A. M. Sanders, *et al.*, "Robonaut 2-the first humanoid robot in space," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, 2011, pp. 2178-2183.

[2] K. Kaneko, F. Kanehiro, M. Morisawa, K. Miura, S. i. Nakaoka, and S. Kajita, "Cybernetic human HRP-4C," in *Humanoid Robots, 2009. Humanoids 2009. 9th IEEE-RAS International Conference on*, 2009, pp. 7-14.

[3] I. Kato, "Development of WABOT 1," *Biomechanism,* vol. 2, pp. 173-214, 1973.

[4] J. Kornblum, "Meet Honda's ASIMO, a helpful Mr. Roboto," *USA-Today,* 2000.

[5] D. Gouaillier, V. Hugel, P. Blazevic, C. Kilner, J. Monceaux, P. Lafourcade, *et al.*, "Mechatronic design of NAO humanoid," in *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*, 2009, pp. 769-774.

[6] T. R. w. site, "The RoboCup web site. http://www.robocup.org" Accessed April 2019.

[7] P. MacAlpine, J. Hanna, J. Liang, and P. Stone, "UT Austin Villa: RoboCup 2015 3D simulation league competition and technical challenges champions," in *Robot Soccer World Cup*, 2015, pp. 118-131.

[8] T. Niemueller, S. Reuter, and A. Ferrein, "Fawkes for the RoboCup logistics league," in *Robot Soccer World Cup*, 2015, pp. 365-373.

[9] S.-J. Yi, S. McGill, H. Jeong, J. Huh, M. Missura, H. Yi, *et al.*, "Robocup 2015 humanoid adultsize league winner," in *Robot Soccer World Cup*, 2015, pp. 132-143.

[10] J. i. Yamaguchi, E. Soga, S. Inoue, and A. Takanishi, "Development of a bipedal humanoid robot-control method of whole body cooperative dynamic biped walking," in *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, 1999, pp. 368-374.

[11] Q. Huang, S. Kajita, N. Koyachi, K. Kaneko, K. Yokoi, H. Arai, *et al.*, "A high stability, smooth walking pattern for a biped robot," in *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, 1999, pp. 65-71.

[12] S. Kajita and K. Tani, "Study of dynamic biped locomotion on rugged terrain-derivation and application of the linear inverted pendulum mode," in *Robotics and Automation, 1991. Proceedings, 1991 IEEE International Conference on*, 1991, pp. 1405-1411.

[13] Y. F. Zheng and J. Shen, "Gait synthesis for the SD-2 biped robot to climb sloping surface," *IEEE Transactions on Robotics and Automation,* vol. 6, pp. 86-96, 1990.

[14] A. Sano and J. Furusho, "Realization of natural dynamic walking using the angular momentum information," in *Robotics and Automation, 1990. Proceedings, 1990 IEEE International Conference on*, 1990, pp. 1476-1481.

[15] T. Takenaka, T. Matsumoto, and T. Yoshiike, "Real time motion generation and control for biped robot-1 st report: Walking gait pattern generation," in *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*, 2009, pp. 1084-1091.

[16] T. Sugihara, Y. Nakamura, and H. Inoue, "Real-time humanoid motion generation through ZMP manipulation based on inverted pendulum control," in *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, 2002, pp. 1404-1409.

[17] S. Kajita, H. Hirukawa, K. Harada, and K. Yokoi, *Introduction to humanoid robotics* vol. 101: Springer, 2014.

[18] S. Kajita, F. Kanehiro, K. Kaneko, K. Yokoi, and H. Hirukawa, "The 3D Linear Inverted Pendulum Mode: A simple modeling for a biped walking pattern generation," in *Intelligent Robots and Systems, 2001. Proceedings. 2001 IEEE/RSJ International Conference on*, 2001, pp. 239-246.

[19] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, *et al.*, "Biped walking pattern generation by using preview control of zero-moment point," in *Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on*, 2003, pp. 1620-1626.

[20] P.-B. Wieber, "Trajectory free linear model predictive control for stable walking in the presence of strong perturbations," in *Humanoid Robots, 2006 6th IEEE-RAS International Conference on*, 2006, pp. 137-142.

[21] K. Nishiwaki and S. Kagami, "Online walking control system for humanoids with short cycle pattern generation," *The International Journal of Robotics Research,* vol. 28, pp. 729-742, 2009.

[22] M. Popovic, A. Hofmann, and H. Herr, "Angular momentum regulation during human walking: biomechanics and control," in *Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on*, 2004, pp. 2405-2411.

[23] A. Hofmann, M. Popovic, and H. Herr, "Exploiting angular momentum to enhance bipedal center-of-mass control," in *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*, 2009, pp. 4423-4429.

[24] S.-k. Yun and A. Goswami, "Momentum-based reactive stepping controller on level and non-level ground for humanoid robot push recovery," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, 2011, pp. 3943-3950.

[25] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, *et al.*, "Resolved momentum control: Humanoid motion planning based on the linear and angular momentum," in *Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on*, 2003, pp. 1644-1650.

[26] C. G. Atkeson and B. Stephens, "Multiple balance strategies from one optimization criterion," in *Humanoid Robots, 2007 7th IEEE-RAS*

International Conference on, 2007, pp. 57-64.

[27] J. E. Fierro, J. A. Pamanes, H. A. Moreno, and V. Nunez, "On the Constrained Walking of the NAO Humanoid Robot," in *Advances in Automation and Robotics Research in Latin America*, ed: Springer, 2017, pp. 13-29.

[28] J. Park and Y. Youm, "General ZMP preview control for bipedal walking," in *Robotics and Automation, 2007 IEEE International Conference on*, 2007, pp. 2682-2687.