Push Recovery Control of NAO Humanoid Robot Based on Capture Point

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Abstract—This paper presents a Push Recovery (PR) controller for an NAO H21 humanoid robot based on the Model Predictive Control (MPC). Different strategies have been used for push recovery, such as the ankle, hip, stepping, and upper-limb rotation Strategies. For balance recovery, a single MPC is applied for guiding the Capture Point (CP) to the desired position. For this purpose, both the Zero Moment Point (ZMP) and the Centroidal Moment Pivot (CMP) has been modulated. Therefore, the purpose of the proposed algorithm is to control the CP. The CMP is used when the CP is outside of the support polygon, and/or the ZMP when the CP is inside the support polygon. This algorithm is executed successfully on a Nao H21 humanoid robot in the presence of severe pushes.

***Keywords—* Push Recovery; Model Predictive Control;Capture Point; Nao Humanoid Robot**

I. INTRODUCTION

Recently, human robots are developed to perform many human activities and they have attracted the attention of many researchers [1, 2]. Since these robots must operate in real environments, it is necessary for these robots to work smoothly and efficiently. Because of under-actuated and unstable nature of the humanoid robot, the ability to recover from unexpected external disturbances is essential [3]. For instance, normal living and room environments are full of potential objects and obstacles the robot could collide with, and the walking surfaces contain surface imperfections such as bumps and cracks the robot could step upon. Even if the environment is quite flat and without the obstacles, simple open loop walk controllers fail due to the incomplete modeling of the humanoid robot [4].

A simple criterion for ensuring dynamic balance during walking is to maintain Zero Moment Point (ZMP) or Center of Pressure (CoP) inside support polygon and it must be considered as an important factor for humanoid robot control. However, this criterion does not provide the understanding of the ability to maintain balance. There are two main approaches that have been used for balancing the humanoid robots in presence of the disturbance: 1-Model Predictive Control (MPC) and 2-controlling the Capture Point (CP) [1-8].

Parashar et al. [2] present several techniques for feature selection to foreshow push recovery for hip, ankle, and knee joint. They have trained the system by the K-Means algorithm and moreover, a test is done on crouch data. In this way, Modulating the ZMP and CMP for stabilizing the capture point to the desired position by using single MPC has been presented in [3]. Furthermore, Yi et al. [4] have proposed a practical hierarchical push recovery strategy that can be readily implemented on a wide range of humanoid robots.

Modern bipedal locomotion research has been influenced by Stephens, Benjamin J, et al. and their Linear Inverted Pendulum Model (LIPM) [5]. It is linearized about vertical and constrained to a horizontal plane, so it is a one-dimensional linear dynamic system representing humanoid motion. When considering ankle torques and the constraints on the location of the ZMP, or zero moment point, it has also been referred to as the "cart-on-a-table" model. An improvement to the LIPM is the AMPM, or Angular Momentum inducing inverted Pendulum Model [6], which generates momentum by applying a non-centroidal torque to the center of mass (CoM).

When an external push is applied to a humanoid robot, its response can be categorized into three strategies: (1) CoP Balancing (ankle strategy), (2) CMP Balancing (hip strategy) and (3) Stepping (change-of-support strategy) [2-4]. In this way, the MPC approach was deployed for Push recovery by stepping strategy using model predictive control [8-11]. These bio-inspired balancing approaches have been combined in a single MPC plan by Aftab [10].

Pratt [7] presented CP by dividing the Center of Mass (CoM) dynamics into stable and unstable parts. The state variable related to the unstable part has been called CP. The CP specifies when and where a humanoid robot must step to in order to have balance; however, it requires a controller for stabilizing unstable nature of dynamic of the capture point.

Shafiee-Ashtiani et al. [12] have employed all three balancing strategies in a single MPC based on the capture point. Shafiee-Ashtiani et al. [14] have developed a push recovery controller for a position control humanoid robot based on the capture point. Goswami, et. al. [13] also studied the procedure of inducing non-zero moment about the CoM in order to balance in detail. They define the ZRAM point (Zero Rate of change of Angular Momentum), which is identical to the CMP.

In this paper, based on [3] and [12] method, a push recovery controller developed for the NAO humanoid robot. The main purpose of this controller is to maintain the CP, CMP, and CoP on the desired location on the center of support polygon in the last step-time of optimization. The proposed algorithm is able of compensating severe pushes while the contact surface is line or point.

II. NAO-H21 HUMANOID ROBOT

NAO is a medium-sized humanoid robot of 0.573 meters height, 0.275 meters width, and has a mass of 5.18 kilograms, which is designed and manufactured by Aldebaran Robotics company in France. NAO-T2, NAO-T14, NAO-H21, NAO-H25 are different classes of this robot that the H25 and H21 series can walk on two legs and develops the robot's Degree-of-Freedom.

The RoboCup edition of the NAO-H21 is shown in Fig. 1, which has a complex mechanism with a great autonomy degree and a multifunctional, non-linear behavior [15]. It is equipped with a set of high-performance sensors, same as a touch sensor on his head, gyroscopes, electrical accelerometer, Inertial Measurement Unit (IMU), four ultrasonic sensors, precise actuators, two Infra-Red (IR) command sender and receiver, and two processor, which makes it suitable for humanoid robots research area.

III. CENTER OF MASS EQUATION

The dynamic equations of a humanoid robot are highly nonlinear and an inverted pendulum with the massless leg is a useful model for the dynamics of the humanoid robot. LIPM assumes that the rate of change of angular momentum is zero and the CoM moves horizontally on constant height.

The equation of motion for LIPM based on these hypotheses can be displayed as follows:

$$\ddot{x}_c = \omega^2 (x_c - p_x) \tag{1}$$

where $\omega^2 = \frac{g}{z_c}$ is natural frequency of LIPM, $R_{com} = [x_c, y_c, z_c]^T$ is the CoM position, $R_{zmp} = [p_x, p_y, 0]^T$is the ZMP position. Based on the constant angular momentum, the Ground Reaction Force (GRF) intersects with CoM. As shown in Fig. 1, the gravitational force F_g has been compensated by F_z. The equilibrium of forces can be achieved by the inertial force $F_r = m\ddot{x}_c$. Moreover, the equations of motion in the frontal and sagittal planes are the same. By applying a disturbance or an external force to the LIPM, one can be improved the dynamic equations as:

$$\begin{aligned} \ddot{x}_c &= \omega^2 (x_c - p_x) + \frac{F_x}{m} \\ \ddot{y}_c &= \omega^2 \left(y_c - p_y\right) + \frac{F_y}{m} \end{aligned} \tag{2}$$

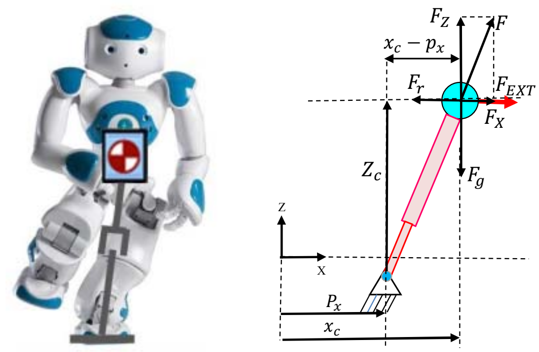


Figure 1. (a).Nao H21 Robot[15] (b).LIP Model [3]

The angular momentums of torso and arms have a significant role in balance recovery. These joints are able to apply torque about the CoM. When the torque about the CoM is zero the CMP and CoP are coincided. The CoP is always inside the support polygon but, CMP can move to out of the foot edge for a non-zero moment about the COM. In order to impose these effects a flywheel added to the LIPM that can be torqued directly as shown by Shafiee-Ashtiani [3]. Therefore, the equation of motion can be written as:

$$\ddot{x}_c = \omega^2 (x_c - p_x) + \frac{\dot{H}_y}{mz} + \frac{F}{m} \tag{3}$$

Where, $\dot{H}$ is the rate of upper-body angular momentum that can be handled by the torque of arm and trunk joints.

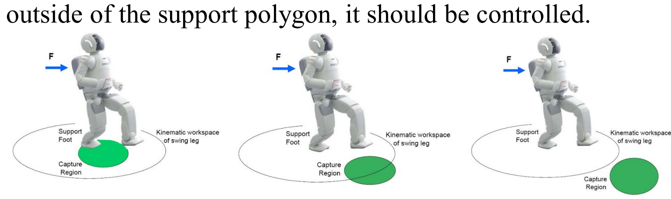
The position of ZMP and CMP are related as [13]:

$$\begin{aligned} CMP_x &= p_x + \frac{\dot{H}_y}{F_z} \\ CMP_y &= p_y - \frac{\dot{H}_x}{F_z} \end{aligned} \tag{4}$$

|By combining Eqs. (3) and (4), it is obtained that:

$$\begin{aligned} \ddot{x}_c &= \omega^2 (x_c - CMP_x) + \frac{F_x}{m} \\ \ddot{y}_c &= \omega^2 \left(y_c - CMP_y\right) + \frac{F_y}{m} \end{aligned} \tag{5}$$

When a disturbance exerted, the CMP and ZMP will diverge and CMP can leave the support polygon. Thus, when CP is outside of the support polygon, it should be controlled.



(a). Ankle Strategy (b). Hip-ankle or steeping Strategy (c).Fail to recover from a disturbance in one step

Figure 2. Human-inspired Balancing strategies

CP is the unstable part of the LIPM [3, 7] and can be written as follow:

$$CP_x = x_c + \frac{\dot{x}_c}{\omega}$$
$$CP_y = y_c + \frac{\dot{y}_c}{\omega} \tag{6}$$

Therefore, the dynamics of the CoM can be written as:

$$\dot{x}_c = \omega(CP_x - x_c)$$
$$\dot{y}_c = \omega(CP_y - y_c) \tag{7}$$

By doing some calculations the following relations have been derived:

$$\dot{CP}_x = \omega(CP_x - CMP_x) + \frac{F_x}{m\omega}$$
$$\dot{CP}_y = \omega(CP_y - CMP_y) + \frac{F_y}{m\omega} \tag{8}$$

As shown in (8), the CP must be controlled in order to push recovery of the robot. When CP is placed inside the support polygon, it can be controlled by ZMP [8], but when it is out of support polygon, it can be controlled by CMP.
Using the concept of CP, we can determine when and where to take a step to recover from a push [3]. If CP is located inside the support polygon, the robot is able to recover from the push without having a stepping. In order to stop in one step, the support polygon must have an intersection with the capture area as shown in Fig. 2 [3, 6]. The robot will fail to recover from a critical push in one step if the capture area doesn't have the intersection with the kinematic workspace of swing foot and may require more steps.
Three strategies in dealing with a disturbance are (1) ankle strategy, (2) hip strategy, (3) stepping strategy.

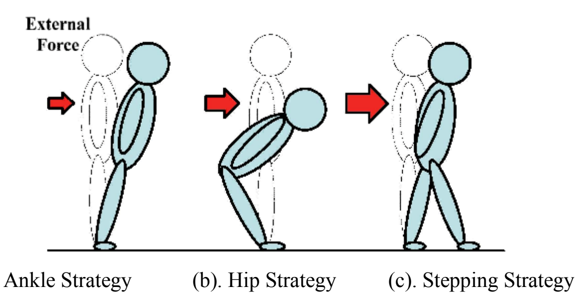


Figure 3. Human-inspired Balancing strategies

Humans use the ankle strategy in dealing with small disturbances in order to regulate CP as shown in Fig.3 (a), although the contact between foot and floor is a unilateral constraint and If the ankle torque will become too large, the ZMP will move beyond the edge of the foot and the foot will start to move. In dealing with a larger push the capture point will be left the support polygon. The Angular momentum of the upper body can be used in the direction of the push by exerting a torque on the hip joint or arm joint as shown in Fig. 3(b). This strategy also called CMP Balancing. With increasing the push the helpful strategy will be stepping, however, stepping is not possible for some situations might occur so In this situation the push recovery by Hip-Ankle strategy is essential[13].

IV. PUSH RECOVERY CONTROLLER

In order to recover the balance of the NAO robot against external disturbances, the Model Predictive Control (MPC) has been used. This approach is able to optimize the behavior of the system in dealing with constraints. On the other hand, this method has predictive ability. For implementing the MPC, the control action is obtained by solving a finite horizon open-loop optimal control problem at each step, using the current state as the initial state. So, pre-computed control gains do not use. For this purpose, the dynamics of the system has been discretized. The QP solver converts the MPC problem optimization problem to a general form of quadratic programming problem.
Suppose T is the sampling time of the system. Then, the discrete time state space model of the system derived as follows [3,12]. The behavior of the system in both frontal and sagittal planes is identical. So, the model of the system in each plane is:

$$x_{t+1} = (1 - \omega T)x_t + \omega T CP_t$$
$$CP_{t+1} = (1 + \omega T)CP_t + -\omega T(p_{x,t} + \frac{\dot{H}_{y,t}}{mg}) + \frac{F}{m\omega}$$
$$p_{x,t+1} = p_{x,t} + \dot{p}_{x,t}T \tag{9}$$
$$\dot{H}_{y,t+1} = \dot{H}_{y,t} + \ddot{H}_{y,t}T$$

The following general state space form of a discrete system has been regarded:

$$\mathbf{X_{t+1}} = \mathbf{A_t X_t} + \mathbf{BU_t}$$
$$\mathbf{Y_K} = \mathbf{CX_K} \tag{10}$$

Where, $\mathbf{X_t} = [x, CP, p_x, \dot{H}_y, F_{EXT}]$ are the states of the system and $\mathbf{U_t} = [\dot{p}_x, \ddot{H}_y]$ are the control inputs [3],[12]:

$$A_t = \begin{bmatrix} (1-\omega T) & \omega T & 0 & 0 & 0 \\ 0 & (1+\omega T) & -\omega T & \frac{-\omega T}{mg} & \frac{1}{m\omega} \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ T & 0 \\ 0 & T \\ 0 & 0 \end{bmatrix}, C = I$$

By solving the linear model (10) by assuming a sequence of control inputs $\widehat{\mathbf{U}}$, it is derived that,

$$\widehat{\mathbf{Y}} = \widehat{\mathbf{A}}\mathbf{X_t} + \widehat{\mathbf{B}}\widehat{\mathbf{U}}$$
$$\widehat{\mathbf{Y}} = [\boldsymbol{Y}_{t+1}^T \quad \boldsymbol{Y}_{t+2}^T \quad \dots \quad \boldsymbol{Y}_{t+N}^T] \tag{12}$$

$$\widehat{\mathbf{U}} = [\boldsymbol{U}_t^T \quad \boldsymbol{U}_{t+1}^T \quad \dots \quad \boldsymbol{U}_{t+N-1}^T]$$

$\widehat{\mathbf{A}}$ And $\widehat{\mathbf{B}}$ have been derived by recursive solving of (11). The rate of the upper-body angular momentum and the rate of change of the ZMP position have been considered as the control inputs. Therefore the core of the proposed MPC is based on combined hip and ankle strategies.

In order to solve the quadratic programming problem, the following cost function has been used.

$$\begin{aligned} J = \frac{1}{2}\sum_{k=1}^{N} (\alpha_{1x}\left(\xi_{x,k+1} - \xi_{xref,k+1}\right)^2 + \alpha_{2x}\left(\dot{P}_{xk}\right)^2 \\ + \alpha_{3x}\left(\dot{H}_{yk}\right)^2 + \alpha_{4x}\left(\ddot{H}_{yk}\right)^2 \\ + \alpha_{1y}\left(\xi_{y,k+1} - \xi_{refy,k+1}\right)^2 \\ + \alpha_{2y}\left(\dot{p}_{yk}\right)^2 + \alpha_{3y}\left(\dot{H}_{xk}\right)^2 \\ + \alpha_{4y}\left(\ddot{H}_{xk}\right)^2) \end{aligned} \tag{13}$$

The term $\xi_{x,k+1} - \xi_{xref,k+1}$ shows the difference between the current CP and its desired value. In order to modulate the ZMP and CMP for CP control the terms $\alpha_{2x}\left(\dot{P}_{xk}\right)^2$ and $\alpha_{3x}\left(\dot{H}_{yk}\right)^2$ have been regarded. The fourth term has been considered for minimizing the rate of change of angular momentum. The α_i shows the weight of each term. This novelty of this cost function is to regard both rotational and linear dynamics of the biped robot. The cost function and the constraints of the system can be transformed to the following terms:

$$\begin{gathered} \min \frac{1}{2}\boldsymbol{Y^T H Y} + \boldsymbol{f^T Y} \\ s.t. \\ \mathbf{CY} + \mathbf{D} = \mathbf{0} \\ \mathbf{EY} + \mathbf{F} \leq \mathbf{0} \end{gathered} \tag{14}$$

Where, H and f are related to the cost function and C, D, E, and F are coefficient matrices related to the constraints.

A. constraints

One of the most important advantages of the MPC method is to consider future constraints. In this optimization problem the following constraints on CP, CMP, and $\dot{H}_y$ at the end of QP (Last step time) has been considered:

$$\begin{gathered} CP_{xN} = CP_{refx} \\ x_{c,N} = CP_{refx} \\ p_{x,N} = CP_{refx} \\ \dot{H}_{y,N} = \mathbf{0} \\ p_{x,i} \in Support\ Polygon \end{gathered} \tag{15}$$

The reference CP (CP_{ref}) is located on the center of support polygon. These constraints state that the final position of the CP and the ZMP must be settled at the center of the support polygon. Moreover, the tilting should be avoided. These constraints are identical in both frontal and sagittal planes.

V. SIMULATION RESULTS

The simulation has been done by using MATLAB. The proposed controller is implemented on the abstract model of NAO H21 humanoid robot. The Parameter that is used in the simulation for MPC and the cost function weights are shown in Table 1. The push recovery time is regarded 2s.

TABLE I. CHRACTRISTIC OF NAO H21 HUMANOID ROBOT

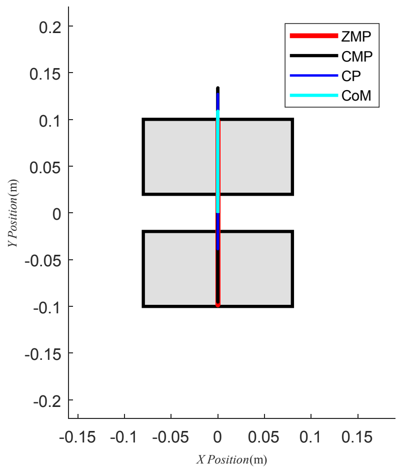
Variable	Value
Height	0.573 m
Mass	5.18 Kg
Foot length	0.16 m
Foot width	0.09 m
α_{1x}	6
α_{1y}	6
α_2	1
α_3	10
α_4	5
T	0.005 s

For evaluating the performance of the proposed algorithm some pushes with different the magnitude and direction have been exerted to the CoM of the robot. The behavior of the robot has been shown in Fig. 4 during 2s. As shown in this figure, the robot is able to recover itself against the exerted push and coming back to its initial condition. A push with magnitude of 250 N on each sagittal and the frontal planes and a push with the magnitude of 100 N in sagittal and 100 N in the frontal plane are exerted on the robot. In each case, the robot is able to come back to its initial position.

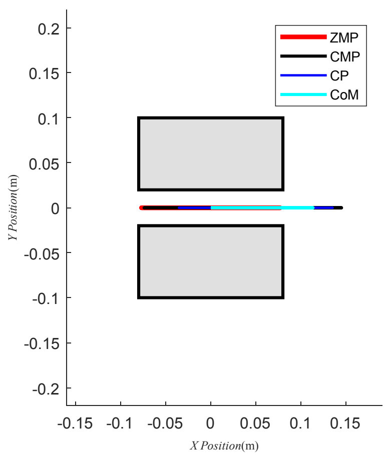
The large push with the magnitude of 300 N in sagittal and 100 N in frontal plane is exerted on the robot. The large disturbance pushes the CP out of the support polygon. The ZMP cannot control the CP and remains on the limits of the support polygon. Therefore, the proposed algorithm generates angular momentum in order to diverge the CMP from the COP. The CMP can leave the support polygon and guides the CP to the desired position. The Maximum requirement torque for Push recovery is about 5 N.m. The trajectory of CP, CoP, CMP, and CoM during balance recovery is shown in Fig. 5.

Moreover, it is assumed that the robot has stood on one leg, that contact surface is a point. In this case, the CMP modulating can maintain the robot against falling because the support polygon is so small and ankle strategy is not useful. In this situation, the CP leaves the support polygon and ZMP holds on the bound of support polygon and CMP pushes the CP to the desired position. As shown in Fig. 6.

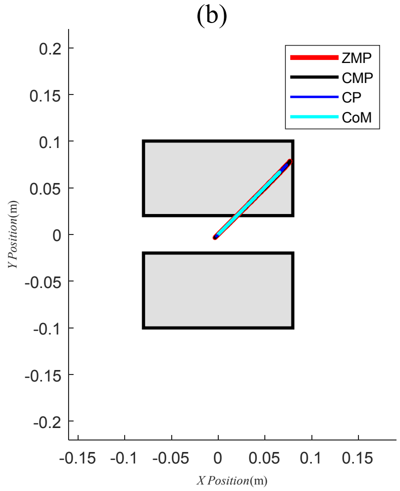
As shown in the simulation results, in the proposed method the regulation of angular momentum is so beneficial during push recovery, especially in the standing small contact surfaces and also the situations that stepping is not possible. The Human-like response in dealing with external disturbance could be generated by the proposed MPC; for example, when the imposed force is small. The ankle strategy has been used for balance recovery. In dealing with large disturbance the angular momentum has been generated and the hip-ankle strategy has been used simultaneously.



(a)



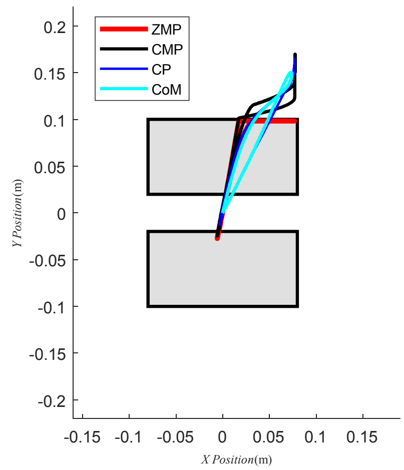
(b)



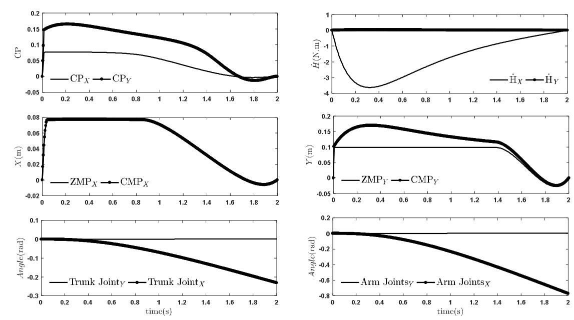
(c)

Figure 4. Simulation results of push recovery controller (Robot has stood on both legs), the push with magnitude of a:(0,250), b:(250,0) and c:(100,100) are exerted on CoM

However, obtaining capture point position during implementation is one of the challenges. Moreover, foot slipping is not considered in this paper.



(a)

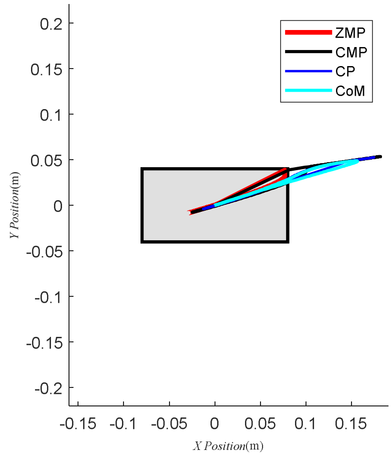


(b)

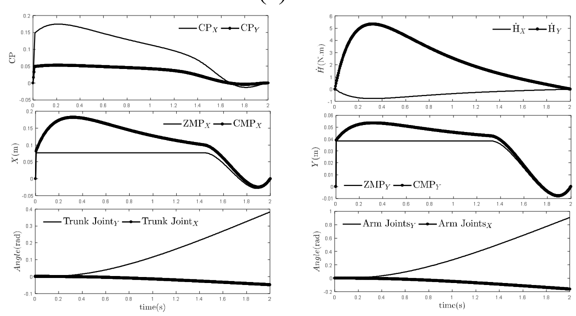
Figure 5. a: Simulation results of push recovery controller (Robot has stood on both legs),b: the push with magnitude of (100,300) is exerted on CoM

I. CONCLUSION AND FUTURE WORK

The capture point approach has been regarded in order to the push recovery of an NAO H21 humanoid robot. For this purpose, a Model Predictive Controller has been used. A combined hip and ankle strategy has been considered to control the capture point by modulating the CMP and ZMP. Simulation results show that the proposed approach is beneficial for removing the effect of severe pushes on the balancing of the robot. The proposed algorithm is also tested when the support polygon is limited to point, and stepping is not allowed. Experimental implementation of this algorithm will be the main challenge of our future work. Moreover, foot slipping is not considered in this paper which can be regarded in the future.



(a)



(b)

Figure 6. (a)Simulation results of push recovery controller (Robot has stood on one leg), (b)the push with magnitude of (300,100) is exerted on CoM

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