Dynamic Walking of Biped Robots with Obstacles Using Predictive Controller

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***Abstract*— This paper proposes a control method for walking of biped robots while stepping over large obstacles, which is a big challenge for these robots. To this end, Nonlinear Model Predictive Control (NMPC) is employed. The main advantage of this approach is that there is no need for trajectory planning. In other words, the robot finds the optimum gait length based on stability of the closed-loop system and going over the obstacles. Simulation results show good performance of the proposed method, where the biped can step over a 40×15cm obstacle in the sagittal plane without colliding with it.**

Keywords-biped robots; dynamic walking; nonlinear model predictive control; obstacles.

I. INTRODUCTION

During the last two decades, walking robots have been considered by many researchers in this area. This is mainly due to the advantages at walking that other robots (like wheeled robots) can not perform. Legged robots can walk in unknown, irregular, rough and sloppy terrains. They can cross over obstacles or pass through ditches; go up and down stairs whereas wheeled robots are not able to do these tasks.

Generally, the obstacles that are considered in almost all papers are very short. There are well-known robots that can step over small obstacles, such as Johnnie that can cross over a 5 cm obstacle [1] and ASSIMO that can step over flat obstacles [2]. Previous studies on walking and stepping over obstacles have designed an off-line trajectory for the tip of the swinging leg and the hip of robot; then, the biped is controlled to trace these predefined paths. In [3], authors have performed this method for HRP-2 robot. In their method, first, an algorithm finds feasibility conditions for stepping over an obstacle. If the answer is yes, then the robot uses the predefined off-line trajectory and crosses over the obstacle. Yagi and Lumelsky considered several trajectories for crossing over different obstacles [4]. The robot senses obstacles and according to an algorithm selects the best predefined trajectory. Then, the robot is controlled using the Zero Moment Point (ZMP) stability criterion. For wide obstacles, Jafri et al. have proposed a method, in which the strategy decides whether the robot can step over the obstacle or should step on it [5]. If the robot cannot step over the obstacle, it stops before that. The humanoid robot BHR-2 can successfully stand on obstacles. In [6] for stepping over obstacles, authors proposed a method to maintain the projection of the Center of Mass (COM) of the robot in the supporting polygon area that can guarantee static stability. However, the HRP-2 robot walks and crosses over obstacles very slow. Preview control in another method that has been used to generate trajectory in order to step over a 15×5cm obstacle by HRP-2 biped [7]. They have used the ZMP criteria to guarantee dynamic stability of the robot. Hwang et al. have proposed a decentralized control method based on fuzzy logic for stepping over obstacles for small size humanoid robots [8]. In [9], Kushida et al. have proposed a hybrid dynamical system (HDS) as a system that has both the continuous and discrete events. HDS can be formulated as a linear inequality, where logical variables are specified by mixed logical dynamical system. In [10], a method has been proposed for HRP-2 (165cm, 30DOF) robot that can cross over 25×5cm obstacle [10]. The feet trajectory is designed off-line but it can become adaptive.

Predefined or off-line trajectory planning has some inherent problems. First, the trajectory must be customized for the robot in hand. Hence, every robot needs its own trajectory. Second, for different terrains different trajectories must be designed. Third, a predefined trajectory does not resemble human walking. Due to these disadvantages, the Model Predictive Control (MPC) method is used in this paper for biped walking and stepping over obstacles without any need for off-line trajectory generation.

In [11] authors used the MPC for generating on-line trajectory and control at the same time. In their method, by considering physical constraints of the robot, an optimal path and control method is created. MPC controller has also been used for dynamically walking of humanoid robot HRP-2 [12]. In this method, the cost function minimizes the error between the real and desired ZMP that is generated off-line. Azevedo et al. have considered some physical and useful constraints for static walking at flat surfaces [13]. However, the problem in this method is that the robot walks very slowly. In [14], a real-time control method based on Nonlinear MPC (NMPC) is proposed for controlling a 7DOF biped robot. The optimization problem is solved using the SQP algorithm. The NMPC uses the dynamic model of robot for prediction. Hence, due to existing of uncertainties in the model, the model prediction is not precise. In [15] authors use nonlinear disturbance observer (NDO) to overcome this problem. Moreover, the gait length is not fixed. The robot's walking is similar to human behavior. However, the robot walks slowly.

This paper is organized as follows. In Section 2, the dynamic model of the robot will be illustrated. The structure of the NMPC controller, the cost function and constraints will be given in Section 3. Section 4 shows simulation results followed by conclusion in Section 5.

II. DYNAMIC OF BIPED ROBOT

The biped robot that is used in the paper is shown in Fig. 1. It can walk in the sagittal plane. The feet have no mass and are considered free friction. One step includes three phases: 1) Double Support Phase (DSP), 2) Single Support Phase (SSP), and 3) SSP impact. The DSP happens when both legs are on the ground. On the other hand, the SSP happens when just one leg (called the supporting leg) is on the ground. The SSP impact is right after the SSP when the tip of the swinging leg contacts the ground. The DSP and SSP have different dynamics and must be considered separately [16].

A. *Single Support Phase*

The dynamic of SSP can be written as [16]

$$D(\theta)\ddot{\theta} + h(\theta,\dot{\theta})\dot{\theta} + G(\theta) = T \tag{1}$$

where $D_{5\times5}$, $h_{5\times1}$, $G_{5\times1}$, and $T_{5\times1}$ are the inertia matrix, the vector of centripetal, the Coriolis torques, the gravity vector, and the vector of joint torques, respectively.

B. *Double Support Phase*

The dynamic of SSP can be presented as [16]

$$D(\theta)\ddot{\theta} + h(\theta,\dot{\theta})\dot{\theta} + G(\theta) = T + J^T(\theta)\lambda \tag{2}$$

where $J_{5\times2}$ and $\lambda_{2\times1}$ are the Jacobian matrix and the Lagrangian vector, respectively.

C. *SSP Impact*

At the end of the SSP, the robot lands its swinging leg. Nevertheless, there is a sudden impact between the ground and the tip of the foot. This impact affects angular velocity. If the impact is large, then the angular position and velocity may incur large changes to the robot, causing instability. Hence, the control method should produce as little impact as possible. The angular velocity immediately right after the contact is

$$\dot{\theta}^{+}_{impact} = \dot{\theta}^{-} + D^{-1}J^T(JD^{-1}J^T)^{-1}(-J\dot{\theta}^{-}) \tag{3}$$

where $\dot{\theta}^{-}$ is the angular speed right before the impact.

III. NMPC CONTROLLER

Model Predictive Control is a general control scheme that is designed to solve online a sequence of optimal control problems with some constraints [13], [14]. One of the advantages of NMPC is that it does not need any off-line trajectory generation. Hence, it is possible to make the robot to walk like human. In the proposed method in this paper, the gait length is not fixed and the robot can stand at a suitable point before the obstacle, even when the normal walking cycle is not completed. In this paper NMPC is used for a biped robot to walk on flat surfaces and then, step over large obstacles. The cost functions for walking on flat surfaces and obstacle avoidance is similar but the constraints are different.

A. *Cost Function*

The cost functions for the DSP as well as the SSP are the same as:

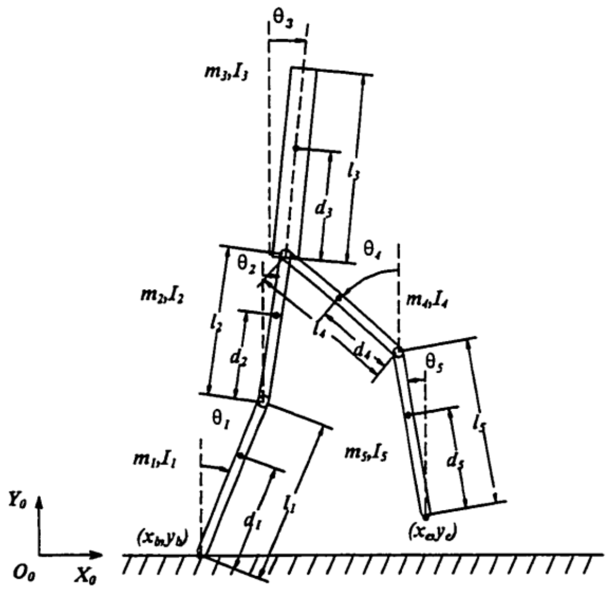

Figure 1. Five link biped robot.

B. *Cost Function*

The cost functions for the DSP as well as the SSP are the same as:

$$\begin{aligned} J = {} & w_1 \sum_{i=0}^{N_c-1} T(t+i\Delta t)^T T(t+i\Delta t) + \\ & w_2 \sum_{j=1}^{N_p} (\dot{x}_{\mathrm{COM}}(t+j\Delta t) - \alpha \dot{x}^{\mathrm{desired}}_{\mathrm{COM}})^2 \end{aligned} \tag{4}$$

where

$$\alpha = 1 - \frac{2}{1+\exp\left(\dfrac{x^{\mathrm{desired}}_{\mathrm{COM}} - x_{\mathrm{COM}}(t+j\Delta t)}{\sigma}\right)} \tag{5}$$

that $\dot{x}^{\mathrm{desired}}_{\mathrm{COM}}$ and $x^{\mathrm{final}}_{\mathrm{COM}}$ are the desired horizontal COM velocity and position of the final stop point right before obstacles, respectively, and σ is a parameter that regulates the acceleration of the robot locomotion. At the beginning of motion, the error $x^{\mathrm{final}}_{\mathrm{COM}} - x_{\mathrm{COM}}$ is maximum and α is 1. When the robot is closed to the final position, the error and α approach zero and the robot stops. Parameters N_p and N_p are the prediction and control horizons, respectively, Δt is the sampling time, and w_1 and w_2 are the weights for the required torques and tracing the desired COM horizontal velocity, respectively.

C. *Constraints*

For every phase of walking, different constraints are needed that are introduced in the followings.

1) *DSP Constraints for Flat Surfaces*

For this phase, the physical, forward motion, stability, and energy optimization constraints are defined as follows:

1. The joints constraints:

$$q_{i,\min} \leq q_i \leq q_{i,\max} \tag{6}$$

where, for the robot in Fig. 2

$$q_1 = \frac{\pi}{2} - \theta_1; q_2 = \pi + \theta_1 - \theta_2; q_3 = \pi + \theta_2 - \theta_3; \\ q_4 = \theta_4; q_5 = \pi + \theta_5 - (\theta_3 + \theta_4) \tag{7}$$

To prevent singularity of Jacobian matrix, the controller should guarantee $q_2 \neq \pi, q_5 \neq \pi$.

2. The actuators torque should be limited:

$$T_{\min} \leq T \leq T_{\max} \tag{8}$$

3. The biped robot should be at erected posture during its locomotion:

$$h_{\min} \leq h_{hip} \leq h_{\max} \tag{9}$$

where h_{hip} is the normal height of the robot hip.

4. The torso is almost 50% of robot's weight and has important role in dynamic stability and it should be upright during walking:

$$\theta_{\min} \leq \theta_{trunk} \leq \theta_{\max} \tag{10}$$

5. Biped robot must only walk forward. Hence, the robot COM speed (in the *x* direction) must be positive: $\dot{x}_{COM} \geq 0$.
6. The tip height of the swinging leg should be above the ground: $y_e = 0$.
7. The support area for dynamic stability is

$$x_e \leq x_{ZMP} \leq x_b + FootLength \tag{11}$$

2) SSP Constraints for Flat Surfaces

For smooth and normal walking at flat surfaces, the following constraints are defined for the SSP phase:

1. The first five constraints are similar to the DSP constraints.
6. The tip height of swinging leg should be restricted:

$$0 \leq y_e \leq H_{\max} \tag{12}$$

7. The horizontal speed of the tip should be adapted to the robot COM velocity:

$$\begin{cases} \dot{x}_e \geq \beta_{\min} \dot{x}_{COM} \sin(\dfrac{\pi y_e}{2H_{\max}}) \\ \dot{x}_e \leq \beta_{\max} \dot{x}_{COM} \sin(\dfrac{\pi y_e}{2H_{\max}}) \end{cases} \tag{13}$$

8. During take off, the vertical speed of the tip must be positive and during landing should be negative and adapted to the robot COM velocity

$$\delta\dot{x}_{COM} \sin(\pi \frac{|x_e - x_b|}{H_{\max}}) \sin(\frac{\pi y_e}{H_{\max}}) \\ + \operatorname{sgn}(x_e - x_b)\dot{y}_e \leq 0 \tag{14}$$

9. Dynamic stability should be guaranteed with limitation of ZMP in the support polygon

$$x_b \leq x_{ZMP} \leq x_b + FootLength \; . \tag{15}$$

3) Stepping over Obstacles

There are three phases for stepping over an obstacle: first, one leg crosses over the obstacle (SSP1); second, the torso move forward (DSP), and third, the back leg passes over the obstacle (SSP2). These phases are shown in Fig. 2.

The constraints for SPP1 and SSP2 phases are:

1. The first five constraints are similar to the DSP constraints.
6. The horizontal speed of the tip should be adapted to the robot COM velocity

$$\begin{cases} \dot{x}_e \geq \beta_{\min} \dot{x}_{COM} \sin(\dfrac{\pi x_e}{x_{O_2} + x_{O_3}}) \\ \dot{x}_e \leq \beta_{\max} \dot{x}_{COM} \sin(\dfrac{\pi x_e}{x_{O_2} + x_{O_3}}) \end{cases} \tag{16}$$

7. The vertical velocity of the tip should be as

$$\begin{cases} x_e < x_{O_2} \Rightarrow \dot{y}_e > 0 \\ x_{O_2} \leq x_e \leq x_{O_3} \Rightarrow \dot{y}_e = 0 \\ x_e > x_{O_3} \Rightarrow \dot{y}_e < 0 \end{cases} \tag{17}$$

8. The tip height of the swinging leg should be restricted

$$\begin{cases} x_e \leq x_{O_2}, x_e \geq x_{O_3} \Rightarrow 0 \leq y_e \leq H_{O,\max} \\ x_{O_2} \leq x_e \leq x_{O_3} \Rightarrow H_{O,\min} \leq y_e \leq H_{O,\max} \end{cases} \tag{18}$$

9. The horizontal position of the knee should not contact with the obstacle:

$$x_{\text{knee}} \leq x_{O_2} + 0.01 \tag{19}$$

10. For dynamic stability, the ZMP must guarantee

$$x_b \leq x_{ZMP} \leq x_b + FootLength. \tag{20}$$

The constraints for DSP phase are:

1. The first seven constraints are similar to the walking DSP constraints.
8. The horizontal position of the knee should not contact with the obstacle like (19).

Fig. 3 shows block diagram of control procedure for walking over flat surfaces and stepping over obstacles. The biped robot walks over the flat terrain normally. If an obstacle is detected in the vicinity of the robot, the controller regulates the gait length (i.e. either making a shorter or longer gait) in order to stop at an appropriate place before the obstacle. If biped robot can step over the obstacle, the controller performs the task; otherwise, the robot stands still because the robot in this paper can just move in sagittal plane.

IV. SIMULATION RESULTS

The biped robot parameters that have been extracted from [16] are given in Table I. Table II shows the minimum and maximum of variables. Other parameters are considered as:

$FootLength = 15$ cm, $\dot{x}_{COM}^{desired} = 1$ m/s, $N_p = 5$, $N_c = 4$,

$w_1 = 100$, $w_2 = 0.01$, $\sigma = 0.03$,

$Obstacle\_Height = 40$ cm, $Obstacle\_Length = 15$ cm

and $\Delta t = 0.02$ s.

Fig. 4 shows several walking cycles and obstacle detecting. The last cycle is shorter than the other cycles because an obstacle is detected (Fig. 5). Three phases of stepping over the obstacle are shown in Fig. 6.
The green shade around the obstacle is considered for the safety clearance. The tip of the swinging leg and the knee should not contact with the safety area around the obstacle (Fig. 7). The biped robot continues walking after passing the obstacle (Figs. 8 and 9). It should be noted that after crossing over the obstacle, the robot's legs are next to each other and it should step a short gait before it can resume its normal walking. Fig. 10 shows that the joint torques limits (±250Nm) are not violated by the controller.

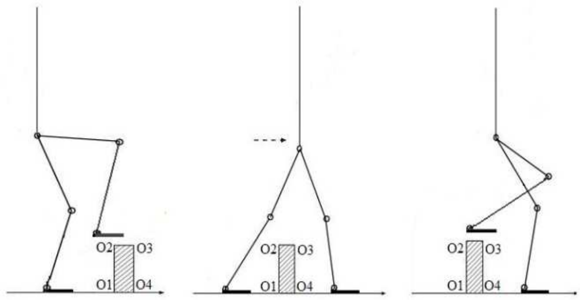

Figure 2. Stepping over obstacle

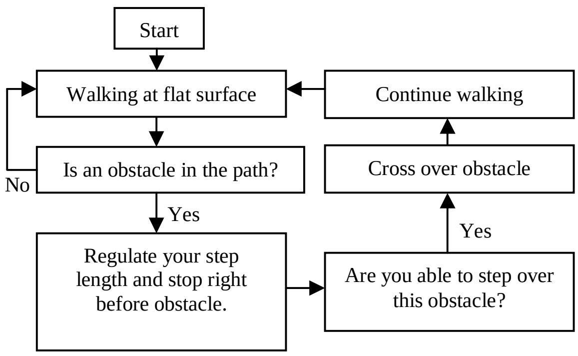

Figure 3. Control procedure

TABLE I. ROBOT PARAMETERS

Link	Robot Parameters			
	Length (m)	***Mass (kg)***	***Inertia (kgm^2)***	***Location of center of mass (m)***
1	0.53	3.7	0.3	0.285
2	0.5	8.55	0.3	.31
3	0.70	25	0.3	0.4
4	0.5	8.55	0.3	.31
5	0.53	3.7	0.3	0.285

TABLE II. MINIMUM AND MAXIMUM OF VARIABLES

Variable	Min. and Max. of Variables	
	Minimum	***Maximum***
h_{hip}	0.98m	1.08m
θ_{trunk}	-3°	3°
T_i	-250N.m	250N.m
H_O	Obs_Height+0.01m	Obs_Height+0.03m
β	4	10

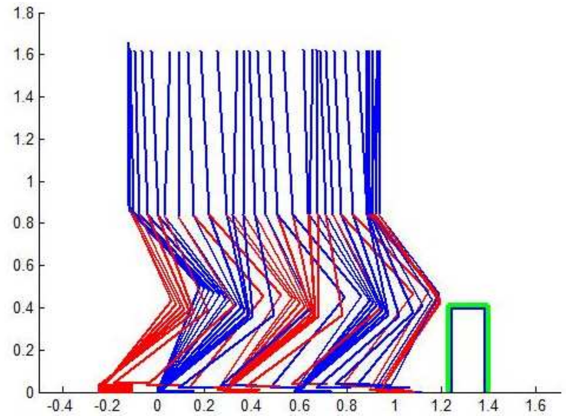

Figure 4. Several cycle and stop before obstacle

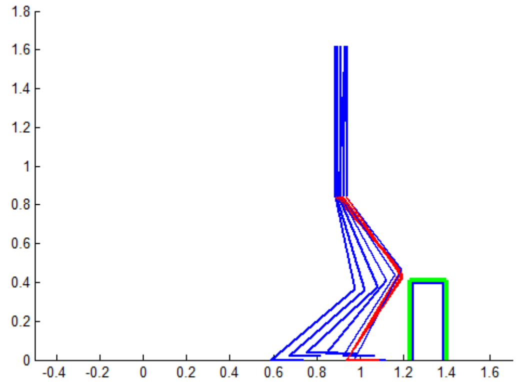

Figure 5. Last and short cycle before stop

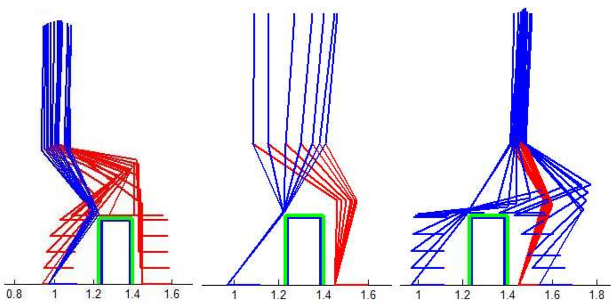

Figure 6. Three phases of stepping over obstacle

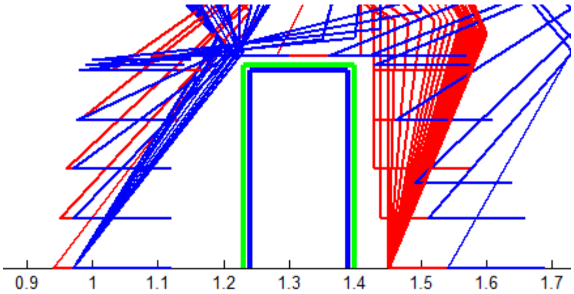

Figure 7. Stepping over obstacle without contact

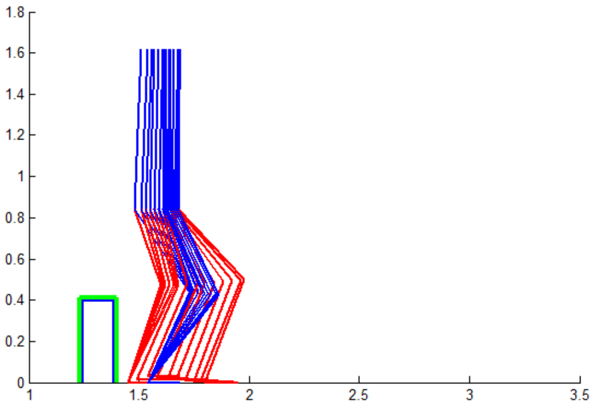

Figure 8. Short gait after crossing over obstacle

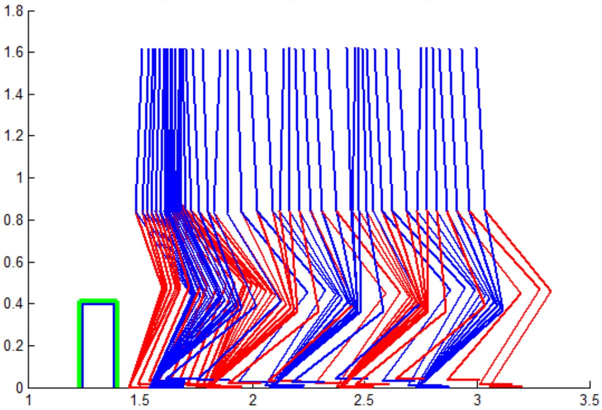

Figure 9. Normal walking after stepping over obstacle

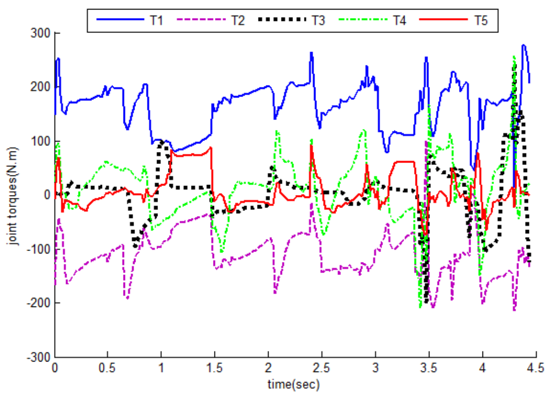

Figure 10. Joint Torques

V. CONCLUSION

This paper proposed a control method for walking and stepping over obstacles by biped robots. The Nonlinear Model Predictive Control (NMPC) is used for controlling the robot without trajectory planning. Due to advantages of NMPC, walking and crossing over obstacle of the biped robot become very similar to human walking strategy. One of advantages of the proposed method is that the step length is not fixed and the NMPC specifies it by solving an optimization problem based on dynamic stability of the robot. Unlike other reported methods in literatures, the robot can step over a relatively tall obstacle while maintaining stability. The biped robot that is used in this paper has a 49.5kg weight and is 1.73m tall and could cross over a 40×15cm obstacle in the sagittal plane (40% of the robot's leg length) with maximum 1m/s speed. Simulation results showed effectiveness of the proposed method.

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