Stepping of Biped Robots Over Large Obstacles Using NMPC Controller

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***Abstract*—One of the main challenges for biped robots is to step over large obstacles during walking. In this paper, a control method is proposed for walking and stepping over large obstacles based on the Nonlinear Model Predictive Control (NMPC) method. One of the main advantages of the proposed method is that it is trajectory free, which gives the robot the ability to step over any feasible obstacle. Moreover, the NMPC guarantees dynamic stability during walking and crossing over the target. In addition, a multilayer perceptron neural network is employed for identification of the dynamic model of the robot. In this way, the proposed method can cope with uncertainties in the robot model. Simulation results show good performance of the proposed method applied to a 173 cm robot stepping over a 40×15cm obstacle dynamically in the sagittal plane while maintaining a safety clearance from it, without any need for reference trajectory.**

I. Introduction

STEPPING over obstacles is a big challenge for biped robots because when robot gets his leg up, the stability is at risk. Hence, it is hard to control a biped robot to cross over obstacles while maintaining its stability. Due to this problem, almost all papers in this area considered small obstacles. There are well-known robots that can step over small obstacles, such as Johnnie that can cross over a 5cm obstacle [1] and ASSIMO that can step over flat obstacles [2].

Previous studies on walking and stepping over obstacles have generated 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 trajectories. This method has performed for HRP-2 humanoid robot [3]. At first, an algorithm finds feasibility conditions for stepping over an obstacle and robot uses the predefined off-line trajectory to crosses over it. In [4], authors considered several trajectories for crossing over different obstacles. 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, this method is developed and the strategy decides whether the robot can step over the obstacle or should step on it [5]. This method is performed on humanoid robot BHR-2 and he can successfully stand on obstacles. Gaun et al. proposed a method for stepping over obstacles to maintain the projection of the Center of Mass (COM) of the robot in the supporting polygon area that can guarantee static stability [6]. It is well known that static stability is much easier to consider than dynamic stability; however, the speed of walking or crossing over obstacles (e.g. HRP-2 robot) is much slower.

Preview control is another method that has been used to generate trajectories in order to step over a 15×5cm obstacle by HRP-2 humanoid robot [7]. The authors 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]. Stasse et al. have proposed a method for HRP-2 humanoid robot to cross over 25×5cm obstacle. This robot has 165 cm legs and 30 Degrees of Freedom (DOF) [9]. Adaptive off-line trajectories for the tip and waist of the robot are generated.

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. To overcome 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.

Diedam et al. have used the MPC to generate on-line trajectories [10]. In their method, by considering physical constraints of the robot, an optimal path and control method is created. The MPC controller has also been used for dynamical walking of humanoid robot HRP-2 [11]. 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 [12]. However, the problem in this method is that the robot walks very slowly. In [13], a real-time control method based on Nonlinear MPC (NMPC) is proposed to control a 7 DOF biped robot.

The NMPC uses the dynamic model of robot for prediction. However, due to existing of uncertainties in the model, the model prediction is not precise. Parsa and Farrokhi have used nonlinear disturbance observer (NDO) to overcome this problem [14]. In their control method, the gait length is not fixed. Hence, the robot's walking is similar to human behavior. However, due to the use of COM method, the robot walks slowly.

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Wang has used Radial-Basis Function (RBF) neural network to identify the dynamic model of the biped robot [18]. His goal is to find Jacobian matrix numerically that is used in his control method. In [19], for solving problem of uncertainties in a 5 DOF biped robot, CMAC neural network is employed. First, the robot learns the desired trajectory and then it is controlled to trace this trajectory. Simulation result showed that with uncertainty in the robot body, he can walk on trajectory with little and acceptable errors. Jaung have used Multi-Layer Perceptron (MLP) neural network to train the robot to walk at a sloppy surface with 5%, 10% and 15% slope with predefined trajectories [20].

Most aforementioned articles have used off-line trajectories for walking or crossing over obstacle. This paper solves the predefined trajectory problem and uses NMPC for simultaneous on-line trajectory planning and controlling of the robot. Some articles use MPC to find off-line optimal trajectory for biped robots but this solution is not as good as free trajectory method that is used in this paper. A few articles employ MPC for on-line trajectory planning but none of them have used this method for stepping over obstacles. Most articles considered small obstacles such that the biped robot doesn't need to raise his leg up; hence, stability is easier guaranteed. In the proposed method in this paper, a larger obstacle is considered that makes the dynamic stability a bigger challenge. The constraints that are considered in this paper are feasible and close to the human walking. Moreover, the gait length is not fixed and robot can walk and stop before obstacles. This approach provides abilities to the controller to define the gait length due to the constraints and the situation of the robot while maintaining stability.

The MPC is a model-based method and this can cause a problem when uncertainties exist in the robot model, which can occur commonly in practical situations. In this paper, MLP neural networks are used to overcome the mentioned problem.

This paper is organized as follows. Section II provides dynamic model of the robot. The structure of the NMPC controller, the cost functions, and constraints for walking at flat surfaces and stepping over obstacles will be given in Section III. Section IV introduces MLP neural network for model identification. Section V shows simulation results followed by conclusion in Section VI.

II. BIPED ROBOT DYNAMICS

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 [15].

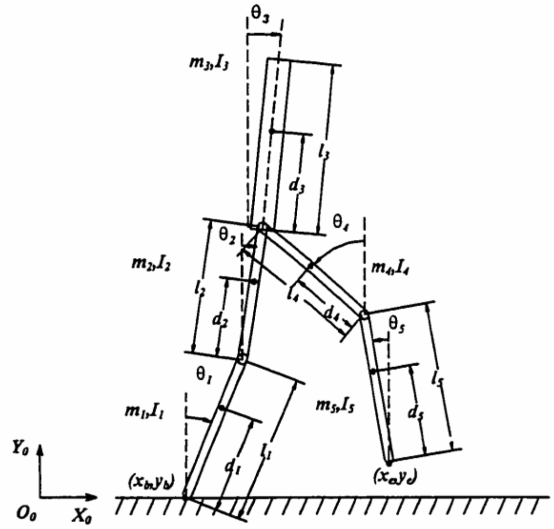

Fig.1. Five link biped robot.

A. Single Support Phase

The dynamic of SSP can be written as [15]

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

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 DSP can be presented as [15]

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

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

C. Single Support Phase 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. In this paper, it is assumed that the impact just affects the 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

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

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

III. NMPC APPROACH

Generally, motion planning method for robots is comprised of two phases: 1) motion planning and 2) trajectory tracking. However, human walking strategy is not based on following a predefined trajectory. Human strategy is performed with some goals and constraints such as optimal energy consumption, guarantee of stability during walking, obstacle avoidance, and being adaptive with the environment and situations. This problem statement can bring new visions to biped robot motion control. The nonlinear model predictive control method that is based on minimizing a cost function under some constraints seems to be very suitable for the biped control.

Model Predictive Control is a general control scheme that is designed to solve on-line a sequence of optimal control problems under some constraints [12], [13]. NMPC consists of two parts: a nonlinear model and an optimizer, which requires an objective function with possible constraints. Some papers have used the MPC just for minimizing the energy. However, in this paper, in addition to minimizing the energy consumption, moving the robot's COM forward and providing better supporting area are considered.

One of the main advantages of MPC 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 , 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, the NMPC method 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. Objective Function

The cost functions for the DSP as well as the SSP are the same and can be written as

$$J = w_1 \sum_{i=0}^{N_c-} T(t+i\Delta t)^T T(t+i\Delta t) + w_2 \sum_{i=1}^{N_p} (\dot{x}_{COM}(t+j\Delta t) - \alpha \dot{x}_{COM}^{desired})^2 \tag{3}$$

where

$$\alpha = 1 - \frac{2}{1+\exp\left(\dfrac{x_{COM}^{final} - x_{COM}(t+j\Delta t)}{\sigma}\right)}$$

and $\dot{x}_{COM}^{desired}$ and x_{COM}^{final} 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 $x_{COM}^{final} - x_{COM}$ is maximum and α is equal to one. When the robot is closed to the final position, the error and α approach zero and the robot stops. Parameters N_p and N_c 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.

B. Constraints

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

1) DSP Constraints

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

1. The joints constraints are $q_{i,\min} \le q_i \le q_{i,\max}$
   where, for the robot in Fig. 1
   $$q_1 = \frac{\pi}{2} - \theta_1; q_2 = \pi + \theta_1 - \theta_2; q_3 = \pi + \theta_2 - \theta_3;$$
   $$q_4 = \theta_4; q_5 = \pi + \theta_5 - (\theta_3 + \theta_4)$$
   To prevent singularities in the Jacobian matrix, the controller should guarantee $q_2 \ne \pi$ and $q_5 \ne \pi$.
2. The actuators torque should be limited
   $$T_{\min} \le T \le T_{\max} .$$
3. The biped robot should be at erected posture during its locomotion
   $$h_{\min} \le h_{hip} \le h_{\max}$$
   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; it should be upright during walking
   $$\theta_{\min} \le \theta_{trunk} \le \theta_{\max} .$$
5. Biped robot must only walk forward. Hence, the robot COM speed (in the *x*-direction) must be positive: $\dot{x}_{COM} \ge 0$.
6. The tip height of the swinging leg should be above the ground: $y_e = 0$.
7. The support area for dynamic stability is
   $$x_e \le x_{ZMP} \le x_b + FootLength .$$

For stepping over obstacles, the following constraint should also be considered

8. The horizontal position of the knee should not contact with the obstacle: $x_{knee} \le x_{O_2} + 0.02$.

2) SSP Constraints

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 the swinging leg should be restricted to $0 \le y_e \le H_{\max}$.
7. The horizontal speed of the tip should be adapted to the robot COM velocity
   $$\begin{cases} \dot{x}_e \ge \beta_{\min} \dot{x}_{COM} \sin(\dfrac{\pi y_e}{2H_{\max}}) \\ \dot{x}_e \le \beta_{\max} \dot{x}_{COM} \sin(\dfrac{\pi y_e}{2H_{\max}}) \end{cases}$$
8. During take off, the vertical speed of the tip must be positive and during landing it should be negative and adapted to the robot COM velocity

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

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

$$x_b \le x_{ZMP} \le x_b + FootLength.$$

For stepping over obstacles, the following constraint should also be considered.

6. The tip height of the swinging leg should be restricted
$$\begin{cases} x_e \le x_{O_2}, x_e \ge x_{O_3} \Rightarrow 0 \le y_e \le H_{O,\max} \\ x_{O_2} \le x_e \le x_{O_3} \Rightarrow H_{O,\min} \le y_e \le H_{O,\max} \end{cases}$$
where O_2 and O_3 are obstacle coordinates.
7. The horizontal speed of the tip should be adapted to the robot COM velocity
$$\begin{cases} \dot{x}_e \ge \beta_{\min} \dot{x}_{COM} \sin(\frac{\pi x_e}{x_{O_2} + x_{O_3}}) \\ \dot{x}_e \le \beta_{\max} \dot{x}_{COM} \sin(\frac{\pi x_e}{x_{O_2} + x_{O_3}}) \end{cases}$$
8. The vertical velocity of the tip should be
$$\begin{cases} x_e < x_{O_2} \Rightarrow \dot{y}_e > 0 \\ x_{O_2} \le x_e \le x_{O_3} \Rightarrow \dot{y}_e = 0 \\ x_e > x_{O_3} \Rightarrow \dot{y}_e < 0 \end{cases}$$
9. For dynamic stability, the support polygon should be guaranteed: $x_b \le x_{ZMP} \le x_b + FootLength$.
10. The horizontal position of the knee should not contact with the obstacle: $x_{knee} \le x_{O_2} + 0.02$.

First, the biped robot walks over a flat terrain normally. If an obstacle is detected in the vicinity of the robot, the controller regulates the gait length (i.e. either making it shorter or longer) in order to stop at an appropriate place before the obstacle. If the biped robot can step over the obstacle, the controller performs the task; otherwise, the robot stands still. Since the robot in this paper can just move in sagittal plane, it can not go around the obstacle.

IV. Multi Layers Perceptron Neural Network

Generally, existing of uncertainties in the dynamic model of a biped robot is unavoidable. The dynamic model is not precise because measurement tools are not precise. Moreover, the mass and inertia of each link can change after some time. Hence, a precise model is not available. The controller that is proposed in this paper (NMPC) uses dynamic model of the robot to predict the robot future behavior (i.e. the NMPC is a model-based method). MLP neural networks are employed in this paper to overcome the mentioned problems. It is well-known that neural networks can approximate any identify any complicated nonlinear model such as biped dynamic model, with desired accuracy.

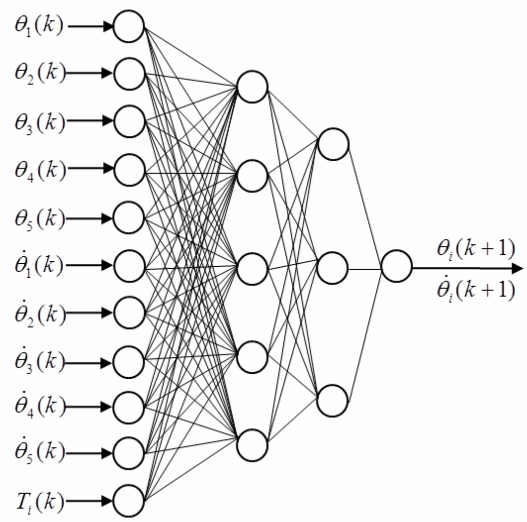

Fig.2. multilayers perceptron neural network structure.

A. Neural Network Structure

The NMPC requires the angular position and velocity of each link to predict the robot behavior and generate required Torques for each joint. The biped robot that is considered in this paper has 5 DOF. Hence, 10 neural networks are needed to predict the angular position and velocities of the robot. The inputs of each NN are the angular position and velocities of all five joints and the torque of the corresponding joint at the current sampling time. The output of each NN is the predicted angular position or velocity of the corresponding joint. Figure 2 shows the structure of the NNs.

The NNs are trained off-line using data collected for the dynamic equations of the robot. The training algorithm is the error back propagation. Two hidden layers with 5 and 3 neurons, respectively are used. The transfer functions of the hidden and output layers are of hyperbolic tangent and linear type, respectively.

V. Simulation Results

The biped robot parameters that have been adopted from [15], are given in Table I. This robot weights 49.5 kg and is 1.73 m tall. Table II shows the minimum and maximum value of variables. Other parameters are

$FootLength = 15$ 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. 3 shows several walking cycles and obstacle detecting. The last cycle is shorter than the other cycles because an obstacle is detected. Three phases of stepping over the obstacle are shown in Fig. 4.

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. ZMP horizontal and tip of the swinging foot and the hip position are shown in Fig. 5 and Fig. 6. It can be observed that ZMP moves forward but stays in the support polygon; that means the dynamic stability is guaranteed. Fig. 7 shows the joint torques, which and within the defined boundaries. MLP neural network is used for model identification. In order to show robustness of the NN against changes in the parameters of the robot, the mass and inertia of torso are increased by 20%.Fig. 8 shows the ZMP horizontal position that is in stable area. As Fig. 9 shows, the tip position of the swing foot and the hip position do not come in contact with the obstacle. Joint torques are shown in Fig. 10.

TABLE I
ROBOT PARAMETERS

Link	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	Minimum	Maximum
h_{hip}	0.98 m	1.08 m
θ_{trunk}	-3°	3°
T_i	-250 N.m	250 N.m
H_O	Obs_Height+.01m	Obs_Height+.03m
β	4	10

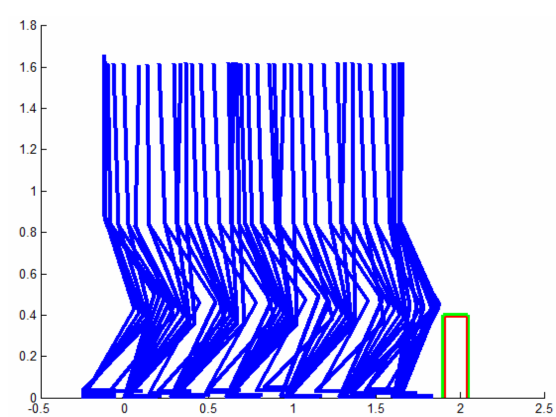
Fig.3. Walking on flat surface and stopping before obstacle.

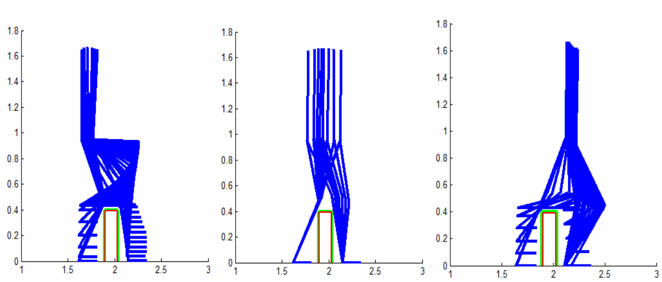
Fig.4. Stepping over obstacle.

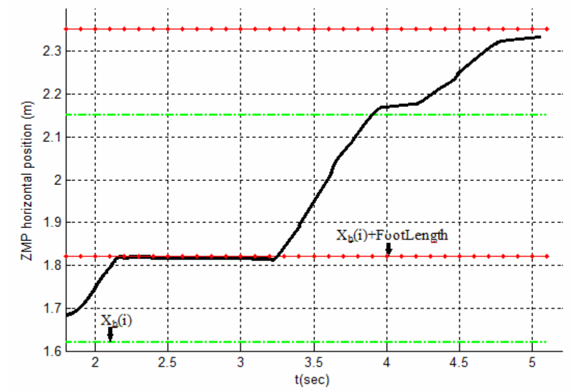

Fig.5. ZMP horizontal position in stepping over obstacle.

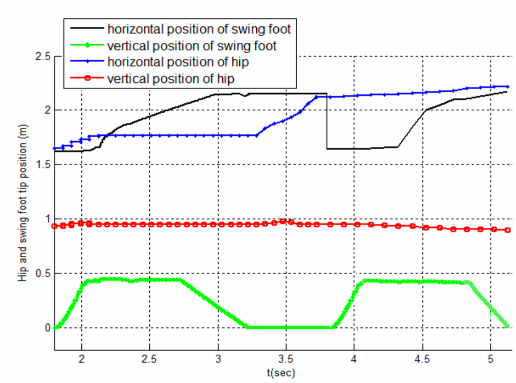

Fig.6. Tip and hip position in stepping over obstacle.

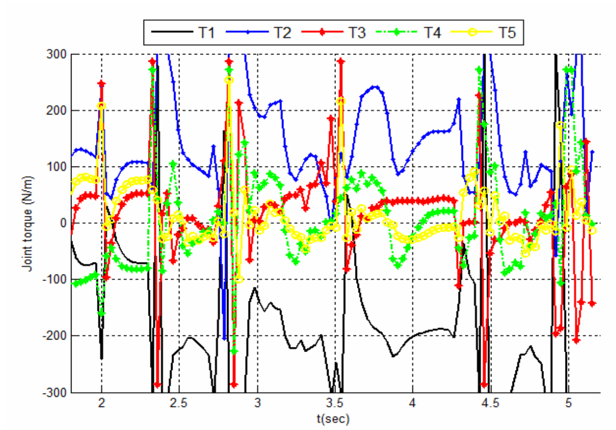

Fig.7. Joint torques in stepping over obstacle.

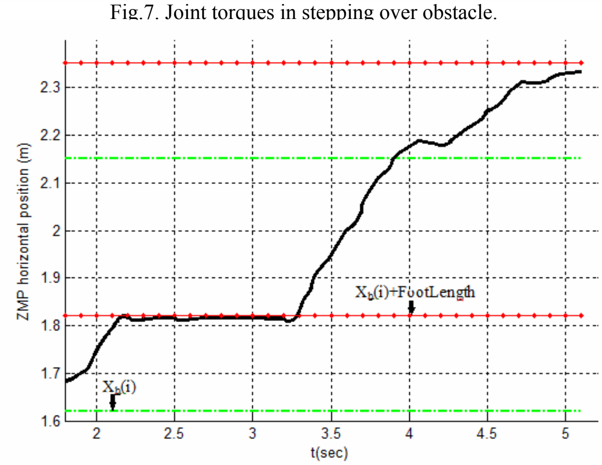

Fig.8. . ZMP horizontal position in stepping over obstacle and model identification with neural network.

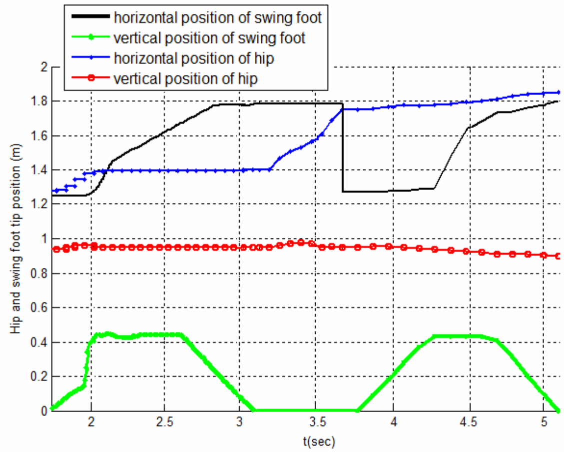

Fig.9. Tip of swing foot and hip position in stepping over obstacle and model identification with neural network.

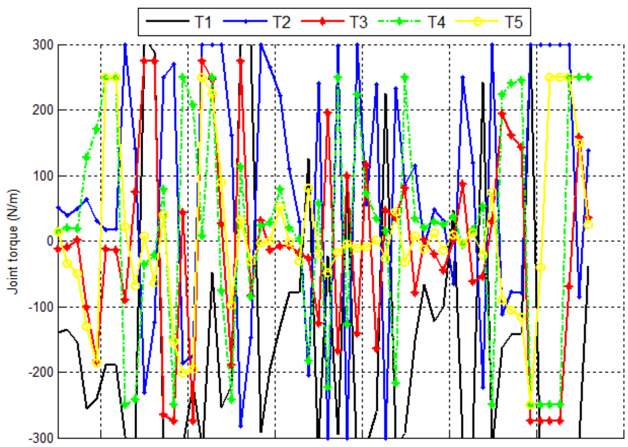

Fig.10. Joint torques in stepping over obstacle and model identification with neural network.

VI. Conclusion

This paper proposed a control method for walking and stepping over obstacles of biped robots. The Nonlinear Model Predictive Control (NMPC) is used for controlling the robot without any off-line trajectory planning. Due to advantages of NMPC, walking and crossing over obstacle of the biped robot become very similar to human walking strategy. The other advantage 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 (40cm) while maintaining stability. Since NMPC is a model-based control method, NNs have been used to identify the model robot as well as handling parameter uncertainties in the robot. The biped robot that is used in this paper has a 49.5 kg weight and is 1.73 m tall; it could cross over a 40×15cm obstacle in the sagittal plane (40% of the robot's leg length) with maximum 1 m/s speed. Simulation results showed effectiveness of the proposed method.

References

[1] J. F. Seara, O. Lorch and G. Schmidt, "Gaze control for goal-oriented humanoid walking," International Conference of Humanoid Robots, 2001.

[2] P. Michel, J. Chestnutt, J. Kuffner and T. Kanade, "Vision-guided humanoid footstep planning for dynamic environments," International Conference of Humanoid Robots, 2005.

[3] Y. Guan, N. E. Sian and K. Yokoi, "Motion planning for humanoid robots stepping over obstacles," International Conference of Intelligent Robots and Systems, August 2005.

[4] M. Yagi and V. Lumelsky, "Biped robot locomotion in scenes with unknown obstacles," IEEE International Conference on Robotics and Automation, May 1999.

[5] A. R. Jafri, Q. Huang, J. Yang, Z. Wang and T. Xiao, "Motion planning for stepping on/off obstacles by humanoid robot," IEEE International Conference of Mechatronics and Automation, August 2007.

[6] Y. Guan, N. E. Sian and K. Yokoi, "Stepping over obstacles with humanoids robots," IEEE Transactions on Robotics, vol. 22, no. 5, pp. 958-973, October 2006.

[7] B. Verrelst, K. Yokoi and O. Stasse and A. H. B. Vanderborght, "Mobility of humanoid robots: stepping over large obstacles dynamically," IEEE International Conference of Robotics and Automation, June 2006.

[8] C. L. Hwang, H. C. Wu and M. L. Lin, "The stepping over an obstacle for the humanoid robot with the consideration of dynamic balance," in Proceeding of SICE Conference, August 2010.

[9] O. Stasse, B. Verrelst, A. H. B. Vanderborght and K. Yokoi, "Strategies for humanoid robots to dynamically walk over large obstacles," IEEE Transactions on Robotics, vol. 25, no. 4, pp. 960-967, August 2009.

[10] H. Diedam, D. Dimitrov, P. B. Wieber, K. Mombaur and M. Diehl, "Online walking gait generation with adaptive foot positioning through linear model predictive control," IEEE International Conference of Intelligent Robots and Systems, September 2008.

[11] P. B. Wieber, "Trajectory free linear model predictive control for stable walking in the presence of strong perturbations," Internional Conference of Humanoid Robots, December 2006.

[12] C. Azevedo, P. Poignet and B. Espiau, "On line optimal control for biped robots," in Proceeding of 15th IFAC World Congress, vol. 16, part 1, 2002.

[13] Z. Zhu, Y. Wang and X. Chen, "Real-time control of full actuated biped robot based on nonlinear model predictive control," Intelligent Robotics and Applications, Vol. 5314, pp. 873-882, 2008.

[14] M. Parsa and M. Farrokhi, "Robust nonlinear model predictive trajectory free control of biped robots based on nonlinear disturbance observer," in Proceeding of ICEE, May 2010.

[15] C. Y. A. Chen, Dynamic modeling, control and simulation of a planar five-link bipedal walking system, Master Thesis, Department of mechanical and Industrial Engineering, University of Manitoba, Canada, 2000.

[16] D. Katić and M. Vukobratović, "Survey of intelligent control techniques for humanoid robots," *International Jornal of Intelligent and Robotic System*, vol. 6, no. 37, pp. 117-141, 2003.

[17] M. Lawrynczuk, " A family of model predictive control algorithms with artificial neural networks, " International Journal of Math. Computer Science, vol. 17, No. 2, pp. 217-232, 2007.

[18] X. Wang, *Balance Control for a Standing Biped and Stability Analysis Using the Concept of Lyapunov Exponent*, Master Thesis, Manitoba University, Department of Mechanical & Manufacturing Engineering, 2008.

[19] C. Sabourin and O. Bruneau, "Robustness of the dynamic walk of a biped robot subjected to disturbing external forces by using CMAC neural networks," *International Jornal of Robotics and Autonomous Systems*, vol. 51, no. 8, pp. 81-99, 2005.

[20] J. G. Juang, "Intelligent locomotion control on sloping surfaces," *International Jornal of Information Sciences*, vol. 147, no. 5, pp. 229-243, 2002.