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On the Design of a Nonlinear Model Predictive Controller based on Enhanced Disturbance Observer for Dynamic Walking of Biped Robots

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Abstract—**In this paper a nonlinear model predictive control strategy based on enhanced nonlinear disturbance observer is proposed to control the dynamic walking of biped robots on the smooth surface considering double support phase, single support phase, and impact. Optimal tracking of reference trajectories via optimal joint torque is established via a nonlinear predictive controller with well-defined cost functions and associated constraints. The implementation of a conventional disturbance observer encounters numerous challenges due to the joint acceleration requirements. The proposed nonlinear disturbance observer here, which only requires the position and angular velocity, helps to estimate the disturbances introduced on the robot and reduce the complications. The simulation results performed on the dynamic walking of a 5-DOF biped robot on flat surface shows the merits of the proposed method in tracking arbitrary trajectories despite the disturbances.**

Index Terms--**Biped robot, dynamic walking, improved nonlinear disturbance observer, nonlinear model predictive control, single and double support phases.**

I. Introduction

The control of biped robots has attracted much attention in the last two decades. The biped robots should have an adaptive and robust performance to be utilized in different environments without being too sensitive to potential uncertainties and disturbances. Imitation of human behavior is one of the best ways to solve the issues related to the robot movement. For this purpose, it is helpful to have a prediction of a few moments later, which makes predictive control approach an optimal solution for them [1-3]. To this aim, in [4-5], the nonlinear model-based predictive control (NMPC) strategy is proposed to control a biped robot for crossing obstacles without a pre-determined trajectory. Also linear MPC is used in [6], to obtain the online position of legs in the dynamic walking scenario despite the external disturbances. This method has been implemented on a 29-DOF humanoid robot and showed acceptable performance. In [7], the linear MPC is employed to generate an online motion trajectory accompanied by optimal velocity and energy consumption.

Disturbances are inevitable in the concept of bipeds and can be addressed via disturbance observers (DOs.) DOs can be designed and analyzed in linear/nonlinear forms. The linear version is designed to eliminate the disturbance in a particular frequency range by considering the inverse of the system nominal model plus a low-pass filter. In linear observer, not only it is necessary to design an appropriate filter [8], but also, it's important to have a minimum phase-type model. However, solutions are proposed in the literature to solve the problem of obtaining the inverse of the non-minimum phase system using the minimum phase system assumptions [9]. Despite all the research studies in the field of linear DOs, the synthesis of these observers is generally based on linear dynamics of the system. Therefore, different DOs are proposed to consider the nonlinear dynamics of the system. In [10-11], a DO is applied on an unmanned aerial vehicle and spacecraft formation flying. An observer with a similar structure is proposed for a manipulator in [12], for a multi-teleoperation system with multi manipulators in [13], a 2-DOF robotic knee exoskeleton in [14], and a knee exoskeleton with time delay in [15]. In the later research, there is only one dynamic in both the manipulator and robotic knee exoskeleton, and the DO is only designed for that dynamic. The truth is that the biped robot has a switching structure with two main dynamics as well an impact phase and a leg change mapping that should be performed constantly. Therefore, a nonlinear disturbance observer (NDO) is necessary to be designed considering both dynamics. In [16], the NDO-based zero dynamic control method is proposed to control a 5-DOF under-actuated biped robot for static walking considering the disturbance dynamics. The MPC based on NDO for free trajectory of biped static walking is presented in [17]. The proposed method for the dynamic walking of the biped robot on the smooth surface considering both dynamics is not yet presented in the literature.

Motivated by the abovementioned review, in this paper, a NDO-based NMPC method is proposed to control the dynamic walking of the biped robot on a smooth surface. By defining a suitable cost function as well as linear and nonlinear constraints, NMPC in here is able to detect efficient reference

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trajectories as well as provide optimal torque. This method depends on robot model subjected to uncertainties of the parameters (here called the internal disturbances) and the external disturbances such as overload, sudden impact and etc. Therefore, the method is enhanced with a NDO. Due to the fact that the biped robot has two main dynamics of single support phase (SSP) and double support phase (DSP), the observer is designed separately for both dynamics, and the controller guaranteed to provide a smooth movement of the robot by switching between those and considering the impact and leg switching maps. The NDO-based NMPC, which is presented for the first time in this paper, can trace the reference trajectories in both dynamics in the presence of model uncertainties, friction, and external disturbances. The proposed NDO only required the position and angular velocity for estimating the disturbance in the absence of angular acceleration.

The remainder of the paper is organized as follows. in Section 2, dynamics of biped robot are presented. The NMPC and cost function with its constraints is introduced in Section 3. Then, the NDO is designed for SSP and DSP dynamics in Section 4. The results of simulation are presented and analyzed in Section 5. Finally, concluding remarks are given in Section 6.

II. Dynamics of Biped Robot

In this paper, a sagittal biped robot with 5-DOF is investigated that involves two thigh links, two shank links, and a trunk link (Fig. 1). The biped robot has two main dynamics of SSP and DSP.

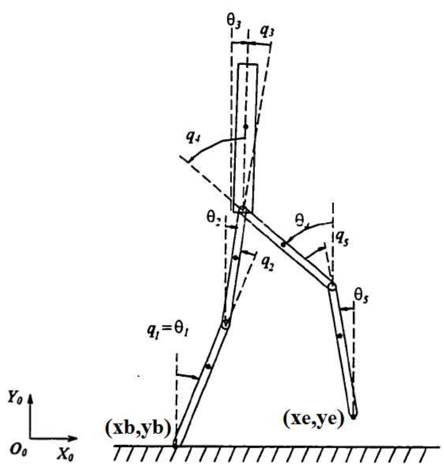

Figure 1. Example Planar 5-DOF biped robot

A. SSP Dynamic

The SSP is when one leg is placed on the ground as support, and the other is moving from the back to the front of the stationary leg. This phase begins when the tip of the swinging leg is removed from the ground and will continue until the swinging leg contacts the ground again. The fixed leg contact point with the ground is considered immobile. Using the Lagrange's method, the dynamics of the robot in SSP dynamic will be represented as follows:

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

where $D(\theta)$ is the given 5×5 positive symmetric matrix of inertia, $H(\theta,\dot{\theta})$ is a 5×1 vector contains terms related to the Coriolis and Centrifugal forces of the robot, $G(\theta)$ is a 5×1 vector containing terms related to the gravity force applied to the robot. $\theta,\dot{\theta},\ddot{\theta},T$ is a four 5×1 vector showing the extended coordinates of position, velocity, acceleration, and torque for the robot. Matrices *D*, *H*, and *G* are considered similar to those applied in [2].

B. DSP Dynamic

In the DSP, both legs are on the ground, and the trunk can move forward slowly. This mode is initiated when the moving leg placed on the ground and ends when the back leg is separated from the ground. Since both legs are fixed on the ground in this phase, some constraints are added to the dynamics of the robot, which can be written as Holonomic constraints. Using the Lagrange equation, the DSP dynamic of the robot can be expressed as follows:

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

where *D*, *H*, *G*, and *T* are the same vectors applied to (1), λ is a 2×1 vector that includes the Lagrange coefficients, and *J* is the Jacobian matrix of dimension 2×5 determined according to [2].

C. Impact

The impact phase occurs instantly when the robot leg contacts the ground. The impact phenomenon changes the velocity of the joints. It's effect is examined by Newton's impact theory and the principle of linear and angular momentum conservation. By assuming that the velocity of the contact points is zero immediately after the impact, and these two points are not raised or slip, we can then write the double impact map for the biped robot as follows:

$$\dot{\theta}^+ = \dot{\theta}^- + D(\theta)^{-1}J(\theta)^T(J(\theta)D(\theta)^{-1}J(\theta)^T)^{-1}(-\nu_e^-) \qquad (3)$$

where $\dot{\theta}^-$ is the velocity vector before the impact and $\dot{\theta}^+$ is the velocity vector after the impact. Also, $\nu_e^- = J(\theta)\dot{\theta}^-$ is the tip velocity of the moving leg at the moment before the impact. It is assumed that the position vector is not altered by the impact [2].

D. Mapping Transformation

After ending the SSP and impact, the robot begins the DSP and this period is repeated for each step. In this case, the leg that was fixed at the previous stage becomes a moving leg and the moving leg of the previous step becomes the fixed leg in the current step. The dynamic equation of the robot will not alter in the new step, but what happens is that the role change occurs between joints and links. For this reason, a transformation function is required that expressed the variables of the new step based on those of the previous step. The required mapping can be stated as [4]:

$$\begin{pmatrix} \theta_{initial} \\ \dot{\theta}_{initial} \end{pmatrix} = \begin{pmatrix} T_{Switch} & 0_{5\times5} \\ 0_{5\times5} & T_{Switch} \end{pmatrix} \begin{pmatrix} \theta^- \\ \dot{\theta}^+_{\mathrm{Im}pact} \end{pmatrix}$$

$$T_{Switch} = \begin{bmatrix} 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

where $\begin{bmatrix} \theta_{initial} & \dot{\theta}_{initial} \end{bmatrix}^T$ represents the vector of the initial variables for the new step, and it transforms to $\begin{bmatrix} \theta^- & \dot{\theta}^+_{\mathrm{Im}pact} \end{bmatrix}^T$, which contains the variables related to the end of the previous step after applying the impact map, using the mapping transformation.

E. Motion Trajectory Design

The trajectory design is an important step in the movement of biped robots. Most of the research studies have focused on trajectory design during SSP, and DSP has been less concerned. The motion over DSP has an important role in high-speed movement and maintaining stability, and this shows the importance of the DSP. Therefore, the motion patterns should consist of both the DSP and SSP. The smooth trajectory design eliminated variation in the velocity because of the impact effect and helps the robot trajectory design parameters to be selected such that the robot stability is always maintained. The trajectory design for biped robots is conducted by polynomial functions which are obtained for the tip position of the moving leg and the waist, and then converted to joint angles by inverse kinematic equations [2].

III. Predictive Control

Predictive control is a problem-solving method with an optimal vision on a limited horizon. In this method, a cost function is defined which captures the requirements of the control objective. Unlike other methods, the predictive control method dose not employ the error history to generate the rules of control, and rather predicts the future behavior of the system. This method helps it making optimal decisions and designing online controller [18-19]. In this paper, the *fmincon* function in MATLAB software is applied for constrained nonlinear optimization. The SSP and DSP models, which have been discussed in the previous section, are used as the prediction model. First, $\ddot{\theta}$ is calculated using the equations, and then, the state vector is obtained by calculating the integral of $\ddot{\theta}$. Finally, the state equations are discretized with appropriate sampling rates.

A. Objective Function

The cost function for tracking the reference trajectories of joint angles, θ_d , and the optimization of torque vector, T, is considered as:

$$J = \sum_{i=1}^{N_c} T(t+i\Delta t)^T w_1 T(t+i\Delta t) + \sum_{j=1}^{N_p} (\theta(t+j\Delta t)-\theta_d)^T w_2 (\theta(t+j\Delta t)-\theta_d) \quad (5)$$

where w_1 and w_2 are the weights associated with the cost of consumed torque and joints tracking, respectively. N_p and N_c are the prediction and control horizons so that $N_p \geq N_c$.

B. Constraints

The appropriate constraints for joint angles are considered as follows:

$$q_{i,\min} \leq q_i \leq q_{i,\max} \quad (6)$$

where, $q_0 = \theta_1$, $q_1 = \theta_1 - \theta_2$, $q_2 = \theta_2 - \theta_3$, $q_3 = \theta_3 + \theta_4$, $q_3 = \theta_3 + \theta_4$, and $q_4 = \theta_4 - \theta_5$ according to Fig. 1. $q_{\min}$ and $q_{\max}$ are minimum and maximum allowable relative angle, respectively. Because the singularity does not occur in the Jacobian matrix, q_2 and q_5 should not be equal to 180 degrees. The constraint related to joint torque is also considered as:

$$T_{\min} \leq T_i \leq T_{\max} \quad (7)$$

where $T_{\min}$ and $T_{\max}$ are minimum and maximum allowable joint torques.

IV. Nonlinear Disturbance Observer

The internal disturbance in this paper is a group of uncertainties in parameters and non-modeled dynamics, which can be input-additive. Also, the external disturbances can be represented by adding to the control input. The variation of mass and inertia of the object causes the distinction of mass and inertia of the links between the model applied to controllers and real values. On the other hand, because of the various devices being installed and the complex structure of links, it is impossible to calculate the accurate values of the mass and inertia for the links. The factors such as joint friction and external force applied to the robot can be the causes of external disturbances. Moreover, the external force may be caused by the collision of the robot with objects in the environment or vice versa. These disturbances will have negative effects on the controller performance and may even cause robot instability. Therefore, it is required to apply suitable control strategies for removing the internal disturbances described above [20].

The proposed controller here is a NMPC that is employed because of its numerous advantages. As the name suggests, it is based on the robot model that can be encountered with some problems due to internal disturbances. Although the NMPC method can deal with external disturbances to a certain extent due to its online performance and optimal behavior, it is extremely susceptible to internal disturbances. The variation in system parameters results in some issues in the predictive performance of the controller, which is the base of its decision-making feature, and this increases the probability of instability. This paper presents an NDO to address this problem.

A. Disturbance Observer in SSP

The dynamics of the biped robot in SSP and presence of disturbances is expressed as follows:

$$\bar{D}(\theta)\ddot{\theta}+\bar{H}(\theta,\dot{\theta})+\bar{G}(\theta)=\bar{\mathrm{T}}+\mathrm{T}_d \tag{8}$$

where $\bar{D},\bar{H},\bar{G},\bar{T}$ are the nominal values of vectors and matrices introduced in (1) and T_d is the disturbance vector. The disturbance vector is assumed as $T_d = T_d^{ex} + T_d^{in}$, where T_d^{ex}, T_d^{in} are the external and internal disturbance signals. The internal disturbance signal can be calculated by the following equation assuming the additive internal disturbances:

$$T_d^{in} = -\delta J\ddot{\theta} - \delta C\dot{\theta} - \delta G \tag{9}$$

If both following conditions are met, the dynamics of disturbance observer can be obtained and its stability can be proved [12, 17]: 1) $J(\theta)$ should be a positive definite matrix bounded $\beta I_n \le J(\theta) \le \alpha I_n$,where $\alpha \ge \beta \ge 0$ and I_n is an identical matrix. 2) Torque, should be limited, and as a result, the $\dot{\theta}$ is placed in a certain range: $\|\dot{\theta}\| \le \dot{\theta}_{\max}$. By defining the disturbance estimation error as $e = T_d - \hat{T}_d$, where $\hat{T}_d$ is the estimated disturbance. Since there is no information about the disturbance derivative with respect to time, it is assumed that $\dot{T}_d = 0$. Considering this assumption, the error estimation dynamic is formulated as:

$$\dot{e} + L\,\bar{D}^{-1}(\theta)e = 0 \tag{10}$$

where L is the gain of the disturbance observer. Here $R(\dot{\theta})$ is defined as follows:

$$R(\dot{\theta}) = L\begin{bmatrix}\dot{\theta}_1 & \dot{\theta}_2 & \cdots & \dot{\theta}_5\end{bmatrix}^T \tag{11}$$

Therefore, the dynamics of observer can be rewritten as follows:

$$\dot{\hat{\mathrm{T}}}_d = L\,\bar{D}^{-1}(\theta)\left(\bar{J}(\theta)\ddot{\theta}+\bar{H}(\theta,\dot{\theta})+\bar{G}(\theta)-\bar{\mathrm{T}}-\hat{T}_d\right) \tag{12}$$

However, the main problem of the above equation is associated with the term of the angular acceleration vector which requires to employ acceleration sensors for its measurements which leads to great expenses and difficulties in practice. The acceleration vector can be eliminated from the observer dynamic by introducing the following variable:

$$\phi = \hat{T}_d - R(\dot{\theta}) \tag{13}$$

$\dot{\hat{T}}_d$ is substituted from (13) into (12) so the dynamics of the disturbance observer is then converted to the following form:

$$\dot{\phi} = L\,\bar{D}^{-1}(\theta)\left(\bar{C}(\theta,\dot{\theta})\dot{\theta}+\bar{G}(\theta)-\bar{\mathrm{T}}-R(\dot{\theta})-\phi\right) \tag{14}$$

Considering the symmetry of the inertia matrix for the biped robot, and as well as the bounded control signal of the predictive controller, conditions of [12, 17] are similar to what defined in the previous section. This DO, can now be applied to the system.

B. Disturbance Observer in DSP

The DSP dynamic of the biped robot is different from the SSP dynamic because of external forces exerted when the moving leg is placed on the ground; For this reason, some changes should be applied to the disturbance observer design. If the disturbance observer in SSP is applied to the DSP dynamic without any change in support mode, the external force exerted by the friction between moving leg and the ground and vertical reaction force of the ground will be recognized as disturbances by the observer and the disturbance observer will try to eliminate them. The elimination of these forces means that the moving leg is removed from the ground and the SSP dynamic occurs for the robot. This generates a deviation in the DSP dynamic. By considering the applied disturbances, the DSP dynamic of the robot is represented the dynamic of the robot in two-leg support state can be expressed as follows:

$$\bar{D}(\theta)\ddot{\theta}+\bar{H}(\theta,\dot{\theta})\dot{\theta}+\bar{G}(\theta)=\bar{\mathrm{T}}+\mathrm{T}_d+J^T\bar{\lambda} \tag{15}$$

where $J^T\bar{\lambda}$ is the external torque applied to the joints with the nominal dynamics of moving leg on the ground. For given $J^T\bar{\lambda}$, $\tilde{T}$ can be defined as:

$$\tilde{T} = \bar{T} + J^T\bar{\lambda} \tag{16}$$

The above equation is similar to the dynamics of the robot during the SSP. Therefore, the disturbance observer can be applied as follows:

$$\dot{\phi} = L\,\bar{D}^{-1}(\theta)\left(\bar{H}(\theta,\dot{\theta})\dot{\theta}+\bar{G}(\theta)-\tilde{\mathrm{T}}-R(\dot{\theta})-\phi\right) \tag{17}$$

To determine $J^T\bar{\lambda}$, $\bar{\lambda}$ should be calculated from:

$$\bar{\lambda} = -\bar{S}_{c2}^{-1}\left(\bar{S}_{a21}\dot{\omega}+\bar{S}_{b2}\left(\bar{\mathrm{T}}+\mathrm{T}_d - \bar{N}\right)\right) \tag{18}$$

in which, $\bar{S}_{c2}$, $\bar{S}_{a21}$, $\bar{S}_{b2}$ and $\bar{N}$ are expressed as [2]. $\bar{T}$ is equal to:

$$\bar{T} = T_{NMPC} - \hat{T}_d \tag{19}$$

where is calculated by controller, so we will have:

$$\bar{\lambda} = -\bar{S}_{c2}^{-1}\left(\bar{S}_{a21}\dot{\omega}+\bar{S}_{b2}\left(\mathrm{T}_{NMPC} + e - \bar{N}\right)\right) \tag{20}$$

in which, the dynamic error of the disturbance observer is calculated by (10).

V. Simulation Results

The parameters of the 5-DOF biped robot are considered as [2]. The initial conditions of joints are defined as follows:

$$\theta_1 = 1.18^\circ, \theta_2 = -31.29^\circ, \theta_3 = 0^\circ, \theta_4 = -10.19^\circ, \theta_5 = -28.14^\circ$$
$$\dot{\theta}_1 = 1.03, \dot{\theta}_2 = -0.16, \dot{\theta}_3 = 0, \dot{\theta}_4 = -1.09, \dot{\theta}_5 = 0.1 (\mathrm{rad/s})$$

The robot velocity and its step length are assumed to be 1m/s and 0.7m, respectively. For the external disturbance, the forces applied by coulomb and viscous friction to the joints is considered as follows:

$$T_f^i = 5 sign(\dot{\theta}_i) + 0.6\dot{\theta}_i \tag{21}$$

In Figs. 2 and 3, the results are indicated for the case without disturbance observer. It is observed that without the disturbance observer, the controller cannot track the reference trajectories with an appropriate performance and this disrupts the robot movement, which is accompanied by a lot of oscillations. The simulation results are presented for the case with the disturbance observer designed in this study. In Fig. 4, curves of joint angles are plotted and their tracking error are presented in Fig. 5.

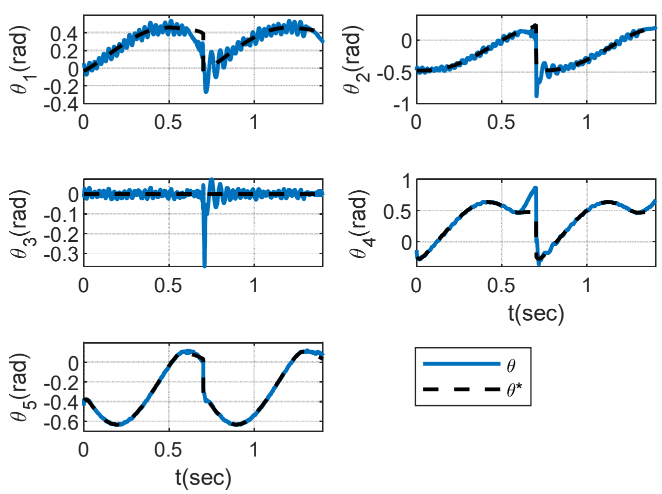

Figure 2. Joint angles without NDO

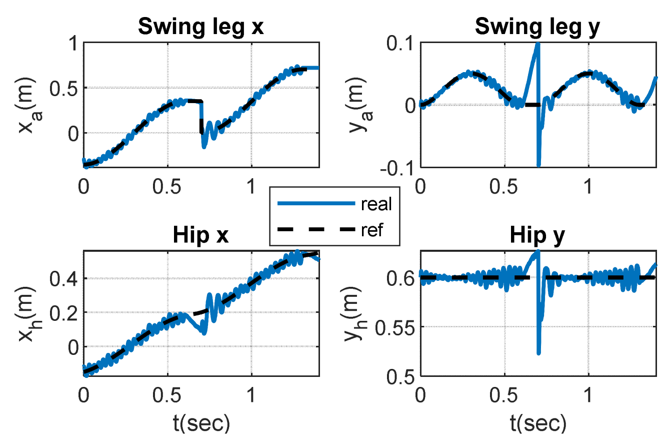

Figure 3. Hip and tip of swinging leg without NDO

The tracking process is conducted with good accuracy and high speed and the tracking error is negligible. In Figs. 6 the position of the tip of the moving leg and waist is presented, which indicates the smooth movement of the robot. In Fig. 7, the torque value is presented for different joints, and it is observed that all of them are in the allowable range. Also, the disturbance torque is accurately estimated in the lowest possible time, as shown in Fig. 8. By increasing the coefficient c, the estimation time can be reduced, but more oscillations are created in the estimation process.

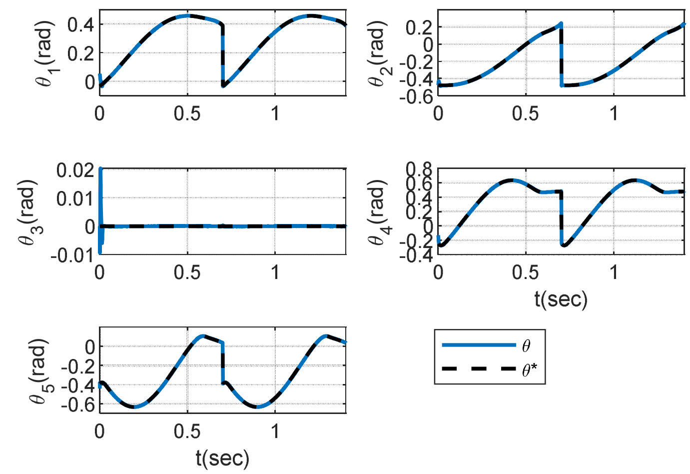

Figure 4. Joint angles with NDO

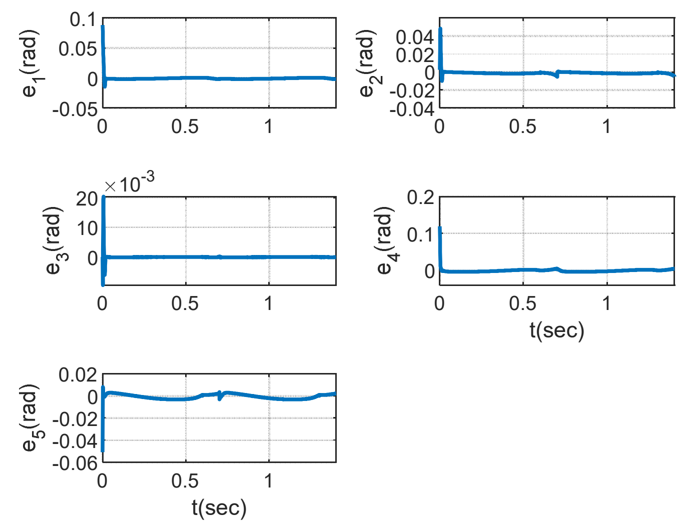

Figure 5. Tracking errors of joint angles with NDO

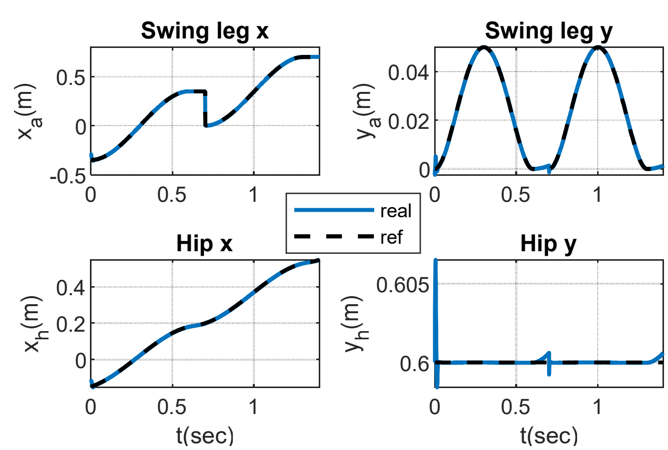

Figure 6. Hip and tip of swinging leg with NDO

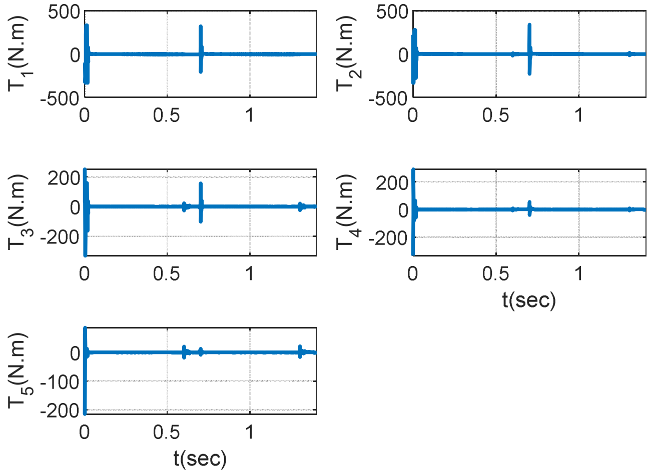

Figure 7. Joint torques

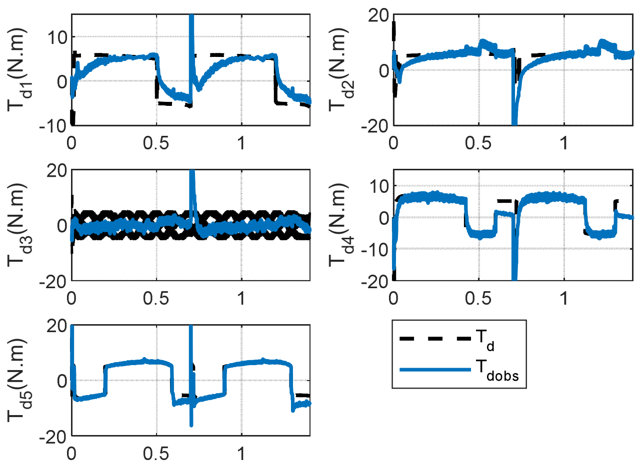

Figure 8. Estimation of disturbance torques

VI. Conclusion

In this paper, a NDO-based predictive control strategy has been designed to control the intended biped. In the robot model, all three dynamics of SSP, DSP, and impact have been considered for scenario of walking on the smooth surface. By defining the appropriate cost function as well as linear and nonlinear constraints for the predictive controller, an improvement has been witnessed in the robot performance when tracing the reference trajectories. To deal with external disturbances and friction in the robot, an enhanced nonlinear disturbance observer has been designed that estimate the disturbance value by using the position of the joints and their angular velocity, and provided them to the controller. The simulation results indicate the good performance and high efficiency of the controller and its proposed observer in the scenario of the stable dynamic walking in the presence of applied external disturbances and friction. Future works will be designing a NMPC based NDO for stepping over or avoiding obstacles.

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