Nonlinear Disturbance Observer for Robot Manipulators in 3D Space

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Abstract. Requirements for fast and accurate motion in industrial robot manipulators demand more advanced control techniques. To meet this problem, several methods have been reported. The Disturbance Observer (DOB) problem has been widely utilized in high-precision and high-speed motion control applications. However, most works done in this area are based on linear control theories even the dynamic of the manipulators are highly nonlinear. In this paper, a nonlinear disturbance observer is proposed for three-DOF robot manipulators operating in 3D space and the stability analysis of the proposed disturbance observer is performed by using Lyapunov's method. Using this nonlinear disturbance observer, it does not require an accurate dynamic model to achieve high precision motion control. The effectiveness of the proposed observer is investigated by numerical simulation. The results show that controller with nonlinear disturbance observer has more superior tracking performance, with a wide range of payloads and in the presence of friction.

Keywords: Nonlinear disturbance observer, Lyapunov's direct method, computed torque method.

1 Introduction

Interest in high speed and high accurate motion control on one hand, and on the other hand, need for attenuation of external and internal disturbances exerted on robot manipulators, have caused the development of various kinds of motion controllers. Disturbance observer [1-2], adaptive robust control [3-4], and Kalman filtering approach [5] are good examples. However, some of these methods are difficult to design and implement such as adaptive controllers, some of them provide high gain feedback to reject disturbances such as robust controllers and some else are designed for certain class of disturbances. Besides the previous methods, disturbance observers except that are very easy to design and implement [6], can be used for large class of disturbances. These methods commonly require the design of a two-loop structure. One is the design of an internal-loop compensator for robustness, and the other is the design of an external-loop controller for desired performance specifications. In such schemes, the internal-loop compensator generates a corrective control input to reject disturbance as much as possible to force an actual system to become a given nominal model.

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Disturbance observers can be used to estimate both internal and external disturbances. So it could be a good substitute for force sensors which it is known that information of force sensors has a lot of noise and by the way, determining of bandwidth of force sensors is a challenging task [7].

There are several methods in designing the disturbance observers, which most of them are based on linear control theories. In the conventional disturbance observer design, the algorithm consists of an inverse of nominal model of the plant dynamics, and a low pass-filter. If the plant has nonminimum phase zeros, then the disturbance observer must be internally unstable. Even for strictly proper systems, the disturbance observer includes derivative operation. So, the high-frequency noise might be amplified. However, using Internal Model (IM), these kinds of problems would be removed [8].

Another technique in disturbance estimation problem which can be applied to both linear and nonlinear systems is state observer design for augmented system. In this approach disturbances are taken as states append to the nominal system. In fact the objective is to estimate the states and the unknown inputs using only the known input and the output information [9-10].

Chen et.al. [11] proposed a nonlinear disturbance observer for two link planer robot manipulators. They choose a Lyapunov's candidate based on Inertia matrix and proved the stability of the observers. This paper extends the nonlinear disturbance observer proposed by Chen et.al. for robot manipulators in 3D space contained large class of robot manipulators. The stability of the proposed observer is analysed based on Lyapunov's direct method.

This paper is organized as follows. Dynamic modeling of manipulator in section 2, formulation of nonlinear disturbance observer is derived in section 3 then the stability analysis of proposed observer is considered in section 4 and at the end the simulation results is presented.

2 Dynamic Model of 3R Robot Manipulator

The manipulator consists of three revolute joints actuated by three motors to rotate the links as shown in Fig. 1. The robot's dynamics are described as

$$J_{act}(q)\ddot{q} + C_{act}(q,\dot{q}) + G_{act}(q) = \tau + f_{dis}\,, \tag{1}$$

where τ is the vector of input torques, and $q \in R^3, \dot{q} \in R^3$ and $\ddot{q} \in R^3$ are vectors of joint angular positions, velocities and accelerations, respectively. $J_{act}(q) \in R^{3\times3}$ is the inertia matrix, $C_{act}(q,\dot{q}) \in R^{3\times1}$ is the vector of coriolis and centrifugal forces, $G_{act}(q) \in R^{3\times1}$ is the gravity loading vector, and $f_{dis} \in R^{3\times1}$ is the disturbance vector which contains the torque due to the unknown load, external force, friction force, torque ripple and unmodeled dynamics. The "act" subscript denotes the actual value of parameters.

Assumption 1. The torque vector τ is bounded, so the angular velocity vector $\dot{q}$ lies in a known bounded set $\Omega_{\dot{q}}$ which $\Omega_{\dot{q}} \triangleq \{\dot{q} : \|\dot{q}\| \le \dot{q}_{\max}\}$.

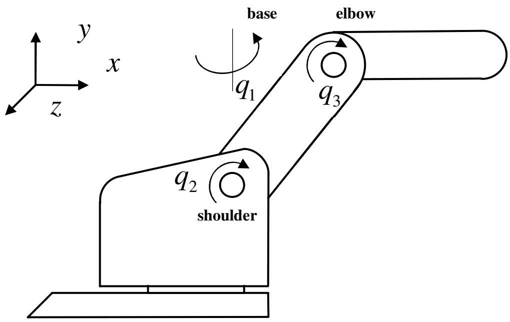

Fig. 1. 3R robot manipulator

After deriving the dynamic equations of manipulator, the inertia matrix elements can be written as below

$$J = \begin{bmatrix} J_1 + X_1 C_{2q_2} + X_2 C_{q_3} + X_2 C_{2q_2+q_3} + X_3 C_{2q_2+2q_3} & & sym. \\ 0 & J_2 + 2X_2 C_{q_3} & \\ 0 & J_3 + X_2 C_{q_3} & J_4 \end{bmatrix}, \qquad (2)$$

where $C_{aq_i+bq_j} = \cos(aq_i + bq_j)$. The parameters J_i and X_i are constants in terms of mass, length and moment of inertia of each link.

3 Nonlinear Disturbance Observer

Using Equations (1), the disturbance vector can be written as

$$f_{dis} = J(q)\ddot{q} + C(q,\dot{q}) + G(q) - \tau\,. \qquad (3)$$

where J, C and G are the nominal values of J_{act}, C_{act} and G_{act} respectively. So, disturbance observer can be proposed as a simple n ordinary differential equation as

$$\dot{\hat{f}}_{dis} = -L(q,\dot{q})\hat{f}_{dis} + L(q,\dot{q})\left(J(q)\ddot{q} + C(q,\dot{q}) + G(q) - \tau\right), \qquad (4)$$

where $L(q,\dot{q}) \in R^{3\times3}$. Since, there is no prior information about the derivative of the disturbance f_{dis}, it is assumed that disturbance in Equation (3) varies slowly (this is reasonable assuming the disturbance is constant during a short sampling period)

$$\dot{f}_{dis} = 0\,, \qquad (5)$$

Define the observer error as a difference between actual disturbance and estimated disturbance

$$e = f_{dis} - \hat{f}_{dis}\,. \qquad (6)$$

By differentiation from observer error, dynamic of error can be written as

$$\dot{e} + L(q,\dot{q})e = 0\,, \qquad (7)$$

where $L(q,\dot{q})$ must be chosen in such a way that the dynamic of error be asymptotically stable.

As it can be seen from Equation (4), acceleration signal $\ddot{q}$ is required to realize the disturbance observer. Since acceleration measurement is a hard task in many robotic applications, the problem is circumvented by defining an auxiliary variable $\psi = \hat{f}_{dis} - p(\dot{q})$. Differentiating the auxiliary variable with respect to time gives

$$\dot{\hat{f}}_{dis} = \dot{\psi} + \frac{\partial p}{\partial \dot{q}} \ddot{q} . \tag{8}$$

Substituting for $\dot{\hat{f}}_{dis}$ from Equation (8) into Equation (4) and defining

$$\frac{\partial p}{\partial \dot{q}} = L(q,\dot{q}) J(q) , \tag{9}$$

Equation (4) can be expressed as below

$$\dot{\psi} = -L(q,\dot{q})\psi + L(q,\dot{q})\big(C(q,\dot{q}) + G(q) - \tau - p(\dot{q})\big) , \tag{10}$$

in which there is no acceleration signal, and estimated disturbance can be obtained by

$$\hat{f}_{dis} = \psi + p(\dot{q}) . \tag{11}$$

3.1 Stability Analysis

The NDO is proposed in Equation (10), while it has two design parameters L and P, which is related to each other by Equation (9), so one of them must be chosen in such a way that the asymptotical stability of the proposed NDO is guaranteed.

Theorem 1. If $p(\dot{q})$ be defined as below

$$p(\dot{q}) = c \begin{bmatrix} \dot{q}_1 & 0 & 0 \\ \dot{q}_1 & \dot{q}_2 & 0 \\ \dot{q}_1 & \dot{q}_2 & \dot{q}_3 \end{bmatrix} , \tag{12}$$

then asymptotical stability of NDO given by Equation (10) is guaranteed.

Proof. Substituting Equation (12) into Equation (9) yields

$$L(q,\dot{q}) = c \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} J^{-1} . \tag{13}$$

In order to simplify the computations, inertia matrix $J(q)$ can be written as

$$J(q) = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \overline{J}(q) \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} . \tag{14}$$

Now, by using Equation (14), $\bar{J}(q)$ becomes

$$\bar{J}(q)=\begin{bmatrix} J_1+J_2+X_1C_{2q_2}+3X_2C_{q_3}+X_2C_{2q_2+q_3}+X_3C_{2q_2+2q_3} & & sym. \\ -J_2+J_3\text{-}X_2C_{q_3} & J_2-2J_3+J_4 & \\ -J_3-X_2C_{q_3} & J_3-J_4+X_2C_{q_3} & J_4 \end{bmatrix}, \quad (15)$$

where $\bar{J}(q)$ is a symmetric matrix. Substituting Equation (14) into Equation (13) yields

$$L(q,\dot{q})=c\bar{J}^{-1}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{bmatrix}. \quad (16)$$

Since $\bar{J}(q)$ is positive definite for all q, a Lyapunov candidate for the observer given in Equations (10) and (11) can be chosen as follow

$$V(e,q)=e^T\bar{J}(q)e. \quad (17)$$

The time derivative of the Lyapunov function along the observer trajectory is

$$\frac{dV(e,q)}{dt}=\frac{\partial V(e,q)}{\partial e}\dot{e}+\frac{\partial V(e,q)}{\partial q}\dot{q}. \quad (18)$$

where, using Equations (7) and (16), the first term can be determined as

$$\frac{\partial V}{\partial e}\dot{e}=-2ce^T\bar{J}\,\bar{J}^{-1}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{bmatrix}e=-e^T\begin{bmatrix} 2c & -c & 0 \\ -c & 2c & -c \\ 0 & -c & 2c \end{bmatrix}e. \quad (19)$$

The second derivative in Equation (18) can be written as

$$\frac{\partial V(e,q)}{\partial q}\dot{q}=e^T\frac{\partial \bar{J}(q)}{\partial q}\dot{q}e=$$
$$-e^T\underbrace{\begin{bmatrix} 2X_1\dot{q}_2S_{2q_2}+3X_2\dot{q}_3S_{q_3}+ & & \\ X_2(2\dot{q}_2+\dot{q}_3)S_{2q_2+q_3}+2X_3(\dot{q}_2+\dot{q}_3)S_{2q_2+2q_3} & & sym. \\ -X_2\dot{q}_3S_{q_3} & 0 & \\ -X_2\dot{q}_3S_{q_3} & X_2\dot{q}_3S_{q_3} & 0 \end{bmatrix}}_{Q}e, \quad (20)$$

By substituting Equations (19) and (20) into Equation (18), the time derivative of the Lyapunov candidate becomes

$$\frac{dV(e,q)}{dt}=-e^T\underbrace{\begin{bmatrix} 2c+2X_1\dot{q}_2S_{2q_2}+3X_2\dot{q}_3S_{q_3}+ & & \\ X_2(2\dot{q}_2+\dot{q}_3)S_{2q_2+q_3}+2X_3(\dot{q}_2+\dot{q}_3)S_{2q_2+2q_3} & & sym. \\ -c-X_2\dot{q}_3S_{q_3} & 2c & \\ -X_2\dot{q}_3S_{q_3} & -c+X_2\dot{q}_3S_{q_3} & 2c \end{bmatrix}}_{Q}e, \quad (21)$$

Now, it must be proved that $\frac{dV(e,q)}{dt} < 0$ for all e and q . For this purpose, it must be shown that P is positive definite matrix. From matrix algebra we know that if each diagonal entry is greater than sum of the absolute values of all other entries in the same row then the matrix will be positive definite. By applying this condition, the parameter c can be chosen as

$$c > 2(X_1 + X_2 + X_3)\dot{q}_{2_{\max}} + 2(3X_2 + X_3)\dot{q}_{3_{\max}} . \tag{22}$$

4 Simulation Results

The simulation result using the presented disturbance observer is shown in this chapter. The controller is designed based on computed torque method. The simulation is

Table 1. Parameters of manipulator

Parameter	Value	Unit
Length of Links	L_1=L_2=L_3=1	m
Mass	m_1=m_2=m_3=2	Kg
Moment of Inertia around axis y	I_{y1}=I_{y2}=I_{y3}=0.166	$Kg.m^2$
Moment of Inertia around axis z	I_{z2}=I_{z3}=0.166	$Kg.m^2$

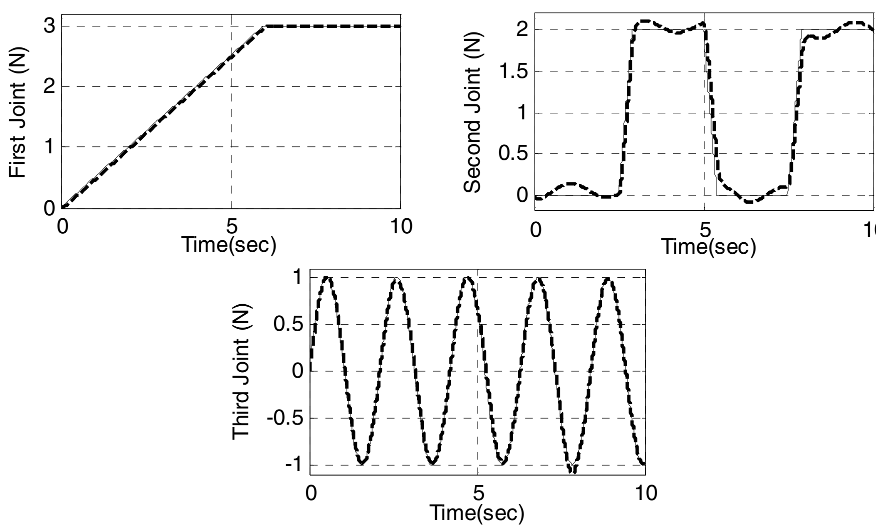

Fig. 2. Actual (thin solid line) and estimated (thick dashed line) disturbance

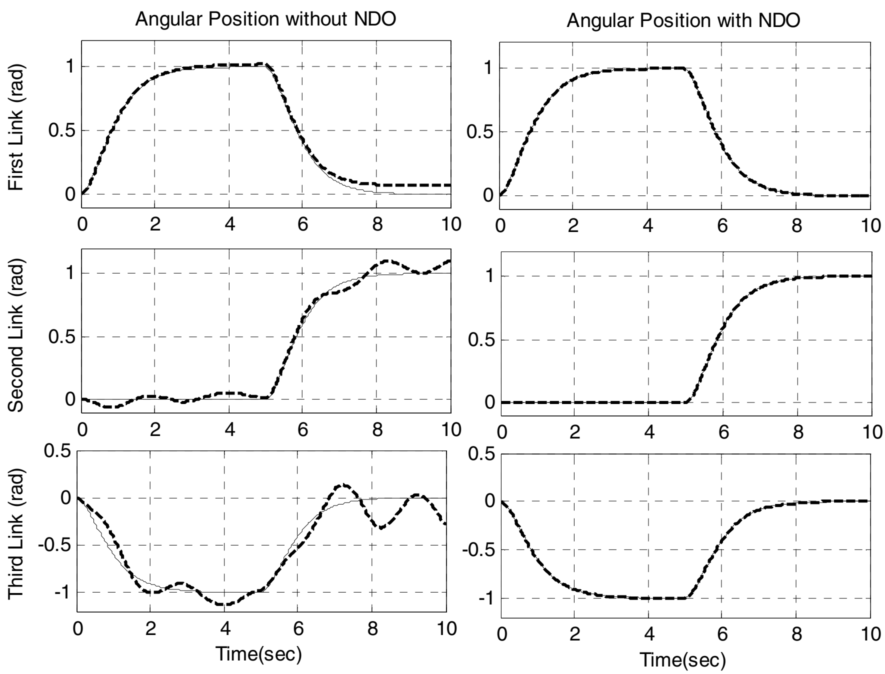

Fig. 3. Angular position with and without NDO in the presence of external disturbance, desired path (thin solid line) and actual path (thick dashed line)

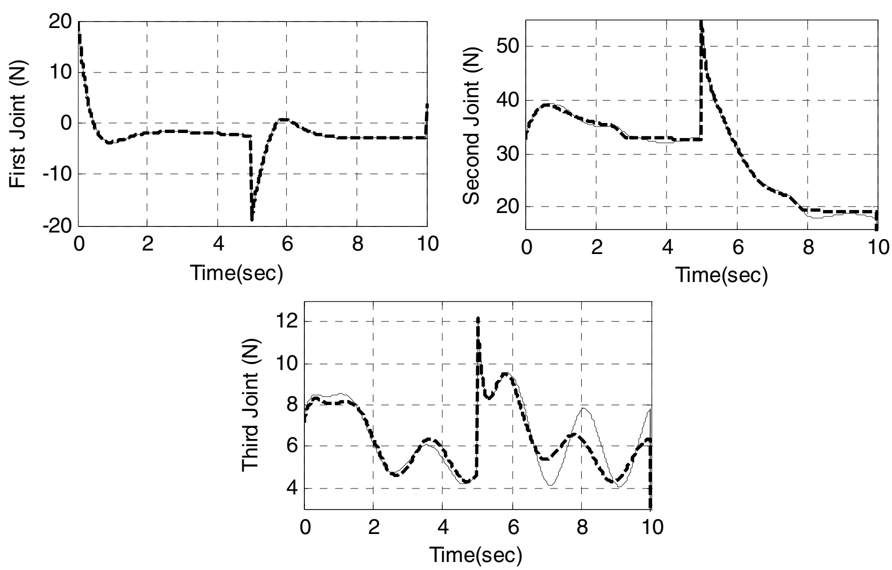

Fig. 4. Control input without NDO (thin solid line) and with NDO (thick dashed line)

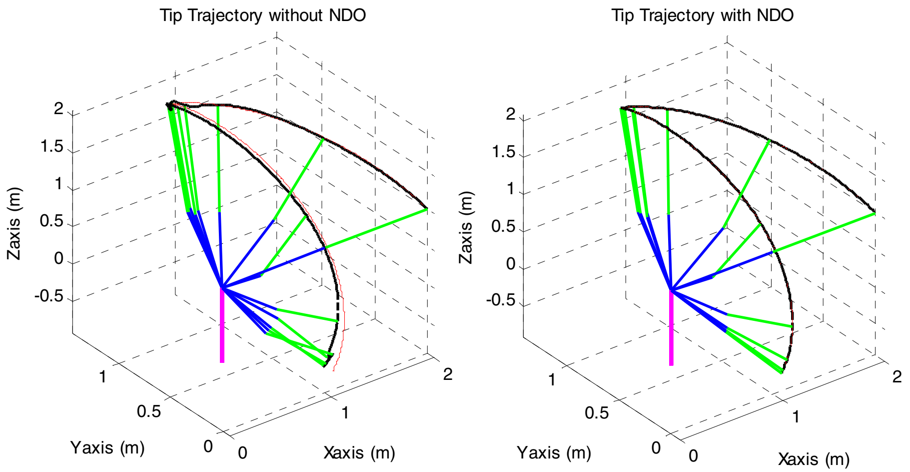

Fig. 5. Tip trajectory with and without NDO, desired path (thin solid line) and actual path (thick dashed line)

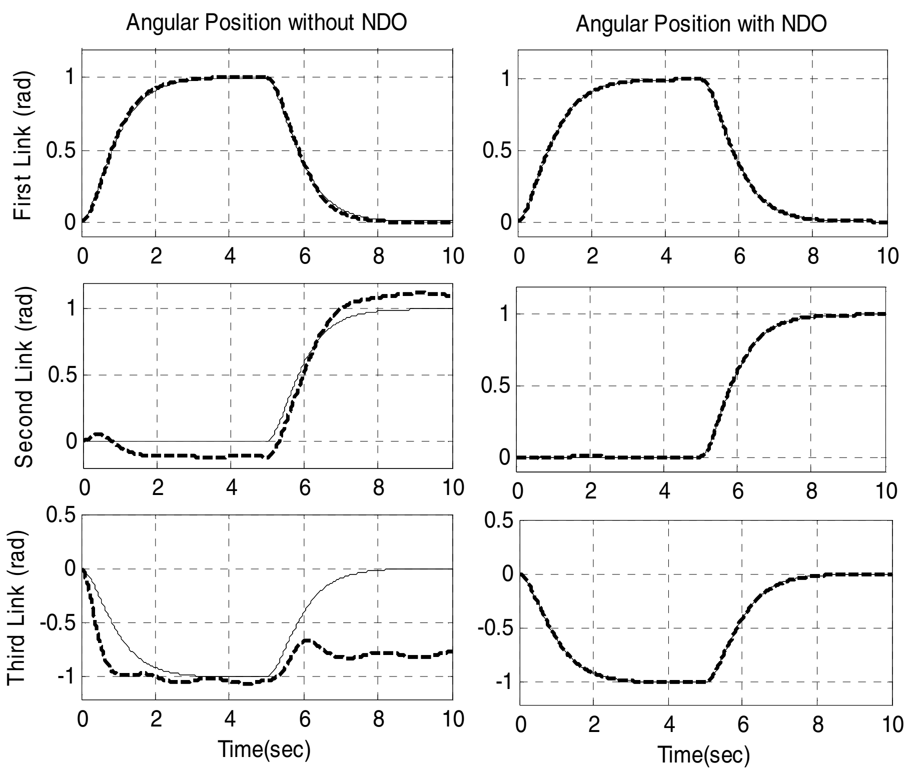

Fig. 6. Angular position with and without NDO in the presence of friction and unknown load, desired path (thin solid line) and actual path (thick dashed line)

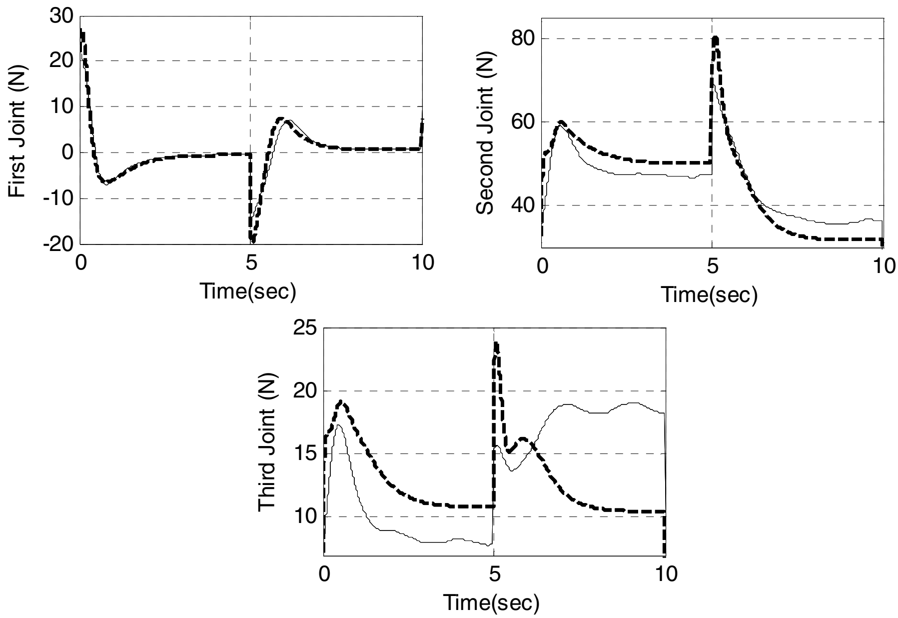

Fig. 7. Control input without NDO (thin solid line) and with NDO (thick dashed line)

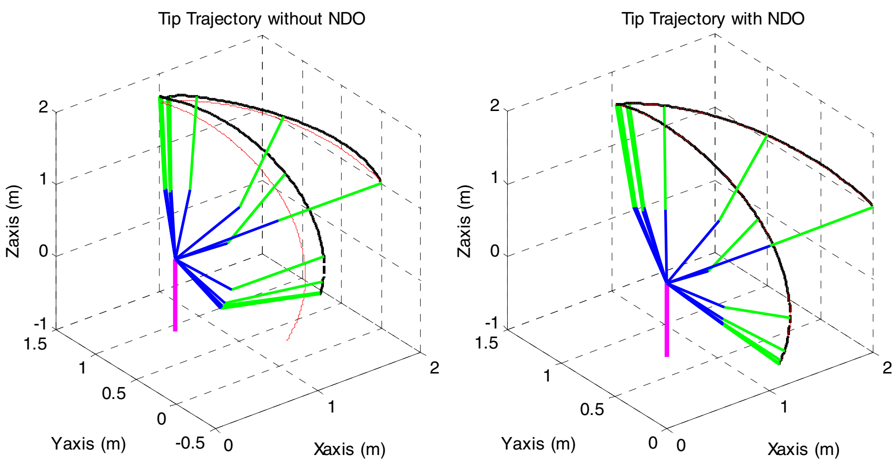

Fig. 8. Tip trajectory with and without NDO, desired path (thin solid line) and actual path (thick dashed line)

done for controller without and with disturbance observer. Unknown load as internal disturbance and torque ripple and friction as external disturbances are taken into account. The simulation is done for two cases: in first one only torque ripple is considered and in the next, both friction in joints and unknown load is considered. The parameter c

for disturbance observer is chosen as 50. Friction model is adopted from [11]. Parameters of manipulator are given in Table 1.

5 Conclusion

A method for constructing the nominal robot dynamic model in the joint space is proposed based on disturbance observer approach for three-link robot manipulators. The stability of the disturbance observer is proved by Lyapunov's direct method and the condition guaranteed the global stability is derived. The salient advantage of the proposed disturbance observer is that it is based on not acceleration but velocity, and it does not require derivative operation. Applicability of the observer is tested by simulation. The simulation results show the effectiveness of disturbance observer in estimating and attenuation of both internal and external disturbances.

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