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Trajectory Tracking Control for a Tele-operation Setup with Disturbance Estimation and Compensation

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Abstract— **In this paper, we tackle the position tracking problem in a robotic tele-operation setup in the presence of perturbations. In order to cope with the disturbance we developed a new disturbance observer. The estimation algorithm uses only position and velocity information and we study the estimation error dynamics in the face of constant and nonconstant exogenous perturbation signals. The disturbance estimator is used in a trajectory tracking controller to improve the performance of the position tracking between the master and the slave robot. The algorithm is tested in simulation on a tele-operation system with two two-link robots.**

I. INTRODUCTION

One of the challenges which is still unsolved in tele-operations is the tracking of the motion of the master robot when the slave is subject to perturbations. In recent years, with the development of robot technology, research on improving the tele-operation performance to achieve better accuracy and higher speed of operation has received a lot of attention. The main challenge to reach this goal is to deal with the difficulties introduced by disturbances, without adding extra sensors which would increase the price of the setup or would even not be possible to install.

Many approaches for disturbance rejection exist. Here we are just recalling some of the algorithms which have been shown to perform well. Reference adaptive control ([1]) ensures that the dynamics of a real robotic manipulator is similar to that of a nominal model. However, this type of algorithm requires a large computational effort to determine the control law. Another approach is to use a Kalman filter to reject disturbances modeled as stochastic models ([2],[3]). Robust controllers such as those based on H^{∞} ([4],[5]) and sliding mode control ([6],[7]) are also powerful methods to deal with disturbances.

Another method which has been successfully applied to many robotic applications is employing disturbance observers ([8],[9],[10],[11]). The main idea of a disturbance observer (DOB) is to estimate the perturbation by comparing the control input to the real system with the virtual control input to a nominal system. The virtual control input is obtained by the system output response filtered through the inverse dynamics of the nominal model. The estimate of the perturbation is fed back as a compensation signal and makes the whole system behave as the nominal system. One can easily see the reason why disturbance observers are so appealing: namely their potential high performance and the fact that there is no need for additional sensors. Disturbance observers have been developed both for linear and nonlinear systems. In the linear case, a DOB algorithm together with a perturbation compensation is designed to produce robust plant behavior by rejecting the perturbation within certain frequency ranges. The algorithm employs an inverse of the dynamics of the nominal model of the robot and a low-pass filter ([12]). The main issues with this method are the use of a low-pass filter for which optimization techniques are used to compute the parameters, which means an extra computational burden, and the fact that the method can only be applied to minimum-phase models. As robot dynamics are highly nonlinear, a more appropriate approach is to use nonlinear disturbance observers. Unfortunately, there are only few nonlinear control schemes using a DOB for which a rigorous stability proof is available ([13],[14],[15],[16],[17]). In [13], a nonlinear disturbance observer is introduced for a two-link robot manipulator. An extension to this result is given in [15] for an n-link manipulator. In both cases, the results consider only constant disturbances. In this paper, we extend these results, by designing a more generic new nonlinear disturbance observer. Similar to [15], we also do not use acceleration information for disturbance estimation. Moreover, we analyse the stability of the estimation error dynamics for both constant and nonconstant disturbances.

Next, this estimator is used in a controller scheme solving the trajectory tracking problem for a robotic tele-operation setup. An ultimate bound on the tracking error given a bound on the disturbance is determined using the stability concept of the input-to-state stability property ([18]). more precisely, this approach provides theoretical ultimate bounds on the tracking error given the bounds on disturbance signal and its time-derivate.

This article is structured as follows; in Section II, we recall some mathematical concepts related to the input-to-state stability property. In Section III, the tele-operation setup and the related tracking problem are presented. A new nonlinear disturbance observer is introduced in Section IV. This nonlinear DOB is used afterwards in Section V to solve the tracking problem for a tele-operation setup. A comprehensive stability proof for the tracking and estimation problem are also given. In Section VI, the theoretical results introduced in the previous sections are tested in simulation on a tele-operation setup consisting of two two-link robotic manipulators. A comparison of the tracking controller with

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and without the disturbance observer shows the usefulness of the estimation of the perturbation. In the final section, we present the conclusions and offer some perspectives for future research.

II. PRELIMINARIES

In this section, we recall some definitions and results concerning the property of input-to-state stability as introduced by Sontag in [18], see also [19]. The input-to-state stability property of nonlinear systems is exploited in the proof of the main result of this article.

Consider the general nonlinear system:

$$\dot{x}(t) = f(x(t), u(t)),\ x(0) = x_0, \tag{1}$$

with solutions $\varphi(t, x_0, u)$, where $f : \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^n$ is continuously differentiable.

Definition 1: The set of all the measurable locally bounded functions $u : \mathbb{R}^+ \to \mathbb{R}^m$, endowed with the supremum norm $\sup\{|u(t)|, t \geq 0\} < \infty$ is denoted as L^m_∞.

Definition 2: A function $\gamma : \mathbb{R}^+ \to \mathbb{R}^+$ is called a class $\mathcal{K}$-function, i.e. $\gamma \in \mathcal{K}$, if it is continuous, strictly increasing and $\gamma(0) = 0$.

A function $\gamma : \mathbb{R}^+ \to \mathbb{R}^+$ is called a class $\mathcal{K}_\infty$-function if $\gamma \in \mathcal{K}$ and $\gamma(s) \to \infty$ as $s \to \infty$.

A function $\beta : \mathbb{R}^+ \times \mathbb{R}^+ \to \mathbb{R}^+$ is a class $\mathcal{KL}$-function if for each fixed $t \geq 0$, $\beta(\cdot, t) \in \mathcal{K}$ and for each fixed $s \geq 0$, $\beta(s, t)$ is decreasing with respect to t and $\beta(s, t) \to 0$ as $t \to \infty$.

Definition 3: [18] System (1) is input-to-state stable (ISS) if there exists a function $\beta \in \mathcal{KL}$ and a function $\gamma \in \mathcal{K}_\infty$ such that, for each input $u \in L^m_\infty$, all initial conditions x_0 and for all $t \geq 0$ the following inequality holds:

$$|\varphi(t, x_0, u)| \leq \beta(|x_0|, t) + \gamma(\sup_{0 \leq \tau \leq t} |u(\tau)|). \tag{2}$$

Definition 4: [18] A smooth function $V : \mathbb{R}^n \to \mathbb{R}$ is called an ISS Lyapunov function for system (1) if there exist functions $\alpha_1, \alpha_2 \in \mathcal{K}_\infty$, $\alpha_3, \chi \in \mathcal{K}$ such that

$$\alpha_1(|x|) \leq V(x) \leq \alpha_2(|x|) \tag{3}$$

and

$$|x| \geq \chi(|u|) \Rightarrow \frac{\partial V(x)}{\partial x} f(x, u) \leq -\alpha_3(|x|) \tag{4}$$

hold for any $x \in \mathbb{R}^n$ and $u \in \mathbb{R}^m$.

Based on the existence of an ISS Lyapunov function satisfying (3) and (4), functions β and γ for which (2) is satisfied can be constructed, as is explained in the following result, which is introduced in [18] and [20].

Theorem 1: If an ISS Lyapunov function exists for system (1), then the system (1) is input-to-state stable with $\beta(\cdot, t) = \alpha_1^{-1} \circ \mu(\alpha_2(\cdot), t)$ (where $\circ$ is the function composition operator) and $\gamma = \alpha_1^{-1} \circ \alpha_2 \circ \chi$, where μ is the solution of the differential equation:

$$\frac{d}{dt}\mu(r, t) = -\alpha_3 \circ \alpha_2^{-1}(\mu(r, t)) \tag{5}$$

with the initial condition $\mu(r, 0) = r$.

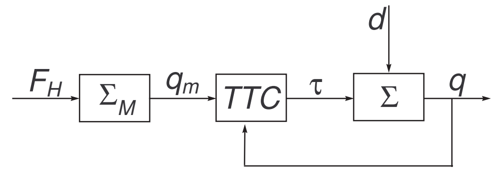

Fig. 1. Tele-operation Setup.

III. PROBLEM STATEMENT

In the sequel, we consider the problem of tele-operation of a slave robotic device in the presence of external disturbances (see Figure 1, where Σ_M and Σ are the models for the master and the slave robot, respectively, q_m and q are the position vectors of the master and the slave robot, TTC is the trajectory tracking controller which delivers the motor torque τ required for the motion tracking of the master by the slave robot, F_H is the human force acting upon master robot and d is the disturbance signal). Consider the following nonlinear dynamic equations of motion of the master:

$$\begin{aligned} M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m) + f_m(q_m, \dot{q}_m) + g_m(q_m) \\ = J_m^T(q_m) F_H, \end{aligned} \tag{6}$$

and the slave manipulator:

$$M(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s) + f(q_s, \dot{q}_s) + g_s(q_s) = \tau + d, \tag{7}$$

where $q_i \in \mathbb{R}^n$ and $\dot{q}_i \in \mathbb{R}^n$ are the generalized coordinates and the generalized velocities, respectively, $M_i(q_i)$ is the inertia matrix, $C_i(q_i, \dot{q}_i)$ is the matrix containing the centripetal and Coriolis terms, $f_i(q_i, \dot{q}_i)$ represents the frictional term, $g_i(q_i)$ contains the gravity terms, with $i \in \{m, s\}$ designating the master and the slave manipulators respectively. Moreover, $J_m^T(q_m)$ is the Jacobian of the master model, F_H is the human force acting at the end-effector of the master robot, $\tau \in \mathbb{R}^n$ is the vector of actuator torques of the slave robot and $d \in \mathbb{R}^n$ is the vector of disturbances acting upon the slave robot. A key assumption made here is that the disturbance can not be measured, which is realistic in many practical tele-operation setups.

For simplifying the notation in the sequel, we are identifying the vector of generalized coordinates of the slave manipulator q_s by q, unless stated otherwise.

The goal of this paper is to design a controller which ensures that the system output vector q (generalized coordinates of the slave) is tracking a trajectory q_m (generalized coordinates of the master), which is generated by a master robotic device actuated by a human operator.

In order to solve the tracking problem for a nonlinear slave system subject to exogenous perturbations, we propose to decompose the control strategy for the slave robot in two parts (see Figure 2):

1) a nonlinear disturbance observer (NDOB) that estimates the perturbation signal;
2) a tracking controller (TTC) that uses the estimated disturbance to achieve high-performance tracking of the master trajectory.

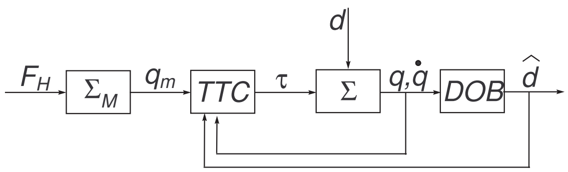

Fig. 2. Tele-operation Setup with Disturbance Observer.

IV. Nonlinear Disturbance Observer

In this section, we introduce a new nonlinear disturbance observer which extends a result developed in [13] and [15]. Let us consider the nonlinear system (7). An expression for the disturbance vector can be given as follows:

$$d = M(q)\ddot{q} + C(q,\dot{q}) + f(q,\dot{q}) + g(q) - \tau. \tag{8}$$

Therefore, similar to [13], we propose to use the following disturbance estimator:

$$\dot{\hat{d}} = -L\hat{d} + L(M(q)\ddot{q} + C(q,\dot{q}) + f(q,\dot{q}) + g(q) - \tau), \tag{9}$$

where $\hat{d} \in \mathbb{R}^n$ is the estimated disturbance vector and $L \in \mathbb{R}^{n\times n}$ is an estimation gain matrix.
The estimator (9) requires knowledge of the acceleration signal $\ddot{q}$. Since obtaining measured acceleration information is a difficult task in most robotic setups, we propose to avoid this problem by introducing the variable:

$$\delta = \hat{d} - p(q,\dot{q}). \tag{10}$$

Note that unlike the work in [15], we allow the function p to depend also on the position variables q. With respect to the result introduced in [15], where the function p is only velocity dependent, the more general function $p(q,\dot{q})$ will provide an easier assessment of the stability of the system for nonconstant disturbance signals.
If we differentiate equation (10) with respect to time, we obtain:

$$\dot{\hat{d}} = \dot{\delta} + \frac{\partial p(q,\dot{q})}{\partial q}\dot{q} + \frac{\partial p(q,\dot{q})}{\partial \dot{q}}\ddot{q}. \tag{11}$$

Let us now design $p(q,\dot{q})$ such that it satisfies

$$\frac{\partial p(q,\dot{q})}{\partial \dot{q}} = LM(q), \tag{12}$$

which means that $p(q,\dot{q})$ should be of the form

$$p(q,\dot{q}) = LM(q)\dot{q} + r(q). \tag{13}$$

Consequently, we then have

$$\frac{\partial p(q,\dot{q})}{\partial q} = L\frac{\partial M(q)\dot{q}}{\partial q} + \frac{\partial r(q)}{\partial q}. \tag{14}$$

Substituting equations (11), (12) and (14) in the expression of the disturbance observer (9) and, subsequently, evaluating the dynamics in terms of the variable δ as defined in (10) gives:

$$\begin{array}{l} \dot{\delta} = -L\delta - \left(L\frac{\partial M(q)}{\partial q}\dot{q} + \frac{\partial r(q)}{\partial q}\right)\dot{q} + \\ \quad +L(C(q,\dot{q}) + f(q,\dot{q}) + g(q) - \tau - p(q,\dot{q})) \end{array}. \tag{15}$$

Expression (15), together with the output equation $\hat{d} = \delta + p(q,\dot{q})$ now represents the nonlinear disturbance observer, where the disturbance estimation is based only on position and velocity information. One can notice that in the expression (13), which defines the function $p(q,\dot{q})$, the function $r(q)$ is freely assignable.
Let us now study the stability and the performance of the nonlinear disturbance observer in the face of nonconstant perturbations d.

A. Stability Analysis

In this section, we study the error dynamics of the disturbance observer (9) applied on the system (7). Define the disturbance error $e_d = d - \hat{d}$. Using (7), (10), (11)-(15), we can construct the following estimation error dynamics:

$$\dot{e}_d = -Le_d + \dot{d}. \tag{16}$$

Contrary to other nonlinear disturbance observers ([13],[15]), we do not restrict ourselves to the case of constant disturbances $\dot{d} = 0$, which in most practical cases is a false assumption. For this reason, in the sequel we study the input-to-state stability (ISS) of the system (16) with respect to the input vector $u = \dot{d}$.
To guarantee stability of the error dynamics, the estimation gain matrix L is designed such that $-L$ is a Hurwitz matrix. One can see that due to the choice of the matrix L, system (16) is a stable linear system with the solution:

$$e_d(t) = e^{-Lt}e_d(0) + \int_0^t e^{-L(t-\theta)}\dot{d}(\theta)d\theta. \tag{17}$$

Using simple linear system theory, we can derive that:

$$\lim_{t\to\infty} |e_d(0)e^{-Lt}| = 0, \tag{18}$$

because $-L$ is a Hurwitz. The steady-state error is also ultimately bounded by:

$$\lim_{t\to\infty} |e_d(t)| \le c \sup_{t\in(0,\infty]} |\dot{d}(t)|, \tag{19}$$

where $c = \int_0^\infty \|e^{-Lt}\|dt$.

V. Tracking Controller

In this section, we design a trajectory tracking controller for system (7) using the disturbance estimation $\hat{d}$ provided by the nonlinear disturbance observer (15) with $\hat{d} = \delta + p(q,\dot{q})$. Given the master trajectory q_m, let us define the position tracking error $e = q - q_m$. Consider the following trajectory tracking controller (TTC):

$$\tau = C(q,\dot{q}) + f(q,\dot{q}) + g(q) - \hat{d} + M(q)\left(\ddot{q}_m - p_1\dot{e} - p_2 e\right), \tag{20}$$

where p_1 and p_2 are feedback gain matrices.
Now, we derive the tracking error dynamics by substituting relation (20) in expression (7):

$$\ddot{e} + p_1\dot{e} + p_2 e = M^{-1}(q)e_d. \tag{21}$$

Define the new vector variable $x = [\ e \quad \dot{e}\ ]^T$ and the matrices:

$$A = \begin{bmatrix} 0_n & I_n \\ -p_1 & -p_2 \end{bmatrix}, \tag{22}$$

and

$$B = \begin{bmatrix} 0_n \\ I_n \end{bmatrix}, \tag{23}$$

where 0_n and I_n are the zero and identity matrices of size $n \times n$, respectively. We also introduce the new input vector $v = M^{-1}(q)e_d$. Using these definitions, the tracking error dynamics in (21) can be rewritten as:

$$\dot{x} = Ax + Bv, \tag{24}$$

with A and B as in (22) and (23), respectively.
As the matrix A is defined by gain matrices p_1 and p_2, we can design it to be Hurwitz, i.e. there exist a positive definite matrix $P = P^T > 0$ and a scalar $\varepsilon > 0$ such that:

$$A^T P + PA < -\varepsilon P. \tag{25}$$

Let us choose the following candidate ISS Lyapunov function $V = x^T Px$. The time-derivative of V along solutions of (24) is:

$$\dot{V} = x^T(A^T P + PA)x + 2v^T B^T Px \leq -\varepsilon x^T Px + 2v^T B^T Px. \tag{26}$$

Using simple matrix inequality manipulation, one can conclude that:

$$\dot{V} \leq -\varepsilon\beta V + \left(-\varepsilon(1-\beta)V + \lambda_2\left(\alpha|Bv|^2 + \frac{1}{\alpha}|x|^2\right)\right), \tag{27}$$

for $\forall\alpha > 0$, $\beta \in (0,1)$ and $\lambda_2 = \max\{eig(P)\}$. From relation (27) the following implication is derived:

$$|x| \geq \sqrt{\frac{\lambda_2\alpha}{(1-\beta)\varepsilon\lambda_1 - \lambda_2/\alpha}}|v| \Rightarrow \dot{V} \leq -\varepsilon\beta V, \tag{28}$$

with $\lambda_1 = \min\{eig(P)\}$. Note that α should be chosen such that $(1-\beta)\varepsilon\lambda_1 - \lambda_2/\alpha > 0$.
Let

$$\rho := \sqrt{\frac{\lambda_2\alpha}{(1-\beta)\varepsilon\lambda_1 - \lambda_2/\alpha}}.$$

Then we can define according to Definition 4 the functions:

$$\alpha_1(r) = \lambda_1 r^2, \tag{29}$$

$$\alpha_2(r) = \lambda_2 r^2, \tag{30}$$

$$\alpha_3(r) = \varepsilon\beta r, \tag{31}$$

$$\chi(r) = \rho r. \tag{32}$$

Since the conditions for Theorem 1 are fulfilled, we can conclude that the system (21) is ISS with respect to the input v, with the ISS property as in (2) characterized by the functions:

$$\beta(r,t) = \sqrt{\frac{\lambda_2}{\lambda_1}}|x(0)|e^{-\frac{\varepsilon\beta}{2}t}, \tag{33}$$

and

$$\gamma(r) = \sqrt{\frac{\lambda_2}{\lambda_1}}\rho r. \tag{34}$$

Assumption 1: The matrix norm $|M(q)|$ is bounded from below, i.e. $\exists\mu > 0$ such that $|M(q)| \geq \mu$, $\forall q \in \mathbb{R}^n$.
This assumption is valid in all robotic setups since it means that there are no mass-less system components.
The norm $|v| = \left|M^{-1}(q)e_d\right| \leq \left|M^{-1}(q)\right||e_d|$ is dependent on $\left|M^{-1}(q)\right|$, but according to Assumption 1 $|M(q)| \geq \mu$, $\forall q \in \mathbb{R}^n$, then $|M^{-1}(q)| \leq 1/\mu$, $\forall q \in \mathbb{R}^n$. Thus, we can conclude that $|v| \leq |e_d|/\mu$.
Since the force estimation error dynamics (e_d) is ISS with respect to the input $\dot{d}$ and the tracking error dynamics (e) is ISS with respect to the input v, we use the result introduced by [21] concerning the series connection of ISS systems to conclude that the closed-loop system from Figure 2 with the controller TTC and nonlinear disturbance estimator $NDOB$ is ISS with respect to the input $\dot{d}$.
Moreover, using convergence of the linear stable system describing the disturbance estimation error dynamics and the convergence manifolds determined for the trajectory tracking errors, we obtain the following bounds on the tracking error:

$$|e(t)| \leq \beta(|e(0)|,t) + \gamma(\sup_{0\leq\tau\leq t}|v(\tau)|), \tag{35}$$

and the increasing monotony of function γ given in ()34, we can conclude that:

$$\lim_{t\to\infty}|e(t)| \leq \lim_{t\to\infty}\gamma(\frac{c}{\mu}\sup_{0\leq\tau\leq t}|\dot{d}(\tau)|), \tag{36}$$

which provides an ultimate bound for the tracking errors with respect to the time-derivative of the perturbation.

Remark 1: Relation (36) provides a quantitative guideline for designing the gain matrices L, p_1 and p_2, such that $\lim_{t\to\infty}|e(t)|$ is small and satisfies tracking performance specifications given bounds on the time-derivatives of the disturbance.

Remark 2: For the case of constant disturbances d (i.e. $\dot{d} = 0$), we can guarantee perfect disturbance estimation ($\lim_{t\to\infty} e_d(t) = 0$), see (19), and perfect tracking ($\lim_{t\to\infty} e(t) = 0$), see (36).

VI. Simulation Results

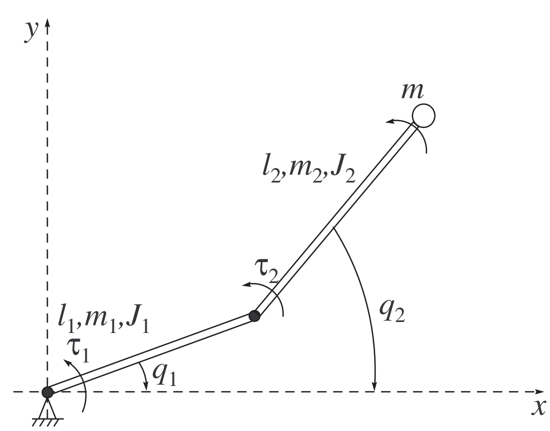

Fig. 3. A two-link robot.

In this section, we will apply the algorithm proposed in the previous section to a tele-operation setup consisting of two two-link robots in the horizontal plane, see Figure 3. We assume that the links are rigid and the joints are frictionless. The dynamics of two robots can be described by:

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i) = \tau_i + d_i, \tag{37}$$

where $M_i(q_i) = [\ M_i^1 \quad M_i^2\ ]$ with $i \in \{m,s\}$ distinguishing between the dynamics of the master and the slave robot, respectively:

$$M_m^1(q_m) = \begin{pmatrix} J_{m,1} + m_{m,1}\frac{l_{m,1}^2}{4} + m_{m,2}l_{m,1}^2 \\ m_{m,2}l_{m,1}\frac{l_{m,2}}{2}cos(q_{m,2}-q_{m,1}) \end{pmatrix}, \tag{38}$$

$$M_m^2(q_m) = \begin{pmatrix} m_{m,2}l_{m,1}\frac{l_{m,2}}{2}cos(q_{m,2}-q_{m,1}) \\ J_{m,2} + m_{m,2}\frac{l_{m,2}^2}{4} \end{pmatrix}, \tag{39}$$

$$C_m(q_m,\dot{q}_m) = \begin{pmatrix} -m_{m,2}l_{m,1}\frac{l_{m,2}}{2}\dot{q}_{m,2}^2 sin(q_{m,2}-q_{m,1}) \\ m_{m,2}l_{m,1}\frac{l_{m,2}}{2}\dot{q}_{m,1}^2 sin(q_{m,2}-q_{m,1}) \end{pmatrix}, \tag{40}$$

$$M_s^1(q_s) = \begin{pmatrix} J_{s,1} + m_{s,1}l_{s,1}^2/4 + m_{s,2}l_{s,1}^2 + ml_{s,1}^2 \\ (m_{s,2}l_{s,1}l_{s,2}/2 + ml_{s,1}l_{s,2})cos(q_{s,2}-q_{s,1}) \end{pmatrix}, \tag{41}$$

$$M_s^2(q_s) = \begin{pmatrix} (m_{s,2}l_{s,1}l_{s,2}/2 + ml_{s,1}l_{s,2})cos(q_{s,2}-q_{s,1}) \\ J_{s,2} + m_{s,2}l_{s,2}^2/4 + ml_{s,2}^2 \end{pmatrix}, \tag{42}$$

$$C_s(q_s,\dot{q}_s) = \begin{pmatrix} -(m_{s,2}/2+m)l_{s,1}l_{s,2}\dot{q}_{s,2}^2 sin(q_{s,2}-q_{s,1}) \\ (m_{s,2}/2+m)l_{s,1}l_{s,2}\dot{q}_{s,1}^2 sin(q_{s,2}-q_{s,1}) \end{pmatrix}. \tag{43}$$

The parameters $l_{i,j}$, $m_{i,j}$ and $J_{i,j}$ are the length, mass and moment of inertia about the center of mass of link j, $j = 1,2$, respectively. For the slave robot we have considered an extra load of mass m positioned at the end-effector. The motors of the master robot do not deliver any torque, this robot is actuated by a human operator applying force $F_H \in \mathbb{R}^2$ at the end-effector, i.e $\tau_m = J^T(q_m)F_H$ with

$$J(q_m) = \begin{pmatrix} -l_{m,1}sinq_{m,1} & -l_{m,2}sinq_{m,2} \\ l_{m,1}cosq_{m,1} & l_{m,2}qsinq_{m,2} \end{pmatrix}, \tag{44}$$

and

$$F_H = \begin{bmatrix} 0.2cos(0.5t) \\ 2sin(0.5t); \end{bmatrix}. \tag{45}$$

For simulation purposes, we consider the following parameter settings: $l_{i,1} = l_{i,2} = 0.6$ m, $m_{i,1} = m_{i,2} = 2$ kg, $J_{i,1} = J_{i,2} = \frac{m_{i,1}l_{i,1}^2}{12} = 0.06$ kgm^2 for the robot links and the mass of the load $m = 30$kg.

The estimation gain matrix L of the nonlinear disturbance observer is designed as follows:

$$L = \begin{bmatrix} 0 & -1 \\ 100 & 10 \end{bmatrix}. \tag{46}$$

The feedback gain matrices for the trajectory tracking controller are chosen: $p_1 = p_2 = 10I_2$, with $I_2 \in \mathbb{R}^{2\times 2}$ the 2×2-identity matrix.

The exogenous signal acting upon the slave system is:

$$d = \begin{bmatrix} 10 + 20sin(0.1t) \\ 50 + 20sin(2t) \end{bmatrix}. \tag{47}$$

In Figure 4, we present the disturbance estimation results

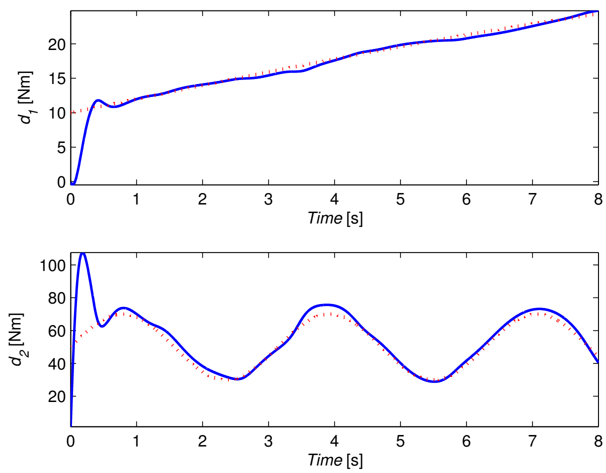

Fig. 4. Disturbance Estimation.

(dotted line: the disturbance, and solid line: the estimation), where $d = [\ d_1 \quad d_2\ ]^T$. One can see that the disturbance observer performs well and we can obtain a good estimate of the exogenous signal $d(t)$. To test the performance increase in the case of using the disturbance observer (see Figure 5), we have applied the tracking controller for two scenarios: without disturbance estimation (dashed line) and with disturbance estimation (solid line). For comparison, one can see the dotted line is the reference.

In Figures 6 and 7, we present the estimation errors

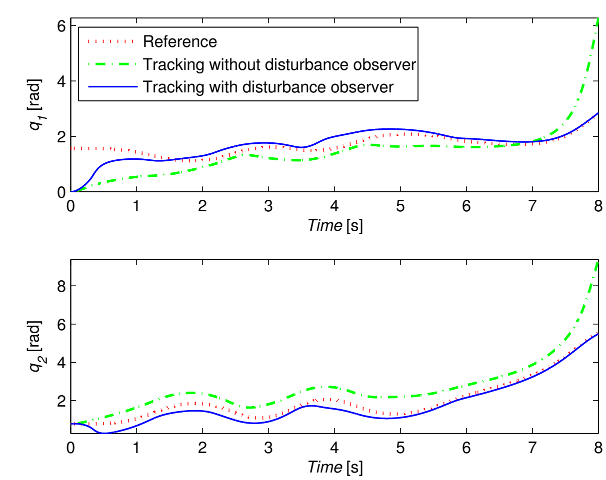

Fig. 5. Trajectory tracking.

$e_d = [\ e_{d_1} \quad e_{d_2}\ ]^T$ and the tracking errors $e = [\ e_1 \quad e_2\ ]^T$ (dashed line for the case without disturbance observer and solid line for the case with disturbance observer), respectively. Clearly the performance is better for in the case in which the nonlinear disturbance observer is used.

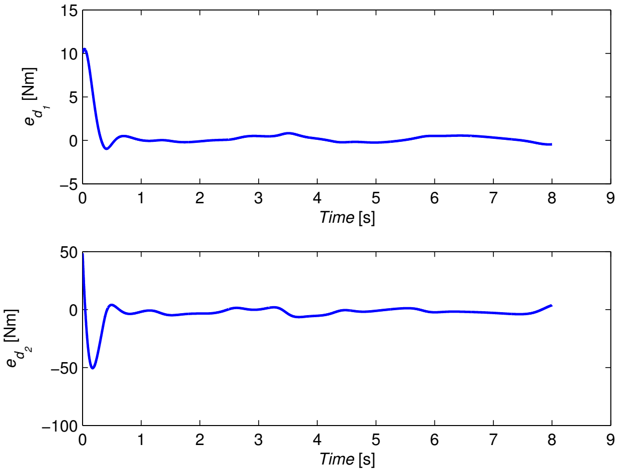

Fig. 6. Estimation errors.

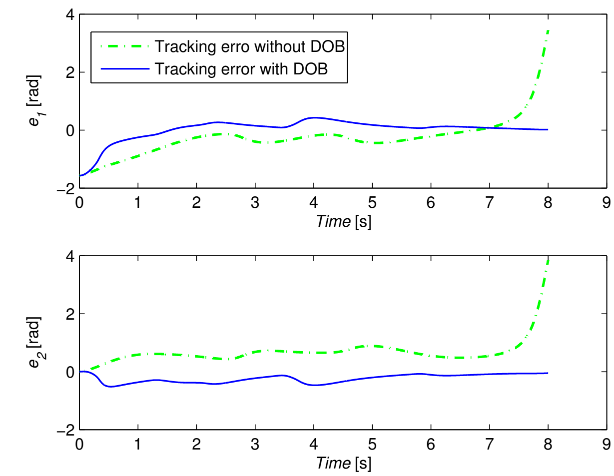

Fig. 7. Tracking errors.

VII. CONCLUSIONS AND PERSPECTIVES

In this paper, we have proposed a tracking control strategy, including a nonlinear disturbance observer, for a robotic tele-operation setup. The nonlinear disturbance observer is more general than those in the literature. Moreover, we have explicitly studied the transient and steady-state performance of the NDOB and the tracking control scheme in the face of nonconstant perturbations acting on the slave robot.

We foresee two extensions of the work in tele-operation. Firstly, the NDOB can be used in force sensor-less teleoperation setups to estimate external forces acting at the slave robot, which can subsequently be used to provide haptic feedback to the master. Secondly, the NDOB can also be used to estimate the human force acting on the master robot, which can be used to enhance the tracking control for the slave robot.

REFERENCES

[1] P. C. Tung, S. R. Wang, and F. Y. Hong, "Application of MRAC theory for adaptive control of a constrained robot manipulator," *International Journal of Machine Tools and Manufacture*, vol. 40, no. 14, pp. 2083–2097, 2000.

[2] T. Lefebvre, H. Bruyninckx, and J. Schutter, "Online statistical model recognition and state estimation for autonomous compliant motion," *IEEE Transactions on Systems, Man and Cybernetics*, vol. 35, no. 1, pp. 16–29, 2005.

[3] R. Cortesao, "On Kalman active observers," *Journal of Intelligent and Robotic Systems*, no. 48, pp. 131–155, 2007.

[4] K. Ohishi, M. Miyazaki, M. Fujita, and Y. Ogino, "H^∞ observer based force control without force sensor," *Proceedings of International Conference on Industrial Electronics, Control and Instrumentation*, pp. 1049 – 1054, 1991.

[5] ——, "Force control without force sensor based on mixed sensitivity H^∞ design method," *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1356 – 1361, 1992.

[6] Y. W. Liang, S. D. Xu, and T. C. Chu, "Robust control of the robot manipulator via an improved sliding mode scheme," *Proceedings of IEEE International Conference on Mechatronics and Automation*, pp. 1593–1598, 2007.

[7] M. F. Khelfi and A. Abdessameud, "Robust H^∞ trajectory tracking controller for a 6 d.o.f puma 560 robot manipulator," *Proceedings of IEEE International Conference on Electric Machines & Drives Conference*, pp. 88–94, 2007.

[8] K. S. Eom, I. H. Suh, and W. K. Chung, "Disturbance observer based path tracking of robot manipulator considering torque saturation," *Mechatronics*, vol. 11, pp. 325–343, 2000.

[9] S. Komada, N. Machii, and T. Hori, "Control of redundant manipulators considering order of disturbance observer," *IEEE Transactions on Industrial Electronics*, vol. 47, 2000.

[10] Z. L. Liu and L. Svoboda, "A new control scheme for nonlinear systems with disturbances," *IEEE Transactions on Control System Technology*, vol. 14, no. 1, pp. 176–181, 2006.

[11] S. K. Park and S. H. Lee, "Disturbance observer based robust control for industrial robots with flexible joints," *Proceedings of International Conference on Control, Automation and Systems*, pp. 584–589, 2007.

[12] B. K. Kim and W. K. Chung, "Advanced disturbance observer design for mechanical positioning systems," *IEEE Transactions on Industrial Electronics*, vol. 50, 2003.

[13] W. H. Chen, D. J. Ballance, P. J. Gawthrop, and J. O'Reilly, "A nonlinear disturbance observer for robotic manipulators," *IEEE Transactions on Industrial Electronics*, vol. 47, 2000.

[14] C. Kravaris, V. Sotiropoulos, C. Georgiou, N. Kazantzis, M. Xiao, and A. J. Krener, "Nonlinear observer design for state and disturbance estimation," *Systems Control Letters*, vol. 56, pp. 730–735, 2007.

[15] A. Nikoobin and R. Haghighi, "Lyapunov-based nonlinear disturbance observer for serial n-link robot manipulators," *Journal of Intelligent and Robotic Systems*, no. 55, pp. 135–153, 2009.

[16] S. Lichiardopol, N. van de Wouw, and H. Nijmeijer, "Boosting human force: A robotic enhancement of a human operator's force," *Proceedings of International Conference on Decision and Control*, pp. 4576–4581, 2008.

[17] ——, "Bilateral teleoperation for force sensorless 1-dof robots," *Proceedings of International Conference on Informatics in Control, Automation and Robotics*, pp. 39–46, 2010.

[18] E. D. Sontag and Y. Wang, "On characterizations of the input-to-state stability property," *Systems & Control Letters*, pp. 351 – 359, 1995.

[19] H. Khalil, *Nonlinear Systems*, 3^{rd} ed. Prentice Hall, 2001.

[20] L. Grüne, "Quantitative aspects of the input-to-state stability property," in *Optimal Control, Stabilization and Nonsmooth Analysis*, ser. Lecture Notes in Control and Information Sciences. Springer-Verlag, Heidelberg, 2004, vol. 301, pp. 215–230.

[21] Z. P. Jiang, I. M. Y. Mareels, and Y. Wang, "A Lyapunov formulation of the nonlinear small-gain theorem for interconnected ISS systems," *Automatica*, vol. 32, no. 1211-1215, 1996.