

## Observer based transparent bilateral teleoperation

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**Abstract:** To achieve transparency in a bilateral teleoperation master–slave scheme it is commonly assumed that the contact force on the slave and the angular velocity in both the master and the slave manipulators are measured. Nevertheless, in some applications it is convenient to remove sensors for a variety of reasons: to reduce costs, the weight of the robot, the size, etc. In this work, we propose an observer–based approach to achieve transparency in a master–slave teleoperator scheme without measure neither the angular velocity nor the contact force, for the non–delayed scenario. A formal proof is given, in which ultimate boundedness stability is guaranteed. Simulation results are presented to illustrate the effectiveness of the proposed approach.

*Keywords:* Robotic manipulators, observers, teleoperation, transparency.

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### 1. INTRODUCTION

A master–slave teleoperation system, roughly speaking, consists of two robotic arms, called the *master* and the *slave* manipulators, an human *operator*, and a *communication channel* as depicted in Figure 1. This architecture permits the human operator to manipulate remote objects by controlling the (local) master robot. To complete the task, the operator can be aided by some kind of feedback, such as auditive, visual, position, velocity, and force of the remote manipulator and the environment. When the teleoperation system presents a significant delay in the communication channel, one major issue is the stability of the system (Anderson and Spong, 1989). The standard approach to guarantee stability in presence of delays is the passivity based approach (Niemeyer and Slotine, 1991; Nuno et al., 2008; Nuño et al., 2009, 2011). An historical revision of this approach up to 2006 is given in Hokayem and Spong (2006).

Another important issue is achieving stability of the teleoperation system without force and/or velocity measurements. The stability of a passivity–based approach without velocity measurement is discussed in Nuño et al.

(2014). The problem of stability in the delayed case without measuring velocity nor force is treated in Daly and Wang (2014), where the authors employ the second order sliding–mode observer presented in Davila et al. (2005).

In the best scenario, the system must provide the operator of the sensation of *telepresence*, that is, making the operator feeling that he/she is directly manipulating the object in the remote environment. To achieve telepresence it is necessary to compensate the dynamics of the local manipulator and feedback to the operator the force that the slave manipulator exerts over the remote environment (Yokokohji and Yoshikawa, 1994). Because of this dynamic compensation, the standard passivity based approach cannot be followed, as it has been shown that passivity and transparency are two contradictory goals for a teleoperation system (Lawrence, 1993). The transparency of teleoperators has been studied in several works, starting in Lawrence (1993) and Yokokohji and Yoshikawa (1994). The transparency issue is also considered in Hashtrudi-Zaad and Salcudean (2002), where a linear model of the robots is considered, and joint velocity and accelerations are measured. Another interesting work focused on transparency is presented

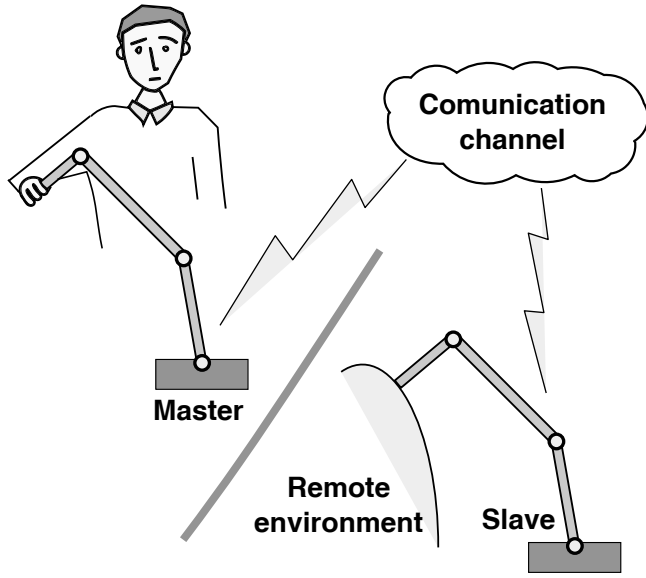


Fig. 1. Master-slave teleoperation.

in Portillo-Vélez et al. (2013), where the virtual surfaces concept is exploded.

In this work, we concentrate in the transparency of a teleoperator scheme without delays on the communication channel over a compliant surface using only joint-position measurements. The work is based on the recent results of the authors for the non-teleoperated force observation problem (Gutiérrez-Giles and Arteaga-Pérez, 2014).

The paper is organised as follows: in Section 2 the mathematical model of the system is given along with some useful properties. In Section 3 is presented the main result, that is, the observer and controller design. A numerical simulation to illustrate the approach is presented in Section 4. Finally, some conclusions are given in Section 5.

## 2. MATHEMATICAL MODEL AND PROPERTIES

Consider a master-slave teleoperation system, consisting of two kinematically similar manipulators, each of them with  $n$ -degrees of freedom. Let  $\mathbf{q}_m \in \mathbb{R}^n$  and  $\mathbf{q}_s \in \mathbb{R}^n$  the so called generalized coordinates for the master and for the slave manipulator, respectively. The dynamic model of the teleoperator is given by

$$\mathbf{H}_m \ddot{\mathbf{q}}_m + \mathbf{C}_m \dot{\mathbf{q}}_m + \mathbf{D}_m \dot{\mathbf{q}}_m + \mathbf{g}_m = \boldsymbol{\tau}_m + \boldsymbol{\tau}_h \quad (1)$$

$$\mathbf{H}_s \ddot{\mathbf{q}}_s + \mathbf{C}_s \dot{\mathbf{q}}_s + \mathbf{D}_s \dot{\mathbf{q}}_s + \mathbf{g}_s = \boldsymbol{\tau}_s + \boldsymbol{\tau}_e, \quad (2)$$

where, for each manipulator ( $i = m, s$ ),  $\mathbf{H}_i = \mathbf{H}_i(\mathbf{q}_i) \in \mathbb{R}^{n \times n}$  is the inertia matrix,  $\mathbf{C}_i \dot{\mathbf{q}}_i = \mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i) \dot{\mathbf{q}}_i \in \mathbb{R}^n$  is the vector of centrifugal and Coriolis forces,  $\mathbf{D}_i \in \mathbb{R}^{n \times n}$  is a diagonal matrix of viscous friction coefficients,  $\mathbf{g}_i = \mathbf{g}_i(\mathbf{q}_i) \in \mathbb{R}^n$  is the vector of gravitational torques,  $\boldsymbol{\tau}_i \in \mathbb{R}^n$  is the vector of input torques,  $\boldsymbol{\tau}_h \in \mathbb{R}^n$  is the

torque imposed by the human operator over the master robot and  $\boldsymbol{\tau}_e \in \mathbb{R}^n$  is the torque exerted by the slave manipulator over the remote environment.

For simplicity, we assume that the robots have only revolute joints. In such a case, for each manipulator the following well-known properties hold (Arteaga-Pérez, 1998).

*Property 2.1.* The inertia matrix is symmetric, positive definite and fulfils  $\lambda_h \|\mathbf{x}\|^2 \leq \mathbf{x}^T \mathbf{H}_i(\mathbf{q}_i) \mathbf{x} \leq \lambda_H \|\mathbf{x}\|^2 \forall \mathbf{x} \in \mathbb{R}^n$ , with  $0 < \lambda_h \leq \lambda_H < \infty$ .  $\square$

*Property 2.2.* With a proper definition of  $\mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i)$ , the matrix  $\dot{\mathbf{H}}_i - 2\mathbf{C}_i$  is skew-symmetric.  $\square$

*Property 2.3.* The vector  $\mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i) \dot{\mathbf{q}}_i$  fulfils  $\mathbf{C}_i(\mathbf{q}_i, \mathbf{x}) \mathbf{y} = \mathbf{C}_i(\mathbf{q}_i, \mathbf{y}) \mathbf{x}, \forall \mathbf{x}, \mathbf{y} \in \mathbb{R}^n$ .  $\square$

## 3. OBSERVER AND CONTROLLER DESIGN

Let  $\mathbf{q}_{1i} = \mathbf{q}_i$  and  $\mathbf{q}_{2i} = \dot{\mathbf{q}}_i$ , for  $i = m, s$ . A state space representation of (1)–(2) is given by

$$\dot{\mathbf{q}}_{1i} = \mathbf{q}_{2i} \quad (3)$$

$$\dot{\mathbf{q}}_{2i} = \mathbf{H}_i^{-1}(\boldsymbol{\tau}_i - \mathbf{N}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i)) + \mathbf{z}_{1i}, \quad (4)$$

where  $\mathbf{N}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i) \triangleq \mathbf{C}_i \mathbf{q}_{2i} + \mathbf{D}_i \mathbf{q}_{2i} + \mathbf{g}_i$ ,  $\mathbf{z}_{1m} = \mathbf{H}_m^{-1} \boldsymbol{\tau}_h$ , and  $\mathbf{z}_{1s} = \mathbf{H}_s^{-1} \boldsymbol{\tau}_e$ .

A local time dependent model is proposed for each term  $\mathbf{z}_{1i}$ , by taking into account the following (Sira-Ramírez et al., 2010).

*Assumption 3.1.* Each vector  $\mathbf{z}_{1i}$  can be written as

$$\mathbf{z}_{1i}(t) = \sum_{j=0}^{p-1} \mathbf{a}_{ij} t^j + \mathbf{r}_i(t), \quad (5)$$

where each  $\mathbf{a}_{ij} \in \mathbb{R}^n$  is a vector of constant coefficients and  $\mathbf{r}_i \in \mathbb{R}^n$  is a residual term. Note that, for simplicity's sake, the degree of the polynomial,  $p$ , for both  $\mathbf{z}_{1m}$  and  $\mathbf{z}_{1s}$  is the same.  $\square$

*Assumption 3.2.* Each vector  $\mathbf{z}_{1i}$  and at least its first  $p$  time derivatives exist (Gutiérrez-Giles and Arteaga-Pérez, 2014).  $\square$

By taking into account Assumptions 3.1 and 3.2, an internal model for each time vector  $\mathbf{z}_{1i}(t)$  can be written as

$$\dot{\mathbf{z}}_{1i} = \mathbf{z}_{2i} \quad (6)$$

$$\dot{\mathbf{z}}_{2i} = \mathbf{z}_{3i} \quad (7)$$

$$\vdots$$

$$\dot{\mathbf{z}}_{(p-1)i} = \mathbf{z}_{pi} \quad (8)$$

$$\dot{\mathbf{z}}_{pi} = \mathbf{r}_i^{(p)}(t). \quad (9)$$

### 3.1 Observers' design

To avoid the measurement of the joint-velocities for each manipulator and the contact force that the slave robot

exerts over the environment, we propose the following linear high-gain observer

$$\dot{\hat{q}}_{1i} = \hat{q}_{2i} + \lambda_{p+1}\tilde{q}_i \quad (10)$$

$$\dot{\hat{q}}_{2i} = H_i^{-1} \left( \tau_i - \hat{N}_i(q_{1i}, \dot{q}_{1i}) \right) + \hat{z}_{1i} + \lambda_p \tilde{q}_i \quad (11)$$

$$\dot{\hat{z}}_{1i} = \hat{z}_{2i} + \lambda_{p-1}\tilde{q}_i \quad (12)$$

$$\dot{\hat{z}}_{2i} = \hat{z}_{3i} + \lambda_{p-2}\tilde{q}_i \quad (13)$$

⋮

$$\dot{\hat{z}}_{(p-1)i} = \hat{z}_{pi} + \lambda_1 \tilde{q}_i \quad (14)$$

$$\dot{\hat{z}}_{pi} = \lambda_0 \tilde{q}_i, \quad (15)$$

where  $\tilde{q}_i \triangleq q_{1i} - \hat{q}_{1i}$ ,  $\lambda_0, \dots, \lambda_{p+1} \in \mathbb{R}^{n \times n}$  are matrices of constant gains, and  $\hat{N}_i(q_{1i}, \dot{q}_{1i}) \triangleq \hat{C}_i(q_{1i}, \dot{q}_{1i})\dot{q}_{1i} + D_i\dot{q}_{1i} + g_i$ . By subtracting (10)–(15) from (3)–(4) and (6)–(9), we obtain the estimation error dynamics

$$\dot{\tilde{q}}_{1i} = \tilde{q}_{2i} - \lambda_{p+1}\tilde{q}_i \quad (16)$$

$$\dot{\tilde{q}}_{2i} = H_i^{-1} (C_i(q_i, -\tilde{q}_{2i} + \lambda_{p+1}\tilde{q}_i)\dot{q}_i - D_i\dot{q}_i) + \tilde{z}_{1i} - \lambda_p \tilde{q}_i \quad (17)$$

$$\dot{\tilde{z}}_{1i} = \tilde{z}_{2i} - \lambda_{p-1}\tilde{q}_i \quad (18)$$

$$\dot{\tilde{z}}_{2i} = \tilde{z}_{3i} - \lambda_{p-2}\tilde{q}_i \quad (19)$$

⋮

$$\dot{\tilde{z}}_{(p-1)i} = \tilde{z}_{pi} - \lambda_1 \tilde{q}_i \quad (20)$$

$$\dot{\tilde{z}}_{pi} = r_i^{(p)}(t) - \lambda_0 \tilde{q}_i, \quad (21)$$

where  $\tilde{q}_{2i} \triangleq q_{2i} - \hat{q}_{2i}$  and  $\tilde{z}_{ji} \triangleq z_{ji} - \hat{z}_{ji}$ ,  $j = 1, \dots, p$ . Also, note that Property 2.3 has been used repeatedly to obtain  $N_i(q_i, \dot{q}_i) - \hat{N}_i(q_{1i}, \dot{q}_{1i}) = C_i(q_i, -\tilde{q}_{2i} + \lambda_{p+1}\tilde{q}_i)\dot{q}_i - D_i\dot{q}_i$ . From (16)–(21), it can be obtained the differential equation

$$\tilde{q}_{1i}^{(p+2)} + \lambda_{p+1}\tilde{q}_{1i}^{(p+1)} + \dots + \lambda_1\dot{\tilde{q}}_{1i} + \lambda_0\tilde{q}_{1i} = f_i^{(p)}(t) + r_i^{(p)}(t), \quad (22)$$

where  $f_i(t) \triangleq H_i^{-1} (C_i(q_i, -\tilde{q}_{2i} + \lambda_{p+1}\tilde{q}_i)\dot{q}_i - D_i\dot{q}_i)$ . Let

$$x \triangleq [\tilde{q}_{1i} \ \dot{\tilde{q}}_{1i} \ \dots \ \tilde{q}_{1i}^{(p+1)}]^T. \quad (23)$$

Then (22) can be written in matrix form as

$$\dot{x} = Ax + Br_f, \quad (24)$$

where

$$A = \begin{bmatrix} O & I & \dots & O \\ \vdots & \vdots & \ddots & \vdots \\ O & O & \dots & O \\ -\lambda_0 & -\lambda_1 & \dots & -\lambda_{p+1} \end{bmatrix} \quad (25)$$

$$B = [O \ O \ \dots \ I]^T. \quad (26)$$

### 3.2 Controllers' design

To achieve transparency in the teleoperation system, the dynamics of the master manipulator must be compen-

sated for the human operator cannot feel this dynamics during the task. We assume that accurate models of both the master and the slave manipulators are available, but we do not measure neither velocity nor acceleration. As a result, we cannot employ a direct computed torque-like compensation. Instead of it, we propose the control law

$$\tau_m = H_m\ddot{q}_m + \hat{C}_m\dot{q}_m + D_m\dot{q}_m + g_m - H_s\hat{z}_{1s}. \quad (27)$$

For the slave manipulator, we use the well-know Slotine–Li algorithm Slotine and Li (1987) with slight modifications. Let

$$\dot{q}_r \triangleq \dot{q}_{1m} - \Lambda(q_s - q_m) \quad (28)$$

$$\dot{q}_{r2} \triangleq \ddot{q}_{1m} - \Lambda(\dot{q}_s - \dot{q}_m) \quad (29)$$

$$s = \dot{q}_s - \dot{q}_r. \quad (30)$$

The corresponding control law is given by

$$\tau_s = H_s\dot{q}_{r2} + \hat{C}_s(q_s, \dot{q}_{1s})\dot{q}_r + D_s\dot{q}_r + g_s - K_v s, \quad (31)$$

where  $K_v \in \mathbb{R}^{n \times n}$  is a positive definite matrix of gains. We now state the main result.

*Proposition 3.1.* Consider the master–slave teleoperator described by (1)–(2). Assume that the forces exerted by the human operator on the master robot and by the slave robot over the remote environment are bounded. Then, by applying the controllers (27) and (31) in closed loop with the observers (10)–(15), the position tracking error,  $q_s - q_m$ , and the velocity error,  $\dot{q}_s - \dot{q}_m$ , between the two manipulators are ultimately bounded. Moreover, the estimates of the articular velocity  $\dot{q}_i$  converges to the real velocities  $\dot{q}_i$ , for  $i = m, s$  and the force experimented by the human operator  $\tau_h$  converges to the force exerted by the slave robot over the remote environment  $\tau_e$ .  $\square$

The stability proof is very similar to the one presented in Gutiérrez-Giles and Arteaga-Pérez (2014). Therefore, only a sketch of it will be given.

For the master manipulator, in closed loop we obtain

$$\tau_h - H_s\hat{z}_{1s} = H_m\ddot{q}_m + (C_m + \hat{C}_m)\dot{q}_m + D_m\dot{q}_m. \quad (32)$$

It can be shown that  $\tilde{q}_m, \dot{\tilde{q}}_m, \dots, \tilde{q}_m^{(p+1)}$  are ultimately bounded by an arbitrary small disk centered at the origin, by locating the poles of  $A$  in (25) far away on the left in the complex plane. Then, roughly speaking  $\tau_h \approx H_s\hat{z}_{1s}$  after the transient response, but since it can also be shown that  $\hat{z}_{1s} \approx z_{1s} = H_s^{-1}\tau_e$ , then  $\tau_h \approx \tau_e$  establishing the transparency of the system.

For the slave subsystem, it can be proposed the following positive definite function

$$V = \sigma^T H_s \sigma, \quad (33)$$

where  $\sigma = \dot{q}_s - \dot{q}_m + \Lambda(q_s - q_m)$ . Differentiating this equation and after some algebraic manipulation, it can be obtained

$$\dot{V} = \sigma^T (-(K_v + D_s)\sigma + h + \tau_e), \quad (34)$$

where

$$\begin{aligned} \mathbf{h} = & \mathbf{H}_s (-\ddot{\mathbf{q}}_{2m} + \lambda_{p+1}\dot{\mathbf{q}}_m + \mathbf{\Lambda}(\ddot{\mathbf{q}}_{2s} - \lambda_{p+1}\dot{\mathbf{q}}_s - \ddot{\mathbf{q}}_{2m} \\ & + \lambda_{p+1}\dot{\mathbf{q}}_m)) + \mathbf{C}_s(\mathbf{q}_s, \dot{\mathbf{q}}_s)(-\ddot{\mathbf{q}}_{2s} + \lambda_{p+1}\dot{\mathbf{q}}_s) \\ & + \mathbf{C}_s(\mathbf{q}_s, \dot{\mathbf{q}}_s)(-\ddot{\mathbf{q}}_{2s} + \lambda_{p+1}\dot{\mathbf{q}}_s) \\ & + \mathbf{D}_s(-\ddot{\mathbf{q}}_{2s} + \lambda_{p+1}\dot{\mathbf{q}}_s) \\ & - \mathbf{K}_v(-\ddot{\mathbf{q}}_{2s} + \lambda_{p+1}\dot{\mathbf{q}}_s + \ddot{\mathbf{q}}_{2m} - \lambda_{p+1}\dot{\mathbf{q}}_m). \end{aligned} \quad (35)$$

It can be shown that

$$\dot{V} < 0 \quad \text{if} \quad \|\boldsymbol{\sigma}\| > \mathbf{K}_v^{-1}(\|\mathbf{h}\| + \|\boldsymbol{\tau}_e\|), \quad (36)$$

where  $\mathbf{h}$  is a bounded function depending on the variables  $\mathbf{q}_m, \mathbf{q}_s$ , and their time derivatives, which has shown to be bounded at this point. This establishes the local ultimate boundedness.

*Remark 3.1.* While the term  $\mathbf{h}$  can be made arbitrarily small by selecting the poles of  $\mathbf{A}$  in (25) far away on the left in the complex plane, the force applied over the environment  $\boldsymbol{\tau}_e$  cannot be made arbitrarily small. This force is only assumed to be bounded, which results in the stated ultimate boundedness stability. Nevertheless, this ultimate bound cannot be made arbitrarily small.  $\square$

#### 4. SIMULATION

A simulation with two identical manipulators was carried out for illustration purposes. For the simulation we considered two-links planar manipulators with revolute joints. The parameters used for the numerical simulation were: mass of the links,  $m_1 = 3.9473[\text{Kg}]$ ,  $m_2 = 0.6232[\text{Kg}]$ , length of the links,  $l_1 = l_2 = 0.38[\text{m}]$ , and viscous friction coefficients,  $d_1 = d_2 = 1.2[\text{N} \cdot \text{m}/\text{rad}]$ . The human operator was modeled as a spring-damper system in work space coordinates with a spring constant of  $k_h = 300[\text{N}/\text{m}]$  and a damping of  $b_h = 200[\text{N} \cdot \text{s}/\text{m}]$ . On the other hand, the compliant environment was modeled also as a spring-damper, with constants  $k_e = 5000[\text{N}/\text{m}]$  and  $b_e = 5[\text{N} \cdot \text{s}/\text{m}]$ . The mapping of this forces in Cartesian coordinates to the torques in configuration coordinates is made by means of the Jacobians

$$\mathbf{J}_i = \begin{bmatrix} -l_1 \sin(\theta_1) - l_2 \sin(\theta_1 + \theta_2) & -l_2 \sin(\theta_1 + \theta_2) \\ l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2) & l_2 \cos(\theta_1 + \theta_2) \end{bmatrix}, \quad (37)$$

where  $\theta_1, \theta_2 \in \mathbb{R}$  are the angular joint-positions.

The task consisted on the operator making the master robot to move forward. A compliant wall with the mentioned spring-damper model is located at  $x = 0.6[\text{m}]$  in base coordinates. Therefore, one can identify three parts in this task: a) free motion, b) collision with the wall, and c) the slave pushes the surface by exerting a force over it.

The gains used for the slave controller were  $\mathbf{K}_v = \text{diag}(10, 10)$ ,  $\mathbf{\Lambda} = \text{diag}(20, 20)$ . For the observer it was set  $p = 3$  and the poles of the observer were chosen at  $p_1 = p_2 = p_3 = p_4 = -100$ .

In Figure 2 the position of both the master and the slave manipulation are shown in Cartesian coordinates.

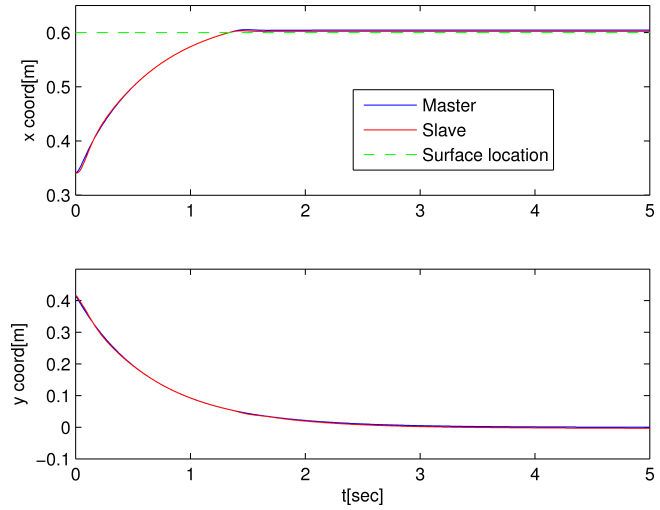


Fig. 2. Trajectories of the manipulators in Cartesian coordinates.

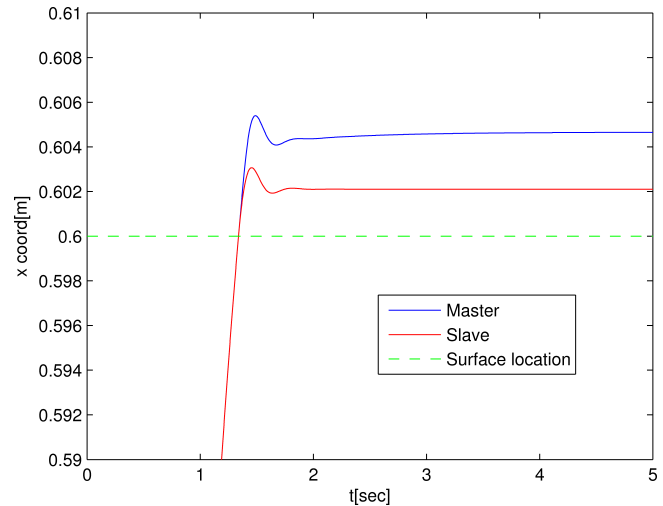


Fig. 3. Zoom of the position trajectory in the  $x$ -coordinate.

In the  $x$ -coordinate graphic, the location of the wall is also shown. In this figure can be appreciated the three scenarios described before. A zoom of the  $x$ -coordinate is shown in Figure 3 in where one can appreciate that the position error in steady state does not reach zero. This is no surprising, for the indirect force control we employed in this work. Nevertheless, note that the error keeps bounded and the behaviour is stable, as our stability proof guarantees.

In Figure 4 we show the force the slave exerts over the environment, the reflected force the human exerts and the force estimated by the proposed observer. We see that after the transient response, the three forces converge. This clearly shows the transparency of the

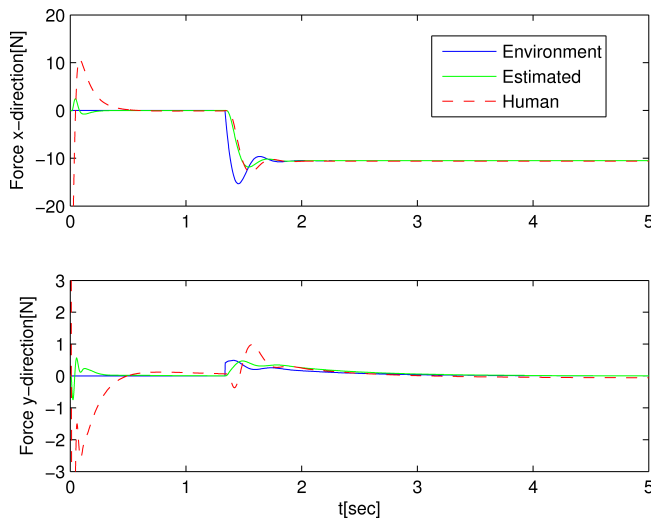


Fig. 4. Force exerted over the surface (—), force estimated (---), and force experienced by the operator (---).

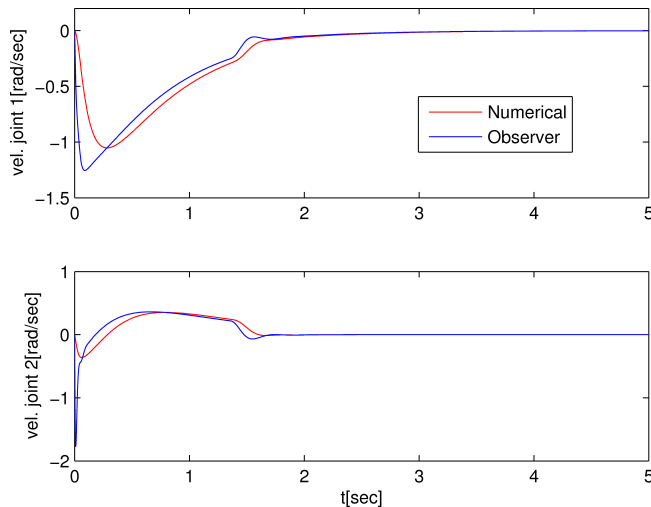


Fig. 5. Joint velocity for the master robot.

teleoperator scheme, what was one of the main goals of this work.

Finally, in Figures 5 and 6 we show the joint velocities for the master and the slave manipulators respectively. In this figures one can see that the estimation of the velocity is pretty accurate and converges in steady state.

## 5. CONCLUSIONS

In this work, the master-slave teleoperation problem was considered. A controller-observer design was presented, making emphasis on the transparency of the system. The proposed algorithm only needs the measure of the joint position of the master and the slave manipulators *i.e.*, it does not need the joint-velocity neither the

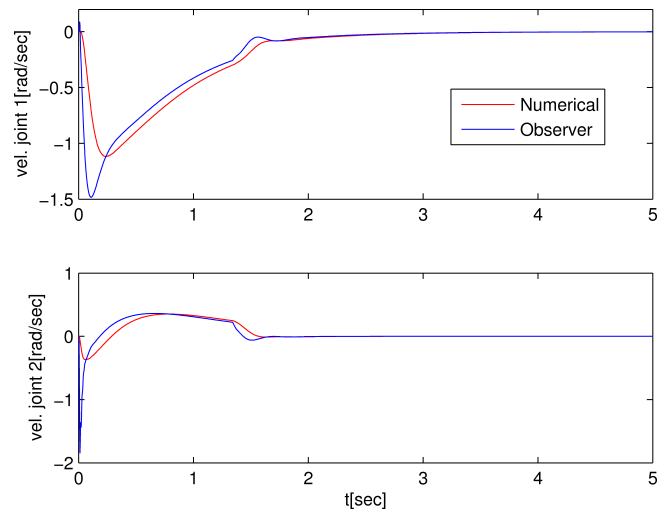


Fig. 6. Joint velocity for the slave robot.

contact force measurements. A stability proof, guaranteeing ultimately boundedness of the position and force trajectories was presented. Also, a numerical simulation was carried out to illustrate the effectiveness of the approach.

## ACKNOWLEDGEMENTS

This work is based on research supported by the **DGAPA-UNAM** under grant No. **IN116314**. Alejandro Gutierrez-Giles thanks the **Conacyt** under scholarship CVU No. **334785**.

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