Memorias del Congreso Nacional de Control Automático
ISSN: 2594-2492

Observer design for bilateral teleoperators with variable time delays

Mauro López * **Marco Arteaga** * **Javier Pliego** **

* *Departamento de Control y Robótica, División de Ingeniería Eléctrica de la Facultad de Ingeniería. Universidad Nacional Autónoma de México. Apdo. Postal 70–256, México, CDMX, 04510, México. Email: marteagp@unam.mx.*
** *Centro de Investigación Científica y de Educación Superior de Ensenada. Email: enzo-jp@hotmail.com*

Abstract: This paper addresses the control–observer design problem for bilateral teleoperation systems that employ communication channels that impose variable time delays. These delays are a function of different factors such as, congestion, bandwidth or distance. Bilateral teleoperators allow people to perform complex tasks in remote or inaccessible environments. When a robots is operated remotely by use of teleoperator robot, it is desirable communicate contact force and position from the slave to master and vice versa. In order to kinesthetically couple the operator to the environment and increase the sense of telepresence, a teleoperation control–observer scheme for bilateral systems with variable time delays is given. It is shown that the velocity observation errors tend to zero while position tracking is achieved in free motion. Additionally, in constrained motion, the human operator applies the desired force on the remote environment. This paper presents only experiments, using the Internet Protocol (TCP/IP) to validate the scheme.

Keywords: Bilateral teleoperators, observer design, variable time delays.

1. INTRODUCTION

A bilateral local–remote teleoperation system is composed by five elements: a human operator exerts forces on a local robot, which is connected through a communication channel to a remote robot that interacts with an environment Anderson and Spong (1989). In this type of systems, it is necessary have a combination of human skills with the benefits of precise, repetitive and cost–effective robotic manipulation. In bilateral teleoperation, the local and remote robot manipulators are connected with a communication channel that often involves long distances or imposes limited data transfer between the local and the remote sites. In these situations, substantial delays of time can appear between the position and force commanded by the human operator and the command is executed by the remote robot. These time delays affects the overall stability of the system Sheridan (1993). In 1965 appeared the first work dealing with time delay in a teleoperation system without force reflection Ferrell (1965), in this case the instability was not a problem. In 1965, force reflection was used in the presence of time delay and the instability was apparent Ferrell (1966).
On the other hand it is difficult to have a criterio of performance, Telepresence, task performance and transparency should be optimized while the stability of the closed–loop system is guaranteed. A good and robust performance are ideal characteristics for telepresence and transparency Nuño et al. (2011), because this way the human operator may use the bilateral system without any special training. In this point, is important to make clear the difference between Transparency and Telepresence, the first one means that the physical medium between the operator and the environment does not impose any dynamical behavior Passenberg et al. (2010), while the second one is rather a subjective objective, meaning that the operator has the feeling of being in the remote environment. For this reason, it is possible to propose criteria to evaluate transparency as a performance measure Lawrence (1993); Yokokohji and Yoshikawa (1994). One of the problems of this type of systems, is that the maneuverability of the system is an intuitive property for human operators, however in pointed out that there various aspects for evaluating the quantitatively performance of the system Raju (1989, 1990).

Another problem in many of the teleoperation systems is the lack of velocity measurements, this is because they do not have velocity sensors Nuño (2016) and those with velocity sensors are often prone to noise and additional velocity filters should be incorporated Namvar (2009). A solution to this problem, an full order globally exponentially convergent velocity observer has been proposed for EL- Systems Astolfi et al. (2010), Astolfi et al. (2009). There are other works that present a observation scheme Sarras et al. (2016) for bilateral teleoperation control, in this work the Immersion and Invariance (I&I) velocity observer is used, however it is necessary to know the system model to guarantee a good performance of the scheme. On the other hand, there are authors who propose teleoperation schemes that need a partial knowledge of the model, Nuño et al. (2017) propose a solution that does not require any observer and guarantees consensus for free movement and boundedness of the tracking errors. Finally in Arteaga-Pérez et al. (2017), a control–observer scheme is proposed where it is guaranteed that position errors are ultimately bounded with an arbitrarily small final bound in free movement or zero when reaching consensus, while observation errors tend to zero for any case. This paper proposes a position and force control scheme for bilateral teleoperation systems with time-varying delays. The proposed scheme does not need the dynamic model of the system and also uses the estimated velocities obtained by an observer.

The rest of the paper is organized as follows. The local and remote robot models, as well as some properties are given in Section 2. The control–observer scheme is proposed in Section 3. Section 4 presents some experimental results. The paper conclusions are stated in Section 5.

2. DYNAMIC MODEL OF A TELEOPERATOR

Consider a local (l)–remote (r) robot teleoperation system composed of two manipulators. Each of them with n–degrees of freedom, but not necessarily with the same kinematic configuration. The local dynamics is given by (Nuño et al., 2014):

$$\boldsymbol{H}_{\mathrm{l}}(\boldsymbol{q}_{\mathrm{l}})\ddot{\boldsymbol{q}}_{\mathrm{l}} + \boldsymbol{C}_{\mathrm{l}}(\boldsymbol{q}_{\mathrm{l}},\dot{\boldsymbol{q}}_{\mathrm{l}})\dot{\boldsymbol{q}}_{\mathrm{l}} + \boldsymbol{D}_{\mathrm{l}}\dot{\boldsymbol{q}}_{\mathrm{l}} + \boldsymbol{g}_{\mathrm{l}}(\boldsymbol{q}_{\mathrm{l}}) = \boldsymbol{\tau}_{\mathrm{l}} - \boldsymbol{\tau}_{\mathrm{h}} \quad (1)$$

while the remote dynamics is modeled by:

$$\boldsymbol{H}_{\mathrm{r}}(\boldsymbol{q}_{\mathrm{r}})\ddot{\boldsymbol{q}}_{\mathrm{r}} + \boldsymbol{C}_{\mathrm{r}}(\boldsymbol{q}_{\mathrm{r}},\dot{\boldsymbol{q}}_{\mathrm{r}})\dot{\boldsymbol{q}}_{\mathrm{r}} + \boldsymbol{D}_{\mathrm{r}}\dot{\boldsymbol{q}}_{\mathrm{r}} + \boldsymbol{g}_{\mathrm{r}}(\boldsymbol{q}_{\mathrm{r}}) = \boldsymbol{\tau}_{\mathrm{e}} - \boldsymbol{\tau}_{\mathrm{r}} \quad (2)$$

where for $i = \mathrm{l}$, r, $\boldsymbol{q}_i \in \mathbb{R}^n$ is the vector of generalized joint coordinates, $\boldsymbol{H}_i(\boldsymbol{q}_i) \in \mathbb{R}^{n\times n}$ is the symmetric positive definite inertia matrix, $\boldsymbol{C}_i(\boldsymbol{q}_i,\dot{\boldsymbol{q}}_i)\dot{\boldsymbol{q}}_i \in \mathbb{R}^n$ is the vector of Coriolis and centrifugal torques, $\boldsymbol{D}_i \in \mathbb{R}^{n\times n}$ is a diagonal positive semidefinite matrix accounting for viscous friction, $\boldsymbol{g}_i(\boldsymbol{q}_i) \in \mathbb{R}^n$ is the vector of gravitational torques and $\boldsymbol{\tau}_i \in \mathbb{R}^n$ is the vector of torques acting on the joints. $\boldsymbol{\tau}_{\mathrm{h}} \in \mathbb{R}^n$ represents the torque applied by the human to the local robot and $\boldsymbol{\tau}_{\mathrm{e}} \in \mathbb{R}^n$ the environment interaction.

3. CONTROL OBSERVER SCHEME

In this section the design of the observation and control scheme will be shown.

3.1 Delayed kinematic correspondence without force feedback

Consider once again $i = \mathrm{l}$, r and define

$$\boldsymbol{q}_{\mathrm{d}i} \overset{\triangle}{=} \boldsymbol{q}_j(t - T_j(t)) \quad (3)$$

$$\boldsymbol{q}_{\mathrm{v}i} \overset{\triangle}{=} \dot{\hat{\boldsymbol{q}}}_j(t - T_j(t)) \quad (4)$$

as desired trajectory and a substitution of the not available $\dot{\boldsymbol{q}}_{\mathrm{d}i}$, respectively, where $\{\hat{\ }\}$ denotes an estimated (observed) value. If $i = \mathrm{l}$, then $j = \mathrm{r}$ and vice versa. The corresponding observation and tracking errors are defined as

$$\boldsymbol{z}_i \overset{\triangle}{=} \boldsymbol{q}_i - \hat{\boldsymbol{q}}_i \quad (5)$$

$$\Delta\boldsymbol{q}_i \overset{\triangle}{=} \boldsymbol{q}_i - \boldsymbol{q}_{\mathrm{d}i}, \quad (6)$$

respectively. Based on Arteaga-Pérez et al. (2006), it is proposed

$$\dot{\boldsymbol{\xi}}_i = \boldsymbol{z}_i \quad (7)$$

$$\dot{\hat{\boldsymbol{q}}}_{\mathrm{o}i} = \boldsymbol{q}_{\mathrm{v}i} - \boldsymbol{\Lambda}_{\mathrm{x}i}\Delta\boldsymbol{q}_i + \boldsymbol{\Lambda}_{\mathrm{z}i}^2\boldsymbol{\xi}_i \quad (8)$$

$$\dot{\hat{\boldsymbol{q}}}_i = \dot{\hat{\boldsymbol{q}}}_{\mathrm{o}i} + 2\boldsymbol{\Lambda}_{\mathrm{z}i}\boldsymbol{z}_i \quad (9)$$

where $\boldsymbol{\Lambda}_{\mathrm{z}i}, \boldsymbol{\Lambda}_{\mathrm{x}i}, \in \mathbb{R}^{n\times n}$ are positive diagonal matrices. The next step consists in designing a tracking controller by using the estimated velocities. Also, based on Arteaga-Pérez et al. (2006) we propose

$$\boldsymbol{s}_i = \dot{\hat{\boldsymbol{q}}}_i - \boldsymbol{q}_{\mathrm{v}i} + \boldsymbol{\Lambda}_{\mathrm{x}i}\Delta\boldsymbol{q}_i \quad (10)$$

$$\boldsymbol{\sigma}_i = \boldsymbol{c}_i|\boldsymbol{s}_i|^{1/2}\mathrm{sign} + \boldsymbol{w} \quad (11)$$

$$\dot{\boldsymbol{w}} = \boldsymbol{b}_i\mathrm{sign}(\boldsymbol{s}_i), \qquad c = 1.5\sqrt{C}; b = 1.1C \quad (12)$$

where $\boldsymbol{K}_{\beta i} \in \mathbb{R}^{n\times n}$ is a positive definite diagonal matrix and $\mathrm{sign}(\boldsymbol{s}_i) = [\mathrm{sign}(s_{i1}), \ldots, \mathrm{sign}(s_{in})]^{\mathrm{T}}$ with s_{ij} element of $\boldsymbol{s}_i$ for $j = 1, \ldots, n$. Equations (11) and (12) are a SMC ST reported in Levant (1993). Consider now

$$\dot{\boldsymbol{q}}_{\mathrm{o}i} = \dot{\hat{\boldsymbol{q}}}_i - \boldsymbol{\Lambda}_{\mathrm{z}i}\boldsymbol{z}_i \quad (13)$$

$$\dot{\boldsymbol{q}}_{\mathrm{r}i} = \boldsymbol{q}_{\mathrm{v}i} - \boldsymbol{\Lambda}_{\mathrm{x}i}\Delta\boldsymbol{q}_i - \boldsymbol{K}_{\gamma i}\boldsymbol{\sigma}_i \quad (14)$$

$$\boldsymbol{s}_{\mathrm{o}i} \overset{\triangle}{=} \dot{\boldsymbol{q}}_{\mathrm{o}i} - \dot{\boldsymbol{q}}_{\mathrm{r}i}, \quad (15)$$

where $\boldsymbol{K}_{\gamma i} \in \mathbb{R}^{n\times n}$ is a positive definite diagonal matrix. Suppose that no force measurements are available, so that the proposed control laws for the local and remote manipulators are given by

$$\boldsymbol{\tau}_{\mathrm{l}} = -\boldsymbol{K}_{\mathrm{al}}\dot{\hat{\boldsymbol{q}}}_{\mathrm{l}} - \boldsymbol{K}_{\mathrm{f\,l}}\boldsymbol{s}_{\mathrm{ol}} \quad (16)$$

$$\boldsymbol{\tau}_{\mathrm{r}} = \boldsymbol{K}_{\mathrm{ar}}\dot{\hat{\boldsymbol{q}}}_{\mathrm{r}} + \boldsymbol{K}_{\mathrm{pr}}\boldsymbol{s}_{\mathrm{or}} \quad (17)$$

respectively, where $\boldsymbol{K}_{\mathrm{al}}, \boldsymbol{K}_{\mathrm{ar}}, \boldsymbol{K}_{\mathrm{pr}}, \boldsymbol{K}_{\mathrm{f\,l}} \in \mathbb{R}^{n\times n}$ are positive definite diagonal matrices. A particular objective of this work is to design an implementable scheme with good performance, so consider the following two assumptions.

Assumption 1. The time delays $T_i(t)$ and their derivatives are bounded by $\overline{T}_i$ and T_i^*, respectively, *i. e.,* $0 \le T_i(t) \le \overline{T}_i < \infty$ and $0 \le |\dot{T}_i(t)| \le T_i^* < \infty$, for $i = \mathrm{l}$, r, meaning that there is no loss of information. △

Assumption 2. The human and environment torques are bounded for all time, *i. e.* there exist positive constants b_{h} and b_{e} such that $\|\boldsymbol{\tau}_{\mathrm{h}}\| \le b_{\mathrm{h}} < \infty$ and $\|\boldsymbol{\tau}_{\mathrm{e}}\| \le b_{\mathrm{e}} < \infty$ $\forall\ t \ge 0$. △

We state the main result of this section.

Consider the bilateral teleoperation system (1)–(2) in closed loop with the observers (7)–(9) and the control laws (16)–(17). Suppose that Assumptions 1 and 2 are satisfied; then for $i, j = \mathrm{l}$, r control and observer gains can always be found such that

i. All tracking and observation errors remain bounded for all time.
ii. The observation errors tend to zero *i. e.*, $\boldsymbol{z}_i, \dot{\boldsymbol{z}}_i \to \boldsymbol{0}$.
iii. In a finite time it holds

$$\|\Delta\boldsymbol{q}_i\| \le \delta_{\max i}, \quad (18)$$

where $\delta_{\max i}$ is a positive constant. Furthermore, it is possible to make the bounds $\delta_{\max i}$ in (18) arbitrarily small for i =r,l.

Below are the cases of interest, a, b and c:

a) Whenever $\boldsymbol{\tau}_\mathrm{h} = \boldsymbol{\tau}_\mathrm{e} = \mathbf{0}$

iv. For small enough values of $\delta_{\max i}$ in (18), even in the presence of variable time delays all tracking errors tend to zero and consensus is achieved, *i. e.* $\boldsymbol{q}_\mathrm{l}(t) = \boldsymbol{q}_\mathrm{r}(t) = \boldsymbol{q}_\mathrm{c}$ for some constant $\boldsymbol{q}_\mathrm{c}$, with the exception given in the following item.

v. If the system trajectories do not tend to constant values, then the robots will have a synchronized movement in the sense that they track each other with a periodic behavior.

b) If $\boldsymbol{\tau}_\mathrm{h} \neq \mathbf{0}$ and $\boldsymbol{\tau}_\mathrm{e} = \mathbf{0}$, then

vi. If the bound $\delta_{\max \mathrm{l}}$ for i=l in (18) is too small, then the human operator will not be able to freely move the local manipulator and items *iv.* and *v.* will still hold

vii. If the bound $\delta_{\max \mathrm{l}}$ for i=l in (18) is not too small, then the human operator will be able to freely move the local end–effector, while the remote tracking error $\|\Delta \boldsymbol{q}_\mathrm{r}\|$ can as before be made arbitrarily small.

c) If $\boldsymbol{\tau}_\mathrm{h} \neq \mathbf{0}$ and $\boldsymbol{\tau}_\mathrm{e} \neq \mathbf{0}$, then

viii. The human operator will have some sense of delayed kinematic correspondence in the sense that he/she will no longer be able to freely move the local end–effector in the direction the remote manipulator is applying the contact force. △

3.2 Force feedback inclusion

At this point, we show how introducing force feedback and control allows to achieve also Case *c.iii*.

First of all, consider the well–known relationship Siciliano et al. (2010)

$$\boldsymbol{\tau}_i = \boldsymbol{J}_i^\mathrm{T}(\boldsymbol{q}_i)\boldsymbol{F}_i, \tag{19}$$

where $\boldsymbol{J}_i(\boldsymbol{q}_i) \in \mathbb{R}^{n\times n}$ is the robot's geometric Jacobian for $i = $ l,r and $\boldsymbol{F}_i \in \mathbb{R}^n$ is either the environmental force $\boldsymbol{F}_\mathrm{e}$ for $i = r$ or the applied human force $\boldsymbol{F}_\mathrm{h}$ for $i = l$. Define the force tracking error as

$$\Delta \boldsymbol{f}_i = \boldsymbol{F}_i - \boldsymbol{F}_{\mathrm{d}i} \equiv \boldsymbol{F}_i - \boldsymbol{F}_j(t - T_j(t)), \tag{20}$$

and the corresponding integral as

$$\Delta \boldsymbol{F}_i = \int_0^t \Delta \boldsymbol{f}_i \mathrm{d}t. \tag{21}$$

As usual, if i = l then j = r and vice versa. Instead of (16)–(17), consider the following control laws

$$\boldsymbol{\tau}_\mathrm{l} = -\boldsymbol{K}_\mathrm{al}\dot{\hat{\boldsymbol{q}}}_\mathrm{l} - \boldsymbol{K}_{\mathrm{f\,l}}\boldsymbol{s}_\mathrm{ol} + \boldsymbol{J}_\mathrm{l}^\mathrm{T}(\boldsymbol{q}_\mathrm{l})(\boldsymbol{F}_\mathrm{dl} - \boldsymbol{K}_\mathrm{fl}\Delta\boldsymbol{F}_\mathrm{l}) \tag{22}$$

$$\boldsymbol{\tau}_\mathrm{r} = \quad \boldsymbol{K}_\mathrm{ar}\dot{\hat{\boldsymbol{q}}}_\mathrm{r} + \boldsymbol{K}_\mathrm{pr}\boldsymbol{s}_\mathrm{or} - \boldsymbol{J}_\mathrm{r}^\mathrm{T}(\boldsymbol{q}_\mathrm{r})(\boldsymbol{F}_\mathrm{dr} - \boldsymbol{K}_\mathrm{fr}\Delta\boldsymbol{F}_\mathrm{r}) \tag{23}$$

Remark 1. Note that the controller allows to stabilize the force applied by the human to a constant value equal to that applied by the remote manipulator to the surface. This, however, may be at the cost of increasing gains too much and to prevent the operator to move the local end–effector at all. For that reason, it is advisable to accomplish only Case of Interest *c*. △

4. EXPERIMENT RESULTS

To show the effectiveness of the proposed scheme, some experiments have been carried out. The teleoperation test bed is composed of two *Geomagic Touch* robots of *3D systems* connected via TCP/IP Internet protocol as shown in Figure 2. The local (L) and remote (R) manipulators are fully actuated 3-DOF mechanical systems. However, it turns out that the round delay $T_\mathrm{l}(t) + T_\mathrm{r}(t)$ is negligible, which does not allow to show the robustness properties of the proposed approach. For that reason, delays were artificially increased by using a normal Gaussian distribution to keep the outcomes valid Salvo-Rossi et al. (2006). For the experiments the statical parameters of the induced delays are 0.37s, 0.05s and 0.35s for the mean, variance and seed, respectively, resulting in $0.72s \leq T_\mathrm{l}(t) + T_\mathrm{r}(t) \leq 0.76s$ as shown in Figure 1. The initial conditions for the local and remote manipulators are $\dot{\boldsymbol{q}}_i = \mathbf{0}[^\circ/\mathrm{s}]$, $\boldsymbol{q}_i = [0, 90^\circ, 90^\circ]$.
The control–observer gains are for i = l,r [1]: $\boldsymbol{\Lambda}_{\mathrm{x}i}$ = diag $\{25, 30, 28\}$, $\boldsymbol{\Lambda}_{\mathrm{z}i}$ = diag $\{13, 13, 13\}$, $\boldsymbol{K}_{\mathrm{a}i} = 0.102\boldsymbol{I}$, $\boldsymbol{K}_{\mathrm{p}i} = 0.2\boldsymbol{I}$, and $\boldsymbol{K}_{\gamma i} = 10\boldsymbol{I}$.

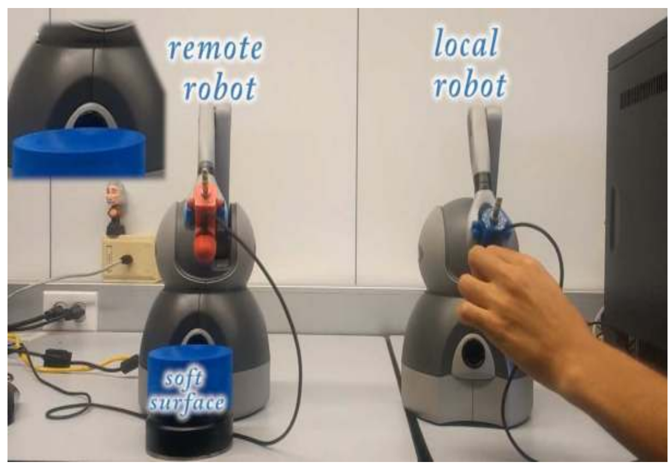


Fig. 1. Bilateral teleoperation system with two Geomagic Touch

For the control–observer scheme, the following parameters have been chosen:

$\boldsymbol{K}_{\mathrm{p}i}$ = diag $\{0.08, 0.09, 0.08\}$, $\boldsymbol{K}_{\mathrm{a}i}$ = diag $\{0.15, 0.1, 0.09\}$, $\boldsymbol{K}_{\gamma i}$ = diag $\{0.01, 0.01, 0.01\}$, $\boldsymbol{\Lambda}_{\mathrm{x}i}$ = diag $\{35, 35, 30\}$, and $\boldsymbol{\Lambda}_{\mathrm{z}i}$ = diag $\{13, 13, 13\}$. The initial positions are $\boldsymbol{q}_i(0) = \hat{\boldsymbol{q}}_i(0) = [0^\circ, 90^\circ, 90^\circ]^\top$.

4.1 Free motion

In these cases (*a and b*), a human operator moves the end-effector of the local manipulator and then drops it, approximately at $t = 11s$; henceforth the systems becomes autonomous. In Figure 3, it can be appreciated how the remote robot is tracking the delayed position of the local robot despite the time variable delays.

In Figure 4, it can be clearly appreciated the effect of the delays and the local robot is not tracking the delayed

[1] The interested reader should look at the references for the meaning of each gain.

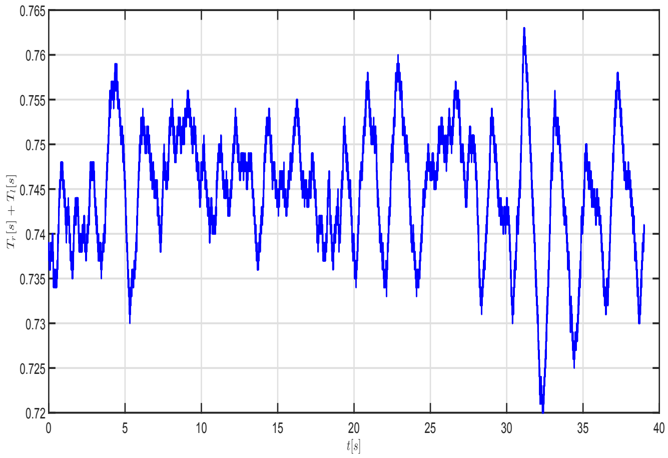


Fig. 2. RTT delays $T_l(t)+T_r(t)$.

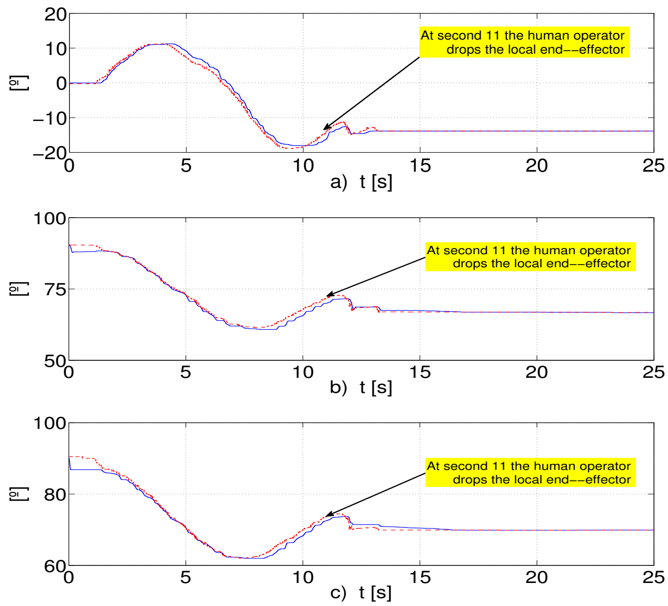


Fig. 3. Free motion. Remote position *vs* delayed local position. a) $q_{r1}(t)$ (——) *vs* $q_{l1}(t-T_l)$ (- - - -) [°]. b) $q_{r2}(t)$ (——) *vs* $q_{l2}(t-T_l)$ (- - - -) [°]. c) $q_{r1}(t)$ (——) *vs* $q_{l1}(t-T_l)$ (- - - -) [°].

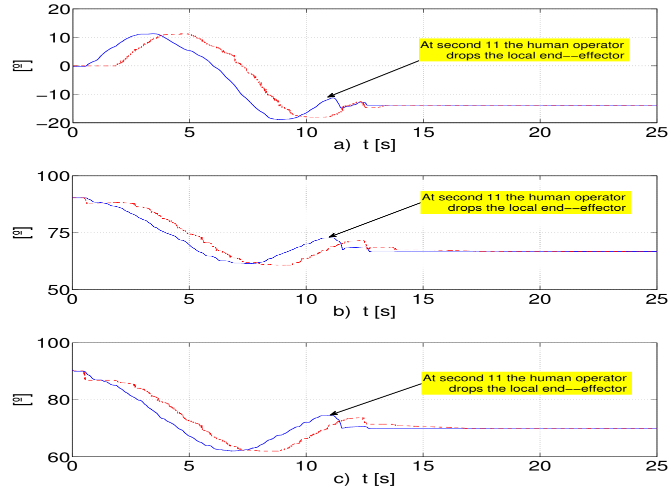
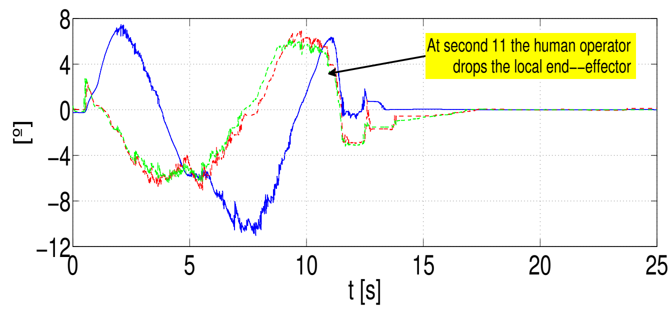
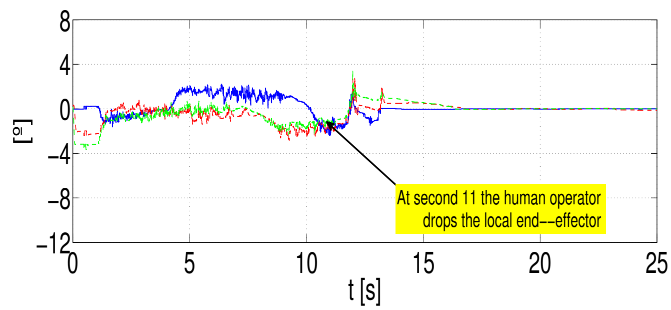


Fig. 4. Free motion. Local position *vs* delayed remote position . a) $q_{l1}(t)$ (——) *vs* $q_{r1}(t-T_r)$ (- - - -) [°]. b) $q_{l2}(t)$ (——) *vs* $q_{r2}(t)$ (- - - -) [°]. c) $q_{l1}(t-T_r)$ (——) *vs* $q_{r1}(t-T_r)$ (- - - -) [°].



(a) $\Delta \boldsymbol{q}_{l1}$(——), $\Delta \boldsymbol{q}_{l2}$(- - -), $\Delta \boldsymbol{q}_{l3}$(- - -)



(b) $\Delta \boldsymbol{q}_{r1}$(——), $\Delta \boldsymbol{q}_{r2}$ (- - -), $\Delta \boldsymbol{q}_{r3}$(- - -)

Fig. 5. Free motion. Position tracking errors.

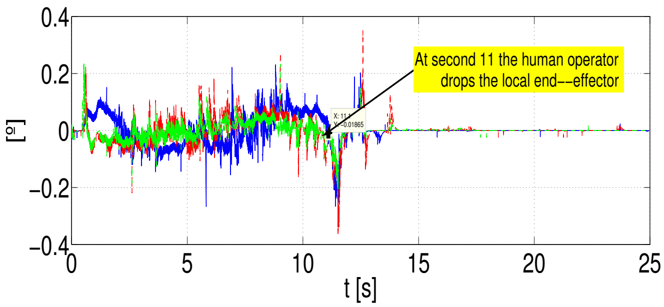
remote position. Note that this has been foreseen in the *main result*. However, once the operator drops the end-effector of the local manipulator position tracking is established. This fact can be appreciated in Figure 5, where the tracking errors are shown to converge to zero.

Figure 6 depicts the observation errors. Note that these errors are bounded and tend to be nearly zero from the beginning. The errors seem to be not affected by the delays. Further, in theory, one can arbitrarily increase the observer gains and thus arbitrarily reduce the observation errors, however performance might be downgraded.

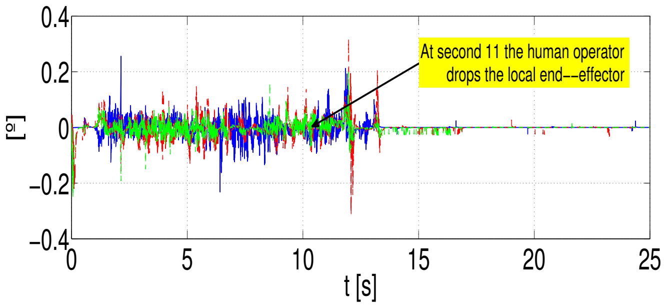
4.2 Constrained Motion

For this case (*case c*), as shown in Figure 1, a soft surface is located in the remote environment. Here the human operator moves down the local robot in order for the remote robot to become in contact with such box. In any case the human operator releases the local robot end effector. In Figure 7 it can be seen that the remote robot is also tracking the delayed position of the local robot. Figure 8 shows the position of local robot *vs* the delayed position of the remote manipulator, where it is possible to see the effect of the delays. In both cases the remote robot tracks the local position. Then, in the Figure 13 it can be shown that the force that the human operator is applying on the side of the local robot is very similar to the force that the remote robot is applying on the surface.

Figures 9 and 10 show the position tracking errors, which are bounded as foreseen in the *main result*. Moreover, in



(a) z_{l1} (——), z_{l2} (- - -), z_{l3} (- - -)



(b) z_{r1} (——), z_{r2} (- - -), z_{r3} (- - -)

Fig. 6. Free motion. Observation errors.

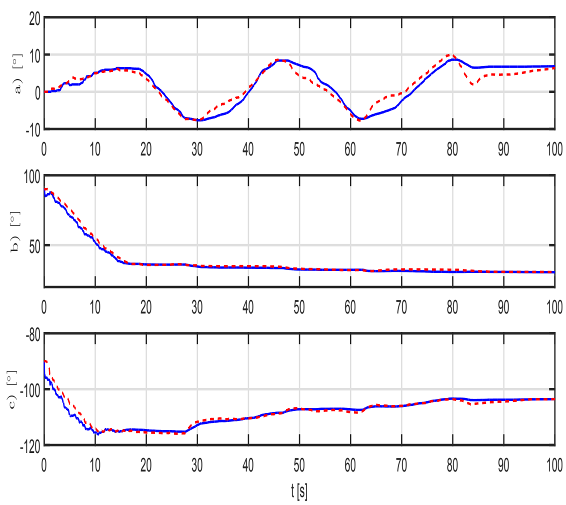


Fig. 7. Constrained motion. Remote position *vs* delayed local position. a) $q_{r1}(t)$ (——) *vs* $q_{l1}(t-T_l)$ (- - - -) [°]. b) $q_{r2}(t)$ (——) *vs* $q_{l2}(t-T_l)$ (- - - -) [°]. c) $q_{r3}(t)$ (——) *vs* $q_{l3}(t-T_l)$ (- - - -) [°].

Figures 11 and 11 one can see that the observation errors are not affected by the delays and they tend to zero when position tracking is established. Note that the observation error also shows good performance as in the free motion case.

Finally, when the remote manipulator gets in touch with the soft surface, the end-effector movement is stopped and the person can feel it since also the local robot cannot move in that direction. Then, the operator has a certain feeling of telepresence. Figure 14 depicts the surface reconstruction by the local manipulator.

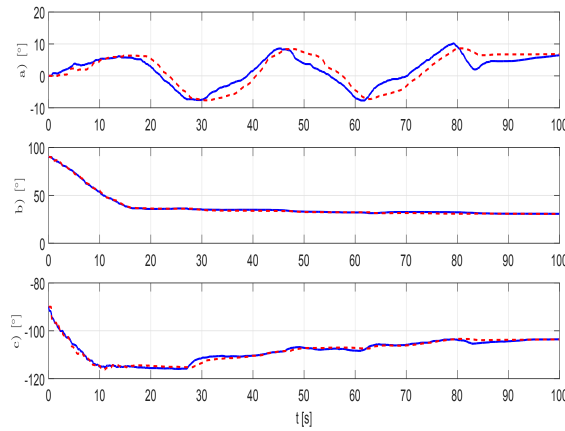


Fig. 8. Constrained motion. Local position *vs* delayed remote position. a) $q_{l1}(t)$ (——) *vs* $q_{r1}(t-T_r)$ (- - - -) [°]. b) $q_{l2}(t)$ (——) *vs* $q_{r2}(t)$ (- - - -) [°]. c) $q_{l3}(t-T_r)$ (——) *vs* $q_{r3}(t-T_r)$ (- - - -) [°].

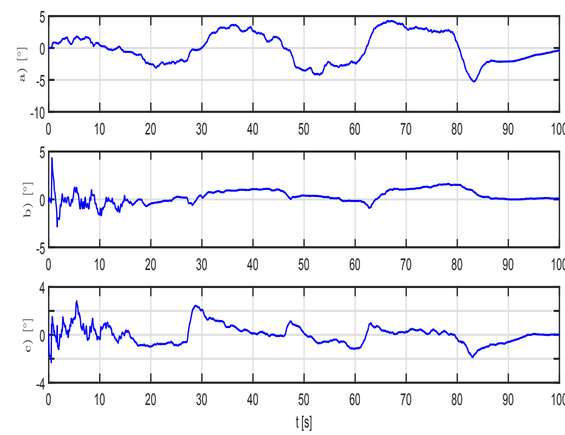


Fig. 9. Constrained motion. Local position error. a) $q_{l1}(t)$ - $q_{r1}(t-T_r)$ [°]. b) $q_{l2}(t)$ - $q_{r2}(t-T_r)$ [°]. c) $q_{l3}(t-T_r)$ - $q_{r3}(t-T_r)$ [°].

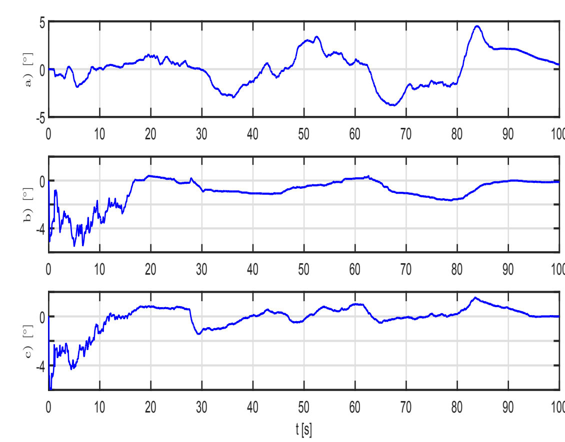
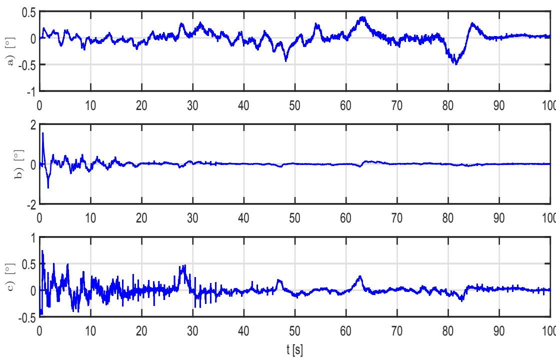
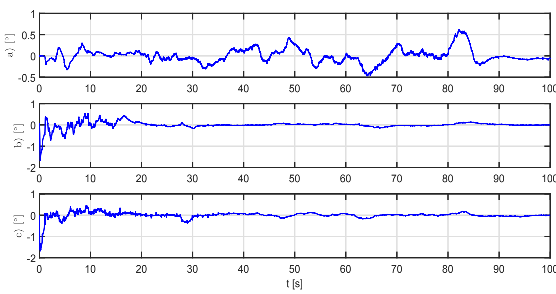


Fig. 10. Constrained motion. Remote position error. a) $q_{r1}(t)$ - $q_{l1}(t-T_l)$ [°]. b) $q_{r2}(t)$ - $q_{l2}(t-T_l)$ [°]. c) $q_{r3}(t-T_r)$ - $q_{l3}(t-T_l)$ [°].



(a) $\boldsymbol{z}_{11}$ (——), $\boldsymbol{z}_{12}$ (- - -), $\boldsymbol{z}_{13}$ (- - -)

Fig. 11. Constrained motion. Observation errors.



(a) $\boldsymbol{z}_{11}$ (——), $\boldsymbol{z}_{12}$ (- - -), $\boldsymbol{z}_{13}$ (- - -)

Fig. 12. Constrained motion. Observation errors.

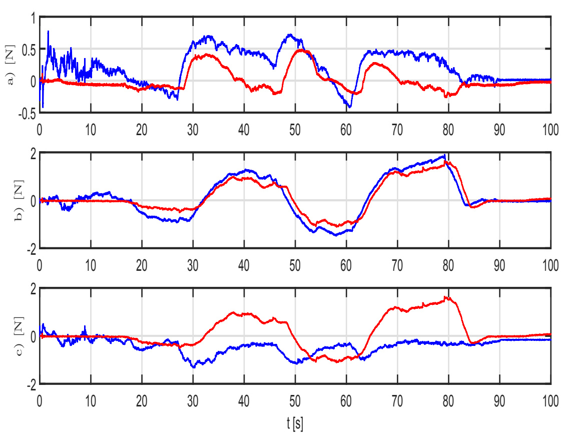


Fig. 13. Constrained motion. Force applied by the human operator *vs* Force applied on the surface. a) $F_{l1}(t)$ (——) *vs* $F_{e1}(t-T_r)$ (- - - -) [°]. b) $q_{l2}(t)$ (——) *vs* $F_{r2}(t-T_r)$ (- - - -) [°]. c) $q_{l3}(t)$ (——) *vs* $F_{r3}(t-T_r)$ (- - - -) [°].

5. CONCLUSIONS

In this work, a new control–observer scheme for time varying delay bilateral teleoperation systems of robot manipulators is introduced. We assume that the communications might induce bounded variable time-delays. It is shown that observation errors tend faster to zero, even than some previously reported observers, while the defined tracking errors are bounded and arbitrarily small. The manipula-

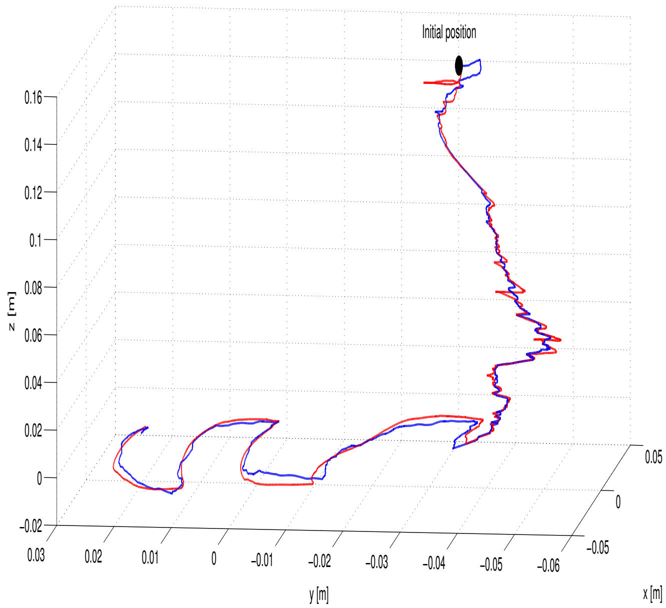


Fig. 14. Constrained motion. Surface reconstruction (local) (——) *vs* actual (remote) (- - -)[m].

tors follow each other in free movement until achieving either synchronization or consensus. However, if a human operator moves the local robot, the remote one will track its delayed trajectory up to an ultimately arbitrarily small final bound of the error. Should it get in touch with a soft surface, the operator will have some feeling of delayed kinematic correspondence. Two experiments have been implemented to test the proposed algorithm. The first is for free movement, where the operator moves the local end-effector and then he/she releases it.The second experiment is for constrained movement, where the remote robot interacts with a soft object. It is shown that the motion of the local robot becomes also constrained, giving the operator the feeling of telepresence. In addition, the force applied by the remote robot on the surface is very similar to the force that the human is applying.

ACKNOWLEDGEMENTS

This work is supported by the **DGAPA-UNAM** under grant **IN114617**.

REFERENCES

Anderson, R.J. and Spong, M.W. (1989). Bilateral control of teleoperators with time delay. *IEEE Transactions on Automatic Control*, 34(5), 494–501.

Arteaga-Pérez, M.A., Castillo-Sánchez, A.M., and Parra-Vega, V. (2006). Cartesian control of robots without dynamic model and observer design. *Automatica*, 42, 473–480.

Arteaga-Pérez, M.A., López-Recillas, L., López, M., and Nuño, E. (2017). Observer design for bilateral teleoperation systems with variable time delays. In *Proc. of the 20th World Congress. The International Federation of Automatic Control*, 14933–14938. Toulouse, France.

Astolfi, A., Ortega, R., and Venkatraman, A. (2009). A globally exponentially convergent immersion and invariance speed observer for n degree of freedom mechanical. *ieeecdac*, (1), 6508–6513.

Astolfi, A., Ortega, R., and Venkatraman, A. (2010). A globally exponentially convergent immersion and invariance speed observer for mechanical systems with non-holonomic constraints. *Automatica*, 46(1), 182–189.

Ferrell, W.R. (1965). Remote manipulation with transmission delay. *IEEE Transactions on Human Factors in Electronics*, 6(1), 24–32.

Ferrell, W.R. (1966). Delayed force feedback. *IEEE Transactions on Human Factors in Electronics*, 8(1), 449–455.

Lawrence, D.A. (1993). Stability and transparency in bilateral teleoperation. *IEEE Transactions on Robotics and Automation*, 9(5), 624–637.

Levant, A. (1993). Sliding order and sliding accuracy in sliding mode control. *International Journal of Control*, 58, 1247–1263.

Namvar, M. (2009). A class of globally convergent velocity observer for robotic manipulators. *ieeetac*, 54(8), 1956–1961.

Nuño, E. (2016). Consensus of Euler–Lagrange systems using only position measurements'. *IEEE Transactions on Control of Network Systems*, DOI: 10.1109/TCNS.2016.2620806.

Nuño, E., Arteaga-Pérez, M., and Espinosa-Pérez, G. (2017). Control of bilateral teleoperators with time delays using only position measurements (doi: 10.1002/rnc.3903). *International Journal of Robust and Nonlinear Control*, DOI: 10.1002/rnc.3903.

Nuño, E., Basañez, L., López-Franco, C., and Arana-Daniel, N. (2014). Stability of nonlinear teleoperators using PD controllers without velocity measurements. *Journal of The Franklin Institute*, 351, 241–258.

Nuño, E., Basañez, L., and Ortega, R. (2011). Passivity-based control for bilateral teleoperation: A tutorial. *Automatica*, 47(3), 485–495.

Passenberg, C., Peer, A., and Buss, M. (2010). A survey of environment-, operator-, and task-adapted controllers for teleoperation systems. *Mechatronics*, 20, 787–801.

Raju, G.J. (1989). Operator adjustable impedance in bilateral remote manipulation.

Raju, G.J. (1990). An experiment in bilateral manipulation with adjustable impedance.

Salvo-Rossi, P., Romano, G., Palmieri, F., and Iannello, G. (2006). Joint end–to–end loss–delay hidden Markov model for periodic UDP traffic over the Internet. *IEEE Transactions on Signal Processing*, 54(2), 530–541.

Sarras, I., Nuño, E., Basañez, L., and Kinnaert, M. (2016). Position tracking in delayed bilateral teleoperators without velocity measurements. *International Journal of Robust and Nonlinear Control*, 26(7), 1437–1455.

Sheridan, T. (1993). Space teleoperation through time delay. *IEEE Transactions on Robotics and Automation*, 9(5), 592–606.

Siciliano, B., Sciavicco, L., Villani, L., and Oriolo, G. (2010). *Robotics: Modelling, Planning and Control*. Springer–Verlag, London, Great Britain.

Yokokohji, Y. and Yoshikawa, T. (1994). Bilateral control of master–slave manipulators for ideal kinesthetic coupling: Formulation and experiments. *IEEE Transactions on Robotics and Automation*, 10(5), 605–620.

