

# On the Control of Bilateral Delayed Teleoperators: Free and Constrained Motion

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**Abstract:** Bilateral local-remote systems allow people to perform complex tasks in a remote or inaccessible environment. The local and remote manipulators are connected via a communication channel that can result in substantial delays. In this work, a teleoperation control-observer scheme is introduced. In free movement and without a human operator, the local and the remote manipulators tend either to a periodic trajectory or to a particular position. When a human operator moves the local robot in free motion, the remote one tends to track the commanded position with the corresponding delay. Additionally, in constrained motion the person will have the feeling of telepresence. Experimental results are provided to test the proposed algorithm.

*Keywords:* Bilateral teleoperators, observer design, time delays

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## 1. INTRODUCTION

Bilateral local-remote systems allow people to perform complex tasks in a remote or inaccessible environment. These schemes combine human skills such as reasoning and decision making with the advantages of robotic manipulation. Task performance and robustness are required features while feeling of presence and transparency are ideal goals. On the other hand, the capabilities of a bilateral robot system rely on the exchange of measured position and force data (Houston et al., 2011). However, the local and remote manipulators are connected via a communication channel that can result in substantial delays between the command induced by the human operator and the moment this command is received by the remote robot, not to mention that the information the later needs to send back endures also a time delay (Nuño et al., 2008, 2009). Due to the delay nature, neither exact tracking position nor transparency in teleoperation can be achieved. For this reason, most control approaches are meant to guarantee only position regulation. A more challenging goal is the consensus problem, where two or more manipulators tend to reach a particular position, both in the presence and in the absence of a leader (Aldana et al., 2015). Also, another particular objective may be the synchronization of a set of robots by inducing periodic position trajectories (Chopra et al., 2008). Furthermore, most algorithms are designed assuming that joint velocities are available.

In this work, a teleoperation control-observer scheme is tested experimentally. The results show that in free movement and without a human operator, the local and the remote manipulators tend either to a periodic trajectory or to a particular position, thus achieving either synchronization or position consensus. When a human operator moves either the local or the remote robot in free motion, the other tends to track the commanded position with the corresponding delay. Additionally, in constrained motion the person will have the feeling of telepresence, but not of transparency. The paper is organized as follows. The control observer scheme is proposed in Section 2, while Section 3 presents some experimental results. The paper concludes in Section 4.

## 2. PROPOSED SCHEME

### 2.1 Dynamic model of a teleoperator system

Consider a local (l)-remote (r) robot system composed by two manipulators each of them with  $n$ -joint degrees of freedom ( $i = l, r$ ) but not necessarily with the same kinematic configuration. The local dynamics is given by (Nuño et al., 2008):

$$H_l(q_l)\ddot{q}_l + C_l(q_l, \dot{q}_l)\dot{q}_l + D_l\dot{q}_l + g_l(q_l) = \tau_l - \tau_h \quad (1)$$

while the remote dynamics is modeled by:

$$H_r(q_r)\ddot{q}_r + C_r(q_r, \dot{q}_r)\dot{q}_r + D_r\dot{q}_r + g_r(q_r) = \tau_e - \tau_r \quad (2)$$

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

## 2.2 Observer design

Suppose there are constant time delays imposed by the communication channel given by  $T_l > 0$  and  $T_r > 0$  and that it is desired to design a position tracking control law while velocity measurements are not available. Consider once again  $i = l, r$ , and define for simplicity

$$\bar{\mathbf{q}}_i = \bar{\mathbf{q}}_i(t) \triangleq \mathbf{q}_i(t - T_i). \quad (3)$$

If  $(\cdot)$  is the estimated value of  $(\cdot)$ , then the observation error is given by

$$\mathbf{z}_i \triangleq \mathbf{q}_i - \hat{\mathbf{q}}_i. \quad (4)$$

Based on Arteaga-Pérez and Kelly (2004), we propose the following observers

$$\dot{\hat{\mathbf{q}}}_i = \dot{\hat{\mathbf{q}}}_{oi} + \boldsymbol{\Lambda}_{zi} \mathbf{z}_i + \mathbf{K}_{di} \mathbf{z}_i \quad (5)$$

$$\dot{\hat{\mathbf{q}}}_{oi} = \mathbf{K}_{di} \boldsymbol{\Lambda}_{zi} \int_0^t \mathbf{z}_i(\vartheta) d\vartheta, \quad (6)$$

where  $\boldsymbol{\Lambda}_{zi}, \mathbf{K}_{di} \in \mathbb{R}^{n \times n}$  are positive diagonal matrices.

## 2.3 Controller design

The next step consists in designing a tracking controller by using the estimated variables. Based on Arteaga-Pérez et al. (2006) we define

$$\dot{\hat{\mathbf{q}}}_{oi} = \dot{\hat{\mathbf{q}}}_i - \boldsymbol{\Lambda}_{zi} \mathbf{z}_i \quad (7)$$

$$\dot{\boldsymbol{\sigma}}_i = \mathbf{K}_{\beta i} \mathbf{s}_i + \text{sign}(\mathbf{s}_i) \quad \boldsymbol{\sigma}_i(0) = \mathbf{0}, \quad (8)$$

where  $i = \{r, l\}$ ,  $\mathbf{K}_{\beta i} \in \mathbb{R}^{n \times n}$  are positive definite diagonal matrices and  $\text{sign}(\mathbf{s}_i) = [\text{sign}(s_{i1}), \dots, \text{sign}(s_{in})]^T$  with  $s_{ij}$  element of  $\mathbf{s}_i$  for  $j = 1, \dots, n$ , where

$$\mathbf{s}_r = \dot{\hat{\mathbf{q}}}_r - \ddot{\bar{\mathbf{q}}}_l + \boldsymbol{\Lambda}_{xr}(\hat{\mathbf{q}}_r - \bar{\bar{\mathbf{q}}}_l) \triangleq \Delta \dot{\hat{\mathbf{q}}}_r + \boldsymbol{\Lambda}_{xr} \Delta \mathbf{q}_r \quad (9)$$

$$\mathbf{s}_l = \dot{\hat{\mathbf{q}}}_l - \ddot{\bar{\mathbf{q}}}_r + \boldsymbol{\Lambda}_{xl}(\hat{\mathbf{q}}_l - \bar{\bar{\mathbf{q}}}_r) \triangleq \Delta \dot{\hat{\mathbf{q}}}_l + \boldsymbol{\Lambda}_{xl} \Delta \mathbf{q}_l, \quad (10)$$

and

$$\bar{\bar{\mathbf{q}}}_i = \hat{\mathbf{q}}_i(t - T_i) \quad \text{and} \quad \bar{\bar{\mathbf{q}}}_i = \dot{\hat{\mathbf{q}}}_i(t - T_i). \quad (11)$$

Consider now the following variables

$$\dot{\hat{\mathbf{q}}}_{rr} \triangleq \ddot{\bar{\bar{\mathbf{q}}}}_l - \boldsymbol{\Lambda}_{xr}(\hat{\mathbf{q}}_r - \bar{\bar{\mathbf{q}}}_l) - \mathbf{K}_{\gamma r} \boldsymbol{\sigma}_r \quad (12)$$

$$\dot{\hat{\mathbf{q}}}_{rl} \triangleq \ddot{\bar{\bar{\mathbf{q}}}}_r - \boldsymbol{\Lambda}_{xl}(\hat{\mathbf{q}}_l - \bar{\bar{\mathbf{q}}}_r) - \mathbf{K}_{\gamma l} \boldsymbol{\sigma}_l, \quad (13)$$

and

$$\mathbf{s}_{oi} \triangleq \dot{\hat{\mathbf{q}}}_{oi} - \dot{\hat{\mathbf{q}}}_{ri}, \quad (14)$$

where  $\mathbf{K}_{\gamma i} \in \mathbb{R}^{n \times n}$  are positive definite diagonal matrices. Based on all previous definitions, the control law for the remote is given by

$$\boldsymbol{\tau}_r = \mathbf{K}_{pr} \mathbf{s}_{or} - \mathbf{g}_r(\mathbf{q}_r). \quad (15)$$

As to the local it is proposed

$$\boldsymbol{\tau}_l = -\mathbf{K}_{al} \dot{\hat{\mathbf{q}}}_l + \mathbf{g}_l(\mathbf{q}_l) - \mathbf{K}_{pl} \mathbf{s}_{ol}, \quad (16)$$

where  $\mathbf{K}_{al}, \mathbf{K}_{pr}, \mathbf{K}_{pl} \in \mathbb{R}^{n \times n}$  are positive definite diagonal matrices.

## 3. EXPERIMENTAL RESULTS

In this section some experimental results are presented. The test bed consists of two *Geomagic Touch* robots, each one with three degrees of freedom as shown in Figure 6, where L-R stands for local and remote, respectively. The algorithms are implemented in Visual Studio C++ Language, and the time delays are programmed via software, so that they can be set arbitrarily. For the control-observer scheme, the following parameters have been chosen:  $\mathbf{K}_{al} = \text{diag}\{0.05, 0.05, 0.05\}$ ,  $\mathbf{K}_{pl} = \text{diag}\{0.025, 0.06, 0.025\}$ ,  $\boldsymbol{\Lambda}_{xl} = \text{diag}\{30, 50, 45\}$ ,  $\boldsymbol{\Lambda}_{xr} = \text{diag}\{10, 15, 10\}$ ,  $\mathbf{K}_{\beta r} = 0.000001\mathbf{I}$ ,  $\mathbf{K}_{\beta l} = 0.000001\mathbf{I}$ ,  $\mathbf{K}_{\gamma r} = 10\mathbf{I}$ ,  $\mathbf{K}_{\gamma l} = 10\mathbf{I}$ ,  $\mathbf{K}_{pr} = \text{diag}\{0.2, 0.26, 0.2\}$ ,  $\mathbf{K}_{dl} = \text{diag}\{90, 90, 90\}$ ,  $\boldsymbol{\Lambda}_{zr} = \text{diag}\{2, 3, 3\}$ ,  $\boldsymbol{\Lambda}_{zl} = \mathbf{I}$ , and  $\mathbf{K}_{dr} = \text{diag}\{45, 45, 41\}$ .

Two experiments were carried out for asymmetric delays, in free and constrained motion.

### 3.1 Free Motion

For the first experiment the time delays are set to  $T_l = 0.3\text{s}$  and  $T_r = 0.7\text{s}$ . The person drops the local end-effector after 6s, and henceforth the system becomes autonomous. Figure 1 shows the local manipulator position *vs* the delayed position of the remote one, while Figure 2 shows the remote robot position *vs* the delayed position of the local one. It is interesting to note that despite the asymmetric delays and the fact that oscillations tend to disappear, in the transient response there is a good match between the current position of each manipulator and the delayed one of the other. Furthermore, the observation errors are bounded and tend to zero in steady state. This can be better appreciated in Figure 3, where tracking and observation errors are shown. Finally, in Figures 4 and 5 the estimated velocities of the local robot are compared with the (delayed) estimated velocities of the remote manipulator, and viceversa. It is interesting to note that the synchronizing effect of our approach can also be appreciated here.

### 3.2 Constrained Motion

For the second experiment the time delays are set to  $T_l = 0.3\text{s}$  and  $T_r = 0.7\text{s}$  and we take into account

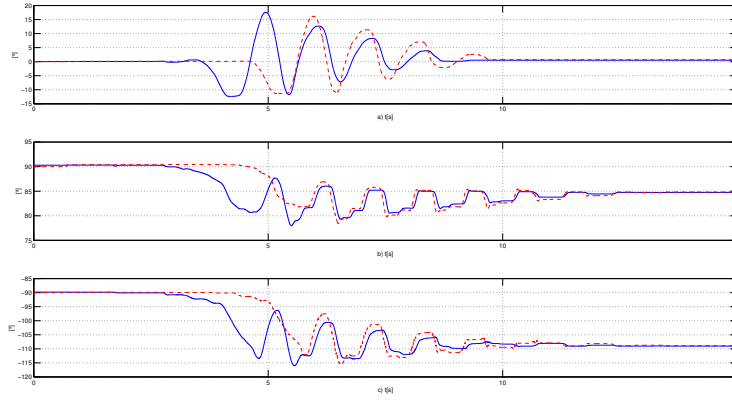


Fig. 1. Free Motion. a)  $q_{11}(t)$  (—) vs  $q_{11}(t - T_r)$  (- - -) [ $^\circ$ ]. b)  $q_{12}(t)$  (—) vs  $q_{12}(t - T_r)$  (- - -) [ $^\circ$ ]. c)  $q_{13}(t)$  (—) vs  $q_{13}(t - T_r)$  (- - -) [ $^\circ$ ].

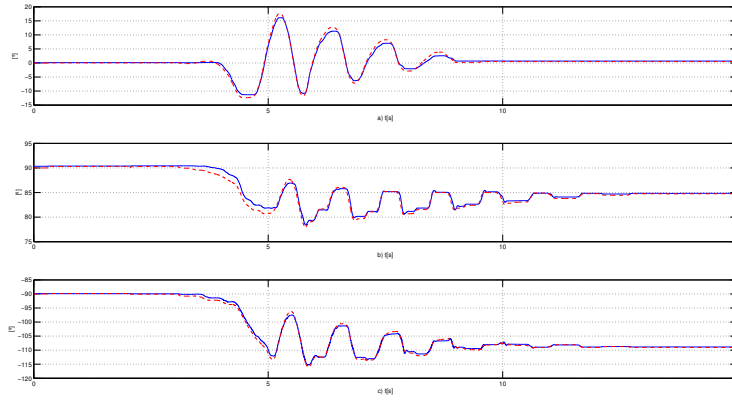


Fig. 2. Free Motion. a)  $q_{11}(t)$  (—) vs  $q_{11}(t - T_l)$  (- - -) [ $^\circ$ ]. b)  $q_{12}(t)$  (—) vs  $q_{12}(t - T_l)$  (- - -) [ $^\circ$ ]. c)  $q_{13}(t)$  (—) vs  $q_{13}(t - T_l)$  (- - -) [ $^\circ$ ].

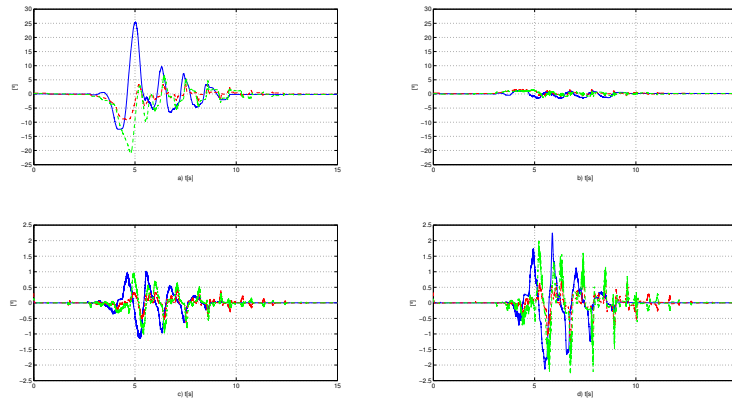


Fig. 3. Free Motion. Tracking and observation errors: a)  $e_{11}$  (—),  $e_{12}$  (- - -),  $e_{13}$  (- - -) [ $^\circ$ ]. b)  $e_{21}$  (—),  $e_{22}$  (- - -),  $e_{23}$  (- - -) [ $^\circ$ ]. c)  $z_{11}$  (—),  $z_{12}$  (- - -),  $z_{13}$  (- - -) [ $^\circ$ ]. d)  $z_{21}$  (—),  $z_{22}$  (- - -),  $z_{23}$  (- - -) [ $^\circ$ ].

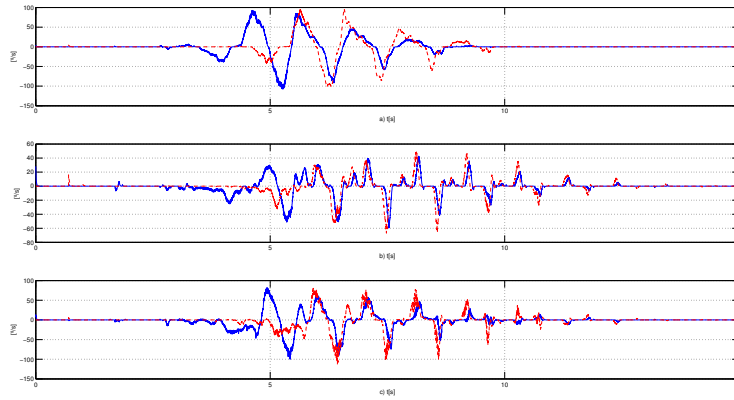


Fig. 4. Free Motion. a)  $\dot{q}_{11}(t)$  (—) vs  $\dot{q}_{r1}(t - T_r)$  (- - -) [ $^{\circ}/s$ ]. b)  $\dot{q}_{12}(t)$  (—) vs  $\dot{q}_{r2}(t - T_r)$  (- - -) [ $^{\circ}/s$ ]. c)  $\dot{q}_{13}(t)$  (—) vs  $\dot{q}_{r3}(t - T_r)$  (- - -) [ $^{\circ}/s$ ].

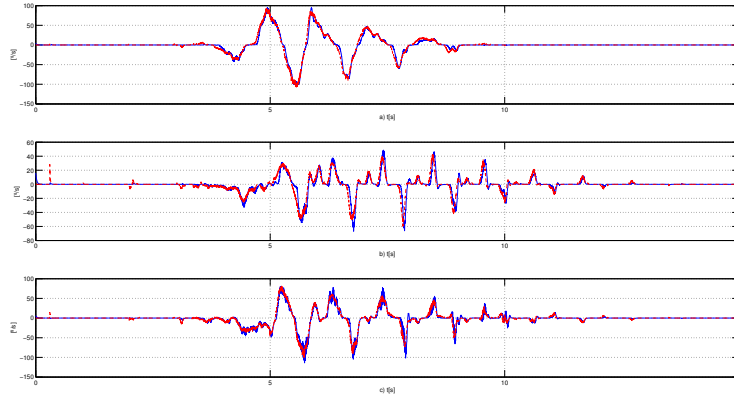


Fig. 5. Free Motion. a)  $\dot{q}_{r1}(t)$  (—) vs  $\dot{q}_{11}(t - T_l)$  (- - -) [ $^{\circ}/s$ ]. b)  $\dot{q}_{r2}(t)$  (—) vs  $\dot{q}_{12}(t - T_l)$  (- - -) [ $^{\circ}/s$ ]. c)  $\dot{q}_{r3}(t)$  (—) vs  $\dot{q}_{13}(t - T_l)$  (- - -) [ $^{\circ}/s$ ].

the scenario when the human operator moves the local manipulator but he/she does not drop the end-effector, while the remote robot motion is constrained by an aluminium box as seen in Figure 6. Figure 7 shows the local position *vs* the delayed position of the remote manipulator, while Figure 8 shows the opposite. Note that this time the remote manipulator tracks the delayed position of the local one, except for those directions where the movement is constrained, because for that case both robots tend to have the same values in joint positions. In Figure 9, tracking and observation errors are shown. The tracking errors are larger, but the observers have the same good performance as before. Finally, Figure 10 shows the actual and virtual surfaces in Cartesian coordinates as recreated by the manipulators. Clearly, the local robot end-effector is depicting a plane, which means that the operator has the feeling of motion on that plane.

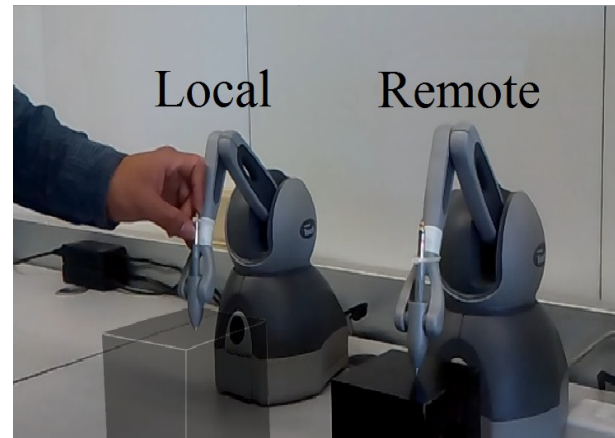


Fig. 6. Remote robot in contact with a rigid environment. The local manipulator is shown with a virtual environment.

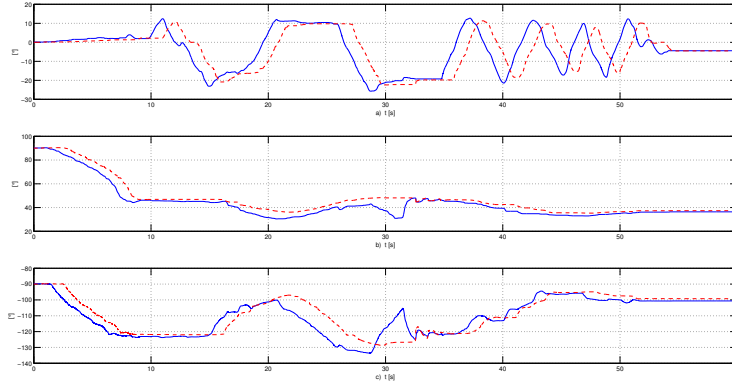


Fig. 7. Constrained Motion. a)  $q_{11}(t)$  (—) vs  $q_{r1}(t - T_r)$  (- - -) [°]. b)  $q_{12}(t)$  (—) vs  $q_{r2}(t - T_r)$  (- - -) [°]. c)  $q_{13}(t)$  (—) vs  $q_{r3}(t - T_r)$  (- - -) [°].

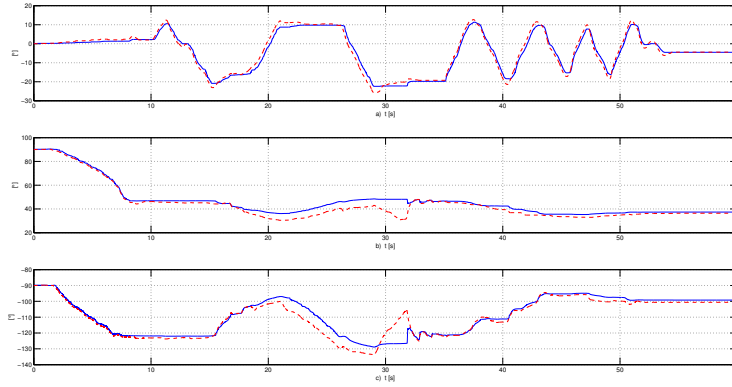


Fig. 8. Constrained Motion. a)  $q_{r1}(t)$  (—) vs  $q_{11}(t - T_1)$  (- - -) [°]. b)  $q_{r2}(t)$  (—) vs  $q_{12}(t - T_1)$  (- - -) [°]. c)  $q_{r3}(t)$  (—) vs  $q_{13}(t - T_1)$  (- - -) [°].

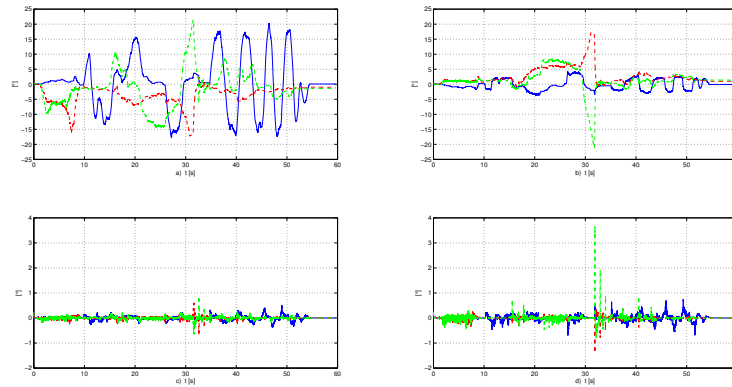


Fig. 9. Constrained Motion. Tracking and observation errors: a)  $e_{11}$  (—),  $e_{12}$  (- - -),  $e_{13}$  (- - -) [°]. b)  $e_{r1}$  (—),  $e_{r2}$  (- - -),  $e_{r3}$  (- - -) [°]. c)  $z_{11}$  (—),  $z_{12}$  (- - -),  $z_{13}$  (- - -) [°]. d)  $z_{r1}$  (—),  $z_{r2}$  (- - -),  $z_{r3}$  (- - -) [°].

### 3.3 Discussion

Based on the experimental results, we claim that the proposed control-observer scheme owns the following

properties.

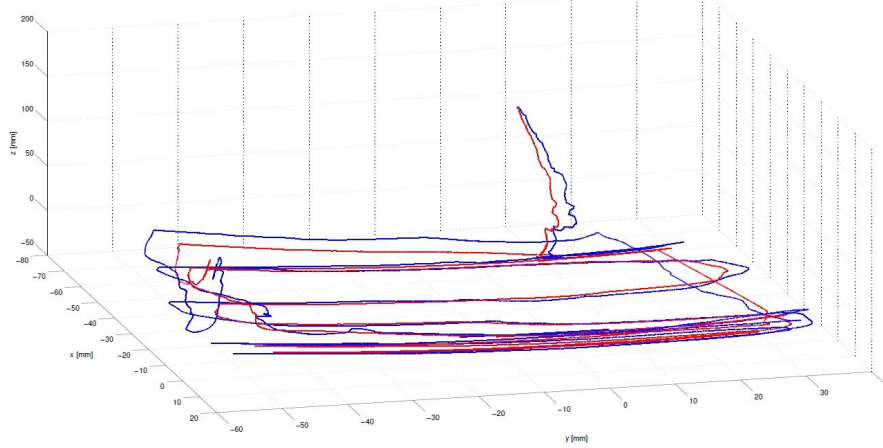


Fig. 10. Constrained Motion. Recreated (local) environment (—) vs actual (remote) environment(---) [mm].

- (1) The observation errors can be made arbitrarily small, *i. e.*  $z_l \approx 0$ ,  $\dot{z}_l \approx 0$ ,  $z_r \approx 0$ , and  $\dot{z}_r \approx 0$
- (2) All tracking errors are bounded
- (3) If  $\tau_h = \tau_e = 0$ , the system trajectories will satisfy  $q_i(t) \approx q_i(t - T_r - T_l)$  and  $\dot{q}_i(t) \approx \dot{q}_i(t - T_r - T_l)$ . In particular  $q_r(t) \approx q_l(t - T_l)$ ,  $q_l(t) \approx q_r(t - T_r)$ ,  $\dot{q}_r(t) \approx \dot{q}_l(t - T_l)$ , and  $\dot{q}_l(t) \approx \dot{q}_r(t - T_r)$  and if the positions tend to a constant value, then all tracking and observation errors tend to zero
- (4) If  $\tau_h \neq 0$ , then remote robot trajectories will satisfy  $q_r(t) \approx q_l(t - T_l)$  and  $\dot{q}_r(t) \approx \dot{q}_l(t - T_l)$
- (5) If  $\tau_h$  is not large enough to overcome the input torque  $\tau_l$  in (16) and the external force  $\tau_e \neq 0$  and bounded, then the movement of the local robot will tend to be only possible in the direction allowed by the actual constraint on the remote side, *i. e.* the human operator will have the feeling of telepresence, but not that of transparency

It remains as future work to provide a mathematical proof of our claims. Note that no force sensors are used in our control scheme, so that it cannot be guaranteed that the force the human operator is feeling when trying to move the local manipulator in the constrained direction is proportional to that being applied by the remote robot to the actual environment.

#### 4. CONCLUSIONS

In this work, a teleoperation control-observer scheme with constant delays is tested experimentally. It is shown that in free movement and without a human operator, the local and the remote manipulators tend either to a periodic trajectory or to a particular position, thus achieving either synchronization or position consensus. When a human operator moves either the local or the remote robot in free motion, then the other one tends to track the commanded position with the corresponding delay. Additionally, in constrained motion the person will have the feeling of telepresence, but not of transparency.

As future research it remains to provide a stability analytical proof for the closed loop system.

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