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PD-like controllers for delayed bilateral teleoperation of manipulators robots

Emanuel Slawiñski*,† and Vicente Mut

Universidad Nacional de San Juan, San Juan, J5400ARL Argentina

SUMMARY

This paper proposes a compensated PD-like controller for delayed bilateral teleoperation of a manipulator robot. The scheme has a PD-like remote controller, a damping into the master, and a compensation strategy. The proposed compensation removes part of potential energy of the user's command depending on the difference between the situation on the remote site and the situation as perceived by the human operator. In addition, the stability of the delayed teleoperation system is analyzed, and a comparison based on experiments is carried out in order to analyze the advantages of using the proposed compensation. Finally, results of a bilateral teleoperation including the proposed control scheme, where the master and slave exchange information by using a low-cost connection of mobile Internet, are shown. Copyright © 2014 John Wiley & Sons, Ltd.

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KEY WORDS: robot teleoperation; force feedback; PD-like control; time delay

1. INTRODUCTION

Robot teleoperation allows the execution of different tasks in remote environments including possibly dangerous and harmful jobs for the human operator [1]. In the teleoperation systems of robots with force feedback, a user does some task physically interacting with an environment through a master–slave system. Nowadays, there are many applications for robot teleoperation, including telemedicine, exploration, entertainment, tele-services, tele-manufacturing, and many more [2]. In addition, the use of Internet increases notably the application of the teleoperation systems in several areas. However, it is known that the presence of time-delay can induce instability or poor performance in a delayed teleoperation system [3–5] as well as a bad transparency [6, 7].

The concept typically used inside the design of control schemes for bilateral teleoperation is the injection of damping into the system in order to assure stability. For example, Anderson and Spong [8] proposed to send the scattering signals to transform the transmission delays into a passive (virtual) transmission line. In the work of Niemeyer and Slotine [9, 10], wave transformations are used to keep the passivity of the communication channel in front of time delay. These strategies inject the so-called apparent damping. In the work of Lee and Spong [11], it is claimed that a simple PD-like scheme, which does not require scattering or wave variable transformations, yields a stable operation including position coordination. From this, Nuno *et al.* [12, 13] and Hua and Liu [14] proved asymptotic stability of PD-like schemes by using a sufficiently large damping injected into the master and slave for the case of constant delays and asymmetric time-varying delays, respectively. However, the papers based on injecting damping have the problem of acting permanently when there is motion. Recent papers propose control strategies in order to limit the system energy, such as Park *et al.* [15] and Lee and Huang [16], or compensation schemes [17] to remove the

*Correspondence to: Emanuel Slawiñski, Universidad Nacional de San Juan, San Juan, J5400ARL Argentina.
†E-mail: slawinski@inaut.unsj.edu.ar

distortion of wave variables. Other recent works such as [18] and [19] modify the way of applying damping into the system. On the other hand, it is known that there exists a trade-off between stability and transparency [6]. Even a stable bilateral teleoperation has not a high performance in practice necessarily. Therefore, the searching of new control schemes that assure stability and also achieve a good behavior in practice is a current area of big interest for teleoperation systems.

This paper addresses a compensated PD-like control scheme that removes energy in order to achieve a delayed bilateral teleoperation of good performance. The proposed strategy is formed by a remote PD-like controller, a local controller based on injecting damping into the local device, and a compensation strategy, which is used to extract, depending on the situation, part of the potential energy from the user's commands. The compensation modifies the user's command taking into account a simplified model of the behavior of the human operator in front of tactile and visual stimuli. Furthermore, the Lyapunov stability of the compensated PD-like scheme is analyzed. Finally, experiments using two low-cost three-dimensional devices Novint Falcon with force feedback and connected by Ethernet network, as well as by using mobile Internet, are shown. These experiments are used to compare the performance of the teleoperation system with and without compensation of the user's command.

2. PRELIMINARY

This paper will analyze bilateral teleoperation systems, where a human operator interacts with a remote environment using a master–slave system. In this system, the user moves the slave through the master while he feels the interaction force between the slave and its environment on his hand, as it is shown in Figure 1.

The typical nonlinear dynamic model to represent the master or local device is used, that is,

$$\mathbf{M_m}(\mathbf{q_m})\ddot{\mathbf{q}}_\mathbf{m} + \mathbf{C_m}(\mathbf{q_m}, \dot{\mathbf{q}}_\mathbf{m})\dot{\mathbf{q}}_\mathbf{m} + \mathbf{g_m}(\mathbf{q_m}) = \boldsymbol{\tau}_\mathbf{m} + \mathbf{f_h} \tag{1}$$

where $\mathbf{q_m}(t) \in R^{n\times 1}$ is the joint position of the master, $\dot{\mathbf{q}}_\mathbf{m}(t)$ is the joint velocity, $\mathbf{M_m}(\mathbf{q_m}) \in R^{n\times n}$ is the inertia matrix, $\mathbf{C_m}(\mathbf{q_m}, \dot{\mathbf{q}}_\mathbf{m}) \in R^{n\times n}$ is the matrix representing centripetal and Coriolis torques, $\mathbf{g_m}(\mathbf{q_m}) \in R^{n\times 1}$ is the gravitational torque, $\mathbf{f_h} \in R^{n\times 1}$ is the torque that occurs from the force applied by the human operator and $\boldsymbol{\tau}_\mathbf{m} \in R^{n\times 1}$ is the control torque applied to the master.

The slave robot is represented similar to (1), as follows:

$$\mathbf{M_s}(\mathbf{q_s})\ddot{\mathbf{q}}_\mathbf{s} + \mathbf{C_s}(\mathbf{q_s}, \dot{\mathbf{q}}_\mathbf{s})\dot{\mathbf{q}}_\mathbf{s} + \mathbf{g_s}(\mathbf{q_s}) = \boldsymbol{\tau}_\mathbf{s} + \mathbf{f_e} \tag{2}$$

where $\mathbf{q_s}(t) \in R^{n\times 1}$ is the vector of the slave joint position, $\dot{\mathbf{q}}_\mathbf{s}(t)$ is the vector of joint velocity, $\mathbf{M_s}(\mathbf{q_s}) \in R^{n\times n}$ is the inertia matrix, $\mathbf{C_s}(\mathbf{q_s}, \dot{\mathbf{q}}_\mathbf{s}) \in R^{n\times n}$ is the matrix of centripetal and Coriolis

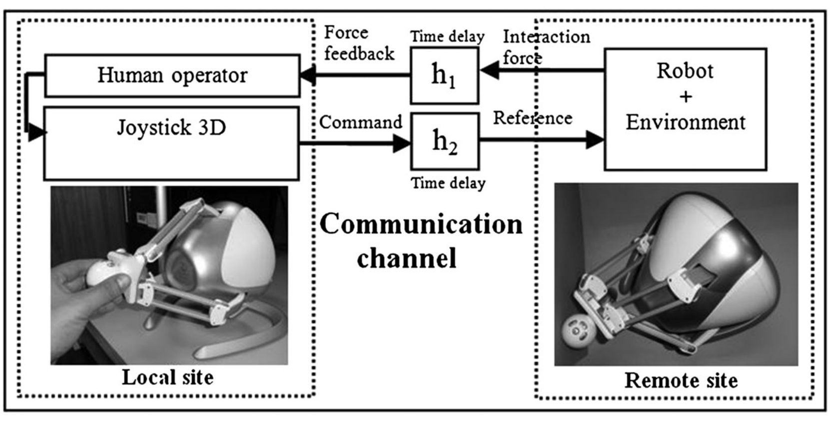

Figure 1. Delayed teleoperation system.

torques, $\mathbf{g_s}(\mathbf{q_s}) \in R^{n\times 1}$ is the gravitational torque, $\mathbf{f_e} \in R^{n\times 1}$ is the torque that occurs from the force exerted by the environment on the robot, and $\boldsymbol{\tau}_\mathbf{s} \in R^{n\times 1}$ is the control torque applied to the slave.

In addition, the signals interchanged between the local device and the remote robot travel by a communication channel, which is represented by a forward time delay $h_1(t)$ (from the master to the slave) and a backward time delay $h_2(t)$ (from the slave to the master). Generally, these delays are time-varying and different between them (asymmetric delays). On the other hand, the following properties, assumptions and lemmas commonly used in the literature of robots teleoperation [13, 20, 21] will be used in this paper:

Property 1
The inertia matrices $\mathbf{M_m}(\mathbf{q_m})$ and $\mathbf{M_s}(\mathbf{q_s})$ are symmetric positive definite functions and there exist positive constants m_1, m_2, m_3, m_4 such that $m_1\mathbf{I} \leqslant \mathbf{M_m}(\mathbf{q_m}) \leqslant m_2\mathbf{I}$ and $m_3\mathbf{I} \leqslant \mathbf{M_s}(\mathbf{q_s}) \leqslant m_4\mathbf{I}$, where $\mathbf{I}$ is the identity matrix of adequate order for each case.

Property 2
The matrices $\dot{\mathbf{M}}_\mathbf{m}(\mathbf{q_m}) - 2\mathbf{C_m}(\mathbf{q_m}, \dot{\mathbf{q}}_\mathbf{m})$ and $\dot{\mathbf{M}}_\mathbf{s}(\mathbf{q_s}) - 2\mathbf{C_s}(\mathbf{q_s}, \dot{\mathbf{q}}_\mathbf{s})$ are skew-symmetric.

Property 3
For all $\mathbf{q_i}, \mathbf{x}, \mathbf{y} \in R^{n\times 1}$, there exist positive scalars a_m and a_s such that the centripetal and coriolis torques verify $\|\mathbf{C_m}(\mathbf{q_i}, \mathbf{x})\,\mathbf{y}\| \leqslant a_m \|\mathbf{x}\|\,\|\mathbf{y}\|$ and $\|\mathbf{C_s}(\mathbf{q_i}, \mathbf{x})\,\mathbf{y}\| \leqslant a_s \|\mathbf{x}\|\,\|\mathbf{y}\|$.

Assumption 1
The human operator behaves in a passive way, that is $\int_0^t -\dot{\mathbf{q}}_\mathbf{m}^T(\sigma)\,\mathbf{f_h}(\sigma)d\sigma \geqslant 0$.

Assumption 2
The environment of the manipulator robot is passive, which implies that $\int_0^t -\dot{\mathbf{q}}_\mathbf{s}^T(\sigma)\mathbf{f_e}(\sigma)\,d\sigma \geqslant 0$.

Assumption 3
The time delays $h_1(t)$ and $h_2(t)$ are bounded, so there exist positive scalars $\bar{h}_1$ and $\bar{h}_2$ such that $0 \leqslant h_1(t) \leqslant \bar{h}_1$ and $0 \leqslant h_2(t) \leqslant \bar{h}_2$ for all t.

Lemma 1 ([14]*)*
For vector functions $\mathbf{a}(.)$ and $\mathbf{b}(.)$ and a time-varying scalar $h(t)$ with $0 \leqslant h(t) \leqslant \bar{h}$, the following inequality holds:

$$-2\mathbf{a}^T(t)\int_{t-h(t)}^{t}\mathbf{b}(\xi)d\xi - \int_{t-h(t)}^{t}\mathbf{b}^T(\xi)\mathbf{b}(\xi)d\xi \leqslant h(t)\mathbf{a}^T(t)\mathbf{a}(t) \leqslant \bar{h}(t)\mathbf{a}^T(t)\mathbf{a}(t) \tag{3}$$

Because the inequality (3) is used in many parts of our paper, we explain its derivation. From the known relation given by,

$$\pm 2\mathbf{a}^T(t)\mathbf{b}(\xi) + \mathbf{b}^T(\xi)\mathbf{b}(\xi) + \mathbf{a}^T(t)\mathbf{a}(t) \geqslant 0$$

where t, ξ are time variables, if in last equation, the integral with respect to $d\xi$ is applied between the limits t and $t-h$, then it can be expressed as,

$$\pm 2\mathbf{a}^T(t)\int_{t-h(t)}^{t}\mathbf{b}(\xi)d\xi + \int_{t-h(t)}^{t}\mathbf{b}^T(\xi)\mathbf{b}(\xi)d\xi + \mathbf{a}^T(t)\mathbf{a}(t)\int_{t-h(t)}^{t}d\xi \geqslant 0$$

$$\pm 2\left|\mathbf{a}^T(t)\right|\left|\int_{t-h(t)}^{t}\mathbf{b}(\xi)d\xi\right| + \int_{t-h(t)}^{t}\mathbf{b}^T(\xi)\,\mathbf{b}(\xi)d\xi + \mathbf{a}^T(t)\,\mathbf{a}(t)\int_{t-h(t)}^{t}d\xi \geqslant 0$$

So, the previous inequalities justify Lemma 1.

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3. CONTROL SCHEME FOR DELAYED BILATERAL TELEOPERATION

In this work, a control scheme applied to delayed bilateral teleoperation of a manipulator robot is proposed. It is known that the PD-like controllers use the damping for stabilizing the system, but it is based on the physics of motion and always acts removing kinetic energy. Instead, our proposal uses a model of the user's reaction in front of visual and tactile stimuli. In practice, the proposed scheme removes potential energy of the user's command only if there is a mismatch between the robot–environment interaction, and the interaction perceived really by him (involving delayed information), as it is illustrated for two cases (A and B) in Figure 2. It is important to remark that one of the strategies most robust for teleoperation before high delays is the one called move-and-wait, where the user generates a command (move) because he predicts because of the previous wait stage that the current situation on the remote site is similar to the situation perceived by him. Then, the human operator stops his command (wait) or, put in another way, the user removes energy of his command, because he knows that the real and perceived situations will be different during the next time interval. This classical strategy has motivated our scheme.

The proposed master–slave teleoperation system is shown in Figure 3, where the PD-like controller is linked with a block called compensation that changes the user's command and the force feedback. In addition, gravity compensation is used in the master and slave.

Now, the control scheme proposes to establish the control actions as follows:

$$\begin{cases} \boldsymbol{\tau}_{\mathbf{m}} = -k_s\left(\mathbf{q_m}\left(t-h_1-h_2\right)-\mathbf{q_s}\left(t-h_2\right)\right)-k_s\boldsymbol{\Delta}_{\mathbf{c}}\left(t-h_2\right)+\mathbf{g_m}\left(\mathbf{q_m}\right)-\alpha_m\dot{\mathbf{q}}_{\mathbf{m}} \\ \boldsymbol{\tau}_{\mathbf{s}} = k_s\left(\mathbf{q_m}\left(t-h_1\right)-\mathbf{q_s}+\boldsymbol{\Delta}_{\mathbf{c}}\right)+\mathbf{g_s}\left(\mathbf{q_s}\right)-\alpha_s\dot{\mathbf{q}}_{\mathbf{s}} \end{cases} \tag{4}$$

where k_s, α_s and α_m are positive constant parameters. The first two parameters represent the proportional gain and damping added by the PD-like controller, α_m is the damping injected in the master, and Δ_c is a compensation signal used to change the user's command and the force feedback.

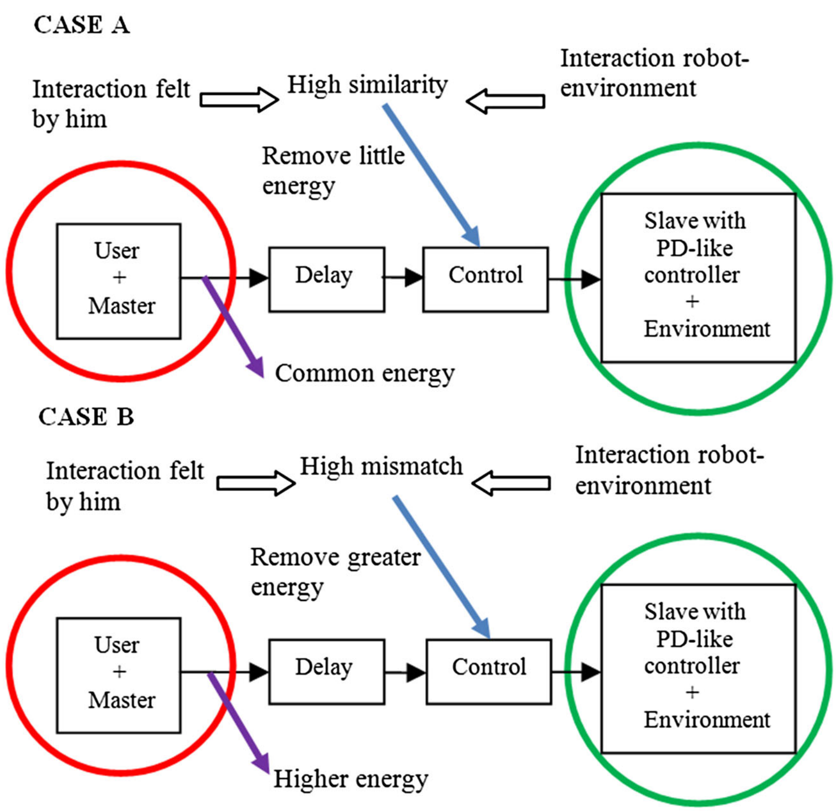

Figure 2. Illustration of the behavior in practice of the proposed control scheme.

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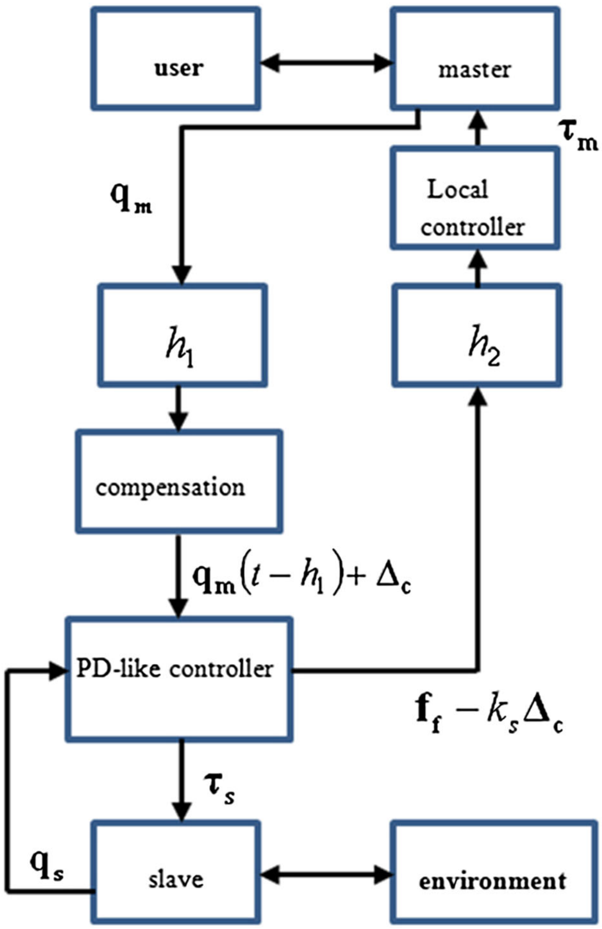

Figure 3. Proposed PD-like control scheme.

The non-compensated force feedback on the local site is defined by,

$$\begin{aligned}\mathbf{f_f}(t-h_2) &= -k_s\left(\mathbf{q_m}(t-h_1-h_2)-\mathbf{q_s}(t-h_2)\right)\\ &= -k_s\left((\mathbf{q_m}-\mathbf{q_s})+\int_{t-h_1-h_2}^{t}\dot{\mathbf{q}}_{\mathbf{m}}d\xi+\int_{t-h_2}^{t}\dot{\mathbf{q}}_{\mathbf{s}}d\xi\right)\end{aligned} \tag{5}$$

That is, $\mathbf{f_f}(t)$ is an estimated value of the interaction force between the slave and the remote environment.

Now, let us represent the user's command $\mathbf{q_m}$ as follows:

$$\mathbf{q_m}(t) = \mathbf{q_m}(t-h_1) + \boldsymbol{\Delta}_\mathbf{c} + \boldsymbol{\varepsilon} \tag{6}$$

where $\boldsymbol{\varepsilon}$ is the estimate error of Δ_c. We assume that $|\boldsymbol{\varepsilon}| \leqslant \beta\left|\int_{t-h_1}^{t}\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi\right|$ with $\beta > 0$ whose value depends on the model used to estimate $\mathbf{q_m}$. For example, a perfect model would cause $\beta = 0$, and if the estimate worsens, β will increase. Of course, a linear prediction like $\Delta_c = h_1\dot{\mathbf{q}}_{\mathbf{m}}(t-h_1)$ could be used, but this linear prediction is based on the supposition that the velocity kept constant, which has a high error in a delayed bilateral teleoperation system. Instead, we propose the use of a simplified model of the local site including the user's reaction before tactile and visual stimuli,

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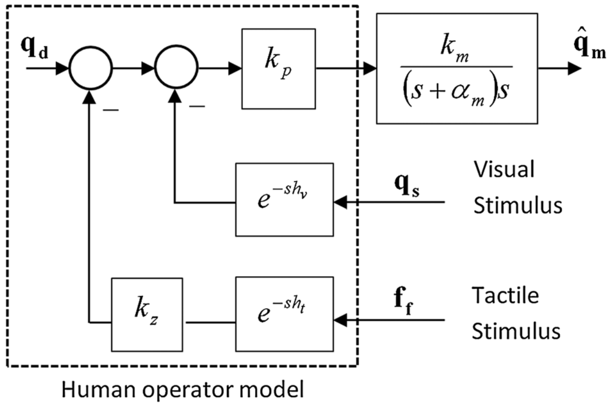

Figure 4. Model of the local site used for compensation considering null delay.

as it is shown in Figure 4 considering a position reference $\mathbf{q_d}$. As all model-based schemes, the performance of the teleoperation system will depend on how good the model is.

It is important to remark that a parametric identification of the model of Figure 4 is outside of the scope of this work, but we stand out the concrete use of its structure in a control scheme applied to bilateral teleoperation of robots. In this paper, such model is used to compute the compensation Δ_c as follows:

$$\begin{aligned}\Delta_c(t) = \hat{\mathbf{q}}_\mathbf{m}(t) - \hat{\mathbf{q}}_\mathbf{m}(t-h_1) &= -k_m \int k_p k_z W\left[\mathbf{f_f}(t-h_t-h_2)\right] dt \\ &+ k_m \int k_p k_z W\left[\mathbf{f_f}(t-h_t-h_1-h_2)\right] dt \\ &- k_m \int k_p W\left[\mathbf{q_s}(t-h_v-h_2)\right] dt + k_m \int k_p W\left[\mathbf{q_s}(t-h_v-h_1-h_2)\right] dt \\ &= -k_{c_1} \int_{t-h_t-h_1-h_2}^{t-h_t-h_2} W\left[\mathbf{f_f}(\xi)\right] d\xi - k_{c_2} \int_{t-h_v-h_1-h_2}^{t-h_v-h_2} W\left[\mathbf{q_s}(\xi)\right] d\xi\end{aligned} \tag{7}$$

where $k_z > 0$ is the human impedance, $k_p > 0$ is the proportional human gain to control position, $k_m > 0$ is the master gain, $W[\cdot]$ is a low-pass filter represented in the Laplace domain s by the transfer function $\frac{1}{s+\alpha_m}$, and finally, h_v and h_t are the mean reaction time before visual and force stimuli, respectively. From now on and only for simplicity in the notation, we set $k_{c_1} = k_p k_z k_m$ and $k_{c_2} = k_p k_m$. Because a linear model is used, then the effect of $\mathbf{q_d}$ is canceled in (7).

Remark 1

The main difference of our proposal with the PD-like controllers present in the current state-of-art on robots teleoperation, such as [14], [12, 13, 20] and [18, 19], is the use of a model of the human operator's reaction in the control scheme to remove potential energy of the user's command in order to complement the stabilizing effect of the damping, which decreases the kinetic energy of the teleoperation system.

Remark 2

The strategy compensates the increase of energy of the teleoperation system caused by the unintentional raising of potential energy on the user's command, which is not necessarily caused by an increment of the time delay but rather by the difference between the current situation on the remote site and the situation as perceived by the human operator. Such mismatch is quantified and used to mitigate at least a part of the energy excess from the user's command.

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3.1. Analysis of stability

The stability analysis is based on Hua and Liu [14], where the theory of Lyapunov–Krasovskii is used for PD-like controllers. Here, a functional $V(t, \mathbf{q_m} - \mathbf{q}_s, \dot{\mathbf{q}}_\mathbf{m}, \dot{\mathbf{q}}_\mathbf{s}) = V_1 + V_2 + V_3 > 0$ positive definite is chosen as,

$$V_1 = \dot{\mathbf{q}}_\mathbf{m}^T \mathbf{M_m}(\mathbf{q_m})\dot{\mathbf{q}}_\mathbf{m} + \dot{\mathbf{q}}_\mathbf{s}^T \mathbf{M_s}(\mathbf{q_s})\dot{\mathbf{q}}_\mathbf{s} + 2\int_0^t \left(-\dot{\mathbf{q}}_\mathbf{m}(\sigma)^T \mathbf{f_h}(\sigma) - \dot{\mathbf{q}}_\mathbf{s}(\sigma)^T \mathbf{f_e}(\sigma)\right) d\sigma \tag{8}$$

$$\begin{aligned} V_2 = & \int_{-\bar{h}_2}^{0}\int_{t+\theta}^{t} \dot{\mathbf{q}}_\mathbf{m}(\xi)^T \dot{\mathbf{q}}_\mathbf{m}(\xi) d\xi d\theta + \int_{-\bar{h}_2}^{0}\int_{t+\theta}^{t} \dot{\mathbf{q}}_\mathbf{s}(\xi)^T \dot{\mathbf{q}}_\mathbf{s}(\xi) d\xi d\theta \\ & + \beta \int_{-\bar{h}_1-\bar{h}_2}^{0}\int_{t+\theta}^{t} \dot{\mathbf{q}}_\mathbf{m}(\xi)^T \dot{\mathbf{q}}_\mathbf{m}(\xi) d\xi d\theta + \beta \int_{-\bar{h}_1}^{0}\int_{t+\theta}^{t} \dot{\mathbf{q}}_\mathbf{m}(\xi)^T \dot{\mathbf{q}}_\mathbf{m}(\xi) d\xi d\theta \end{aligned} \tag{9}$$

$$V_3 = k_s(\mathbf{q_m} - \mathbf{q_s})^T(\mathbf{q_m} - \mathbf{q_s}) \tag{10}$$

The time derivatives of V_1, V_2, V_3 along the system trajectories (1) and (2), including the proposed control actions (4) and considering the properties 1 and 2 and the assumptions 1 and 2, are the following ones:

$$\begin{aligned} \dot{V}_1 = & 2\dot{\mathbf{q}}_\mathbf{m}^T(-k_s(\mathbf{q_m}(t-h_1-h_2) - \mathbf{q_s}(t-h_2)) - k_s\Delta_c(t-h_2) - \alpha_m\dot{\mathbf{q}}_\mathbf{m}) \\ & + 2\dot{\mathbf{q}}_\mathbf{s}^T(k_s(\mathbf{q_m}(t-h_1) - \mathbf{q_s} + \Delta_c) - \alpha_s\dot{\mathbf{q}}_\mathbf{s}) \end{aligned} \tag{11}$$

$$\begin{aligned} \dot{V}_2 = & \bar{h}_2\dot{\mathbf{q}}_\mathbf{m}^T\dot{\mathbf{q}}_\mathbf{m} - \int_{t-\bar{h}_2}^{t} \dot{\mathbf{q}}_\mathbf{m}^T(\xi)\dot{\mathbf{q}}_\mathbf{m}(\xi)d\xi \\ & + \bar{h}_2\dot{\mathbf{q}}_\mathbf{s}^T\dot{\mathbf{q}}_\mathbf{s} - \int_{t-\bar{h}_2}^{t} \dot{\mathbf{q}}_\mathbf{s}^T(\xi)\dot{\mathbf{q}}_\mathbf{s}(\xi)d\xi \\ & + (\bar{h}_1 + \bar{h}_2)\beta\dot{\mathbf{q}}_\mathbf{m}^T\dot{\mathbf{q}}_\mathbf{m} - \beta\int_{t-\bar{h}_1-\bar{h}_2}^{t} \dot{\mathbf{q}}_\mathbf{m}^T(\xi)\dot{\mathbf{q}}_\mathbf{m}(\xi)\, d \\ & + \bar{h}_1\beta\dot{\mathbf{q}}_\mathbf{m}^T\dot{\mathbf{q}}_\mathbf{m} - \beta\int_{t-\bar{h}_1}^{t} \dot{\mathbf{q}}_\mathbf{m}^T(\xi)\dot{\mathbf{q}}_\mathbf{m}(\xi)d \\ \leqslant & \bar{h}_2\dot{\mathbf{q}}_\mathbf{m}^T\dot{\mathbf{q}}_\mathbf{m} - \int_{t-h_2}^{t} \dot{\mathbf{q}}_\mathbf{m}^T(\xi)\dot{\mathbf{q}}_\mathbf{m}(\xi)d\xi \\ & + \bar{h}_2\dot{\mathbf{q}}_\mathbf{s}^T\dot{\mathbf{q}}_\mathbf{s} - \int_{t-h_2}^{t} \dot{\mathbf{q}}_\mathbf{s}^T(\xi)\dot{\mathbf{q}}_\mathbf{s}(\xi)d\xi \\ & + \beta(\bar{h}_1 + \bar{h}_2)\dot{\mathbf{q}}_\mathbf{m}^T\dot{\mathbf{q}}_\mathbf{m} + \beta\bar{h}_1\dot{\mathbf{q}}_\mathbf{m}^T\dot{\mathbf{q}}_\mathbf{m} \end{aligned} \tag{12}$$

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$$
\begin{aligned}
& -\beta \int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{m}}^T(\xi)\,\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi - \beta \int_{t-h_1-h_2}^{t-h_2} \dot{\mathbf{q}}_{\mathbf{m}}^T(\xi)\dot{\mathbf{q}}_{\mathbf{m}}(\xi)\,d\xi \\
& -\beta \int_{t-h_1}^{t} \dot{\mathbf{q}}_{\mathbf{m}}^T(\xi)\,\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi \\
\leqslant\ & \bar{h}_2\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} - \int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{m}}^T(\xi)\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi \\
& + \bar{h}_2\dot{\mathbf{q}}_{\mathbf{s}}^T\dot{\mathbf{q}}_{\mathbf{s}} - \int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{s}}^T(\xi)\dot{\mathbf{q}}_{\mathbf{s}}(\xi)d\xi \\
& + \beta\left(\bar{h}_1+\bar{h}_2\right)\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} + \beta\bar{h}_1\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} \\
& -\beta \int_{t-h_1-h_2}^{t-h_2} \dot{\mathbf{q}}_{\mathbf{m}}^T(\xi)\dot{\mathbf{q}}_{\mathbf{m}}(\xi)\,d\xi - \beta \int_{t-h_1}^{t} \dot{\mathbf{q}}_{\mathbf{m}}^T(\xi)\dot{\mathbf{q}}_{\mathbf{m}}(\xi)\,d\xi
\end{aligned}
$$

$$
\dot{V}_3 = 2k_s\left(\dot{\mathbf{q}}_{\mathbf{m}} - \dot{\mathbf{q}}_{\mathbf{s}}\right)^T\left(\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}}\right) \tag{13}
$$

Taking into account (6) and (7), and considering the relation established previously between $\boldsymbol{\varepsilon}$ and β, $\dot{V}_1$ can be expressed as,

$$
\begin{aligned}
\dot{V}_1 =\ & \\
& 2\dot{\mathbf{q}}_{\mathbf{m}}^T\left(-k_s\left(\mathbf{q}_{\mathbf{m}}(t-h_1-h_2) - \mathbf{q}_{\mathbf{s}}(t-h_2)\right) - k_s\Delta_{\mathrm{c}}(t-h_2) - \alpha_m\dot{\mathbf{q}}_{\mathbf{m}}\right) \\
& + 2\dot{\mathbf{q}}_{\mathbf{s}}^T\left(k_s\left(\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}} - \boldsymbol{\varepsilon}\right) - \alpha_s\dot{\mathbf{q}}_{\mathbf{s}}\right) \\
=\ & -2\alpha_m\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} - 2k_s\dot{\mathbf{q}}_{\mathbf{m}}^T\left(\mathbf{q}_{\mathbf{m}}(t-h_2) - \mathbf{q}_{\mathbf{s}}(t-h_2) - \boldsymbol{\varepsilon}(t-h_2)\right) \\
& + 2\dot{\mathbf{q}}_{\mathbf{s}}^T\left(k_s\left(\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}} - \boldsymbol{\varepsilon}\right) - \alpha_s\dot{\mathbf{q}}_{\mathbf{s}}\right) \\
=\ & -2\alpha_m\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} \\
& - 2k_s\dot{\mathbf{q}}_{\mathbf{m}}^T\left(\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}} - \mathbf{q}_{\mathbf{m}} + \mathbf{q}_{\mathbf{s}} + \mathbf{q}_{\mathbf{m}}(t-h_2) - \mathbf{q}_{\mathbf{s}}(t-h_2) - \boldsymbol{\varepsilon}(t-h_2)\right) \\
& - 2\alpha_s\dot{\mathbf{q}}_s^T\dot{\mathbf{q}}_s + 2\dot{\mathbf{q}}_{\mathbf{s}}^T\left(k_s\left(\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}} - ''\right)\right) \\
\leqslant\ & -2\alpha_m\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} - 2k_s\dot{\mathbf{q}}_{\mathbf{m}}^T\left(\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}}\right) \\
& + 2k_s\beta\left|\dot{\mathbf{q}}_{\mathbf{m}}^T\right|\left|\int_{t-h_2-h_1}^{t-h_2} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi\right| + 2k_s\dot{\mathbf{q}}_{\mathbf{m}}^T\int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi \\
& - 2k_s\dot{\mathbf{q}}_{\mathbf{m}}^T\int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{s}}(\xi)d\xi - 2\alpha_s\dot{\mathbf{q}}_{\mathbf{s}}^T\dot{\mathbf{q}}_{\mathbf{s}} + 2k_s\dot{\mathbf{q}}_{\mathbf{s}}^T\left(\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}}\right) \\
& + 2k_s\beta\left|\dot{\mathbf{q}}_{\mathbf{s}}^T\right|\left|\int_{t-h_1}^{t} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi\right|
\end{aligned} \tag{14}
$$

In order to deal with the integrals of (14), Lemma 1 is used to obtain the following inequalities taking terms from (12) and (14):

$$
\begin{aligned}
2k_s\dot{\mathbf{q}}_{\mathbf{m}}^T \int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi - \int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)^T\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi &\leqslant \bar{h}_2 k_s^2 \dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} \\
-2k_s\dot{\mathbf{q}}_{\mathbf{m}}^T \int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{s}}(\xi)d\xi - \int_{t-h_2}^{t} \dot{\mathbf{q}}_{\mathbf{s}}(\xi)^T\dot{\mathbf{q}}_{\mathbf{s}}(\xi)d\xi &\leqslant \bar{h}_2 k_s^2 \dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} \\
2k_s\beta\left|\dot{\mathbf{q}}_{\mathbf{s}}^T\right|\left|\int_{t-h_1}^{t} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi\right| - \beta\int_{t-h_1}^{t} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)^T\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi &\leqslant \beta\bar{h}_1 k_s^2 \dot{\mathbf{q}}_{\mathbf{s}}^T\dot{\mathbf{q}}_{\mathbf{s}} \\
2k_s\beta\left|\dot{\mathbf{q}}_{\mathbf{m}}^T\right|\left|\int_{t-h_2-h_1}^{t-h_2} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi\right| - \beta\int_{t-h_2-h_1}^{t-h_2} \dot{\mathbf{q}}_{\mathbf{m}}(\xi)^T\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi &\leqslant \beta\bar{h}_1 k_s^2 \dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}}
\end{aligned}
\tag{15}
$$

Next, joining (12), (13) and (14) considering (15), $\dot{V}$ can be constructed as follows:

$$
\begin{aligned}
\dot{V} &= \dot{V}_1 + \dot{V}_2 + \dot{V}_3 \\
&\leqslant \left[-2\alpha_m + \left(1+2k_s^2\right)\bar{h}_2 + \beta\left(2\bar{h}_1 + \bar{h}_2 + k_s^2\bar{h}_1\right)\right]\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} \\
&\quad + \left[-2\alpha_s + \bar{h}_2 + \beta\bar{h}_1 k_s^2\right]\dot{\mathbf{q}}_{\mathbf{s}}^T\dot{\mathbf{q}}_{\mathbf{s}}
\end{aligned}
\tag{16}
$$

Now, if the damping coefficients α_m and α_s are sufficiently great such that (16) is semi-definite negative, then the delayed teleoperation system is stable ($\dot{V} \leqslant 0$). Therefore, the velocities $\dot{\mathbf{q}}_{\mathbf{m}}, \dot{\mathbf{q}}_{\mathbf{s}}$ and position error $\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}}$ are bounded. Now, it is important to analyze that happens if $\mathbf{f}_{\mathbf{h}}$ and $\mathbf{f}_{\mathbf{e}}$ are zero. In this situation, the Barbalat's lemma can be applied. Deriving (16), it is possible to appreciate that $\ddot{V}$ is bounded only if the signals $\ddot{\mathbf{q}}_{\mathbf{m}}, \ddot{\mathbf{q}}_{\mathbf{s}}$ are bounded. Now, from (2) and (3) and considering (4), (5), (6) and (7) as well as the properties 1 and 3, the following conservative expressions can be written:

$$
\begin{aligned}
\ddot{\mathbf{q}}_{\mathbf{m}} &\leqslant m_1^{-1}\left(-k_s\left(\mathbf{q}_{\mathbf{m}}(t-h_1-h_2) - \mathbf{q}_{\mathbf{s}}(t-h_2)\right) - k_s\Delta_{\mathrm{c}}(t-h_2) - \alpha_m\dot{\mathbf{q}}_{\mathbf{m}} + a_m\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}}\right) \\
&\leqslant m_1^{-1}k_s\left(\left|\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}}\right| + \alpha_m\left|\dot{\mathbf{q}}_{\mathbf{m}}\right| + a_m\dot{\mathbf{q}}_{\mathbf{m}}^T\dot{\mathbf{q}}_{\mathbf{m}} + \beta\left|\int_{t-h_2-h_1}^{t-h_2}\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi\right| + \beta\left|\int_{t-h_2}^{t}\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi\right|\right. \\
&\qquad\left. + \left|\int_{t-h_2}^{t}\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\right|\xi + \left|\int_{t-h_2}^{t}\dot{\mathbf{q}}_{\mathbf{s}}(\xi)d\xi\right|\right)
\end{aligned}
\tag{17}
$$

$$
\begin{aligned}
\ddot{\mathbf{q}}_{\mathbf{s}} &\leqslant m_3^{-1}\left(a_s\dot{\mathbf{q}}_s^T\dot{\mathbf{q}}_s + k_s\left(\mathbf{q}_{\mathbf{m}}(t-h_1) - \mathbf{q}_{\mathbf{s}} + \Delta_{\mathrm{c}}\right) - \alpha_s\dot{\mathbf{q}}_s\right) \\
&\leqslant m_3^{-1}\left(a_s\dot{\mathbf{q}}_s^T\dot{\mathbf{q}}_{\mathbf{s}} + a_s\left|\dot{\mathbf{q}}_s\right| + k_s\left|\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}}\right| + k_s\beta\left|\int_{t-h_1}^{t}\dot{\mathbf{q}}_{\mathbf{m}}(\xi)d\xi\right|\right)
\end{aligned}
\tag{18}
$$

Thus, because $\dot{\mathbf{q}}_{\mathbf{m}}, \dot{\mathbf{q}}_{\mathbf{s}}$ and $\mathbf{q}_{\mathbf{m}} - \mathbf{q}_{\mathbf{s}}$ are bounded, (18) and (19) also are bounded, causing $\dot{V} \to 0$ (16) as $t \to \infty$. Therefore, $\dot{\mathbf{q}}_{\mathbf{m}}$ and $\dot{\mathbf{q}}_{\mathbf{s}}$ tend to zero for this particular case ($\mathbf{f}_{\mathbf{h}}$ and $\mathbf{f}_{\mathbf{e}}$ null).

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Remark 3
The stability analysis gives a conservative condition (16) based on the worst-case criterion. In addition, to estimate $\bar{h}_1$ and $\bar{h}_2$ with exactitude is difficult, for example, when an Internet-based teleoperation is carried out. Thus, this analysis is taken in practice as a qualitative guide to set the damping while the compensation parameters were calibrated by trial and error. However, the last procedure is helped by the conceptual meaning of each parameter of the reaction model.

Remark 4
The robot teleoperation systems could include other time delays apart from the delay added by the communication channel, such as an actuator input delay [22]. In this case, predictors of the future state of master and slave should be added because the control schemes used for robots teleoperation generally must act depending on the current state immediately. On the other hand, the dynamics of the actuators can be included in the models (1) and (2), without modifying the analysis carried out in this section.

4. EXPERIMENTS

This section shows the experimental results obtained for delayed bilateral teleoperation of a manipulator robot with force reflection. The performance of two PD-like controllers (without and with compensation) is compared using two Novint Falcon devices (http://home.novint.com). They are linked via a local network as well as by mobile Internet, using the IP/UDP protocol.

It is important to remark that in the state-of-art of network-based control, generally, the delayed sampled-data systems can be represented mathematically as a delayed continuous-time system, where the maximum bound of the time delay depends on the time sampling, the channel induced delays, and the data packet dropouts [23]. In this type of system, the controller is driven-event. On the contrary, most of the bilateral teleoperation systems include controllers into the local site as well as the remote site. Thus, these controllers must be implemented in a clock-driven way, and therefore, some strategy is used to obtain the delayed signals in each sampling time, although these data arrive by the network in an asynchronous way. In practice, commonly, the packets received by the network are used to overwrite a memory buffer, which is read in each sampling time by the controller (like in this paper). However, there are other methods used to estimate the delayed signals in each sampling time, from the past values received by the network (for example, using a Kalman filter).

Now, in order to quantify the performance of the system, we measure the energies of the master and slave, the time to complete the task T_c, the maximum overshoot of force F_o, and the force in stationary state F_t. The mean results obtained for 10 experiments with a non-delayed teleoperation system are taken as our reference. They are compared with the one obtained using both controllers for different time delays (10 experiments for each pair formed by a controller-type and a delay-type).

Regarding the setting of parameters, the condition established in (16) represent a sufficient condition but not necessary for assuring stability. Under this context, the controller is calibrated in practice as follows: first, the proportional gain k_s is set to control the position in free-space; second, the compensation parameters k_{c_1} and k_{c_2} are established for trial and error but taking into account their conceptual meaning; and finally, the damping is increased gradually until an adequate performance is achieved.

4.1. Bilateral teleoperation of a manipulator robot

In this section, a simple experiment where a user touches an object and keeps a small force of contact (situation defined as stationary state for this task) is analyzed. Here, a PD-like controller is compared with the compensated PD-like controller (4) taking as reference for these experiments the performance of a non-delayed teleoperation system. All controllers are implemented with the same damping parameters and proportional gain k_s. They are set to $\alpha_m = 2$ N s cm^{-1}, $\alpha_s = 1$ N s cm^{-1} and $k_s = 2$ N cm^{-1}. In addition, the compensation (7) uses mean reaction times $h_v = 0.5$ s and

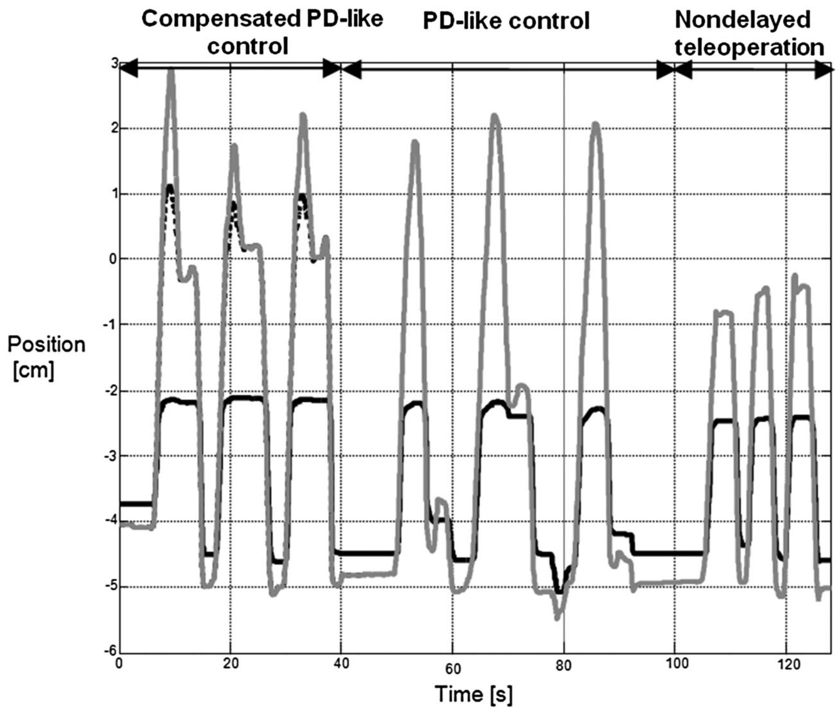

Figure 5. Position of the slave (black bold line), user's command (gray bold line) and compensated command (dotted line).

$k_t = 0.2$ s [24], and compensation gain $k_{c_1} = 0.0015$ cm N^{-1} and $k_{c_2} = 0.1$. On the other hand, the types of time delay tested are the following: (i) symmetric constant with $h_1 = h_2 = 1$, (ii) asymmetric constant with $h_1 = 1.3$ and $h_2 = 0.7$, (iii) asymmetric constant with $h_1 = 0.7$ and $h_2 = 1.3$, and (iv) asymmetric variable where h_1 and h_2 have sawtooth waveform but using different slopes, set to ± 0.2 and ± 0.1, respectively, and different maximum magnitudes set to 1 for h_1 and 1.5 for h_2. The experiment is such that the interaction between the slave and the object is mainly executed in one direction (only for simplicity). On the other hand, the motors of the device used have a dead zone about 1.5 N. Figure 5 shows the position of the master, slave and reference on the remote site for a type-I time delay, defined by $h_1 = 1\ s$ and $h_2 = 1\ s$ (constant and symmetric delay), by using both controllers, which are compared with a non-delayed teleoperation system ($h_1 = h_2 = 0$). The last figure shows three sequences of a simple task using each controller, for example, the compensated PD-like controller runs until about 45 s, the PD-like controller is tested between 45 and 100 s, while the case of null delay runs from 100 s onwards. It is possible appreciate that the scheme with compensation changes the reference produced by the user.

Figure 6 shows how the time-to-complete the task T_c, overshoot of force F_o, and force in stationary state F_t are computed for one experiment. The blue arrows describe the features of the non-delayed teleoperation, the green arrows show the features of the PD-like scheme, while the red arrows represent the features of the compensated PD-like scheme. The time-to-complete the task is defined as the elapsed time from that the slave begins its motion until a time instant where the force between the slave and the environment is kept about constant. This force is called here force in stationary state. Finally, the maximum overshoot of the slave force also is saved. The reference features obtained using a non-delayed teleoperation are the following: maximum force $\bar{F}_{o_{ref}} = 3.85$ N, force in stationary state $\bar{F}_{t_{ref}} = 3.8$ N, and time-to-complete the task $\bar{T}_{c_{ref}} = 3.5$ s. Table I shows the errors $e_{F_o} = \left|\bar{F}_o - \bar{F}_{o_{ref}}\right|$, $e_{F_t} = \left|\bar{F}_t - \bar{F}_{t_{ref}}\right|$ and $e_{F_o} = \left|\bar{T}_c - \bar{T}_{c_{ref}}\right|$ obtained from the experiments. The compensated PD-like controller has errors smaller than the other one for all the computed features. On the other hand, Table II shows the energy of the master and slave

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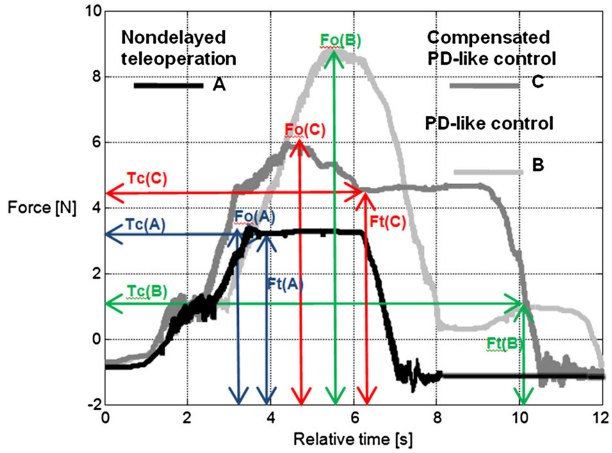

Figure 6. Overshoot of slave force, force in stationary state, and time-to-complete the task for a non-delayed teleoperation and the tested controllers.

Table I. Evaluation of metrics for both controllers.

Control	PD-like			Compensated PD-like		
Feature	e_{F_o}	e_{F_t}	e_{T_c}	e_{F_o}	e_{F_t}	e_{T_c}
Error	5.8 N	2 N	5.1 s	3 N	1.5 N	2.5 s

Table II. Energy of the master and slave.

Control energy	Non-delayed teleoperation	PD-like	Compensated PD-like
Energy of the master	3 N cm	6.6 N cm	6.6 N cm
Energy of the slave	2.4 N cm	3.4 N cm	3 N cm

in N cm. They are computed by the average value considering all experiments where the energy in each experiment is calculated from $\int_0^{T_c} \dot{\mathbf{q}}_\mathbf{m}^T \boldsymbol{\tau}_\mathbf{m} dt$ and $\int_0^{T_c} \dot{\mathbf{q}}_\mathbf{s}^T \boldsymbol{\tau}_\mathbf{s} dt$. The energy of the master for a delayed teleoperation system is greater than the energy used in a teleoperation system without time delay.

The proposed scheme removes more total energy than the non-compensated PD-like scheme, but it is important to remark again that the strategy does not remove necessarily energy when the robots are in motion such as the damping effect. Therefore, the proposed scheme needs to dissipate a lower kinetic energy through the damping.

4.2. *Bilateral teleoperation of a manipulator robot*

This section shows an experiment using mobile Internet of low baud-rate to link two Novint Falcon devices in front of high time delay, where different companies (Movistar and Personal) are employed for the connection of master and slave in a day and time of high traffic. The control parameters are set like those in Section 4.1.

Figure 7 shows the round-trip delay produced by mobile Internet during the experiment, which is greater than the mean value that typically there is between different countries by using an Internet

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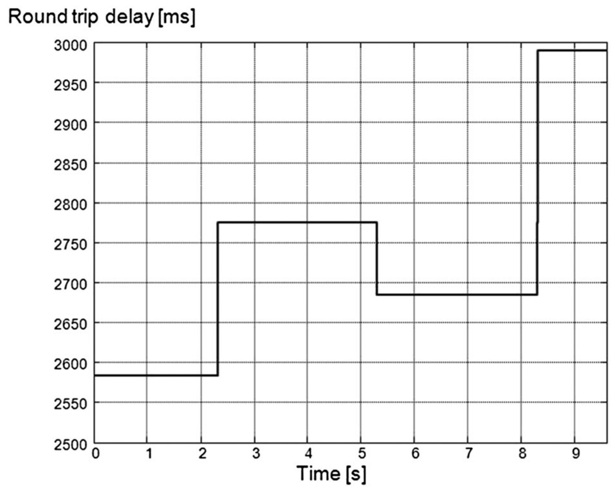

Figure 7. Time delay in milliseconds measured online.

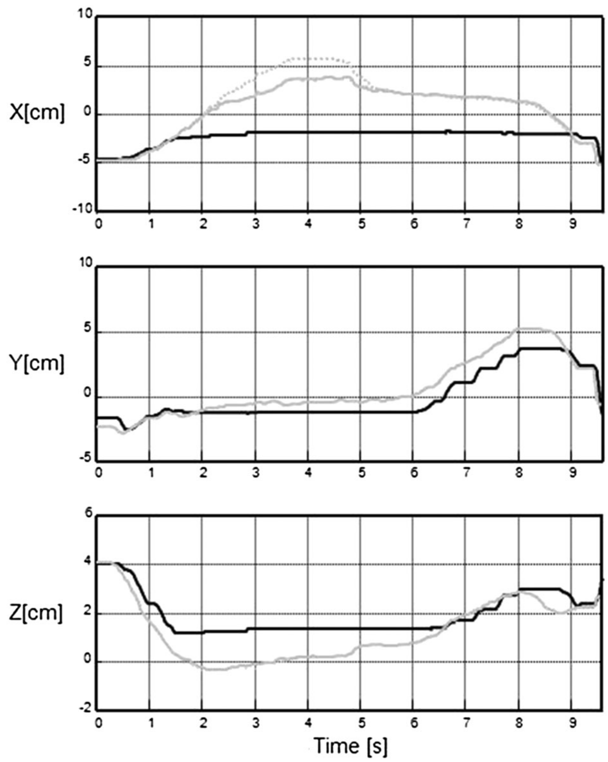

Figure 8. Position on the axes X, Y, and Z of the reference (gray dotted line), slave (black bold line) and compensated reference on the remote site (gray bold line).

connection of high-speed [25]. Such delay is computed from the average of measurements obtained in a time window of 3 s. Figure 8 shows the user's command measured on the remote site (position reference), the compensated user's command and the slave position for the axes X, Y, and Z.

Finally, Figure 9 shows the task in the three-dimensional space, where the user, helped by the proposed control scheme, can touch and feel the vertical contour of the remote object in spite of the time delay added by mobile Internet. The controller diminishes the potential energy of the reference generated by the user only during the time intervals where a difference Δ_c happens.

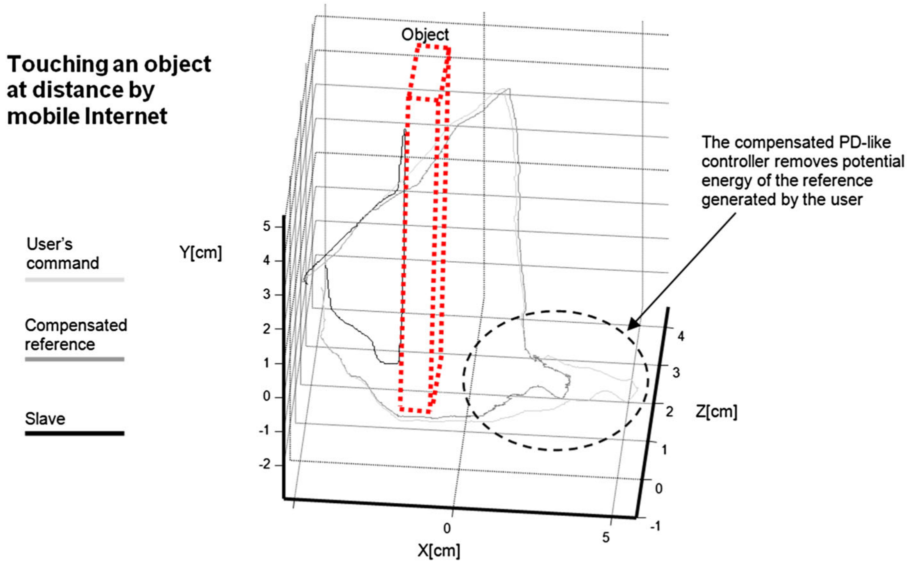

Figure 9. Three-dimensional Position of the user's command, slave and compensated reference, all measured on the remote site.

5. CONCLUSIONS

In this paper, a control scheme, applied to delayed bilateral teleoperation of a manipulator robot with force reflection the user, is proposed. The designed compensation changes the user's command taking into account a model of the user's reaction. In practice, the compensation strategy removes a greater potential energy of the user's command as the difference between the current robot–environment interaction, and the interaction really felt by the user is higher.

The analyzed features as well as the system energies were measured and compared for a PD-like scheme without and with the proposed compensation. The compensated PD-like controller has a behavior more similar to the one achieved by a non-delayed teleoeperation system. Thus, the results obtained indicate that the compensated PD-like controller has a better performance than the scheme without compensation.

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