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Transparent Bilateral Control for Time-Delayed Teleoperation by State Convergence

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Abstract— **This paper presents a new bilateral control scheme for time-delayed teleoperation designed to achieve transparency. The control scheme allows that the slave follows the master in spite of the time delay, ant that the force displayed to the operator was exactly the reaction force from the environment. In addition, the interaction force of the slave with the environment is adapted to the master/slave ratio when it is reflected to the operator, improving the transparency of the system. The bilateral control scheme can be used in contact situations or non-contact situations of the slave with the environment. Together with the control scheme, the paper describes an analytical design method that allows the obtaining of the control gains.**

I. INTRODUCTION

In a telerobotics system the slave is controlled to follow the motion of the master that is manipulated by the human operator. Habitually, the interaction force of the slave with the environment is reflected to the operator to improve the task performance. In this case, the teleoperator is bilaterally controlled [1]. The existence of time delays in the communication channel between the master and the slave can destabilize the bilateral teleoperation systems [2]. A lot of bilateral control systems have been proposed to overcome the time delay problem [3].

From a control point of view, the main goals of the bilateral control schemes are to maintain the stability of the closed-loop system, and to achieve the transparency of the system between the environment and the operator [4]. The teleoperation system is transparent if, ideally, the human feels as if he/she is directly performing the task in the remote environment [5]. Or alternatively, the system is transparent if the master and slave positions are equal, and the force displayed to the human is exactly the reaction force from the environment [6]. In order to design the bilateral control schemes, a tradeoff between stability and transparency must be achieved.

In [7] a design and bilateral control method of teleoperation systems with constant time delay was presented. The design method allows that the slave follows the master in spite of the time delay, and to establish the dynamics of the teleoperation system. However, the transparency of the teleoperation system is drastically reduced in order to assure the stability with time delay. This paper describes a new bilateral control scheme, based in the previous control scheme, that achieves the transparency and improves the performance of the teleoperation system.

The paper is organized as follows. Section 2 explains the limitations of the previous bilateral control scheme by state convergence that have motivated the development of the new control scheme. In Section 3, the new transparent bilateral control method of telerobotics with time delay is described. Section 4 shows some simulation results to verify the performance of the new control scheme. Finally, Section 5 summarizes the key features of this control scheme.

II. MOTIVATION

In [7] a bilateral control scheme of teleoperation systems by state convergence was presented. Fig. 1 shows the modelling on the state space of this control scheme, where F_m is the operator force, and Delay represents a constant time delay of T seconds.

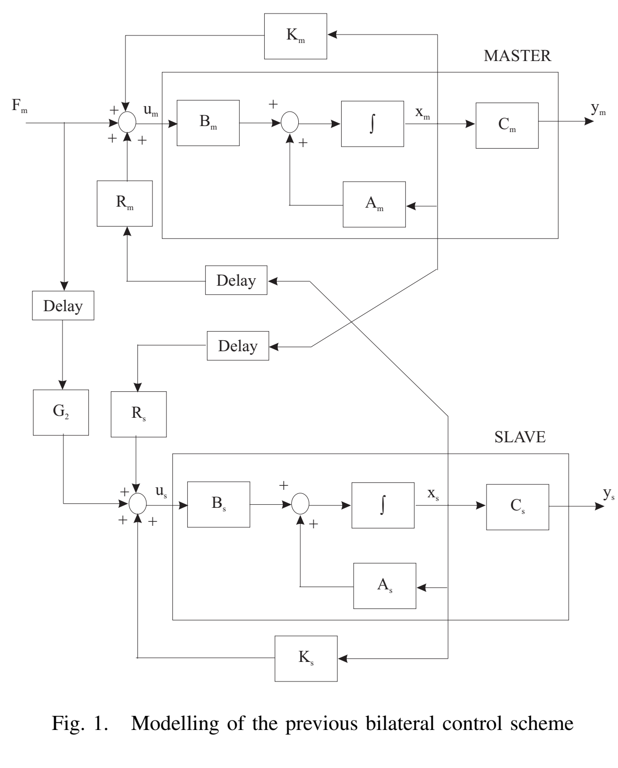

Fig. 1. Modelling of the previous bilateral control scheme

A teleoperation system of one dof was considered to explain the design and control method. The simplified linear model of an element with one dof is:

$$J\ddot{\theta}(t) + b\dot{\theta}(t) = u(t) \tag{1}$$

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where J is the inertia of the element, $\theta(t)$ is the rotate angle, b is the viscous friction coefficient, and $u(t)$ is the control torque applied. The representation on the state space of the master and the slave is obtained considering as state variables the position ($x_1(t) = \theta(t)$) and the velocity ($x_2(t) = \dot{\theta}(t)$).

The environment was modelled through a stiffness k_e and a viscous friction b_e. In this way the reaction force of the slave with the environment is given by:

$$f_s(t) = k_e \theta_s(t) + b_e \dot{\theta}_s(t) \tag{2}$$

The structure of the matrix K_s to incorporate the interaction of the slave with the environment in the modelling is:

$$K_s = \left[\begin{array}{cc} k'_{s1} - k_e & k'_{s2} - b_e \end{array}\right] \tag{3}$$

And the structure of the matrix R_m to consider force feedback from the slave to the master is:

$$R_m = \left[\begin{array}{cc} r_{m1} & r_{m2} \end{array}\right] = \left[\begin{array}{cc} k_f k_e & k_f b_e \end{array}\right] \tag{4}$$

where k_f is the force feedback gain.

K_m, K_s, R_s, and $G_2 = g_2$ are the control gains. The design method to obtain these control gains is based on the state convergence between the master and slave states.

This control method has some important advantages: the slave follows the master in spite of the time delay, and it is able also to establish the desired dynamics of this convergence and the dynamics of the slave manipulator. However this control scheme has the next limitations:

- From the control scheme shown in Fig. 1, the master control signal is:

$$\begin{aligned} u_m(t) &= K_m x_m(t) + R_m x_s(t-T) + F_m(t) \\ &= K_m x_m(t) + k_f f_s(t-T) + F_m(t) \end{aligned} \tag{5}$$

  Therefore, the force displayed to the human is not exactly the reaction force from the environment $f_s(t-T)$, but it is affected by the master state feedback $K_m x_m(t)$. So, the transparency is not achieved in the bilateral control scheme by state convergence.
- Considering that the operator exerts the same force, the final position of the slave does not depend on the environment, but it depends on the desired dynamics of the slave [8].
- The control scheme by state convergence can be only applied to contact situations of the slave with the environment.
- Finally, it would be suitable that the reaction force of the slave displayed to the human was adapted (amplified or reduced) to the master/slave ratio.

III. TRANSPARENT BILATERAL CONTROL SCHEME WITH TIME DELAY

This section presents the new bilateral control scheme for telerobotics with time delay. This control scheme solves the limitations described in the last section.

A. Modelling of the Teleoperation System

The next changes have been made in the modelling of the teleoperation system shown in Fig. 1:

- The control by state feedback in the master has been removed, i.e. the matrix K_m has been eliminated.
- The force feedback gain (k_f) has been removed from the matrix R_m:

$$R_m = \left[\begin{array}{cc} r_{m1} & r_{m2} \end{array}\right] = \left[\begin{array}{cc} k_e & b_e \end{array}\right] \tag{6}$$

- A new control gain $G_1 = g_1$ has been inserted in the control scheme. This gain adapts the reaction force of the slave to the master/slave ratio.

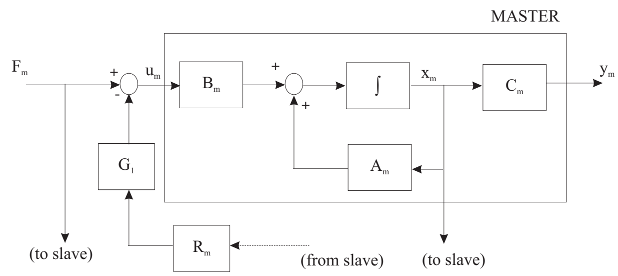

Fig. 2. Modelling of the master side in the new bilateral control scheme

Fig. 2 shows the changes in the master side of new control scheme. The slave side has not changed. The elimination of K_m in the master improves the transparency of the system, because the force displayed to the human is exactly the interaction force of the slave with the environment. In addition, the final position of the master (and the slave) is not independent of the environment, but depends on the environment. If the slave does not contact with the environment, the master (and the slave) will have free motion, and the final position of the master and slave will not reach a established constant value.

The master and the slave system are represented on the state space like:

$$\begin{aligned} \dot{x}_m(t) &= A_m x_m(t) + B_m u_m(t) \\ y_m(t) &= C_m x_m(t) \end{aligned} \tag{7}$$

$$\begin{aligned} \dot{x}_s(t) &= A_s x_s(t) + B_s u_s(t) \\ y_s(t) &= C_s x_s(t) \end{aligned} \tag{8}$$

Considering one dof, the representation in the state space of the master is:

$$\left[\begin{array}{c} \dot{x}_{m1}(t) \\ \dot{x}_{m2}(t) \end{array}\right] = \left[\begin{array}{cc} 0 & 1 \\ 0 & -\frac{b_m}{J_m} \end{array}\right] \left[\begin{array}{c} x_{m1}(t) \\ x_{m2}(t) \end{array}\right] + \left[\begin{array}{c} 0 \\ \frac{1}{J_m} \end{array}\right] u_m(t) \tag{9}$$

$$y_m(t) = \left[\begin{array}{cc} 1 & 0 \end{array}\right] \left[\begin{array}{c} x_{m1}(t) \\ x_{m2}(t) \end{array}\right] \tag{10}$$

and the slave is represented in a similar way.

In the new control scheme, the master control signal, $u_m(t)$, and the slave control signal, $u_s(t)$, are respectively:

$$u_m(t) = F_m(t) - g_1 R_m x_s(t-T) \tag{11}$$

$$u_s(t) = K_s x_s(t) + R_s x_m(t-T) + g_2 F_m(t-T) \tag{12}$$

If the master and slave control signal in the master state equation (7) and in the slave state equation (8) are replaced respectively by the expressions (11) and (12), next state equations are obtained:

$$\dot{x}_m(t) = A_m x_m(t) - g_1 B_m R_m x_s(t-T) + B_m F_m(t) \tag{13}$$

$$\begin{aligned}\dot{x}_s(t) &= (A_s + B_s K_s) x_s(t) + B_s R_s x_m(t-T) + \\ &\quad + g_2 B_s F_m(t-T)\end{aligned} \tag{14}$$

Using the Taylor expansion of first order to approximate the time delayed signals in (13) and (14), and considering a constant operator force, the next state equations are obtained:

$$\begin{aligned}\dot{x}_m(t) &= A_m x_m(t) - g_1 B_m R_m x_s(t) \\ &\quad + T g_1 B_m R_m \dot{x}_s(t) + B_m F_m(t)\end{aligned} \tag{15}$$

$$\begin{aligned}\dot{x}_s(t) &= (A_s + B_s K_s) x_s(t) + B_s R_s x_m(t) \\ &\quad - T B_s R_s \dot{x}_m(t) + g_2 B_s F_m(t)\end{aligned} \tag{16}$$

Merging (15) and (16), the next state equation is obtained:

$$\begin{bmatrix} \dot{x}_s(t) \\ \dot{x}_m(t) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_s(t) \\ x_m(t) \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} F_m(t) \tag{17}$$

where

$$A_{11} = S(A_s + B_s K_s + T g_1 B_s R_s B_m R_m) \tag{18}$$
$$A_{12} = S(B_s R_s - T B_s R_s A_m) \tag{19}$$
$$A_{21} = M(T g_1 B_m R_m (A_s + B_s K_s) - g_1 B_m R_m) \tag{20}$$
$$A_{22} = M(A_m + T g_1 B_m R_m B_s R_s) \tag{21}$$
$$B_1 = S(g_2 B_s - T B_s R_s B_m) \tag{22}$$
$$B_2 = M(B_m + T g_1 g_2 B_m R_m B_s) \tag{23}$$
$$M = (I + T^2 g_1 B_m R_m B_s R_s)^{-1} \tag{24}$$
$$S = (I + T^2 g_1 B_s R_s B_m R_m)^{-1} \tag{25}$$

B. Design Methodology by State Convergence

There are six control gains in the new bilateral control scheme: $K_s = \begin{bmatrix} k_{s1} & k_{s2} \end{bmatrix}$, $R_s = \begin{bmatrix} r_{s1} & r_{s2} \end{bmatrix}$, $G_1 = g_1$ and $G_2 = g_2$. To calculate these control gains, six design equations must be obtained. In order to get these design equations, the state convergence methodology is going to be applied [7].

If the next linear transformation is applied to (17):

$$\begin{bmatrix} x_s(t) \\ x_s(t) - x_m(t) \end{bmatrix} = \begin{bmatrix} I & 0 \\ I & -I \end{bmatrix} \begin{bmatrix} x_s(t) \\ x_m(t) \end{bmatrix} \tag{26}$$

the next state equation is obtained:

$$\dot{\tilde{x}}(t) = \begin{bmatrix} \tilde{A}_{11} & \tilde{A}_{12} \\ \tilde{A}_{21} & \tilde{A}_{22} \end{bmatrix} \tilde{x}(t) + \begin{bmatrix} \tilde{B}_1 \\ \tilde{B}_2 \end{bmatrix} F_m(t) \tag{27}$$

where

$$\tilde{x}(t) = \begin{bmatrix} x_s(t) \\ x_s(t) - x_m(t) \end{bmatrix} \tag{28}$$
$$\tilde{A}_{11} = A_{11} + A_{12} \tag{29}$$
$$\tilde{A}_{12} = -A_{12} \tag{30}$$
$$\tilde{A}_{21} = (A_{11} - A_{21}) + (A_{12} - A_{22}) \tag{31}$$
$$\tilde{A}_{22} = -(A_{12} - A_{22}) \tag{32}$$
$$\tilde{B}_1 = B_1 \tag{33}$$
$$\tilde{B}_2 = B_1 - B_2 \tag{34}$$

Let $x_e(t)$ be the error between the slave and the master, $x_e(t) = x_s(t) - x_m(t)$, the error state equation between the slave and the master will be:

$$\dot{x}_e(t) = \tilde{A}_{21} x_s(t) + \tilde{A}_{22} x_e(t) + \tilde{B}_2 F_m(t) \tag{35}$$

If the error evolves as an autonomous system, the slave-master error can be eliminated, and the slave will follow the master. To achieve that the error evolves as an autonomous system, the next equations must be verified:

$$\tilde{B}_2 = B_1 - B_2 = 0 \tag{36}$$

$$\tilde{A}_{21} = A_{11} - A_{21} + A_{12} - A_{22} = 0 \tag{37}$$

From (36) the next design equation is obtained:

$$-J_m g_2 + T r_{s2} + J_s + T g_1 g_2 r_{m2} = 0 \tag{38}$$

Operating in (37) the next design equations are obtained:

$$\begin{aligned}&-J_m k_{s1} - T g_1 r_{m1} r_{s2} + T g_1 r_{m2} k_{s1} - \\ &\quad g_1 r_{m1} J_s - J_m r_{s1} + T g_1 r_{m2} r_{s1} = 0\end{aligned} \tag{39}$$

$$\begin{aligned}&-T^2 g_1 r_{s2} r_{m1} - J_m b_s + k_{s2} J_m - g_1 J_s T r_{m1} \\ &+ g_1 T r_{m2} b_s - g_1 T r_{m2} k_{s2} + g_1 r_{m2} J_s + r_{s2} J_m \\ &- T J_m r_{s1} + T r_{s2} b_m + T^2 g_1 r_{m2} r_{s1} + J_s b_m = 0\end{aligned} \tag{40}$$

Therefore satisfying the equations (38) – (40) the error will evolve as an autonomous system. In this case, the dynamics of the system will be given by the next characteristic polynomial:

$$\det(sI - (A_{11} + A_{12})) \det(sI - (A_{22} - A_{12})) = 0 \tag{41}$$

where the first determinant defines the slave dynamics, and the second establishes the error dynamics. The poles of the error dynamics must be placed in the left part of the s plane to eliminate the error between the slave and the master, and the poles of the slave must be also placed in the left part of the s plane to assure the system stability.

Operating in (41), the following equations must be verified if it is wished that the characteristic polynomial of the slave and the error would be, respectively, $p(s) = s^2 + p_1 s + p_0$ and $q(s) = s^2 + q_1 s + q_0$:

$$\frac{J_m k_{s1} + T g_1 r_{m1} r_{s2} + J_m r_{s1}}{J_s J_m + T^2 g_1 r_{s2} r_{m2}} = -p_0 \tag{42}$$

$$T^2 g_1 r_{s2} r_{m1} + J_m b_s - k_{s2} J_m - T g_1 r_{m2} r_{s2} \\ - J_m r_{s2} + T J_m r_{s1} - T r_{s2} b_m = \\ p_1 (J_s J_m + T^2 g_1 r_{s2} r_{m2}) \quad (43)$$

$$\frac{r_{s1}(-J_m + T g_1 r_{m2})}{J_s J_m + T^2 g_1 r_{s2} r_{m2}} = -q_0 \quad (44)$$

$$T^2 g_1 r_{m2} r_{s1} + J_s b_m - T g_1 r_{m2} r_{s2} + J_m r_{s2} \\ - T J_m r_{s1} + T r_{s2} b_m = q_1 (J_s J_m + T^2 g_1 r_{s2} r_{m2}) \quad (45)$$

Seven design equations have been obtained, equations (38) – (40) and equations (42) – (45), and there are six control gains (g_1, g_2, R_s and K_s). Therefore, the dynamics of the slave and the error can not be completely established. Since g_1 must adapt the reaction force displayed to the human to the master/slave ratio, it is calculated in this way:

$$g_1 = \frac{J_m}{J_s} \quad (46)$$

As g_1 has been calculated, there are seven design equations that must be solved in order to calculate the five control gains (g_2, R_s and K_s). Therefore, five design equations can only be considered. Since equations (38) – (40) must be always satisfied to achieve the evolution of the error as an autonomous system, only the dynamics of the slave or the error can be established. Both dynamics can not be fixed. It has been verified that the control gains can be only calculated fixing the error dynamics. In this case the design equations are (38) – (40), (44) and (45). Solving these equations, the next control gains are obtained:

$$\begin{aligned} g_2 &= \alpha(1 + q_1 T + q_0 T^2) J_s & (47) \\ r_{s1} &= \alpha J_s q_0 (T b_m + J_m) & (48) \\ r_{s2} &= \alpha(J_s J_m (q_1 + q_0 T) - b_m J_s) & (49) \\ k_{s1} &= -\alpha J_s (g_1 r_{m1} (1 + q_1 T + q_0 T^2) \\ &\quad + q_0 (J_m + T b_m)) & (50) \\ k_{s2} &= -\alpha(g_1 r_{m2} (J_s + T(b_s + J_s q_1) + T^2 (b_s q_1 + J_s q_0) \\ &\quad + b_s T^3 q_0) - T J_s g_1 r_{m1} (1 + q_1 T + q_0 T^2) \\ &\quad + (J_m + T b_m)(q_1 J_s - b_s)) & (51) \end{aligned}$$

where

$$\alpha = \frac{1}{J_m + T b_m - T g_1 r_{m2} (1 + q_1 T + q_0 T^2)} \quad (52)$$

C. Remarks

The control gains can be only calculated if the following restriction is verified, see (52):

$$J_m + T b_m - T g_1 r_{m2} (1 + q_1 T + q_0 T^2) \neq 0 \quad (53)$$

However, since q_0 and q_1 are selected to fix the error dynamics, they can be selected in order to verify this restriction.

In addition, to calculate the matrix (24) and (25), and to obtain the control gains, the next restriction must be also verified:

$$J_s \neq T b_e \quad (54)$$

If $J_s = T b_e$ the design method can not be used. In this case there are two options:

- To use a time delay T for the design method slightly different to the real time delay.
- To use a viscous friction b_e of the environment for the design method slightly different to the identified viscous friction. If the environment is only modelled using the stiffness k_e, i.e. $b_e = 0$, the restriction is always verified.

In order to apply the design method modifying one of the design parameters, the robustness of the control method against variations in these parameters must be previously verified [8].

On the other hand, since the slave dynamics can not be established, the stability of the slave dynamics must be analyzed. The dynamics of the slave is given by the next characteristic polynomial, see (42) and (43):

$$p(s) = s^2 + \frac{g_1 r_{m2} + b_m - T g_1 r_{m1}}{J_m - T g_1 r_{m2}} s + \frac{r_{m1} g_1}{J_m - T g_1 r_{m2}} \quad (55)$$

The slave dynamics will be stable if the next conditions are verified:

$$J_m > T \tfrac{J_m}{J_s} b_e \quad (56)$$

$$\tfrac{J_m}{J_s}(b_e - T k_e) + b_m > 0 \quad (57)$$

From these conditions, the next comments are obtained:

- The increment of the environment stiffness k_e and viscous friction b_e, and the increment of the time delay T affects negatively to the system stability.
- If the slave is bigger than the master ($J_m < J_s$), the system will be stable for longer time delay and more stiff environments, than if the master is bigger that the slave ($J_m > J_s$).

The error dynamics and the slave dynamics, i.e. the dynamics of the teleoperation system, have been obtained and analyzed considering the state equation of the teleoperation system with the time delay approximation (17). However, the stability of the teleoperation system must be analyzed considering the state equation of the teleoperation system without the time delay approximation:

$$\begin{bmatrix} \dot{x}_s(t) \\ \dot{x}_m(t) \end{bmatrix} = \begin{bmatrix} A_s + B_s K_s & 0 \\ 0 & A_m \end{bmatrix} \begin{bmatrix} x_s(t) \\ x_m(t) \end{bmatrix} + \\ \begin{bmatrix} 0 & B_s R_s \\ -g_1 B_m R_m & 0 \end{bmatrix} \begin{bmatrix} x_s(t-T) \\ x_m(t-T) \end{bmatrix} + \\ \begin{bmatrix} 0 \\ B_m \end{bmatrix} F_m(t) + \begin{bmatrix} g_2 B_s \\ 0 \end{bmatrix} F_m(t-T) \quad (58)$$

The asymptotic stability of the teleoperation system has been analyzed using the criteria based in the frequency domain proposed by Su, Fong, and Tseng [9]. These criteria allow the testing of the asymptotic stability of a system with time delay represented on the state space. They determine if the system is asymptotically stable independently of time delay and, if is not possible to assure the stability independently of time delay, they establish the maximum delay which guarantees the asymptotic stability. In the next section, the stability of the teleoperation systems considered has been analyzed using these criteria.

IV. SIMULATION RESULTS

This section shows the simulation results obtained using the new bilateral control scheme. A teleoperation system where the slave is bigger than the master is considered. The next parameters have been considered:

$$J_m = 1kgm^2 \quad b_m = 2\frac{Nm}{rad/s}$$
$$J_s = 10kgm^2 \quad b_s = 60\frac{Nm}{rad/s}$$

In all cases, the force exerted by the operator over the master has been simulated as a constant step of 1 Nm.

First it is considered that the slave interacts with a hard environment ($k_e = 100Nm/rad$ and $b_e = 0\frac{Nm}{rad/s}$). If there is a time delay of 0.1s and the error poles are placed in the position -11 of the s plane, the system is asymptotically stable for time delays smaller than 0.004245s. As the error poles are placed nearer to the origin, the system is stable for bigger time delays. For example, if the error poles are placed in the position -1 of the s plane, the system is stable for time delays smaller than 0.0849823s. However, the teleoperation system can not be designed satisfying the stability and transparency considering a time delay of 0.1s.

If a time delay T=0.01s is considered, and the error poles are placed in the position -1 of the s plane, the system designed is stable for time delays smaller than 0.08s, and the slave poles are stablished in the position $-0.95 \pm 3.0162i$. Fig. 3 shows the master and slave evolution. It can be verified that the slave position and velocity follow without error the master position and velocity, respectively, in spite of the time delay. Fig. 4 shows the master and slave control signals (top part), and the operator force and the reaction force displayed to the human (bottom part). The reaction force displayed to the operator is adapted to the master/slave ratio. This reaction force opposes to the operator force. When the reaction force displayed to the human is equal to the operator force, the master and the slave stop in the same final position.

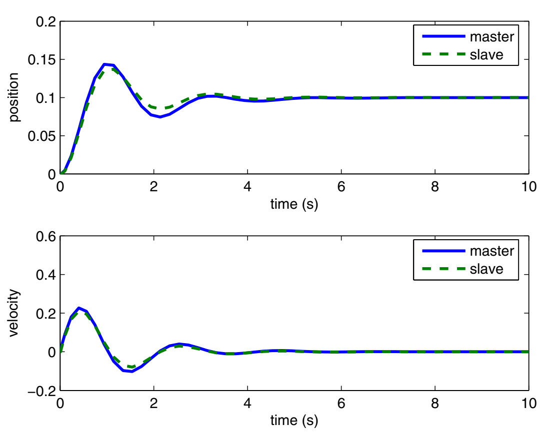

Fig. 3. Position and velocity of the master and slave considering a hard environment

Top part of Fig. 5 shows the master and slave position considering that the slave interacts with a soft environment

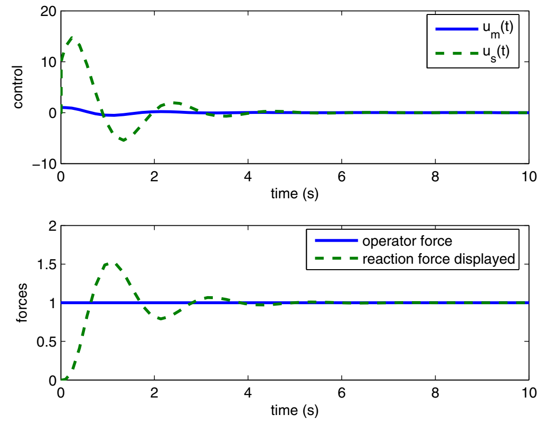

Fig. 4. Master and slave control signals (top part), and operator force and reaction force displayed to the operator (bottom part) considering a hard environment

($k_e = 10Nm/rad$ and $b_e = 0\frac{Nm}{rad/s}$), there is a time delay of T=0.1s, and the error poles are placed in the position -1 of the s plane. The system is stable for time delays smaller than 0.35s, and the error poles are established in the position $-0.95 \pm 0.312249i$. As in the previous case the slave position follow without error the master position in spite of the time delay. However, comparing with Fig. 3, as the environment stiffness decreases, the final position of the slave (and the master) increases because the opposition to the slave advance is lesser. On the other hand, as the environment stiffness decreases, the system is stable for bigger time delays . The bottom part of Fig. 5 shows the master and slave position when the slave does not interact with any environment (free motion), there is a time delay of 0.5s, and the slave poles are placed in the position -11 of the s plane. In this case the slave follows the master and they do not stop in a constant position because there is not any opposition to the slave motion. Therefore the control scheme can be used in contact and non-contact situations of the slave with the environment.

The new control scheme has been compared with the previous control scheme by state convergence shown in Fig. 1. It has been assumed that $k_f = 0.1$, and the slave and error poles are placed in the location -11 of the s plane. Fig. 6 shows the simulation results when the slave interacts with the hard environment and there is a time delay of 0.01s. The slave follows the master, however, the final position of the slave and the master does not depend on the environment, but it depends on the desired dynamics of the slave. If a different environment or free motion of the slave is considered, similar results are obtained. On the other hand, the force displayed to the operator is not only the weighted reaction force, but it is the weighted reaction force plus the master state feedback. Therefore the teleoperation system is not transparent. Both problems have been solved with the new bilateral control scheme.

Finally, some simulation results have been obtained con-

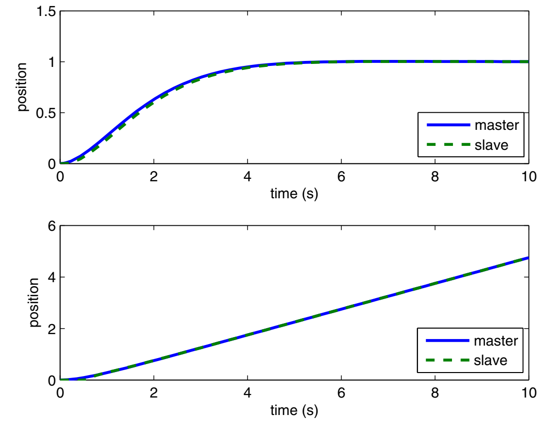

Fig. 5. Master and slave position considering a soft environment (top part), and free motion (bottom part)

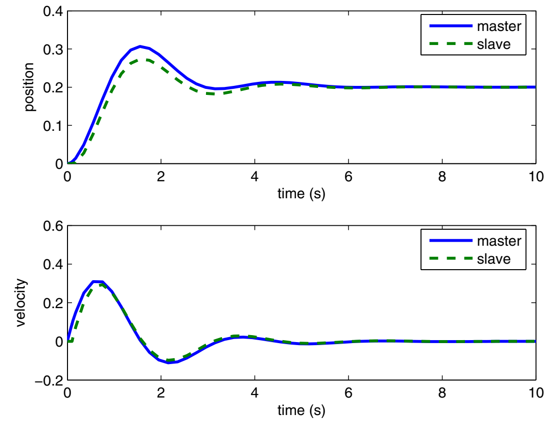

Fig. 7. Position and velocity of the master and slave

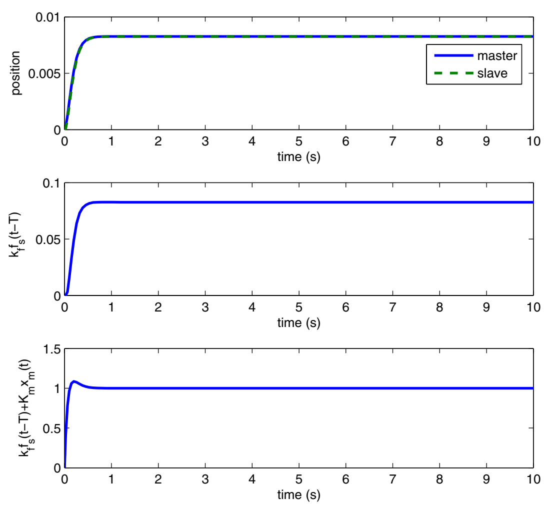

Fig. 6. Master and slave position (top part), reaction force weighted by k_f (central part), and force displayed to the human (bottom part) in the previous scheme by state convergence

sidering that the master is bigger than the slave, the slave interacts with a very soft environment ($k_e = 0.5Nm/rad$), e.g. in a telesurgical system, and there is a time delay of 0.1s. The next parameters have been considered:

$$J_m = 1kgm^2 \qquad b_m = 2\frac{Nm}{rad/s}$$
$$J_s = 0.1kgm^2 \quad b_s = 0.06\frac{Nm}{rad/s}$$

To design the control system, the error poles have been placed in the position -1 of the s plane. Fig. 7 shows the master and slave evolution. In spite of the fact that the reaction force is amplified by $g_1 = 10$ when it is displayed to the human, the slave follows the master without any error, and the system is stable.

V. CONCLUSIONS AND FUTURE WORKS

A new transparent bilateral control scheme by state convergence for telerobotics with time delay has been presented. The characteristics of this control scheme are the next:

- The slave follows the master in spite of the time delay. In addition, the error dynamics is established.
- The system is transparent because the force displayed to the human is the reaction force of the slave with the environment.
- The reaction force displayed to the operator is adapted according to the master/slave ratio, improving the transparency of the system.

Compare to the previous control scheme, the new scheme is stable for shorter time delays, but assures the transparency.

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