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Bilateral Controller Design based on Transparency in the State Convergence Framework

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Abstract— **This paper describes a new methodology for designing bilateral controllers based on transparency that applies a modified scheme of control by state of convergence. The design is based on modelling the behavior of the master and slave which regard state space equations, and also taking into account that perfect transparency cannot be reached. This methodology allows designing the controllers in order to obtain the convergence between the state of the master and the slave. Furthermore, it consequently provides a higher degree of transparency to the operator. The paper explains criteria in achieving convergence between the master and the slave, and so as with transparency on a steady state. A set of equations that calculate controller gains have been obtained by applying such criteria. In order to verify this new methodology, a master-slave system of 3 DoF have been used.**

I. INTRODUCTION

The main goal of bilateral controllers is to link the behavior of two devices, usually called master and slave, so that the master guides the slave and reproduces its haptic interactions [1], [2], [3]. The slave represents a robot that executes the remote task such as manipulation or movement. The master is handled by a user in order to control the slave in the remote environment. Master-slave interaction is carried out by exchanging movements and forces. Therefore, the corresponding controllers have to be designed in order to guarantee stability and transparency for the bilateral systems [4]. The classic control theory approach is very suitable for simple controllers such as position-position or force-position when communication time delays can be disregarded [5]. More complex techniques must be applied when communication time delay is significant. In these cases, the passivity theory and wave variables approach are usually applied [6], [7], [8], [9]. These techniques are based on the concepts of storing and dissipating power.

The state convergence methodology represents an alternative approach for designing bilateral controllers. It was firstly introduced in [10] and [11]. This methodology is based on modelling the master and slave devices according to their space state equations. The design equations of the controllers are obtained in order to assure the convergence between the master and the slave, and to establish the dynamics of the teleoperation system. However, the transparency conditions are not considered in this design method. Therefore, the transparency of the teleoperation system is drastically reduced when this methodology is applied.

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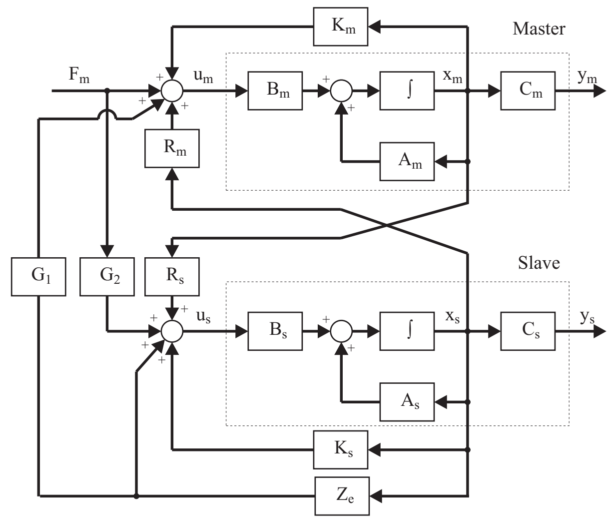

Fig. 1. Modified bilateral control scheme by state convergence

This paper is focused on imposing transparency conditions in the state convergence methodology in order to design a bilateral control system where the slave follows the master and a high degree of transparency is achieved. Considering the state convergence and transparency conditions, a set of design equations to calculate the control gains are obtained. The paper is organized as follows. Section II shows the conditions required for complying the state convergence between the master and slave. Section III describes the conditions to achieve the transparency on steady state. The experimental results obtained when a teleoperation system of 1 DoF has been controlled using this new methodology are shown in Section IV. Finally, conclusions from this work are pointed out and discussed in the last section.

II. DESIGN OF BILATERAL CONTROLLERS USING THE STATE CONVERGENCE METHODOLOGY

A. Bilateral System Modelling

A new version of the bilateral control scheme by state convergence [10] [11] is shown in Fig. 1.

These scheme considers all the possible interactions that could appear in the operator-master-slave-environment set. Different from [10] [11], this new version of the control scheme includes G_1 and Z_e matrixes: G_1 is a scalar that feedbacks the slave-environment interaction to the master, and Z_e is a matrix that represents the remote environment impedance.

The signals included in Fig. 1 are defined as follows:

- $F_m(t)$ represents the force applied to the master by the operator.
- $U_m(t)$ and $U_s(t)$ represent the forces (torques) applied to the master and slave devices.
- $X_m(t)$ and $X_s(t)$ represent the master and slave state vectors.
- $Y_m(t)$ and $Y_s(t)$ represent the master and slave outputs.

The following matrixes of Fig. 1 represent the master and slave dynamics:

- $A_{m(n\times n)}$ and $A_{s(n\times n)}$ are the master and slave system matrixes.
- $B_{m(n\times 1)}$ and $B_{s(n\times 1)}$ are the master and slave input matrixes.
- $C_{m(1\times n)}$ and $C_{s(1\times n)}$ are the master and slave output matrixes.

And the next six matrixes of Fig. 1 represent the control gains of the bilateral system:

- $G_{1(1\times 1)}$: Influence in the master of the interaction force of the slave with the environment.
- $G_{2(1\times 1)}$: Influence in the slave of the force that the operator applies to the master.
- $K_{m(1\times n)}$: Master state feedback matrix, which allows adjusting the master dynamics.
- $K_{s(1\times n)}$: Slave state feedback matrix, which allows adjusting the slave dynamics.
- $R_{m(1\times n)}$: Master to slave state feedback matrix.
- $R_{s(1\times n)}$: Slave to master state feedback matrix.

According to the control scheme, the state equations of a bilateral system are:

$$\begin{bmatrix} \dot{x}_m(t) \\ \dot{x}_s(t) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_m(t) \\ x_s(t) \end{bmatrix} + \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix} f_m(t) \quad (1)$$

where:

$$\begin{aligned} A_{11} &= A_m + B_m K_m \\ A_{12} &= B_m(R_m + G_1 Z_e) \\ A_{21} &= B_s R_s \\ A_{22} &= A_s + B_s(K_s + Z_e) \\ B_{11} &= B_m \\ B_{21} &= G_2 B_s \end{aligned} \quad (2)$$

It is considered that the master and slave are represented by mathematical models of dimension n. Therefore, to define the bilateral controllers it is required to calculate $4n+2$ parameters, since K_m, K_s, R_m and R_s have dimension n, and G_1 and G_2 have dimension 1. To calculate these control gains, a set of design equations must be obtained. The procedure to obtain these design equations is explained in the following sections. This procedure considers the state convergence and transparency conditions to obtain the design equations. The designed bilateral control system will allow that the slave follows the master, and the transparency will be achieved on steady state.

B. State Convergence Methodology

The state convergence methodology has been applied to get the design equations that assure the convergence between the master and slave states. This way, the slave will follow the master.

If the next linear transformation is applied to the system (1):

$$\widetilde{x}(t) = \begin{bmatrix} x_m(t) \\ x_m(t) - x_s(t) \end{bmatrix} = \begin{bmatrix} I & 0 \\ I & -I \end{bmatrix} \begin{bmatrix} x_m(t) \\ x_s(t) \end{bmatrix} \quad (3)$$

the following state equation is obtained:

$$\dot{\widetilde{x}}(t) = \widetilde{A}\widetilde{x}(t) + \widetilde{B} f_m(t) \Rightarrow$$

$$\begin{bmatrix} \dot{x}_m(t) \\ \dot{x}_e(t) \end{bmatrix} = \begin{bmatrix} \widetilde{A}_{11} & \widetilde{A}_{12} \\ \widetilde{A}_{21} & \widetilde{A}_{22} \end{bmatrix} \begin{bmatrix} x_m(t) \\ x_e(t) \end{bmatrix} + \begin{bmatrix} \widetilde{B}_{11} \\ \widetilde{B}_{21} \end{bmatrix} f_m(t) \quad (4)$$

where:

$$x_e(t) = x_s(t) - x_m(t) \quad (5)$$

$$\widetilde{A}_{11} = A_m + B_m(K_m + R_m + G_1 Z_e) \quad (6)$$

$$\widetilde{A}_{12} = -B_m(R_m + G_1 Z_e) \quad (7)$$

$$\begin{aligned} \widetilde{A}_{21} = A_m + B_m(K_m + R_m + G_1 Z_e) - \\ A_s - B_s(R_s + K_s + Z_e) \end{aligned} \quad (8)$$

$$\widetilde{A}_{22} = A_s + B_s(K_s + Z_e) - B_m(R_m + G_1 Z_e) \quad (9)$$

$$\widetilde{B}_{11} = B_m \quad (10)$$

$$\widetilde{B}_{21} = B_m - G_2 B_s \quad (11)$$

Let $x_e(t)$ be the error between the slave and the master. From (4), the error state equation between the slave and the master is:

$$\dot{x}_e(t) = \widetilde{A}_{21} x_m(t) + \widetilde{A}_{22} x_e(t) + \widetilde{B}_{21} f_m(t) \quad (12)$$

If $\widetilde{A}_{21} = \widetilde{B}_{21} = 0$ then (12) represents an autonomous system. In this case, the error can be eliminated, and the slave will follow the master in any condition. The matrix $\widetilde{A}_{22}$ determines the bilateral system stability, therefore it requires that their eigenvalues be located in the left half of the s-plane.

Design Condition $\sharp 1$: Error state as an autonomous system I.

The first condition to achieve the evolution of the error as an autonomous system is that $\widetilde{A}_{21} = 0$. Therefore, according to (8), the next condition must be verified:

$$\begin{aligned} A_m + B_m(K_m + R_m + G_1 Z_e) = \\ A_s + B_s(K_s + R_s + Z_e) \end{aligned} \quad (13)$$

This equation can be satisfied for any environment if:

$$B_m G_1 = B_s \quad (14)$$

In this case, (13) can be expressed as:

$$A_m + B_m(K_m + R_m) = A_s + B_s(K_s + R_s) \quad (15)$$

The equation (13) provides n conditions to calculate the bilateral controllers. However, if condition (14) is satisfied, then $n+1$ conditions are obtained.

Design Condition $\sharp 2$: Error state as an autonomous system II.

The second condition to achieve the evolution of the error as an autonomous system is that $\tilde{B}_{21}=0$. Therefore, considering (11), the following condition must be satisfied:

$$B_m = G_2 B_s \tag{16}$$

The equation (16) provides 1 additional condition to calculate the control gains.

III. Conditions of Transparency in State Convergence

This section describes the transparency conditions that must be verified in order to achieve the transparency of the teleoperation system on steady state. These conditions provide additional design equations to obtain the control gains.

The ideal transparency implies that impedance reflected to operator is equal to impedance of the remote environment, i.e.:

$$\frac{f_m(s)}{v_m(s)} = Z_e(s) \tag{17}$$

The equation (17) does not appear in the control scheme as shown in Fig. 1, but transparency conditions can be obtained applying some transformations. Fig. 2 shows a simplified version of the control scheme shown in Fig. 1 that includes the design conditions $\sharp 1$ and $\sharp 2$. From this control scheme, the transfer functions between the input and the different outputs is given by:

$$G(s) = \tilde{C}[sI-\tilde{A}]^{-1}\tilde{B}+\tilde{D} \tag{18}$$

$$\left\{ \begin{array}{c} \tilde{C}=I \\ \tilde{D}=0 \end{array} \right\} \Rightarrow G(s) = I[sI-\tilde{A}]^{-1}\tilde{B} \tag{19}$$

Therefore $G(s)$ can be expressed as:

$$G(s) = \frac{[adj(sI-\tilde{A})]^t}{\Delta}\left[\begin{array}{c} B_m \\ 0 \end{array} \right] \tag{20}$$

where:

$$\Delta = \left|sI-\tilde{A}\right| = \left|sI-\tilde{A}_{11}\right|\left|sI-\tilde{A}_{22}\right| \tag{21}$$

$G(s)$ represents a matrix of transfer functions among the master state and the user force (input of the system). Δ represents the $G(s)$ characteristic polynomial, so the stability and poles of the $G(s)$ transfer functions are defined by Δ. Regarding its order, it can be calculated from (21) as the sum of the dimension of both determinants. Therefore the dimension of Δ is $2n$.

The transparency condition can be applied to $G(s)$. However, it is required to take into account that ideal transparency cannot be obtained, because it derives from non-causal systems. Therefore, transparency conditions have been softened. It is considered that the transparency is achieved if the stiff and viscous components of the environment are perceived by the operator on steady state. This definition allows obtaining the following additional design condition.

Design Condition $\sharp 3$: Transparency based design.
For environments that are predominantly elastic, the transparency of the teleoperation system can be redefined by using the next condition:

$$\lim_{t\to\infty}\frac{x_m(t)}{f_m(t)} = \frac{-1}{k_e} \tag{22}$$

where k_e represent, the stiffness of the environment.

If the user input is modelled as an unit step, then the previous condition can be transform as:

$$\lim_{t\to\infty}\frac{x_m(t)}{f_m(t)} = \lim_{s\to 0} sG_1(s)\frac{1}{s} = G_1(0) = \frac{-1}{k_e} \tag{23}$$

where $G_1(s)$ represent, the relation between master position (first state variable) and user force. Note that these transfer functions do not have any relation to the control gains G_1 and G_2.

The expressions (23) define four new design conditions. Therefore, $n+5$ design conditions have been obtained: (13), (16) and (23). If condition (14) is satisfied then $n+6$ conditions are defined. These conditions provide a set of design equations to calculate the gains of the control scheme. These conditions assure the state convergence between the master and slave, and the transparency on steady state.

The number of parameters that can be assigned without any constraint depends on the dimension of the system. Following section shows the application of this methodology for a system of second order. Higher orders can be solved in a similar way.

IV. State Convergence Methodology for Second Order Systems

A. Design Equations and Control Gains

In a teleoperation system of 1 DoF, the master and the slave can be modelled using the following second order simplified linear model:

$$u(t) = J\ddot{\theta}(t) + b\dot{\theta}(t) \tag{24}$$

where J is the inertia of the element, b is the viscous friction coefficient, $u(t)$ is the torque applied, and $\theta(t)$ is the rotation angle.

If the angular position and angular velocity are chosen as the state variables for both devices, then:

$$x_1(t) = \theta(t) \tag{25}$$

$$\dot{x}_1(t) = \dot{\theta}(t) = x_2(t) \tag{26}$$

$$\dot{x}_2(t) = \ddot{\theta}(t) = \frac{-b}{J}x_2(t) + \frac{1}{J}u(t) \tag{27}$$

Therefore, the equations on the state space for the master and slave are:

$$\left[\begin{array}{c} \dot{x}_{m1} \\ \dot{x}_{m2} \end{array} \right] = \left[\begin{array}{cc} 0 & 1 \\ 0 & \frac{-b_m}{J_m} \end{array} \right]\left[\begin{array}{c} x_{m1} \\ x_{m2} \end{array} \right] + \left[\begin{array}{c} 0 \\ \frac{1}{J_m} \end{array} \right] u_m(t) \tag{28}$$

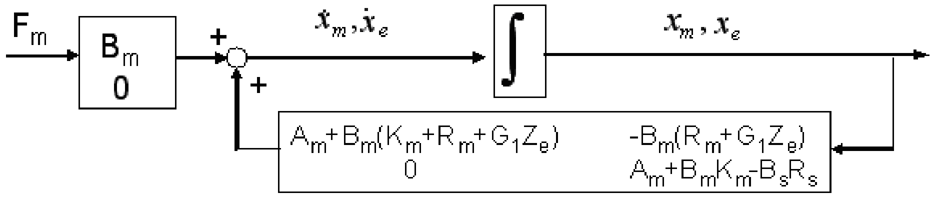

Fig. 2. Diagram of the state convergence control including design conditions 1 and 2

$$\begin{bmatrix} \dot{x}_{s1} \\ \dot{x}_{s2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \frac{-b_s}{J_s} \end{bmatrix} \begin{bmatrix} x_{s1} \\ x_{s2} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{J_s} \end{bmatrix} u_s(t) \tag{29}$$

and:

$$A_m = \begin{bmatrix} 0 & 1 \\ 0 & \frac{-b_m}{J_m} \end{bmatrix} B_m = \begin{bmatrix} 0 \\ \frac{1}{J_m} \end{bmatrix} \tag{30}$$

$$A_s = \begin{bmatrix} 0 & 1 \\ 0 & \frac{-b_s}{J_s} \end{bmatrix} B_s = \begin{bmatrix} 0 \\ \frac{1}{J_s} \end{bmatrix} \tag{31}$$

If the master and slave are similar, the next equation is obtained from (14):

$$G_1 = 1 \tag{32}$$

In this case, the design condition ♯1 is simplified to:

$$K_m + R_m = K_s + R_s \tag{33}$$

On the other hand, if the master and slave are similar, from the design condition ♯2, it is obtained:

$$G_2 = 1 \tag{34}$$

The design condition ♯3 is more complex to apply since:

$$G_1(s) = \frac{x_m(s)}{f_m(s)} = \tag{35}$$

$$\frac{b_{m2}(s^2 - s(a_{m22} + b_{m2}k_{m2} - b_{s2}r_{s2}) - b_{m2}k_{m1} + b_{s2}r_{s1})}{(s^2 - s(a_{m22} + b_{m2}(g_1 b_e + k_{m2} + r_{m2})) - b_{m2}(k_{m1} + r_{m1} + g_1 k_e))} \cdots$$

$$\overline{(s^2 - s(a_{m22} + b_{m2}k_{m2} - b_{s2}r_{s2}) - (b_{m2}k_{m1} - b_{s2}r_{s1}))}$$

According to these equations, stability of $G_1(s)$ implies that:

$$a_{m22} + b_{m2}(g_1 b_e + k_{m2} + r_{m2}) = -\delta_1 < 0 \tag{36}$$

$$b_{m2}(k_{m1} + r_{m1} + g_1 k_e) = -\delta_2 < 0 \tag{37}$$

$$a_{m22} + b_{m2}k_{m2} - b_{s2}r_{s2} = -\delta_3 < 0 \tag{38}$$

$$b_{m2}k_{m1} - b_{s2}r_{s1} = -\delta_4 < 0 \tag{39}$$

The equation (23) for a second order system is:

$$\frac{-1}{k_e} = \frac{-1}{k_{m1} + r_{m1} + g_1 k_e} \tag{40}$$

Analyzing (40) further, the following equation is derived:

$$k_{m1} + r_{m1} = 0 \tag{41}$$

Substituting (41) to (37), it can be deduced that δ_2 depends on the physical parameters of the robot

$$\delta_2 = \frac{-k_e}{J_m} \tag{42}$$

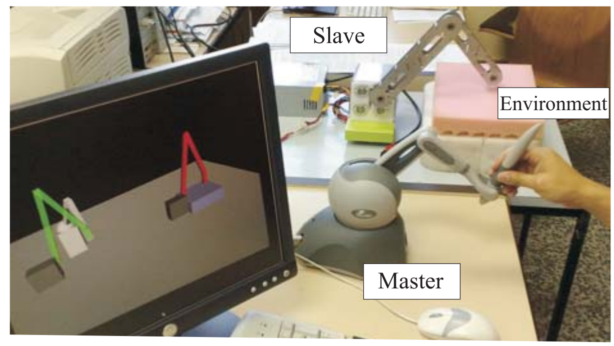

Fig. 3. Testbed used for the experiments

Therefore, considering δ_1,it is then possible to vary the master dynamics (according to the value of δ_2). The dynamics of the error between the master and the slave is defined completely by δ_3 and δ_4.

Therefore, there are 8 design equations: (32), (33) (2 scalar equations), (34), (41) , (36), (38) and , (39). On the other hand, there are 10 control gains: K_m, K_s, R_m, R_s , G_1 and G_2. Therefore, 2 gains must be assigned according to the suitability for the control system. In our case $A_m = A_s$ and $B_m = B_s$, then the simplest solution to comply with the Design Condition ♯1 according to (33) is to set $R_m = \begin{bmatrix} 0 & 0 \end{bmatrix}$. This case does not imply that the slave state is not feedback, since the slave interaction force is feedback to the master and this information depends on the slave position and velocity. Solving the design equations, the following control gains are obtained:

$$g_1 = \frac{b_{s2}}{b_{m2}} = 1 \tag{43}$$

$$g_2 = \frac{b_{m2}}{b_{s2}} = 1 \tag{44}$$

$$R_m = \begin{bmatrix} 0 & 0 \end{bmatrix} \tag{45}$$

$$K_m = \begin{bmatrix} 0 & (-\delta_1 J_m + b_m - b_e) \end{bmatrix} \tag{46}$$

$$R_s = \begin{bmatrix} (\delta_4 J_s) & (-\delta_1 J_m - b_e + \delta_3 J_s) \end{bmatrix} \tag{47}$$

$$K_s = \begin{bmatrix} (-\delta_4 J_s) & (b_m - \delta_3 J_s) \end{bmatrix} \tag{48}$$

The effects of δ_1, δ_3 and δ_4 are important to take into account, since it represents the poles of (35). It thereby δ_1, δ_3 and δ_4 establishes dynamics of the master and determines the velocity of state error to converge to zero.

B. Experimental Results

The new methodology for designing bilateral controllers has been tested on a teleoperated system, Fig. 3. The master robot is a haptic device (Phantom Omni - Sensable). It was programmed to have the same mechanical characteristic of the slave manipulator using virtual constrains [12]. The slave manipulator is a serial robot of 3 DoF. It is controlled by a board PC104 (TS-5600) with a real time operative system (QNX) and EPOS controller (Maxonmotors). The Communication between the master and the slave is via LAN (UDP).

The performed control task is aimed to applying operators force over the master in order to guide the slave in the environment. In the experiment, the last link of the slave has the same orientation at all times (vertical orientation), hence the motor that corresponds to the third joint does not change in position due to its movement transmission system.

The master and slave joint parameters are represented by the table I.

TABLE I
JOINTS PARAMETERS

Parameter	Joint I	Joint II
J_m (Kgm^2)	0.0276	0.054
b_m	0.05	0.05
δ_2	362.32	185.19

Therefore, for the first joint, the master and slave state equations are represented by the following matrixes:

$$A_s = \begin{bmatrix} 0 & 1 \\ 0 & -1.812 \end{bmatrix} \quad B_s = \begin{bmatrix} 0 \\ 36.23 \end{bmatrix} \tag{49}$$

and for the second joint, the master and slave state equations are represented by the following matrixes:

$$A_s = \begin{bmatrix} 0 & 1 \\ 0 & -0.926 \end{bmatrix} \quad B_s = \begin{bmatrix} 0 \\ 18.52 \end{bmatrix} \tag{50}$$

A_m and B_m were taken with the same values of A_s and B_s respectively, as the haptic device is servocontrolled to have these characteristics.

An environment that is predominantly elastic has been considered to verify the performance of the bilateral control scheme. The remote environment impedance that have been considered for each joint is the following:

$$Z_e = \begin{bmatrix} k_e & b_e \end{bmatrix} \tag{51}$$

where $k_e = -10Nm/rad$ and $b_e = -1Nm/(rad/s)$ in both environments.

Considering $\delta_1 = 38.313$, $\delta_3 = 46$ and $\delta_4 = 529$ for the first joint, the obtained poles are -17, -21.3 (master dynamics poles) and -23, -23 (error dynamics poles). Considering $\delta_1 = 27.2$, $\delta_3 = 10$ and $\delta_4 = 21$ for the second joint, the obtained poles are -14, -13.2 (master dynamics poles) and -3, -7 (error dynamics poles).

Solving the equations of design: (43) to (48), control gains of table II are obtained.

The figures 4 and 5 show the position evolutions of the master and slave joints when the slave interacts with the environment. It can be observed that the slave follows the master. The minor errors in the second joint is probably due to a more complex system present in movement transmission.

Figures 6 and 7 show the torques of the joints corresponding to the environment and master forces.

Finally, figures 8 and 9 show the relation between the position and the force of the joints. A very similar relation for both cases can be observed.

TABLE II
CONTROL GAINS

control gain	Joint I	Joint II
$g_1 = g_2$	1	1
K_m	[0 -0.0074353]	[0 -0.42029]
K_s	[-14.6004 -1.2196]	[-1.134 -0.49]
R_m	[0 0]	[0 0]
R_s	[14.6004 1.2122]	[1.134 0.069714]

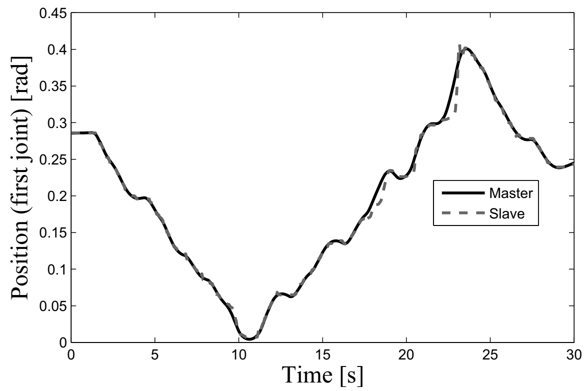

Fig. 4. Position of the first joint

V. CONCLUSION

A novel methodology for designing bilateral controllers based on transparency has been presented in this paper. The methodology uses state of convergence framework so as to obtain a set of equations of design that calculate control gains.

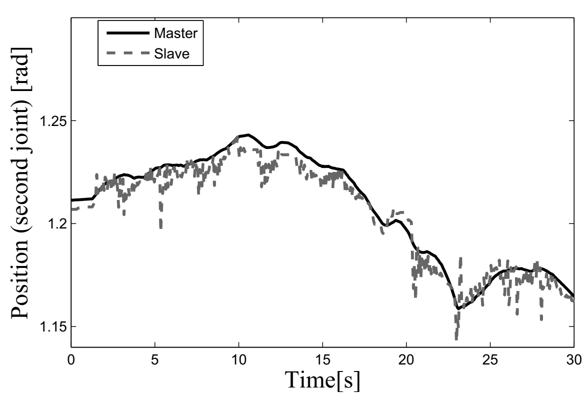

Fig. 5. Position of the second joint

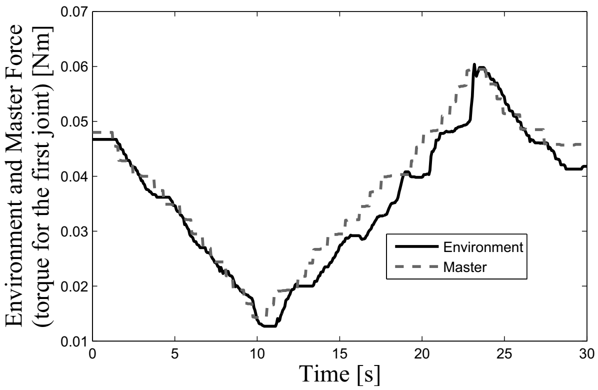

Fig. 6. First joint torque corresponding to the environment and master force

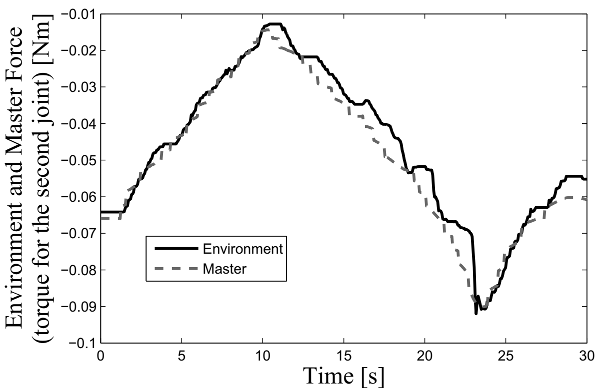

Fig. 7. Second joint torque corresponding to the environment and master force

The design method assures the state convergence between the master and the slave. It obtains transparency on a steady state. The parameter δ_2 is defined by the transparent condition, δ_1 defines the dynamics of the master. δ_3 and δ_4 define the dynamics of the error convergence.

The methodology has been verified in a master-slave system of 3 DoF. The experimental results have been successful since controllers made the slave follow the master. They also provide the operator a higher degree of transparency.

The methodology has been tested considering a second order system for the master and the slave. Moreover, this methodology can also be applied in higher order systems of teleoperation models.

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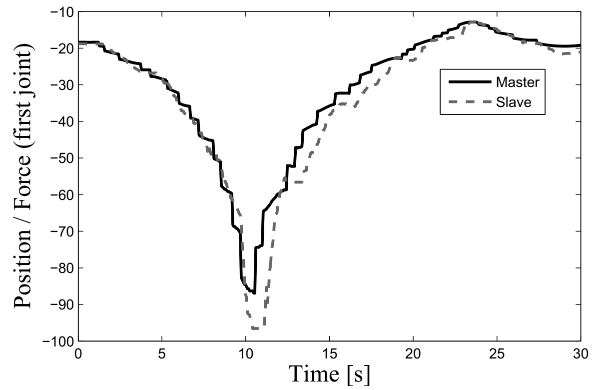

Fig. 8. Relation of the position over the force - first joint

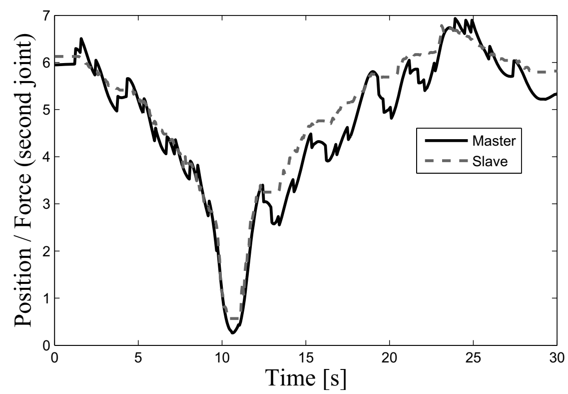

Fig. 9. Relation of the position over the force - second joint

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