Development of a Master-Slave Testbed for Validating Linear and non Linear Control Strategies

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This paper presents the design and application of a master-salve Testbed for the implementation and validation of control strategies. The testbed has one degree of freedom and it is possible to use it as teleoperation system or to use master and the slave isolate. Due to the implementation is performed under Matlab® environment, models and control strategies are easy and quickly implemented for students. The model of the system is made in the space state, and, as example, a non-linear control algorithm has been formulated in the state space (convergence of the state) and the gains are adjusted through an adaptative method.

1. Introducción

In the study of bilateral control, it is important to advance towards the analysis of a series of schemes and designed control techniques in order to obtain the best performance of teleoperation for the entire system.

Adaptative Control is a technique already applied in telerobotics and teleoperation [1]-[5]; however, there are still lots of problems to be solved in this field. In applications of adaptative control of teleoperated systems, despite its difficulty, research and development have been focused on this line so as to obtain ideal solutions in a real master-slave system.

Some of the early studies in the field of adaptative control in robotics have been focused on control of flexible arms [1], [5]. J.-J Slotine and W. Li [6] have shown a scheme of an adaptative controller whose parameter of adaptation fits according to the performance error. In 1991, G. Niemeyer and J.-J. Slotine [7] have presented a hybrid control scheme based on adaptative control scheme SL [6]. However, this scheme shows a problem of dynamics that arises whenever the master-slave system interacts with a human operator or with the environment. It is not surprising that such problem contributes to time delay and thereby deteriorates the performance of the entire system. Furthermore, there are errors of designs in both the master and the slave, and in the communications channel. The control scheme is not efficient. In order to solve some of these inconveniences, an indirect adaptative bilateral control scheme based on [2], and the control architecture of Hannaford [9] are proposed on [8]. In the same manner, Lee et al. [10] propose an adaptative control scheme based on the general structure of the teleoperated system from Lawrence [11] and two-port approach. Moreover, an adaptative bilateral control in which stability is guaranteed in order to be applied in the control structure of position and velocity in [12].

A new adaptative method for bilateral regulators of teleoperated systems is developed in this article. The control algorithm is fundamentally based on the implementation of adaptative methods that guarantee a good perception from the operator against variations from the remote environment. This methodology can be applied to the time delay case since it is based in state of convergence method [13].

2. SCHEME OF BILATERAL CONTROL SYSTEM

2.1 Modeling of the teleoperated system

$$\begin{aligned}\dot{\mathbf{x}}_{\mathbf{m}}(t) &= \mathbf{A}_{\mathbf{m}}\mathbf{x}_{\mathbf{m}}(t)+\mathbf{B}_{\mathbf{m}}\breve{u}_m(t)\\ \mathbf{y}_{\mathbf{m}}(t) &= \mathbf{C}_{\mathbf{m}}\mathbf{x}_{\mathbf{m}}(t)\end{aligned} \tag{1}$$

$$\begin{aligned}\dot{\mathbf{x}}_{\mathbf{s}}(t) &= \mathbf{A}_{\mathbf{s}}\mathbf{x}_{\mathbf{s}}(t)+\mathbf{B}_{\mathbf{s}}\breve{u}_s(t)\\ \mathbf{y}_{\mathbf{s}}(t) &= \mathbf{C}_{\mathbf{s}}\mathbf{x}_{\mathbf{s}}(t)\end{aligned} \tag{2}$$

where $\mathbf{A_m} \in R^{n\times n}$, $\mathbf{B_m} \in R^{n\times 1}$ and $\mathbf{C_m} \in R^{1\times n}$ are respectively the system matrix, the input and the output of the master and $\mathbf{A_s} \in R^{n\times n}$, $\mathbf{B_s} \in R^{n\times 1}$ and $\mathbf{C_s} \in R^{1\times n}$ are the corresponding slave. In Fig.1, the scheme in which the new adaptative method will be applied is shown. This scheme includes all the possible interactions that can arise in the operator-master-slave-environment though the control gains $\mathbf{K_m}$, $\mathbf{K'_S}$, $\mathbf{R_M}$, $\mathbf{R_S}$, $\mathbf{G_1}$ and $\mathbf{G_2}$ as shown in Table I. These gains can be calculated by applying the algorithm of control based on state convergence as shown in [13]. The values obtained of the gains represent the initial values for the regulators in $\mathbf{t = t_0}$.

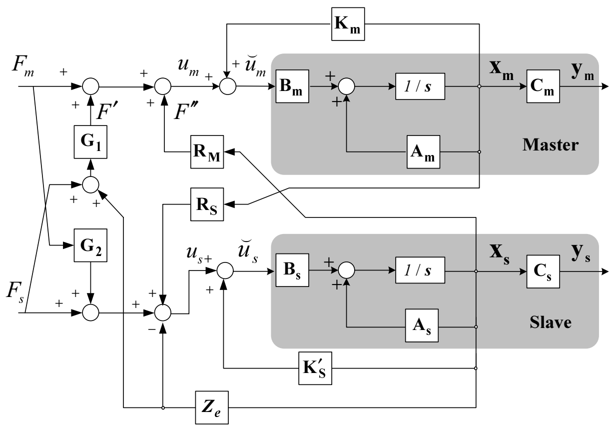

Figure. 1. Diagram of blocks for a bilateral teleoperated system.

TABLE I: MODELLING OF A BILATERAL SYSTEM BASED ON MASTER AND SLAVE STATE.

Control gains	Description
$\mathbf{G_1} \in R^{1\times 1}$	Matrix of consideration for pre-application of load or exerted force in the master and force contact of the slave with the environment.
$\mathbf{G_2} \in R^{1\times 1}$	Influence of the force exerted by the operator on the master in the slave.
$\mathbf{R_M} \in R^{1\times n}$	Matrix of consideration for contact forces of the slave with the environment.
$\mathbf{R_S} \in R^{1\times n}$	Master-slave interaction.
$\mathbf{K_m} \in R^{1\times n}$	Feedback matrix of the master state. It defines the dynamic of the master.
$\mathbf{K'_S} \in R^{1\times n}$	Feedback matrix of the slave status. It defines the dynamic of the slave.

In the scheme of Fig. 1, control law for the master $\breve{u}_m(t)$ and the slave $\breve{u}_s(t)$ are respectively:

$$\breve{u}_m(t) = \mathbf{K_m x_m(t)} + \mathbf{R_M x_s(t)} + F_m(t) + \mathbf{G_1} \boldsymbol{Z_e} \mathbf{x_s(t)} + \mathbf{G_1} F_s(t) \quad (3)$$

$$\breve{u}_s(t) = \mathbf{K'_S x_s(t)} + \mathbf{R_S x_m(t)} + \mathbf{G_2} F_m(t) + F_s(t) - \boldsymbol{Z_e} \mathbf{x_s(t)} \quad (4)$$

where $F_m = k_{op} x_{m1}$ represents the force that the operator exerts on the master and F_s represents the possible load that is applied on the slave, such as weight or load of manipulated object.

Supposed F_s is null in all posterior developments, the slave will be on force f_e provoked by its interaction with the environment $\boldsymbol{z_e}$, so the dynamic model of the environment can be defined [13]:

$$f_e(t) = k_e \mathbf{x_s}(t) + b_e \dot{\mathbf{x}}_\mathbf{s}(t) \quad (5)$$

having k_e and b_e as stiffness and viscous friction respectively, and $\mathbf{x_s}$ as the position of the slave. Contact force of the slave with the environment can be feedback towards the master through F'' signal, having F' as null, thereby having the matrix structure $\mathbf{R_M}$ as:

$$\mathbf{R_M} = \begin{bmatrix} g_1 k_e & g_1 b_e \cdots & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \cdots & 0 \end{bmatrix} \quad (6)$$

2. Adaptative Control by State Convergence

In case of uncertainty from the dynamic parameters of all elements, a control strategy is considered in order to allow overcoming inconveniences such as adaptative control. In this manner, errors that arise can be corrected upon determining the kind of environment, load or force exerted on a slave. Considering such points, the regulators involved in the scheme as shown in Figure 1 have to adapt their parameters in order to ensure stability, robustness and transparency of the system.

The design of the adaptation law as shown in this study is based on Stability Lyapunov Theory. It allows stability of the entire system to be guaranteed. A differential equation of error $\dot{\mathbf{e}}(\mathbf{t})$ that contains the parameters of the law of adaptation is further obtained. A candidate of Lyapunov function is then derived as mechanism of adaptation in order to get error $\mathbf{e(t)}$ to converge to zero. In order to reach the objective of adaptative control, the following are considered:

Definition 1: It is defined as the state of error $\mathbf{e(t)}$. The difference between the state of the master and the state of the slave therefore defines:

$$\mathbf{e(t)} = \mathbf{x_s(t)} - \mathbf{x_m(t)} \quad (7)$$

Substituting (3) and (4) in expressions (1) and (2) respectively, equations below are:

$$\dot{\mathbf{x}}_\mathbf{m}\mathbf{(t)} = \tilde{\mathbf{A}}_\mathbf{m} \mathbf{x_m(t)} + \mathbf{B_m R_M x_s(t)} + \mathbf{B_m} F_m(t) + \mathbf{B_m G_1} F_s(t) \quad (8)$$

$$\begin{aligned} \dot{\mathbf{x}}_\mathbf{s}\mathbf{(t)} = {} & \mathbf{A_s x_s(t)} + \mathbf{B_s K'_S x_s(t)} + \mathbf{B_s R_S x_m(t)} + \mathbf{B_s G_2} F_m(t) \\ & + \mathbf{B_s} F_s(t) - \mathbf{B_s} \boldsymbol{Z_e} \mathbf{x_s(t)} \end{aligned} \quad (9)$$

where $\tilde{\mathbf{A}}_\mathbf{m} = \mathbf{A_m} + \mathbf{B_m K_m}$. Initial conditions $\mathbf{t} = \mathbf{t_0}$ have to be set up so that the slave state converges to the master state [18], therefore these conditions are as follows:

$$\mathbf{A_s} - \tilde{\mathbf{A}}_\mathbf{m} = \mathbf{B_m R_m} - \mathbf{B_s R_s} - \mathbf{B_s K'_s} \quad (10)$$

$$\mathbf{B_s} - \mathbf{B_m G_1} = \mathbf{0} \quad (11)$$

$$\mathbf{B_s G_2} - \mathbf{B_m} = \mathbf{0} \quad (12)$$

where $\mathbf{K'_s}$, $\mathbf{R_m}$, $\mathbf{R_s}$, $\mathbf{G_1}$ and $\mathbf{G_2}$ are control gains calculated at time $\mathbf{t} = \mathbf{t_0}$ according to [18]. Calculating (7) further, according to (8) and (9), the derivative of the state error can be expressed as follows:

$$\dot{\mathbf{e}}(\mathbf{t}) = \left(\tilde{\mathbf{A}}_{\mathbf{m}} - \mathbf{B}_{\mathbf{s}}\mathbf{R}_{\mathbf{s}}\right)\mathbf{e}(\mathbf{t}) + \mathbf{B}_{\mathbf{s}}\left(\mathbf{K}'_{\mathbf{S}} - \mathbf{K}'_{\mathbf{s}}\right)\mathbf{x}_{\mathbf{s}}(\mathbf{t}) + \mathbf{B}_{\mathbf{s}}\left(\mathbf{R}_{\mathbf{S}} - \mathbf{R}_{\mathbf{s}}\right)\mathbf{x}_{\mathbf{m}}(\mathbf{t}) \\ - \mathbf{B}_{\mathbf{m}}\left(\mathbf{R}_{\mathbf{M}} - \mathbf{R}_{\mathbf{m}}\right)\mathbf{x}_{\mathbf{s}}(\mathbf{t}) - \mathbf{B}_{\mathbf{s}}\boldsymbol{Z}_{e}\mathbf{x}_{\mathbf{s}}(\mathbf{t}) \tag{13}$$

Definition 2: control gains that represent the dynamics of slave $\mathbf{K}'_{\mathbf{S}}$, the interaction of master-slave $\mathbf{R}_{\mathbf{S}}$ and the moderation of forces $\mathbf{R}_{\mathbf{M}}$ are defined

$$\mathbf{K}'_{\mathbf{S}} = \tilde{\vartheta}'_{\mathbf{S}} = \vartheta'_{\mathbf{s}} + \hat{\vartheta}'_{\mathbf{S}}$$
$$\mathbf{R}_{\mathbf{S}} = \tilde{\vartheta}_{\mathbf{S}} = \vartheta_{\mathbf{s}} + \hat{\vartheta}_{\mathbf{S}}$$
$$\mathbf{R}_{\mathbf{M}} = \tilde{\vartheta}_{\mathbf{M}} = \vartheta_{\mathbf{m}} + \hat{\vartheta}_{\mathbf{M}}$$

where $\hat{\vartheta}'_{\mathbf{S}}$ $\hat{\vartheta}_{\mathbf{S}}$ and $\hat{\vartheta}_{\mathbf{M}}$ are estimates of control gains so that error $\mathbf{e}(\mathbf{t})$ converges to zero. The method allows maintaining or not initial values of gains $\vartheta'_{\mathbf{s}}$, $\vartheta_{\mathbf{s}}$ and $\vartheta_{\mathbf{m}}$ for $\mathbf{t} = \mathbf{t}_0$ (last values) according to [13]. Then (13) can be rewritten as

$$\dot{\mathbf{e}}(\mathbf{t}) = \tilde{\mathbf{A}}\mathbf{e}(\mathbf{t}) + \mathbf{B}_{\mathbf{s}}\left(\tilde{\vartheta}'_{\mathbf{S}} - \vartheta'_{\mathbf{s}}\right)\mathbf{x}_{\mathbf{s}}(\mathbf{t}) + \mathbf{B}_{\mathbf{s}}\left(\tilde{\vartheta}_{\mathbf{S}} - \vartheta_{\mathbf{s}}\right)\mathbf{x}_{\mathbf{m}}(\mathbf{t}) \\ - \mathbf{B}_{\mathbf{m}}\left(\tilde{\vartheta}_{\mathbf{M}} - \vartheta_{\mathbf{m}}\right)\mathbf{x}_{\mathbf{s}}(\mathbf{t}) - \mathbf{B}_{\mathbf{s}}\boldsymbol{Z}_{e}\mathbf{x}_{\mathbf{s}}(\mathbf{t}) \tag{14}$$

or

$$\dot{\mathbf{e}}(\mathbf{t}) = \tilde{\mathbf{A}}\mathbf{e}(\mathbf{t}) + \boldsymbol{\Phi}\left(\hat{\vartheta} - \vartheta\right) \tag{15}$$

where $\boldsymbol{\Phi}$ is a signal matrix (reference, output, etc) related to the parameters to be adjusted and $\hat{\vartheta} - \vartheta$ is the vector of parameters error. Considering the candidate function of Lyapunov in the function of error between the signals of states and the parameters error such as;

$$V(\mathbf{e}, \hat{\vartheta}) = \mathbf{e}^{T} P \mathbf{e} + \left(\hat{\vartheta} - \vartheta\right)^{T} \Upsilon^{-1}\left(\hat{\vartheta} - \vartheta\right) \tag{16}$$

with $P \in \mathrm{R}^{n \times n}$ symmetry positive definite and $\Upsilon^{-1} \in \mathrm{R}^{n \times n}$ diagonal positive definite. The stability will be guaranteed if dV/dt is negative definite

$$dV/dt = -\mathbf{e}^{T} Q \mathbf{e} + 2\left(\hat{\vartheta} - \vartheta\right)\boldsymbol{\Phi}^{T} P \mathbf{e} + 2\left(\hat{\vartheta} - \vartheta\right)^{T} \Upsilon^{-1} d\hat{\vartheta}/dt \\ = -\mathbf{e}^{T} Q \mathbf{e} + 2\left(\hat{\vartheta} - \vartheta\right)^{T}\left(\Upsilon^{-1} d\hat{\vartheta}/dt + \boldsymbol{\Phi}^{T} P \mathbf{e}\right) \tag{17}$$

Matrix $Q \in \mathrm{R}^{n \times n}$ is positive definite since it verifies the equation of Lyapunov $\tilde{\mathbf{A}}^{\mathbf{T}} P + P\tilde{\mathbf{A}} = -Q$. The first term of the second member of (17) is negative definite, a possible solution is having the rest equal to zero. A law of adaptation of parameters is then defined as;

$$d\hat{\vartheta}/dt = -\Upsilon \boldsymbol{\Phi}^{T} \boldsymbol{P} \mathbf{e} \tag{18}$$

where $\mathbf{e}$ is the state error and Υ is adaptation gains matrix that defines speed of adaptation of every parameter.

4. Experimental Results

Figure 2 shows the bench of the experimental teleoperation used in validating the proposed control strategies. It is formed by a master and a slave both having one degree of freedom. The manipulators are controlled through RE118797 Maxon motors with encoders of 500 pp. The encoder signals are sent to a servo-amplifier card (4-Q-CC ADS 50/5 Maxon) and downloaded on a computer (Pentium IV) through a data acquisition card *National Instruments* 6024E.

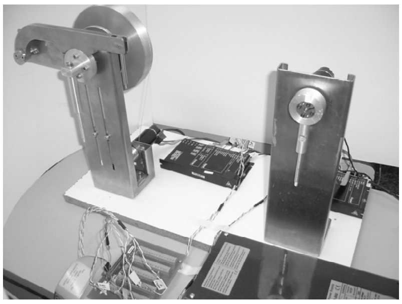

Figure. 2. Experimental teleoperated system of one degree of freedom.

In Fig. 3 and 4, the control schemes in position with the identified physical values of every CC motor are shown, considering the dynamics connected to the axis, where $u_{m,s}(t)$ is the reference stress input, $\dot{\theta}_{m,s}(t)$ is the measurement of velocity, and $\theta_{m,s}(t)$ is the angular position for the master and the slave.

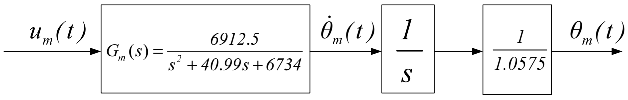

Figure 3. Control scheme in the position of the master in open loop.

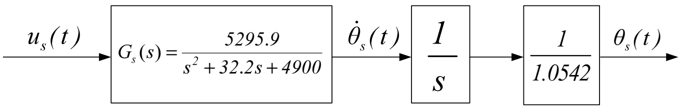

Figure. 4. Control scheme in the position of the slave in open loop.

Previous to the implementation of the algorithm carried out simulations modifying the poles of both dynamics, being obtained a better performance to the error poles and the slave poles are place that lie on the ***s*** plane in 110 and 50 respectively. As better performance it is the die for smaller time of establishment and smaller time of state convergence. Take gain $\mathbf{G_1} = 0.1$ and the obtained control gains for $\mathbf{t} = \mathbf{t_0}$ according to [13], are the conditions taken into account for the design.

$\mathbf{R_m} = [0 \quad 0 \quad 0]$, $\mathbf{R_s} = [240.06 \quad 5.733 \quad 0.036]$, $\mathbf{K_m} = [-19.12 \quad -0.117 \quad -0.017]$, $\mathbf{K'_s} = [-264.95 \quad -6.25 \quad -0.059]$, $\mathbf{G_2} = 1.301$

In the experiment, the operator moves the master arm in such a way that the slave performs several connections with an environment of unknown dynamics (soft object). Since no force/torque sensor is available on the system, a force interaction f_e equal to the intensity of the current of the slave motor was considered. However, in order to know the real values to which some $\hat{\boldsymbol{\vartheta}}$ parameters have to converge, stiffness constant $k_e = 40\ N/m$ was experimentally obtained. In the same manner, values $k_{op} = 20\ N/m$ were obtained. As main objective of this work it is the validation the proposed control strategies, next the experimentation is presented.

1) *Adaptation of gains* $\mathbf{K'_S} = \tilde{\boldsymbol{\vartheta}}'_{\mathbf{S}}$. Table 2 shows the parameter for the conditions of the operation and followed by results of experiment. Fig. 5 shows the response of the slave toward the position of the master until the moment that the slave cannot follow the advancement due to its interaction with the environment.

A delay on the slave position while the master proceeds with its advancement can be observed. The state of convergence is achieved as the parameters $\tilde{\boldsymbol{\vartheta}}'_{\mathbf{S}}$ adapt its estimated value through algorithm of adaptation. Fig. 6 shows the state of error of the master-slave where the system converges to zero in function of the speed of variation and the adaptation of the parameters of $\tilde{\vartheta}'_S$ (Fig. 7).

TABLE 2:CONTROLLERS OF THE TELEOPERATED SYSTEM

Parameters	Control Gains
$\mathbf{R_M} = \mathbf{G_1} Z_e$	$\mathbf{K}'_s = \vartheta'_s = [-264.95 \quad -6.25 \quad -0.059]$
$\mathbf{R_S} = \mathbf{R_s}$	$\hat{\vartheta}'_S = [45.2 \quad 1.13 \quad 0.0113]$
$\mathbf{K}'_S = \tilde{\vartheta}'_S$	$\tilde{\vartheta}'_S = [-219.7 \quad -5.12 \quad -0.048]$
	$\gamma_1 =$ 2.2e-005
	$\gamma_2 = -$1.47e-007
	$\gamma_3 = -$1.35e-011

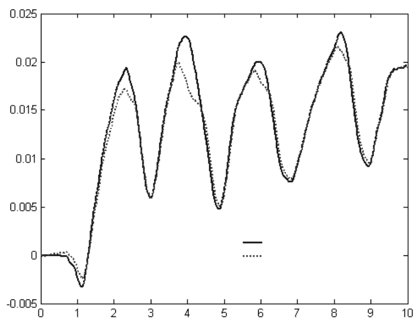

Figure 5. Position of the master and slave.

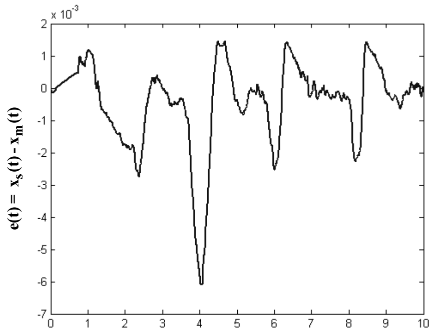

Figure 6. Error of the master-slave state *e(t)*

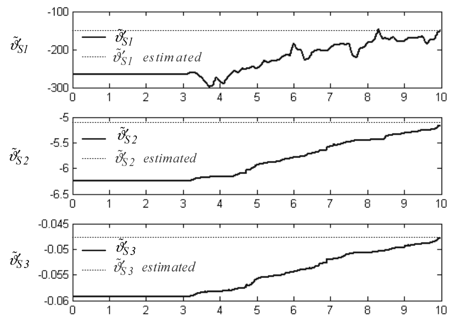

Figure 7. Variation of $\tilde{\vartheta}'_S$ parameters.

CONCLUSION

This article presents a master-slave testbed with one degree of freedom. This testbed is useful for the implementation and validation of control strategies as it was shown in the experimental results. All the software is developed in the MatLab environment so it very easy to change paramenters.
The test bed was modelled in the state space however it is possible to change the slave dynamic through the environment parameters. Consequently, the system's dynamic and the controller must be updated.
This bank has been used by many students in subjects related to the automatic control and it was very good accepted.

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