CONTROL THROUGH STATE CONVERGENCE OF TELEOPERATION SYSTEMS WITH VARYING TIME DELAY

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Abstract: Teleoperation systems that use Internet as communication channel must deal with varying time delays. In these situations, the system can become unstable due to the irregular variations of the time delay. In this paper, a control method of teleoperation systems that we presented considering constant time delays is applied to control a teleoperation system with varying time delays. The control gains obtained with a constant time delay can be used to control the teleoperation system with varying time delays because of the control method robustness. Experimental results are presented to illustrate the validity of the method.

1 INTRODUCTION

In a teleoperation system, the human operator controls the master manipulator to achieve that the slave manipulator performs a remote task. In a bilateral system, to improve the task performance, the interaction force of the slave with the environment is reflected to the operator. The existence of time delays in the information transmission between the local and remote environment can destabilize bilateral teleoperation systems.

In traditional teleoperation systems, private transmission media are used to perform the master – slave communication. In these cases, a constant time delay is assumable. Different teleoperation control systems can be found in the literature to overcome the constant time delay problem (Arcara and Melchiorri, 2002).

The evolution of computer networks, as Internet, has powered to consider this media as communication channel in teleoperation systems. However, in this media the communication time delay is not constant, but it varies depending of the network traffic. It is possible that bilateral control systems designed considering a constant time delay would be destabilized when varying time delays appear (Kosuge et al., 1996). Several control systems have been proposed in teleoperation with varying time delay: (Kosuge et al., 1996), (Oboe and Fiorini, 1997), (Chopra et al., 2003), etc.

In (Azorín et al., 2003a) we have proposed a new

design and control method of bilateral systems with constant time delay. This method allows that the slave manipulator follows the master in spite of the time delay by means of the state convergence between the master and the slave. The method is able also to establish the desired dynamics of this convergence and the dynamics of the slave manipulator. In this paper, the control method through state convergence is used when varying time delays exist in the communication channel. A constant time delay is considered to obtain the control gains of the system. However these control gains are applied to control the system when there are varying time delays. Experimental results show the validity of the method.

The paper is organized as follows. Section 2 describes the design and control method of the teleoperation system considering a constant time delay. The experiments carried out with this control method with varying time delays are presented in Section 3. Finally, Section 4 summarizes the conclusions of the paper.

2 DESIGN AND CONTROL METHOD OF THE TELEOPERATION SYSTEM

In this section the modelling of the teleoperation system and the control method considering a constant

time delay is summarized. For more details see (Azorín et al., 2003a). The teleoperation system with time delay has been modelled in the state space and it has been controlled through state convergence. The control method allows that the slave follows the master in spite of time delay. Also it allows to establish the dynamics of the slave and the dynamics of the master - slave error.

2.1 Modelling of the Teleoperation System

The teleoperation system has been modelled in the state space. It has been considered a simplified linear model of one dof for the master and the slave. The representation in the state space of the master selecting as state variables the position ($x_1(t) = \theta(t)$) and the velocity ($x_2(t) = \dot{\theta}(t)$) is:

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

$$y_m(t) = \left[\begin{array}{cc} 1 & 0 \end{array} \right] \left[\begin{array}{c} x_{m1}(t) \\ x_{m2}(t) \end{array} \right] \qquad (2)$$

where J_m and b_m are, respectively, the inertia and the viscous friction coefficient of the master. The representation of the slave is analogous.

All possible interactions that could appear in the operator-master-slave-environment set have been considered, see Figure 1, where:

- A_m, B_m and C_m are the matrices that model the master.

- A_s, B_s and C_s are the matrices that model the slave.

- F_m represents the force that the operator applies in the master.

- u_m and u_s are, respectively, the master and the slave control signals.

- $R_m = \left[\begin{array}{cc} r_{m1} & r_{m2} \end{array} \right]$ allows modelling the force reflection to the master.

- $G_2 = g_2$, $R_s = \left[\begin{array}{cc} r_{s1} & r_{s2} \end{array} \right]$, $K_m = \left[\begin{array}{cc} k_{m1} & k_{m2} \end{array} \right]$, and $K_s = \left[\begin{array}{cc} k_{s1} & k_{s2} \end{array} \right]$ are control gains to obtain.

- Delay represents a constant time delay of T seconds.

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

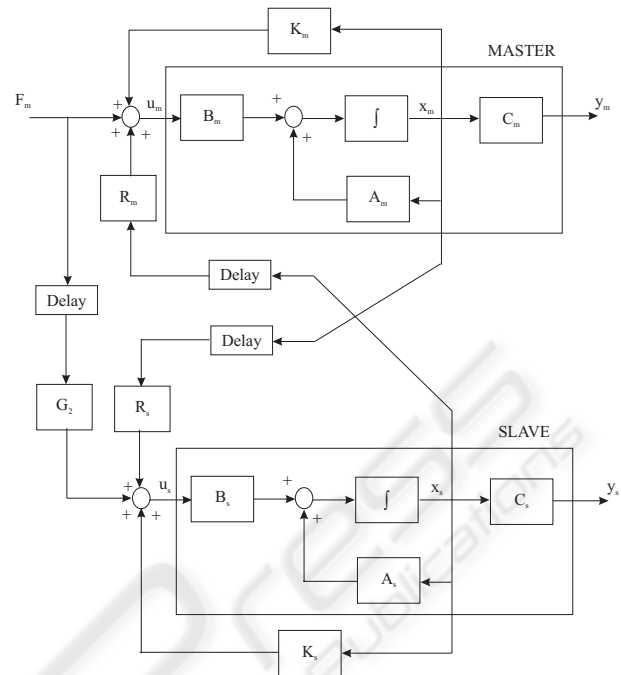$$K_s = \left[\begin{array}{cc} k'_{s1} - k_e & k'_{s2} - b_e \end{array} \right] \qquad (3)$$

Figure 1: Modelling of the teleoperation system with time delay.

where k_e and b_e are, respectively, the stiffness and the viscous friction of the environment. In this way the reaction force of the slave with the environment,

$$f_s(t) = k_e \theta_s(t) + b_e \dot{\theta}_s(t) \qquad (4)$$

will oppose to the slave control signal. To consider force feedback from the slave to the master, the structure of the matrix R_m must be:

$$R_m = \left[\begin{array}{cc} r_{m1} & r_{m2} \end{array} \right] = \left[\begin{array}{cc} k_f k_e & k_f b_e \end{array} \right] \qquad (5)$$

where k_f is the force feedback gain.

2.2 Control Method through State Convergence

From the model shown in Figure 1, it could be observed that the master control signal, $u_m(t)$, and the slave control signal, $u_s(t)$, are respectively:

$$u_m(t) = K_m x_m(t) + R_m x_s(t - T) + F_m(t) \qquad (6)$$

$$u_s(t) = K_s x_s(t) + R_s x_m(t-T) + G_2 F_m(t-T) \qquad (7)$$

Considering that the characteristic polynomial wished of the slave and the error would be, respectively, $p(s) = s^2 + p_1 s + p_0$ and $q(s) = s^2 + q_1 s + q_0$, the control parameters are obtained solving the following equations system:

$$J_m g_2 - T r_{s2} - J_s + T g_2 r_{m2} = 0 \qquad (8)$$

$$J_m k_{s1} - Tr_{m1}r_{s2} - J_s r_{m1} + Tr_{m2}k_{s1} +$$
$$+ J_m r_{s1} - Tr_{s2}k_{m1} + Tr_{m2}r_{s1} = 0 \qquad (9)$$

$$T^2 r_{s2}r_{m1} + J_m(k_{s2} - b_s) - Tr_{s2}r_{m2} -$$
$$- J_s r_{m2} + J_s Tr_{m1} + Tr_{m2}(k_{s2} - b_s) +$$
$$+ J_m(r_{s2} - Tr_{s1}) - Tr_{s2}(k_{m2} - b_m) - \quad (10)$$
$$- T^2 r_{m2}r_{s1} - J_s(k_{m2} - b_m) + Tr_{m2}rs2 = 0$$

$$\frac{J_m k_{s1} - Tr_{m1}r_{s2} + J_m r_{s1} - Tr_{s2}k_{m1}}{J_s J_m - T^2 r_{s2}r_{m2}} = -p_0$$
$$(11)$$

$$\frac{n_p}{J_s J_m - T^2 r_{s2}r_{m2}} = -p_1 \qquad (12)$$

$$\frac{J_s k_{m1} - Tr_{m2}r_{s1} - J_m r_{s1} + Tr_{s2}k_{m1}}{J_s J_m - T^2 r_{s2}r_{m2}} = -q_0$$
$$(13)$$

$$\frac{n_q}{J_s J_m - T^2 r_{s2}r_{m2}} = -q_1 \qquad (14)$$

where:

$$n_p = T^2 r_{s2}r_{m1} + J_m(k_{s2} - b_s) - Tr_{m2}r_{s2} +$$
$$+ J_m(r_{s2} - Tr_{s1}) - Tr_{s2}(k_{m2} - b_m) \quad (15)$$

$$n_q = T^2 r_{m2}r_{s1} + J_s(k_{m2} - b_m) - Tr_{m2}r_{s2} -$$
$$- J_m(r_{s2} - Tr_{s1}) + Tr_{s2}(k_{m2} - b_m) \quad (16)$$

Therefore to obtain the control gains of the teleoperation system shown in Figure 1 only these seven equations must be solved.

2.3 Varying Time Delays

The control method presented in this section considers a constant time delay in the communication channel. This control method is robust to the uncertainty of the design time delay (Azorín et al., 2003b). So the control method allows successfully to control the teleoperation system in spite of that the communication time delay would be different to the design time delay. When there are varying time delays, the communication time delay in each moment can be different of the design time delay. However, the control gains obtained considering a constant time delay can be used to control the teleoperation system when varying time delays appear because of the control method robustness.

3 EXPERIMENTAL RESULTS

We have tested the control method with varying time delays using the experimental platform shown in Figure 2. This platform consists of a master and a slave of one dof. Both manipulators are driven by Premotec brushless DC motors. These motors provide
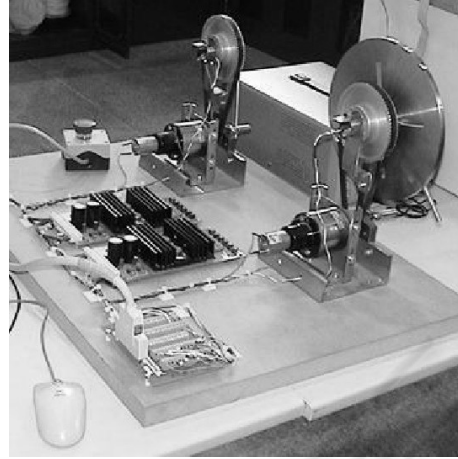

Figure 2: Experimental teleoperation system of one dof.

the joint velocities using tachometers. The joint angles are detected by Spectrol potentiometers. The controller has been implemented on the computer using the Matlab/Simulink real time toolbox. A simple time of 0.01s has been used. The I/O interface utilized between the controller and the experimental platform has been a National Instruments 6024E card. To simulate that Internet is used as transmission channel between the local and remote environment, a random time delay lesser than 1 s has been generated in the communication between the master and the slave. However, a constant time delay of 0.1 s has been considered to design the control system.

It has been explained previously that the slave is driven by a brushless DC motor. In this case the slave torque is proportional to the current intensity of the motor armature. So the contact force of the slave with the environment ($f_s(t)$) can be obtained from the slave motor intensity.

To calculate the slave control signal it is necessary to know the operator force applied over the master ($F_m(t)$). In the experimental setup there is not any force sensor. For this reason the operator force has been calculated as a spring force:

$$F_m(t) = k_{op}\theta_m(t) \qquad (17)$$

where $k_{op} = 100 Nm/rad$.

The experiment performed consists of guiding the slave against a sponge until that the slave can not advance more due to the environment reaction force. The parameters that model this environment are: $k_e = 20 Nm/rad$ and $b_e = 0 Nm/(rad/s)$.

Figure 3 shows the position of the teleoperation system when varying time delays exist. It can be observed that the slave follows the master in spite of the time delays until that the slave can not advance because of the interaction with the environment.
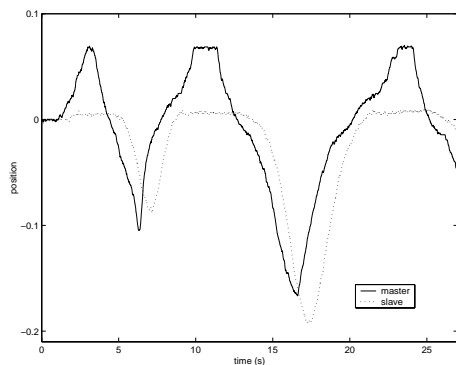
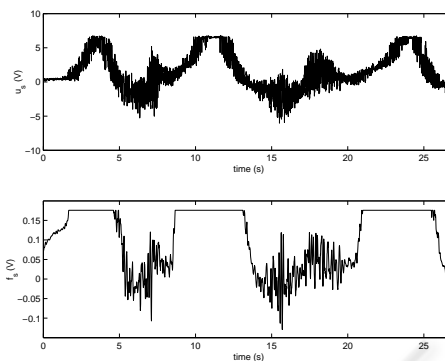Figure 3: Master and slave position obtained experimentally.

Figure 4: Operator force (top part) and master control signal (bottom part).

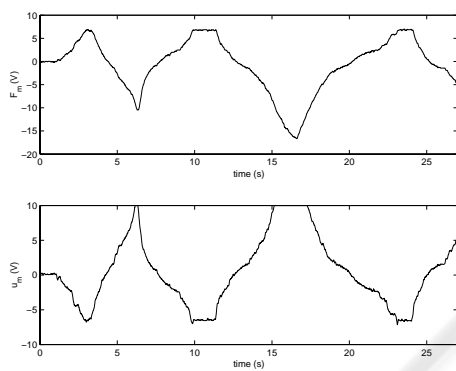Figure 5: Slave control signal (top part) and reaction force of the slave with the environment (bottom part).

4 CONCLUSION

In this paper, a design and control method that we presented to control teleoperation systems with constant time delays is used to control teleoperation systems with varying time delays. To obtain the control gains a constant time delay is considered. However these control gains can be used when varying time delays appear due to the control method robustness. The control method has been verified experimentally in a teleoperation system of one dof. Our future work will be to study the asymptotic stability of the system when there are varying time delays.

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In Figure 4 the operator force (top part) and the master control signal (bottom part) are shown. It can be observed that the master control signal opposites the operator force. In this way the operator feels the force exerted by the slave in the remote environment, and the slave advance is stopped.

Figure 5 shows the slave control signal (top part) and the force reaction of the slave with the environment (bottom part). In this figure it can be observed that as a bigger control action is applied over the slave, bigger values of the reaction force are produced. These values correspond to the instants when the slave can not advance more due to the environment opposition, and the operator continues applying its force over the master to achieve the slave advance.

As it has been shown in this section, the control method through state convergence can be used when varying time delays exist in the communication channel in spite of considering a constant time delay to obtain the control gains.