Advances in Control of Teleoperation System by State Convergence

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ABSTRACT

In this work, we propose a control strategy by state convergence applied to bilateral control of a nonlinear teleoperator system with constant delay.
The bilateral control of the teleoperator system considers the case when the human operator applies a constant force on the local manipulator and when the interaction of the remote manipulator with the environment is considered passive.
The stability analysis is performed using Lyapunov-Krasovskii functional, it showed that using an control algorithm by state convergence for the case with constant delay, the nonlinear local and remote teleoperation system is asymptotically stable, also speeds converge to zero and position tracking is achieved.
This work also presents the implementation of an experimental platform. The mechanical structure of the arm that is located in the remote side has been built and the electric servomechanism has been mounted to control their movement.

Keywords: nonlinear; teleoperation; state convergence; Lyapunov-Krasovskii; timedelay; stability

1. INTRODUCTION

The teleoperator device allows the human operator to perform mechanical actions that are usually performed by human hands and arms. Since the introduction of the first modern master/slave manipulator in the late 1940s, teleoperation systems have been used for a number of different tasks, for example, toxic and harmful material handling operation in remote environments such as submarine or space and perform tasks that require extreme precision and continue to play a role each even more important for this type of applications in the future [1].

Stability is an important aspect to build a teleoperation system with a high level of telepresence. Certainly, if a system exhibits unstable or closely unstable behavior, the illusion of the operator to be virtually present at the remote end can be destroyed, as well as possibly making the task difficult or impossible to implement. For applications of teleoperation in which the remote side is really remote, time delays are the major cause of stability issues.

The first work dealing with the problem of delay was published in [2], where the system was operated in open-loop, so not presents problems of instability [3]. In 1966 and later was determined that a time equal to or less than 50 ms delay can destabilize the bilateral controllers [3]. The problem is due to the generation of energy in the communication channel that makes this component of the system is not passive [3]. A way of solving this problem is the addition of damping to the master and the slave to absorb the energy generated in the system. However, this technique does not guarantee the stability and cause poor performance [4], [5]. As an alternative, is possible to modify the bilateral control in a way such that the communication channel acts as a line without loss of transmission [3].

There is several control schemes proposed in the literature to deal with specific problems in the field of robotics teleoperation [6]. The proposed control schemes use different non-linear control techniques, such as passivity, sliding mode control, adaptive control or robust [7] [8], [9], [10] which allow to stabilize the master-slave system when the communication channel presents small delays and the environment is considered soft. However, in the design of the control algorithms is considered a linear dynamic for the teleoperator and the effect of the delay are analyzed using linear approaches [5], [6].

A first step towards the unification of the analysis of stability for teleoperators with time delay was presented in [11]. They propose a general function as Lyapunov candidate, which with a slight modification, allows analyzing stability of different schemes of control, ranging from constant time delay to variable, with or without transformation of dispersion, and with or without position tracking.

The work presented here is a continuation of the method of design and control presented in [12], which is based on the development of the teleoperation system as a linear system of order n in state space, the control signal allows the remote manipulator follow to the local manipulator through the state convergence even if it has a delay in the communication channel.

The objective of this work is to develop the bilateral control of a nonlinear teleoperator system with constant delay, it is proposed a control strategy for state convergence applied to nonlinear systems.

2. NONLINEAR SYSTEM OF STATE CONVERGENCE

The local and remote manipulator robot are modeled by Lagrange - Euler formulation as a couple of serial links serial of n degrees of freedom with rotational joint.

$$\begin{aligned} M_l(q_l)\ddot{q}_l + C_l(q_l,\dot{q}_l)\dot{q}_l + g_l(q_l) &= \tau_{lc} + F_h \\ M_r(q_r)\ddot{q}_r + C_r(q_r,\dot{q}_r)\dot{q}_r + g_r(q_r) &= \tau_{rc} - F_e \end{aligned} \tag{1}$$

Where $\ddot{q}_i, \dot{q}_i, q_i \in R^n$ correspond to the acceleration, speed and position of the joint $i = \{l, r\}$

$l \rightarrow$ local manipulator robot
$r \rightarrow$ remote manipulator robot

$M_i(q_i) \in R^{n\times n}$	Inertia matrix
$C_i(q_i,\dot{q}_i) \in R^{n\times n}$	Coriolis and centrifugal forces matrices
$g_i(q_i) \in R^n$	Gravitational forces vector
$\tau_{ic} \in R^n$	Signal control torques
$F_h \in R^n$	Human operator interaction force
$F_e \in R^n$	Environment interaction force

In the block diagram of the teleoperator system, Fig. 1, the dynamics of the local and remote manipulator is given by Eq. (1). It is presumed that the interaction of the human operator with the local handle is a constant force in the following way [13]:

$$F_h = F_{op} \text{ Constant vector } \in R^n \tag{2}$$

The interaction of the environment with the remote manipulator is considered passive.

$$F_e = K_e q_r + B_e \dot{q}_r \tag{3}$$

K_e, B_e are definite positive matrix $\in R^{n\times n}$

We proposed the control law Eq. (4) [14], as show in Fig. 1 this control law is the compensation of gravitational forces, so that the control torques τ_{ic} are given by:

$$\tau_{lc} = \tau_l + g_l(q_l), \quad \tau_{rc} = \tau_r + g_r(q_r) \tag{4}$$

Replacing Eq. (4) in Eq. (1) yields:

$$\begin{aligned} M_l(q_l)\ddot{q}_l + C_l(q_l,\dot{q}_l)\dot{q}_l &= \tau_l + F_{op} \\ M_r(q_r)\ddot{q}_r + C_r(q_r,\dot{q}_r)\dot{q}_r &= \tau_r - F \end{aligned} \tag{5}$$

Consider the local and remote manipulator Eq. (1) connected via a communication channel with a constant delay, T, as show in Fig.1.

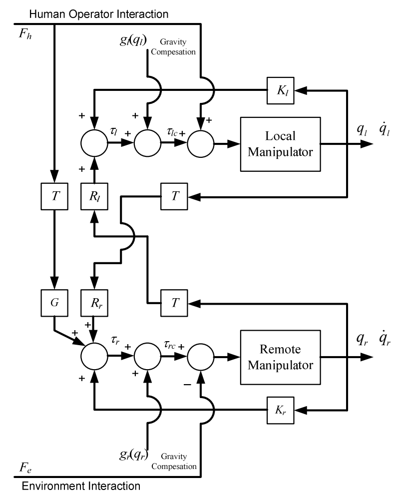

Figure 1. Block diagram of nonlinear control of teleoperation system considering delay.

Consider the control algorithm for state convergence for the non-linear case, the coupling torque for the local and remote manipulator is given by:

$$\begin{aligned} \tau_l &= K_{l1}q_l + K_{l2}\dot{q}_l + R_{l1}q_r(t-T) + R_{l2}\dot{q}_r(t-T) \\ \tau_r &= K_{r1}q_r + K_{r2}\dot{q}_r + R_{r1}q_l(t-T) + R_{r2}\dot{q}_l(t-T) + G_2F_{op}(t-T) \end{aligned} \tag{6}$$

Where:

$$K_l = [K_{l1} \quad K_{l2}], R_l = [R_{l1} \quad R_{l2}], K_r = [K_{r1} \quad K_{r2}], R_r = [R_{r1} \quad R_{r2}]$$

Where: K_{l1}, K_{l2}, R_{l1}, R_{l2}, K_{r1}, K_{r2}, R_{r1} and R_{r2} are order nxn matrices constant diagonal positive definite. G_2 is a constant.

The equilibrium points of the position of local and remote manipulator are defined as $\bar{q}_l \in R^n$ y $\bar{q}_r \in R^n$ then by using Eq. (2), Eq. (3), Eq. (5) and Eq. (6).

$$\begin{aligned} 0 &= \bar{F}_{op} + K_{l1}\bar{q}_l + R_{l1}\bar{q}_r \\ 0 &= K_{r1}\bar{q}_r + R_{r1}\bar{q}_l + G\bar{F}_{op}(t-T) - K_e\bar{q}_r \end{aligned} \tag{7}$$

Defining new position variables:

$$\tilde{q}_l(t)=q_l(t)-\bar{q}_l \rightarrow q_l(t)=\tilde{q}_l+\bar{q}_l \quad (8)$$

$$\tilde{q}_r(t)=q_r(t)-\bar{q}_r \rightarrow q_r(t)=\tilde{q}_r+\bar{q}_r \quad (9)$$

Replacing Eq. (6), Eq. (8) and Eq. (9) in Eq. (5), the dynamics of bilateral teleoperation in closed-loop system is given by:

$$\begin{aligned} M_l\ddot{\tilde{q}}_l+C_l\dot{\tilde{q}}_l &= K_{l1}\tilde{q}_l+R_{l1}\tilde{q}_r(t-T)+K_{l2}\dot{\tilde{q}}_l++R_{l2}\dot{\tilde{q}}_r(t-T) \\ M_r\ddot{\tilde{q}}_r+C_r\dot{\tilde{q}}_r &= K_{r1}\tilde{q}_r+R_{r1}\tilde{q}_l(t-T)+K_{r2}\dot{\tilde{q}}_r+R_{r2}\dot{\tilde{q}}_l(t-T)-K_e\tilde{q}_r-B_e\dot{\tilde{q}}_r \end{aligned} \quad (10)$$

Theorem 2.1:

For the bilateral teleoperation system given by Eq. (10), making the following considerations

$$\begin{aligned} &K_{l1}=-K, \quad K_{l2}=-3K_1, \quad K_{r1}=-K, \quad R_{l2}=2K_1 \\ &R_{l1}=K, \quad K_{r2}=-3K_1, \quad R_{r1}=K, \quad R_{r2}=2K_1 \end{aligned} \quad (11)$$

Where: K_1 and K are positive definite constant diagonal matrices.

If the following is satisfied:

$$K_1-\frac{\alpha_1}{2}K-\frac{T^2}{2\alpha_2}K>0, \quad K_1-\frac{\alpha_2}{2}K-\frac{T^2}{2\alpha_1}K>0 \quad (12)$$

Where α_1, α_2 and T are scalar constants, then

$$\lim_{t\to\infty}\tilde{q}_l=\lim_{t\to\infty}\tilde{q}_r=\lim_{t\to\infty}\dot{\tilde{q}}_l=\lim_{t\to\infty}\dot{\tilde{q}}_r=0$$

Reflection Static Force

Consider the non-linear teleoperator system described by Eq. (5) and the control law given by Eq. (6) for the range of control given by Eq. (12), you have the following:

$$0=\bar{F}_{op}+K_{l1}\bar{q}_l+R_{l1}\bar{q}_r$$

Where $K_{l1}=-K, \quad R_{l1}=K$, $K_{r1}=-K, \quad R_{r1}=K$

$$\begin{aligned} &\bar{F}_{op}=K(\bar{q}_l-\bar{q}_r) \\ &0=-F_e+K_{r1}\bar{q}_r+R_{r1}\bar{q}_l+G_2\bar{F}_{op} \quad (13) \\ &0=-F_e+K(\bar{q}_l-\bar{q}_r)+G_2\bar{F}_{op} \\ &\bar{F}_{op}=\frac{F_e}{(1+G_2)} \quad (14) \end{aligned}$$

Local-Remote Manipulator Position Coordination

If $F_{op}=F_e=0$, Eq. (13) and Eq. (14) can be written as $\bar{q}_l-\bar{q}_r=0$.

This implies that the equilibrium points of the local and remote manipulator are identical. Then, the position coordination error $\tilde{q}(t)=q_l(t)-q_r(t)$

Tends to zero like

$$\lim_{t\to\infty}\tilde{q}(t)=\lim_{t\to\infty}(q_l(t)-q_r(t))=0$$

Then, there is positions coordination between the local and remote manipulator.

3. SIMULATION

Control law Eq. (4) and Eq. (6) applied to the dynamics of the teleoperation system Eq. (1) have been simulated using Matlab™ and Simulink®. As local manipulator we use a PHANTOM Omni®, haptic device of Sensable Technologies. As remote manipulator will use a planar serial arm of three degrees of freedom, actuated by DC motors [20]:

$$\begin{aligned} M_l(q_l)\ddot{q}_l+C_l(q_l,\dot{q}_l)\dot{q}_l+g_l(q_l)+f_l(\dot{q}_l)&=\tau_{lc}+F_{op} \\ M_r(q_r)\ddot{q}_r+C_r(q_r,\dot{q}_r)\dot{q}_r+g_r(q_r)+f_r(\dot{q}_r)&=\tau_e-F_e \end{aligned}$$

$f(\dot{q})\in R^n$ It is a static model of joints friction, defined by [14]:

$$f_l(\dot{q}_l)=f_r(\dot{q}_r)=f(\dot{q})=\begin{bmatrix}0.05 & 0 & 0\\ 0 & 0.05 & 0\\ 0 & 0 & 0.05\end{bmatrix}\begin{bmatrix}\dot{q}_1\\ \dot{q}_2\\ \dot{q}_3\end{bmatrix}$$

All the simulations have been realized using a communication channel time delay of the $T = 0.5$ s.

The inertia matrix M_r, the coriolis and centrifugal forces matrix C_r, the force of gravity matrix g_r of remote manipulator are defined by:

$$M_r=\begin{bmatrix}M_{11} & M_{12} & M_{13}\\ M_{21} & M_{22} & M_{23}\\ M_{31} & M_{32} & M_{33}\end{bmatrix}, \quad C_r=\begin{bmatrix}C_{11} & C_{12} & C_{13}\\ C_{21} & C_{22} & C_{23}\\ C_{31} & C_{32} & C_{33}\end{bmatrix}$$

$$g_r=\begin{bmatrix}g_1\\ g_2\\ g_3\end{bmatrix}$$

Where:

$$M_{11} = 0.045879 + 0.03176\cos(q_2)$$
$$M_{12} = M_{21} = 0.012801 + 0.01588\cos(q_2)$$
$$M_{13} = M_{31} = 0.0014037$$
$$M_{22} = 0.012801$$
$$M_{23} = M_{32} = 0.0014037$$
$$M_{33} = 0.0014037$$
$$C_{11} = C_{13} = 0$$
$$C_{12} = -0.01588\sin(q_2)(\dot{q}_2 + 2\dot{q}_1)$$
$$C_{21} = 0.01588\sin(q_2)\dot{q}_1$$
$$C_{22} = C_{23} = 0, \quad C_{31} = C_{32} = C_{33} = 0$$
$$g_1 = -0.739\sin(q_1)\cos(q_2) - 0.739\cos(q_1)\sin(q_2) - 1.6409\sin(q_1)$$
$$g_2 = -0.739\cos(q_1)\sin(q_2) - 0.739\sin(q_1)\cos(q_2)$$
$$g_3 = 0$$

Considering the gains K y K_1 in Eq. (13) as:

$$K_1 = \begin{bmatrix} 40 & 0 & 0 \\ 0 & 30 & 0 \\ 0 & 0 & 10 \end{bmatrix}, \quad K = \begin{bmatrix} 79 & 0 & 0 \\ 0 & 59 & 0 \\ 0 & 0 & 15 \end{bmatrix}$$

The controller parameters K_{l1}, K_{l2}, K_{r1}, K_{r2}, R_{l1}, R_{l2}, R_{r1} and R_{r2} they are determined by Eq. (12), in addition G = 1.

Simulations have been carried out considering that the case in which the remote manipulator does not interact with the environment and the case when there is interaction with the environment. In order to assess the stability of the contact, in simulations, is considered a soft environment modeled by means of a spring -damper system, with the spring and damper gains as:

$$K_e = \begin{bmatrix} 25 & 0 & 0 \\ 0 & 25 & 0 \\ 0 & 0 & 25 \end{bmatrix} N/m, \quad B_e = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} N \cdot s/m$$

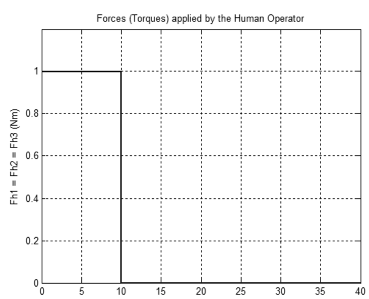

Figure 2. Force (torque) applied by the human operator.

Fig. 2 show the force (torque) applied by the human operator to the local manipulator.

Without Environment Interaction

Fig. 3 and Fig. 4 show the joints positions of the local and remote manipulator. From simulations can be show that is guaranteed stability for the considered time-delay.

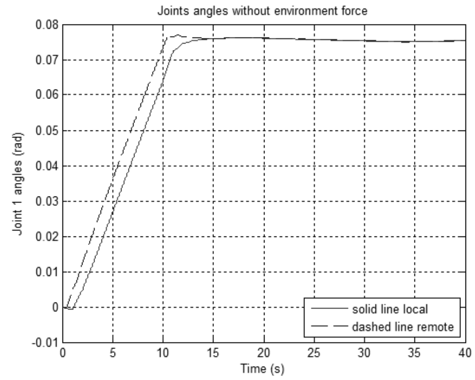

Figure 3. Joint 1 angles position of local and remote manipulator (rad) Vs. Time (s).

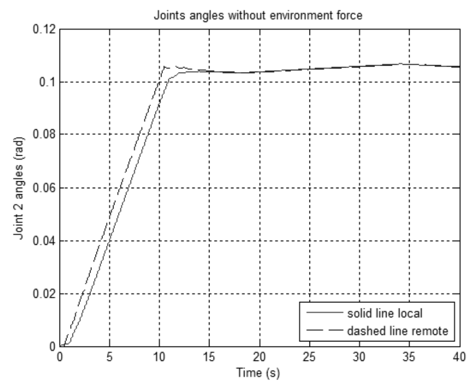

Figure 4. Joint 2 angles position of local and remote manipulator (rad) Vs. Time (s).

Environment Interaction

Fig. 5 and Fig. 6 show the joints positions of the local and remote manipulator.

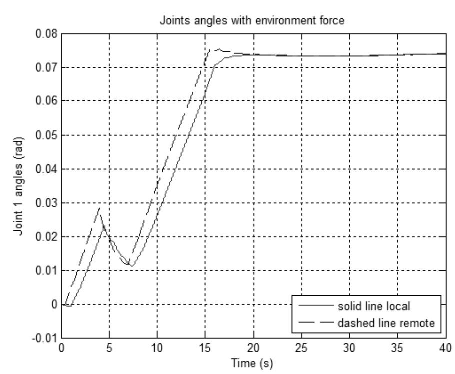

Figure 5. Joint 1 angles position of local and remote manipulator (rad) Vs. Time (s).

In Fig.4 and Fig. 5 it can be observed how the local and remote position coordination is achieved. In this case, the remote manipulator does not interact with environment and the operator force is negligible (0 – 4 sec and 7-40 sec).

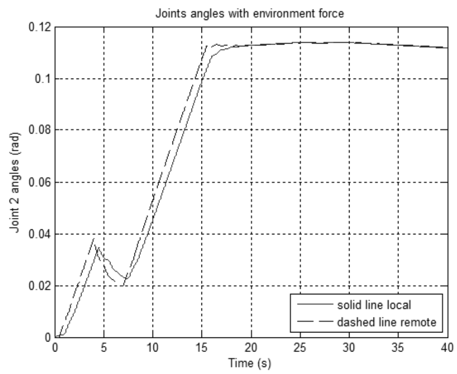

Figure 6. Joint 2 angles position of local and remote manipulator (rad) Vs. Time (s).

It can be clearly seen that the control scheme proposed renders a stable behavior of the teleoperator system during the interaction with environments and also provides it with good position tracking capabilities of trajectories in free space motion.

4. EXPERIMENTAL SETUP

The experimental test of the Teleoperation system has been developed, as shown in Fig. 7.

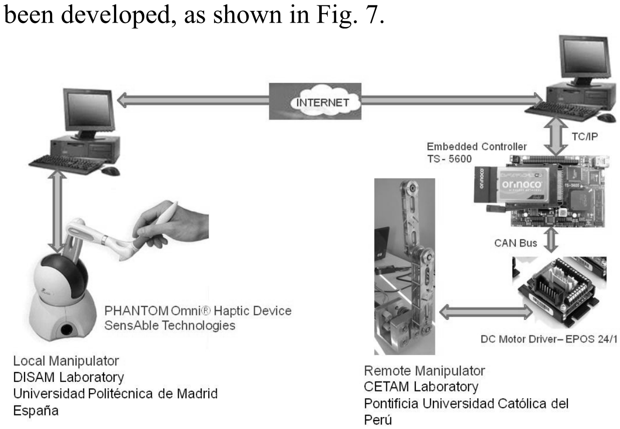

Figure 7. A real-time experimental setup for Teleoperation System.

The elements of the experimental setup are described below.

Local Manipulator

Local side uses a haptic device PHANTOM Omni® from SensAble Technologies as local manipulator.

Remote Manipulator

Remote manipulator is three degrees of freedom planar serial manipulator, Fig. 8. One of the main disadvantages of serials with electrical actuators robots is their relationship load vs. weight. Because of this a robot designed is one that the motors are located at the base. For this reason the arm is implemented with a series of transmissions leading the movement to each of the joints. Transmissions are performed using bearings and toothed belts polyurethane with steel fibers which provide the Sync feature which is essential for the control of the robot [20]. The material used for the manufacture of the links in the arm is stainless steel, aluminum has been considered for other elements. The developed mechanical structure is compact and lightweight.

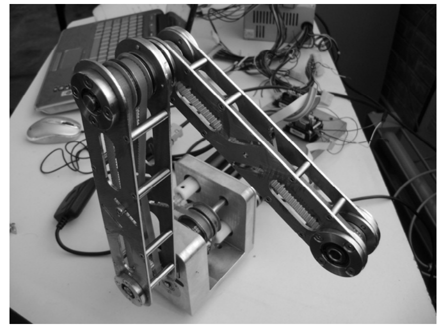

Figure 8. Remote Manipulator Structure.

Motion Control Board EPOS 24/1

The actuator system consists of the electric brushless DC motors and power drivers EPOS 24/1.Because there are multiple devices EPOS, the CANopen Protocol is used. Has developed the drives for the management of the operations of the remote manipulator: send/reception of position, speed, acceleration and current data through a CAN network.

Embedded Controller: PC104 Board

The TS-5600 is a compact, single Board Computer with all the features of a compatible computer, based on the AMD Elan520 processor, at 133 MHz frequency.

The PC support allows rapid development, because you can use tools based on DOS and Linux Operating Systems and QNX Embedded Real-Time Operating Systems.

Internet Communications

Two transport protocols usually applied to the development of networked robot applications, one which is packet oriented (User Datagram Protocol, UDP) and the other which is stream oriented (Transport Control Protocol, TCP).

TCP/IP networking was designed to work over highly unpredictable and unreliable communication channels.

The TCP protocol is defined as a reliable protocol while the UDP protocol is defined as unreliable [21]. TCP is suitable for applications that require guaranteed delivery (e.g., static data transfer), where delay is not of the first concern, but accurate and complete reception may be the more important thing [22].

On the other hand, the User Datagram Protocol (UDP) is connectionless. Data is sent in packets, there is no error correction or detection above the network layer and there is no handshake. UDP supplies minimized transmission delay by omitting the connection setup process, acknowledgement, and retransmission [22]. UDP is commonly applied to the transmission of low level commands. These commands are related to low-level control robot movements which demand different network requirements.

In this control systems implementation, the UDP protocol will be used. Because, it is better suited structurally to the control problem and is much simpler to use. Coupled with a reliable link layer, it should be appropriate for control of teleoperation system.

5. CONCLUSIONS

We have shown in this paper that it is possible to control a bilateral teleoperator system with the proposed framework state convergence. The method is based on the state space formulation and it allows the remote manipulator to follow the local manipulator through state convergence.

This paper has presented the study of bilateral control of the nonlinear teleoperator system when the passivity of the human operator is not guaranteed. Specifically, we considered the case when the human operator applies a constant force on the local manipulator and the interaction of the remote manipulator with the environment is considered to be passive, and is modeled as a spring damper system.

Considering a constant delay, when the local and remote manipulator are coupled using proposed framework, developed analysis shows the stability of the nonlinear teleoperation system both local and remote, and position coordination. The range of the corresponding proportional gains was established using Lyapunov analysis.

We performed some simulations that validate the theoretical results of this paper.

Implemented structure will allow and facilitate implementation of proposed nonlinear state convergence control in real-time for teleoperated system in the presence of delays in communication.

Experimental results are currently under way and will be reported in the near future.

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