REAL-TIME BILATERAL CONTROL OF A NONLINEAR TELEOPERATION SYSTEM

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[1] Fellowship – Fundación Carolina, Spain

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Goal

- The goal 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.

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Teleoperation System

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Manipulator Dynamic Model

$$\mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\mathbf{q}_l,\dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l + \mathbf{g}_l(\mathbf{q}_l) = \boldsymbol{\tau}_{lc} + \mathbf{F}_h$$

$$\mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r,\dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r + \mathbf{g}_r(\mathbf{q}_r) = \boldsymbol{\tau}_{rc} - \mathbf{F}_e$$

Inertia Matrix **M,** coriolis and centrifugal matrix forces **C**, gravity forces matrix **g** are definde by:

$$\mathbf{M}_l = \mathbf{M}_r = \mathbf{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}, \mathbf{C}_l = \mathbf{C}_r = \mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

$$\mathbf{g}_l = \mathbf{g}_r = \mathbf{g} = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix}$$

Interaction of the human operator with the local handle

$$\mathbf{F}_h = \mathbf{F}_{op}$$

$\mathbf{F}_{op}$ is a constant vector $\in \mathbf{R}^n$

The interaction of the environment with the remote manipulator

$$\mathbf{F}_e = \mathbf{K}_e\mathbf{q}_r + \mathbf{B}_e\dot{\mathbf{q}}_r$$

$\mathbf{K}_e$, $\mathbf{B}_e$ are definite positive matrix $\in \mathbf{R}^{(nxn)}$

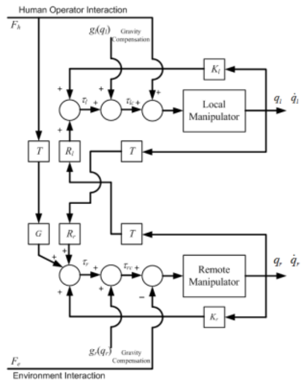
Compensation of gravitational forces

$$\boldsymbol{\tau}_{lc} = \boldsymbol{\tau}_l + \mathbf{g}_l(\mathbf{q}_l), \quad \boldsymbol{\tau}_{rc} = \boldsymbol{\tau}_r + \mathbf{g}_r(\mathbf{q}_r)$$

$$\mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\mathbf{q}_l,\dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l = \boldsymbol{\tau}_l + \mathbf{F}_{op}$$

$$\mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r,\dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r = \boldsymbol{\tau}_r - \mathbf{F}_e$$

Sate Convergence Nonlinear System



State Covergence Control Law

$$\boldsymbol{\tau}_l = \mathbf{K}_{l1}\mathbf{q}_l + \mathbf{K}_{l2}\dot{\mathbf{q}}_l + \mathbf{R}_{l1}\mathbf{q}_r(t-T) + \mathbf{R}_{l2}\dot{\mathbf{q}}_r(t-T)$$

$$\boldsymbol{\tau}_r = \mathbf{K}_{r1}\mathbf{q}_r + \mathbf{K}_{r2}\dot{\mathbf{q}}_r + \mathbf{R}_{r1}\mathbf{q}_l(t-T) + \mathbf{R}_{r2}\dot{\mathbf{q}}_l(t-T) + G_2\mathbf{F}_{op}(t-T)$$

$$\mathbf{K}_l = [\mathbf{K}_{l1} \quad \mathbf{K}_{l2}], \mathbf{R}_l = [\mathbf{R}_{l1} \quad \mathbf{R}_{l2}], \mathbf{K}_r = [\mathbf{K}_{r1} \quad \mathbf{K}_{r2}], \mathbf{R}_r = [\mathbf{R}_{r1} \quad \mathbf{R}_{r2}]$$

Where $\mathbf{K}_l$, $\mathbf{R}_l$, $\mathbf{K}_r$, $\mathbf{R}_r$ are matrices $\in \mathbf{R}^{(nxn)}$ G_2 is a constant

Dynamics of bilateral teleoperation in closed-loop system

Defining new position variables:

$$\tilde{\mathbf{q}}_l(t) = \mathbf{q}_l(t) - \bar{\mathbf{q}}_l$$

$$\tilde{\mathbf{q}}_r(t) = \mathbf{q}_r(t) - \bar{\mathbf{q}}_r$$

$$\mathbf{M}_l\ddot{\tilde{\mathbf{q}}}_l + \mathbf{C}_l\dot{\tilde{\mathbf{q}}}_l = \mathbf{K}_{l1}\tilde{\mathbf{q}}_l + \mathbf{R}_{l1}\tilde{\mathbf{q}}_r(t-T) + \mathbf{K}_{l2}\dot{\tilde{\mathbf{q}}}_l + \mathbf{R}_{l2}\dot{\tilde{\mathbf{q}}}_r(t-T)$$

$$\mathbf{M}_r\ddot{\tilde{\mathbf{q}}}_r + \mathbf{C}_r\dot{\tilde{\mathbf{q}}}_r = \mathbf{K}_{r1}\tilde{\mathbf{q}}_r + \mathbf{R}_{r1}\tilde{\mathbf{q}}_l(t-T) + \mathbf{K}_{r2}\dot{\tilde{\mathbf{q}}}_r + \mathbf{R}_{r2}\dot{\tilde{\mathbf{q}}}_l(t-T) - \mathbf{K}_e\tilde{\mathbf{q}}_r - \mathbf{B}_e\dot{\tilde{\mathbf{q}}}_r$$

Theorem[1]: For the nonlinear bilateral teleoperation close loop system, making the following considerations:

$$\mathbf{K}_{l1} = -\mathbf{K}, \quad \mathbf{K}_{l2} = -3\mathbf{K}_1, \quad \mathbf{K}_{r1} = -\mathbf{K}, \quad \mathbf{R}_{l2} = 2\mathbf{K}_1$$

$$\mathbf{R}_{l1} = \mathbf{K}, \quad \mathbf{K}_{r2} = -3\mathbf{K}_1, \quad \mathbf{R}_{r1} = \mathbf{K}, \quad \mathbf{R}_{r2} = 2\mathbf{K}_1$$

Where $\mathbf{K}_1$ y $\mathbf{K}$ are positive definite constant diagonal matrices.
If the following is satisfied :

$$\mathbf{K}_1 - \frac{\alpha_1}{2}\mathbf{K} - \frac{T^2}{2\alpha_2}\mathbf{K} > \mathbf{0}, \quad \mathbf{K}_1 - \frac{\alpha_2}{2}\mathbf{K} - \frac{T^2}{2\alpha_1}\mathbf{K} > \mathbf{0}$$

Where α_1, α_2 and T are scalar constants, then:

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

[1] For stability analysis Lyapunov-Krasovskii was used

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Therefore the origin of the system

$$\dot{\tilde{\mathbf{q}}}_l, \dot{\tilde{\mathbf{q}}}_r, \tilde{\mathbf{q}}_l, \tilde{\mathbf{q}}_r$$

is asymptotically stable and

$$\lim_{t\to\infty}\mathbf{q}_l(t) = \bar{\mathbf{q}}_l, \lim_{t\to\infty}\mathbf{q}_r(t) = \bar{\mathbf{q}}_r$$

This guarantees the stability of the teleoperation system**!!!**

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Position Coordination- Local and Remote Manipulator

If

$$\mathbf{F}_{op} = \mathbf{F}_e = \mathbf{0}$$

Then

$$\bar{\mathbf{q}}_l - \bar{\mathbf{q}}_r = \mathbf{0}$$

This implies that the equilibrium points of the local and remote manipulator are identical

$$\tilde{\mathbf{q}}(t) = \mathbf{q}_l(t) - \mathbf{q}_r(t)$$

$$\lim_{t\to\infty}\tilde{\mathbf{q}}(t) = \lim_{t\to\infty}(\mathbf{q}_l(t) - \mathbf{q}_r(t)) = \mathbf{0}$$

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

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Simulation

Simulation were performer using Matlab™ and Simulink® for an identical local and remote manipulator of three degrees of freedom.

$$\mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\mathbf{q}_l, \dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l + \mathbf{g}_l(\mathbf{q}_l) + \mathbf{f}_l(\dot{\mathbf{q}}_l) = \boldsymbol{\tau}_{lc} + \mathbf{F}_{op}$$
$$\mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r, \dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r + \mathbf{g}_r(\mathbf{q}_r) + \mathbf{f}_r(\dot{\mathbf{q}}_r) = \boldsymbol{\tau}_e - \mathbf{F}_e$$

$$\mathbf{M}_l = \mathbf{M}_r = \mathbf{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}, \mathbf{C}_l = \mathbf{C}_r = \mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

$$\mathbf{g}_l = \mathbf{g}_r = \mathbf{g} = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix}$$

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$$M_{11} = 0.045879 + 0.03176\cos(q_2)$$
$$M_{12} = M_{21} = 0.012801 + 0.01588\cos(q_2)$$
$$M_{13} = M_{31} = 0.0014037$$
$$M_{22} = 0.012801$$
$$M_{23} = M_{32} = 0.0014037$$
$$M_{33} = 0.0014037$$

$$C_{11} = C_{13} = 0$$
$$C_{12} = -0.01588\sin(q_2)(\dot{q}_2 + 2\dot{q}_1)$$
$$C_{21} = 0.01588\sin(q_2)\dot{q}_1$$
$$C_{22} = C_{23} = 0, \quad C_{31} = C_{32} = C_{33} = 0$$

$$g_1 = -0.739\sin(q_1)\cos(q_2) - 0.739\cos(q_1)\sin(q_2) - 1.6409\sin(q_1)$$
$$g_2 = -0.739\cos(q_1)\sin(q_2) - 0.739\sin(q_1)\cos(q_2)$$
$$g_3 = 0$$

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

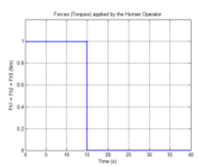
$$\mathbf{K}_l = \begin{bmatrix} 40 & 0 & 0 \\ 0 & 30 & 0 \\ 0 & 0 & 10 \end{bmatrix}, \quad \mathbf{K} = \begin{bmatrix} 79 & 0 & 0 \\ 0 & 59 & 0 \\ 0 & 0 & 15 \end{bmatrix}$$

$$\mathbf{F}_e = \mathbf{K}_e\mathbf{q}_r + \mathbf{B}_e\dot{\mathbf{q}}_r$$

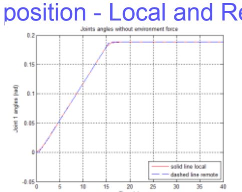
$$\mathbf{K}_e = \begin{bmatrix} 25 & 0 & 0 \\ 0 & 25 & 0 \\ 0 & 0 & 25 \end{bmatrix} \mathrm{N/m}, \quad \mathbf{B}_e = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathrm{N \cdot s/m}$$

Case A: Without environment interaction

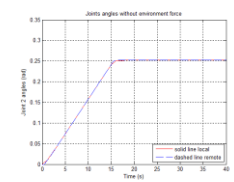
Operator Force



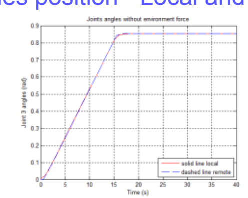
Joint 1 angles position - Local and Remote Manipulator



Joint 2 angles position - Local and Remote Manipulator

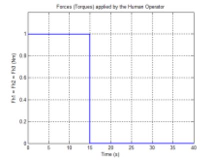


Joint 3 angles position - Local and Remote Manipulator

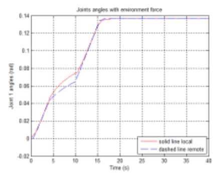


Case B: With Environment Interaction

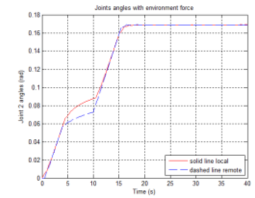
Operator Force



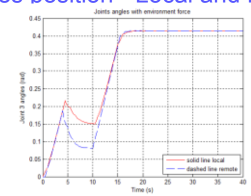
Joint 1 angles position - Local and Remote Manipulator



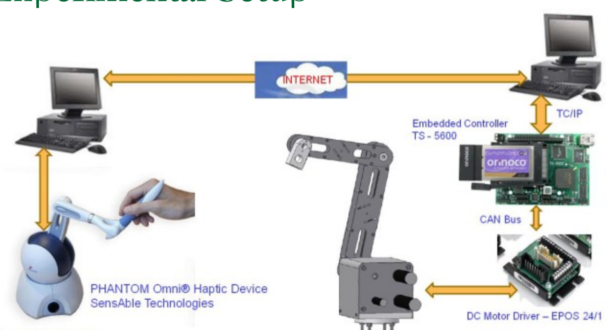
Joint 2 angles position - Local and Remote Manipulator



Joint 3 angles position - Local and Remote Manipulator



Experimental Setup



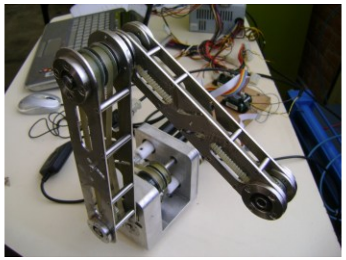
Local Manipulator
DISAM Laboratory
Universidad Politécnica de Madrid
España

Remote Manipulator
CETAM Laboratory
Pontificia Universidad Católica del Perú

- Human operator interacts physically with a haptic device which reflects the forces of the environment as well as the interaction forces.
- The computer processes the information from the haptic device and sensors (force and encoders) in order to send signals of control towards a PC104 card.
- Communication between the computer and the PC104 card is done through a router using the UDP Protocol (User Datagram Protocol).
  - The PC104 card in controls the motors trough CAN Network (Controller Area Network)

Remote Manipulator Arm

- Remote manipulator is three degrees of freedom planar serial manipulator.
- The actuator system consists of the electric brushless DC motors and power drivers EPOS 24/1.



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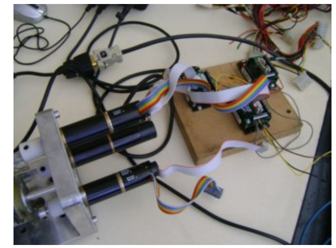
Motion Control Board EPOS 24/1

- Maxon motor EPOS 24/1 is a digital motion controller.
  - Devices EPOS used the CANopen Protocol.
  - The individual devices in the network are commanded by the CANopen master.



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Local Manipulator Arm

- Local side uses a haptic device PHANTOM Omni® from SensAble Technologies as local manipulator.
- remote arm reproduces the movements of the operator on this device.

Internet Communications

- In this control systems implementation, the UDP protocol will be used.
  - 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.

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Conclusions

- Considering a constant delay, when the local and remote manipulator are coupled using an control algorithm's of state convergence, developed analysis shows the stability of the nonlinear teleoperation system both local and remote, and moreover follow-up of position
- This article has presented the study of bilateral control of the nonlinear teleoperator system 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.
- We performed some simulations that validate the theoretical results of this paper.

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Future Work

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

Thanks!!!

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