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A multi-master multi-slave bilateral teleoperation architecture using the two-layer approach

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***Abstract*—In this contribution, a two-layer architecture for multi-master multi-slave bilateral teleoperation systems with communication delay is presented. The novelty with respect to previous works is the use of a single energy tank to reduce the conservativeness due to the passivity approach and to increment the level of transparency.**

***Index Terms*—Teleoperation, Passivity, Multi-Master Multi-Slave Systems**

I. Introduction

In a bilateral teleoperation system the operator moves a haptic device, the master robot, and the position information is sent to a remote robot, the slave robot, that replicates the motion of the master. During the interaction with the environment, the interaction force is sent back to the master side in order to provide the user with the feeling of being directly interacting with the remote environment. The communication between master and slave sides is not usually over a dedicated channel and so the system is affected by an unknown and time-varying communication delay. See [1], [2] for some use of this technology.

When dealing with complex tasks, the single-master-single-slave (SMSS) teleoperation may not provide the necessary level of dexterity and flexibility and it would be necessary to resort to Multi-master-multi-slave (MMMS) teleoperation.

We extend the two-layer architecture proposed in [3] to the multi-master-multi-slave teleoperation. A naive solution would be to decompose the MMMS system into pairs of master-slave robots and to implement the standard two-layer architecture on each pair. This approach is conceptually very simple but it would imply the implementation of a coordination strategy among the transparency layers. Furthermore, the presence of many energy tanks may lead to energetic inconsistencies that may cause an excess of conservatism and degrade the performance of the MMMS teleoperation system. Finally, in general the number of master robots may be different from the number of slaves and, therefore, a pairwise decomposition may not be possible. To avoid these problems and to keep the simplicity of the two-layer architecture, we propose to use only two shared energy tanks, one for the masters and the other for the slaves. The *passivity layer* will manage the passive exchange of energy between the tanks and between each tank and the robots. The *transparency layer* will compute the desired behavior for the whole multi-master side and for the multi-slave side.

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II. Control Architecture

We consider a system composed by N_m masters and N_s slave robots, fully actuated and locally gravity compensated. Each robot can be modeled as the following n-DOFs Euler-Lagrang system:

$$\Lambda_{w_i}\left(x_{w_i}(t)\right)\ddot{x}_{w_i}(t) + \mu_{w_i}\left(x_{w_i}(t), \dot{x}_{w_i}(t)\right)\dot{x}_{w_i}(t) = F^{\tau}_{w_i}(t) + F^{ext}_{w_i}(t)$$

where $w \in \{m, s\}$ (the subscripts m for the master and s for the slave side), $x_{w_i}(t) \in \mathbb{R}^n$, $i = 1, \dots, N_w$ is the coordinate vector of the end-effectors in the task space, $\Lambda_{w_i}\left(x_{w_i}(t)\right) \in \mathbb{R}^{n\times n}$ is the symmetric and positive-definite inertia matrix and $\mu_{w_i}\left(x_{w_i}(t), \dot{x}_{w_i}(t)\right) \in \mathbb{R}^{n\times n}$ is the Coriolis/centrifugal matrix. The term $F^{\tau}_{w_i}(t) \in \mathbb{R}^n$ represents the control inputs while $F^{ext}_{wi}(t) \in \mathbb{R}^n$ is the vector of generalized external forces, i.e. the force applied by the user or the force applied by the environment. It is possible to build a Euler-Lagrangian model of the whole master and slave sides. Defining $x_w(t) = [x^T_{w_1}(t), ..., x^T_{w_{N_w}}(t)]^T$, $\Lambda_w\left(x_w(t)\right) = diag\{\Lambda_{w_1}, ..., \Lambda_{w_{N_w}}\}$, $\mu_w\left(x_w(t), \dot{x}_w(t)\right) = diag\{\mu_{w_1}, ..., \mu_{w_{N_w}}\}$, $F^{\tau}_w(t) = [F^{\tau^T}_{w_1}(t), ..., F^{\tau^T}_{w_{N_w}}(t)]^T$ and $F^{ext}_w(t) = [F^{ext^T}_{w_1}(t), ..., F^{ext^T}_{w_{N_w}}(t)]^T$, we can model each side of the teleoperation system as

$$\Lambda_w(x_w(t))\ddot{x}_w(t) + \mu_w(x_w(t), \dot{x}_w(t))\dot{x}_w(t) = F^{\tau}_w(t) + F^{ext}_w(t).$$

The model of each side of the system is augmented introducing an energy tank at both master and slave sides [4]. The block diagram of the teleoperation architecture for a 2-master 2-slave system is shown in Figure 1 where the communication channel is explicitly indicated.

Implementing on each robot a controlled dissipation in order to harvest some energy for filling the energy tank when necessary and a power preserving interconnection between all the robots and the shared energy tank, we will end up with the system

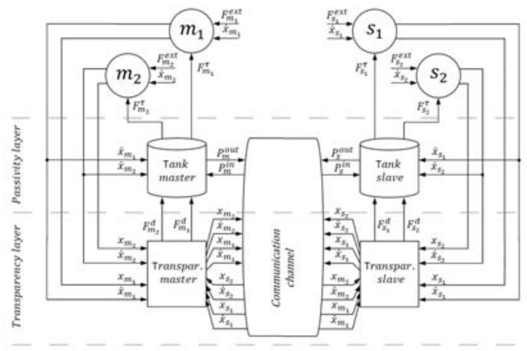

Fig. 1. Coupling of two generic master devices m_1 and m_2 with two slave devices s_1 and s_2 and one tank per side by means of the communication channel.

$$\begin{cases} \Lambda_m \ddot{x}_m + \mu_m \dot{x}_m + D_m \dot{x}_m = \omega_m x_{t_m} + F_m^{ext} \\ \dot{x}_{t_m} = \dfrac{\sigma_m}{x_{t_m}} \dot{x}_m^T D_m \dot{x}_m + \dfrac{1}{x_{t_m}} (\sigma_m P_m^{in} - P_m^{out}) - \omega_m^T \dot{x}_m \\ \Lambda_s \ddot{x}_s + \mu_s \dot{x}_s + D_s \dot{x}_s = \omega_s x_{t_s} + F_s^{ext} \\ \dot{x}_{t_s} = \dfrac{\sigma_s}{x_{t_s}} \dot{x}_s^T D_s \dot{x}_s + \dfrac{1}{x_{t_s}} (\sigma_s P_s^{in} - P_s^{out}) - \omega_s^T \dot{x}_s \end{cases} \tag{1}$$

where D_m, D_s are the time-varying positive semi-definite matrices defining the variable local dampings, ω_m, ω_s are the modulation factors to extract/inject energy from/in the tanks, $P_m^{in}, P_s^{in} \geq 0$ and $P_m^{out}, P_s^{out} \geq 0$ are incoming and outgoing power flows that the tanks can exchange with each other by means of the communication channel. We refer the reader to [5] for more details. In the transparency layer a *Position-Force teleoperation* is implemented where the desired commands are modulated according to the available energy.

The following proposition can be proven, [5].

Proposition 2: *The teleoperation system is passive with respect to the pair* $((F_{m_1}^{ext},...,F_{m_{N_m}}^{ext}, F_{s_1}^{ext},...,F_{s_{N_s}}^{ext}),(\dot{x}_{m_1},...,\dot{x}_{m_{N_m}},\dot{x}_{s_1},...,\dot{x}_{s_{N_s}}))$.

III. Experimental Results

The experimental setup shown in Figure 2 is composed of

- Master side: a laparoscopic 4-DOF Simball Joystick coupled with two 6-DOF Geomagic Touch haptic devices,
- Slave side: a KUKA LWR 4+ 7-DOF robot and a Universal Robots UR5 6-DOF manipulator endowed with 3D printed laparoscopic-like tools.

We consider a surgical-like robotic platform since this work is part of the EU funded H2020 project SARAS[1]. The goal of SARAS is to develop an autonomous robotic assistant and this platform is needed to collect the data to train the AI subsystems.

[1]https://saras-project.eu

Fig. 2. The 2-master 2-slave experimental setup.

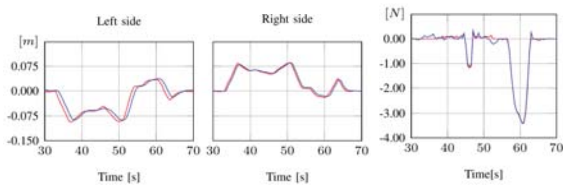

Fig. 3. Left, Middle: Cartesian position of the master devices (red line) and of the slave device (blue line) for the right side and the left side. Right: Desired force (red line) and applied force (blue line) on the master devices.

The laparoscopic tools on the slave robots were teleoperated in order to interact with a soft material, replicating a simplified interaction with human tissue. Figure 3 shows the Cartesian position of the master and of the slave devices. The communication delay introduced in the control architecture causes an evolution of the tracking error characterized by a maximum absolute value of $0.032m$ for the left side and of $0.014m$ for the right side. Figure 3 also shows the forces exchanged on the master-left side that highlights a good behavior of the overall system.

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