Energy-shared two-layer bilateral teleoperation architecture

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I. INTRODUCTION

Bilateral teleoperation allows to extend the reach of human beings allowing to interact with a remote environment while locally feeling the interaction force. A local operator moves a robot, the master, and the position information is sent to a remote robot, the slave, that replicates the motion of the master. During the interaction with the environment, the interaction force is sent back to the local side and replicated on the master in order to provide the user with the feeling of being directly interacting with the remote environment. Bilateral teleoperation has been used for many applications like surgical procedures [1].

When dealing with complex tasks, the single-master-single-slave (SMSS) teleoperation may not provide the necessary level of dexterity and flexibility. Multi-master-multi-slave (MMMS) teleoperation can provide the desired level of remote mobility and interaction capabilities. An example of MMMS teleoperation is the well-known Da Vinci robot[1].

This work is part of the H2020 European project SARAS[2]. The goal of SARAS is to develop an autonomous robotic assistant for a surgeon doing laparoscopic surgery. For achieving this objective, it is necessary to capture the behavior of the human assistant for reproducing and generalizing it. To this aim, we need to develop a multi-arms bilateral teleoperation system for allowing the assistant surgeon to tele-assist the main surgeon.

Stability and transparency are the main problems when controlling a bilateral teleoperation system. Unstable behaviors may arise because of the delay in the communication channel and while interacting with poorly known environments (e.g. the human body). In [2] a two layer approach for the control of a SMSS teleoperation has been proposed. Exploiting the concept of energy tanks, this approach splits the control architecture into two separate layers. The hierarchical higher layer is used to implement a strategy that addresses the desired transparency while the lower layer ensures that passivity is not violated. This work extends the two layer architecture proposed in [2] to the multi-master-multi-slave teleoperation. The main contributions of this work are: a novel two layer architecture for MMMS based on the concept of shared energy tank that allows operations while guaranteeing high fidelity and transparent behavior, and an experimental validation of the overall control architecture in the surgical scenario of the SARAS project.

II. THE BILATERAL CONTROL ARCHITECTURE

A. *master and slave side*

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[3]:

$$\Lambda_{w_i}\left(x_{w_i}(t)\right)\ddot{x}_{w_i}(t)+\mu_{w_i}\left(x_{w_i}(t),\dot{x}_{w_i}(t)\right)\dot{x}_{w_i}(t)=F^{\tau}_{w_i}(t)+F^{ext}_{w_i}(t) \tag{1}$$

where $w \in \{m,s\}$, where the subscripts m and s indicate the master and the slave side, respectively, and $i = 1,\dots,N_w$, $x_{w_i}(t) \in \mathbb{R}^n$ are the coordinates of the configuration of the end-effector 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 $F^{ext}_w(t) = [F^{ext^T}_{w_1}(t),...,F^{ext^T}_{w_{N_w}}(t)]^T$ and exploiting (1) we can model each side of the teleoperation system as the following Euler-Lagrange system.

$$\Lambda_w(x_w(t))\ddot{x}_w(t)+\mu_w(x_w(t),\dot{x}_w(t))\dot{x}_w(t)=F^{\tau}_w(t)+F^{ext}_w(t) \tag{2}$$

We split the control input of each robot $F^{\tau}_{w_i}$ into the sum of two terms: $\phi^d_{w_i}$ and $\phi^t_{w_i}$. The first term is exploited for implementing a variable local damping by setting $\phi^d_{w_i} = -D_{w_i}(t)\dot{x}_{w_i}(t)$, where $D_{w_i}(t) \in \mathbb{R}^{n\times n}$ is a time-varying positive semi-definite matrix. By embedding the damping injection into (1) we get the following damped Euler-Lagrangian model for each robot.

$$\Lambda_{w_i}\left(x_{w_i}\right)\ddot{x}_{w_i}+\mu_{w_i}\left(x_{w_i},\dot{x}_{w_i}\right)\dot{x}_{w_i}+D_{w_i}\dot{x}_{w_i}=\phi^t_{w_i}+F^{ext}_{w_i} \tag{3}$$

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[3]For ease of notation we will consider that all the robots have the same number of DOFs. All the results can be easily generalized to the case where the robots have a different number of DOFs.

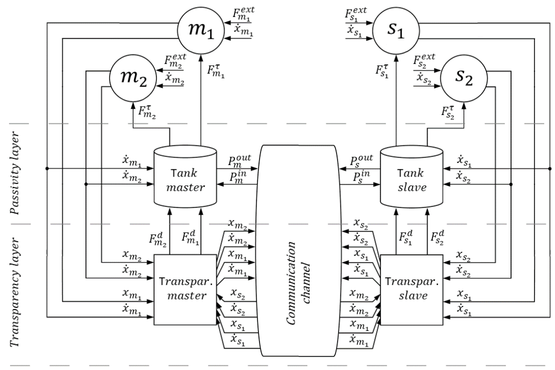

Fig. 1. Coupling of two generic master devices m_1 and m_2 with two slave devices s_1 and s_2 and one tank per side by means of the communication channel

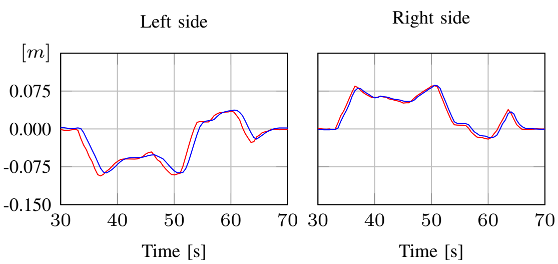

Fig. 2. Cartesian position of the master devices (red line) and of the slave device (blue line) for the right side and the left side

A shared energy tank is then placed at each side of the MMMS teleoperation system. The energy tank is an energy storing element that can be represented by:

$$\begin{cases} \dot{x}_{t_w} = \frac{\sigma_w}{x_{t_w}} \sum_{i=1}^{N_w} \dot{x}_{w_i}^T D_{w_i}(t) \dot{x}_{w_i} + u_{t_w} \\ y_{t_w} = \frac{\partial T_w}{\partial x_{t_w}} \end{cases} \tag{4}$$

where $x_{t_w} \in \mathbb{R}$ is the state of the tank, $(u_{t_w}, y_{t_w}) \in \mathbb{R} \times \mathbb{R}$ is the power port through which the tank can exchange energy with the rest of the world and $T_w(x_{t_w}) = \frac{1}{2}x_{t_w}^2$ is the energy stored in the tank. With the following power preserving interconnection, each robot is interconnected to the energy tank in order to exploit the energy stored in the tank for implementing the desired input:

$$\begin{cases} \phi_{w_i}^t = \omega_{w_i} y_{t_w} \\ u_{t_w} = -\sum_{i=1}^{N_w} \omega_{w_i}^T \dot{x}_{w_i} \end{cases} \qquad i = 1, \ldots, N_w \tag{5}$$

By grouping (3) and by considering (4) and (5), it is possible to model each side of the MMMS teleoperation system as:

$$\begin{cases} \Lambda_w \ddot{x}_w + \mu_w \dot{x}_w + D_w \dot{x}_w = \omega_w x_{t_w} + F_w^{ext} \\ \dot{x}_{t_w} = \dfrac{\sigma_w}{x_{t_w}} \dot{x}_w^T D_w \dot{x}_w - \omega_w^T \dot{x}_w \end{cases} \tag{6}$$

where $D_w(t) = diag\{D_{w_1}(t), \ldots, D_{w_{N_w}}(t)\}$ and $\omega_w = [\omega_{w_1}, ..., \omega_{w_{N_w}}]^T$. The term σ_w is a design parameter that is used to bound the energy stored into the tank.

B. Master-slave coupling

In order to interconnect master and slave sides by means of a delayed communication channel, we endow each tank with two power inputs. The overall architecture is shown in Fig. (1) and it can be decomposed into two layers: a *Transparency Layer* and a *Passivity Layer*. In the Transparency Layer, master and slave devices exchange position, velocity and force information that are used for computing the desired inputs. The exchanged forces are sent to the Passivity Layer, whose role is to passively implement them using the energy stored in the tanks. Master and slave energy tanks can exchange power for balancing the amount of energy stored at master and slave sides. Formally, the overall architecture with N_m master devices, N_s slave devices and one tank per side can be modeled as

$$\begin{cases} \Lambda_m \ddot{x}_m + \mu_m \dot{x}_m + D_m \dot{x}_m = \omega_m x_{t_m} + F_m^{ext} \\ \dot{x}_{t_m} = \dfrac{\sigma_m}{x_{t_m}} \dot{x}_m^T D_m \dot{x}_m + \dfrac{1}{x_{t_m}} (\sigma_m P_m^{in} - P_m^{out}) - \omega_m^T \dot{x}_m \\ \Lambda_s \ddot{x}_s + \mu_s \dot{x}_s + D_s \dot{x}_s = \omega_s x_{t_s} + F_s^{ext} \\ \dot{x}_{t_s} = \dfrac{\sigma_s}{x_{t_s}} \dot{x}_s^T D_s \dot{x}_s + \dfrac{1}{x_{t_s}} (\sigma_s P_s^{in} - P_s^{out}) - \omega_s^T \dot{x}_s \end{cases} \tag{7}$$

In the surgical scenario considered in this work, the transparency layer can be modeled as follow:

$$\begin{cases} F_{m_j}^d = F_{ca_j} + F_{s_j}^{ext} \\ F_{s_z}^d = -K_p(x_{m_z} - x_{s_z}) - K_d(\dot{x}_{m_z} - \dot{x}_{s_z}) \end{cases} \tag{8}$$

where $F_{ca_j}(t) \in \mathbb{R}^n$ represents a force introduced for providing a feedback to avoid collisions between the slave devices, $F_{s_j}^{ext}(t) \in \mathbb{R}^n$ is the external force applied to the slave arm j that can be measured by using a force/torque sensor, K_p and K_d are the position error gain and the velocity error gain, respectively, and $j = 1, ..., N_m$ while $z = 1, ..., N_s$. The strategy illustrated so far guarantees the passivity of the teleoperation system. The performances of the teleoperation system are reported in figure (2).

III. Conclusions and Future Work

In this work we have developed a novel two-layer architecture based on the concept of shared energy tank for multi-master/multi-slave bilateral teleoperation. In order to improve the surgical experience during teleoperation, future works will aim at introducing delayed visual feedback to the user and integrating inputs coming from intraoperative sensing.

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