Optimizing Damping Factors in a 3DoF Passive Two-layer Approach for Bilateral Telemanipulation

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***Abstract*— One of the main goals of haptic systems is to convey realistic forces (transparency) to the user. In bilateral telemanipulation control, factors such relaxed grasp of the user, time delays and stiff environments may compromise the stability of the system. Ensuring passivity in the system, *i.e.* does not generate energy by itself, can prevent unstable behaviour. To preserve passivity, a 3DoF two-layer approach based on energy tanks is implemented; the energy provided to the slave side is limited by the energy obtained from the user at the master side. This energy is generated by a damping-like element that is activated when destabilizing factors occur. This work presents a strategy to prioritize damping coefficients to achieve higher transparency along a number of desired directions. The method consists of solving a quadratic optimization problem that minimizes the projection of the damping force on different directions while maintaining passivity.**

I. INTRODUCTION

Bilateral manipulation can be represented as a close-loop circuit between a human operator (master interface) and a robot manipulator (slave interface) [1]. This remote operation creates an interesting control problem to solve, since the stability of a fully transparent system is affected by destabilizing factors such as time delays, stiff environments, or a soft grasp of the user on the master device. Transparency is defined as the full display of the environment impedance to the human operator when this interacts with the robot [2]. As described in [3], the transparency of the haptic device acts as an ideal system when the forces (τ_s) and velocities $(\dot{q}_s)$ of the slave side are equally reflected on the master side $(\tau_m, \dot{q}_m)$ as shown in (1):

$$\begin{cases} \tau_m(t) = \tau_s(t) \\ \dot{q}_m(t) = \dot{q}_s(t). \end{cases} \tag{1}$$

Various studies based on passivity control have been developed to provide a solution to such a problem, ([4], [5], [6], [7]). Passive systems are capable to store and consume energy, in contrast with active systems that can provide energy [8].

An elegant solution proposed in [9], where two energy tanks are introduced in order to control the energy flow between the master and the slave. With this technique, every movement done by the slave will have an energetic cost. The master and slave constantly exchange a certain amount of energy through a communication channel, and when the slave movements exceed the current energy budget, the master side acts as damping element, which can obtain energy from the user, thus, replenishing the tanks with energy.

As shown in Figure 1, the transparency layer exchanges the information of positions and velocities between the master and the slave side. In the passivity layer, the two energy tanks (one in each side) store energy which is used to apply forces on the master and slave sides. The total amount of energy (H_T)in the system is given by the sum of energy of the master tank (H_m), slave tank (H_s) and the flowing energy in the communication channel (H_c). As presented in (2):

$$H_T(t) = H_m(t) + H_c(t) + H_s(t). \tag{2}$$

The user defines a desired level (H_d) of the tank in the master side, because of the energy exchange between the tanks, the levels of the master and the slave reach the same value if no activity consumes it

$$H_d = H_s. \tag{3}$$

When the master or slave side needs to be actuated, the required force is limited according the amount of energy contained in the tanks. This work presents a method to optimize the forces relayed to the master side in order to increase transparency along different prioritized directions.

II. METHOD

The implementation used on this project follows a similar approach to the work of Franken in [9]; as show in (4) the force given by the passivity layer is related to the energy budget contained on the tank.

$$\tau_{PL}(k) \begin{cases} 0, & \text{if} \quad H(\overline{k+1}) \leq 0 \\ \tau_{TL}(k) + \tau_{TLC}(k) & \text{if} \quad 0 < H(\overline{k+1}) < H_d \\ \tau_{TL}(k), & \text{otherwise} \end{cases} \tag{4}$$

where $H(\overline{k+1})$ is the energy tank level in the next sample period, τ_{TL} is the transparency layer force, and τ_{TLC} represents the tank level controller force. If the energy tank level predicted at the next instant is lower than zero, all forces will be cut off. When the energy level is under the desired level the force is limited by the passivity layer. Finally, if the tank level is greater than the desired level, the system becomes fully transparent. The aim of this paper is to find a suitable τ_{TLC} such that the energy levels are kept above the desired level while prioritizing transparency along different directions.

Let $\dot{q}(k)$ be the vector of current velocities, P_i be a scalar that defines a priority of a given direction A_i, where the

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columns of A_i are the basis of a subspace S_i. The projection matrices are obtained using

$$T_i = A_i(A_i^T A_i)^{-1} A_i^T. \tag{5}$$

The objective is to minimize the function J show in equation (6):

$$J = \sum_{i=1}^{m} P_i(k) \left\| T_i(k) \tau_{TLC}(k) \right\|^2 \tag{6}$$

Using a damping-like correction:

$$\tau_{TLC}(k) = -B(k)\dot{q}(k). \tag{7}$$

where B is a symmetric matrix that contains the damping coefficients. The minimization of J using quadratic programming (QP) requires that it is put in the standard form:

$$\min_{x} \quad \frac{1}{2} x^T M x + c^T x \quad s.t. \quad Ax \geq b. \tag{8}$$

where x is the vector enclosing the minimum damping coefficients. Replacing (7) in (6) :

$$\begin{aligned} J(B, P_i, T_i) &= \sum_{i=1}^{m} P_i \tau_{TLC}^T(k) T_i^T(k) T_i(k) \tau_{TLC}(k) \\ &= \sum_{i=1}^{m} P_i \dot{q}^T(k) B^T(k) T_i^T(k) T_i(k) B(k) \dot{q}(k) \\ &= \dot{q}^T(k) B^T(k) \underbrace{\left[\sum_{i=1}^{m} P_i(k) T_i^T(k) T_i(k)\right]}_{\text{R(k)}} B(k) \dot{q}(k). \end{aligned} \tag{9}$$

By putting the elements of the symmetric matrix $B \in \mathbb{R}^{3\times3}$, in a vector $x \in \mathbb{R}^{6\times1}$ one can obtain the equation

$$B(k) \cdot \dot{q} = Q(k) \cdot x \tag{10}$$

We reach the desired form

$$J = x^T(k) \underbrace{Q^T(k) R(k) Q(k)}_{M} x(k). \tag{11}$$

Now the changes on the tank level depends on the quantity of energy in the tank, the difference of energy exchange with the transparency layer and the damping force:

$$H(\overline{k+1}) = H(k) - \tau_{TL}^T(k)\dot{q}(k) + \dot{q}^T(k) B(k) \dot{q}(k). \tag{12}$$

A constraint is added to ensure that the tank level does not drop below a given desired level H_d:

$$H(\overline{k+1}) \geq H_d(k). \tag{13}$$

Shaping equation (13) on (14):

$$H(k) - \tau_{TL}^T(k)\dot{q}(k) + \dot{q}^T(k) Q(k) x(k) \geq H_d(k). \tag{14}$$

Using the quadratic programming form on (8) the terms for the constraints are:

$$\underbrace{\dot{q}^T(k) Q(k)}_{A} x(k) \geq \underbrace{H_d(k) - H(k) + \tau_{TL}^T(k)\dot{q}(k)}_{\text{b}} \tag{15}$$

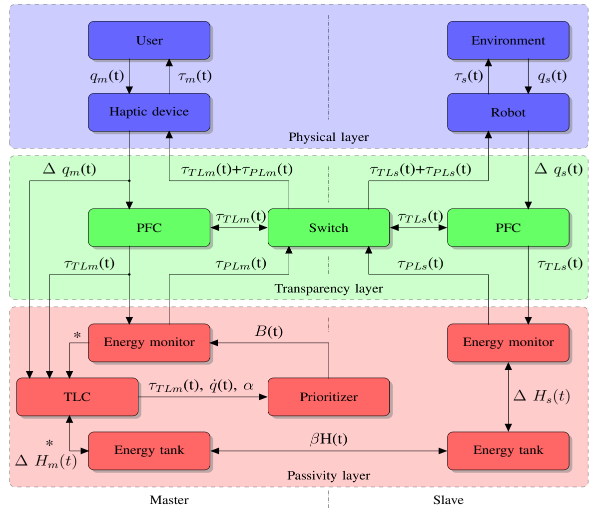

Fig. 1. Two-layer controller system. The physical layer of the system represents the real world, where the interaction between the user and the robot occurs. The two-layer approach applies to the controller. In the transparency layer a Position Force Controller (PFC) exchanges information between the physical layer and the passivity layer. A switch controlled by the user selects to operate in full transparency mode or passivity controlled mode. Finally, the passivity layer presents the energy monitors to check the energy flow in the system, the energy tanks contains the used energy, the Tank Level Controller (TLC) actuates the damping generator if needed, and the prioritizer executes the damping factor optimization. (*) represents $\Delta H_m(t)$.

III. CURRENT WORK

In this work, a mathematical derivation of a prioritization of feedback forces has been achieved, the next step is to find an experimental procedure to choose suitable subspace bases and priorities (A_i, P_i) for different tasks. This set up must guarantee the passivity condition at all moments and display the desire behaviour. Currently, research is being developed on a virtual environment using ROS and the Omega.3 haptic device. In the future, the goal is to implement the method in a real environment and test it on different application scenarios.

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