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Passive Bilateral Control of Teleoperators under Time Delay and Scaling Factors

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***Abstract*—Reliability and efficiency of tele-micromanipulation systems with haptic feedback over the Internet face to strong problems due to the nonlinear nature of microenvironment and time-varying delays in communication lines. In this paper, a bilateral controller for a micro-teleoperation system is presented using passivity approaches. We showed that the application of wave variable formalism allows the passivity of the system in spite of external perturbations. Mainly, the communication varying delays between the master and the slave and the specific scale factors modeling the interaction between the slave and the environment (structural and surface interactions) are considered. A design framework demonstrates regions where scaling factors keep the passivity of the overall micro-teleoperation system. Finally, the validity of the proposed method is demonstrated by simulations for a pick-and-place micromanipulation task with constant and variable time-delay.**

I. INTRODUCTION

Force reflecting micro-teleoperation systems allow a human operator (master) to handle micro-objects (slave) in a dangerous or inaccessible environment from a distant site. The current applications concern the biological remote control handling or the assembly of microsystems. In most of these applications, master and slave sites are separated by a long distance and communicate through an Internet support. Variable delays are then inevitable, inducing oscillations and strong instabilities. Furthermore, considering the variety of micro-objects to be manipulated (soft, fragile), a strong variability of the scaling factors in position and in force exists. Colgate [1] has shown that a synthesis of a controller that takes into account the variability of scaled factors could improve drastically the overall performances of the closed loop system (i.e. the robustness as well as the transparency).

Only a few works analyze these subjects collectively. A large part of the literature on the teleoperation is so dedicated to the study of the stability. A first approach, developed by [2] consists in using the theory of robust control: H_∞ or μ-synthesis. These methodologies require a linear model for the master and the slave. It allows to develop a closed loop system robust to a class of uncertainties as well as to specify a performance level. In this case, the delay is modeled as an inverse multiplicative uncertainty [2]. Nevertheless, these methods are limited to the case of constant delays that is rather restrictive. Other techniques like the sliding mode control [3] has been developed to take into account more complicated nonlinear models, but the problem of the performances (or of transparency) is not completely solved yet. Finally, a popular technique in robotics and in tele-robotics uses the principle of passivity or dissipativity adapted to the teleoperation system. It is obtained by interconnecting, in a passive way, passive blocks. So, if we suppose that the master, the slave and the environment are passive quadripoles, it remains to ensure the passivity of the block of communication in spite of the delays and scale factors. By analogy with the transmission lines, [4] suggests either the study of the passivity by using power variables: force and velocity but by using wave variables (ingoing and outgoing waves). The idea is to transmit the wave variables through the communication channel and no more the power variables. We can then easily show that this simple bijective transformation leads to a teleoperation system robust to communication delays. On the other hand, the presence of waves reflected at the manipulator makes the performances and transparency specifications difficult to ensure. Moreover, [3,5,6] have shown that a time varying delay could destabilize the system controlled in the waves space.

In this paper, we proposed the synthesis of a bilateral controller which ensures the passivity of the block of communication line. It takes into account the varying delays of communication and the variable scaling factors. We developed the controller in waves space. This allows a larger flexibility to the choice of parameters in order to stabilize the system. Section 3 is dedicated to the study of a first method involving time varying delay. First controllers ensuring the passivity and minimizing the error of position are then presented. In Section 4, we developed a wave-based controller for a teleoperation system subject to time delays and varying scaling factors. Finally in Section 5, results of simulation prove the effectiveness of our method.

II. WAVE-BASED BILATERAL CONTROLLER

A force reflecting teleoperation system is constituted by a haptic interface $P_m(s)$ (master) to which a human operator applies a force f_h and a micromanipulator $P_s(s)$ (slave), interacting with the micro-environment via a force f_e. The architecture of control can be represented by figure Fig.1 where e^{-T1}, e^{-T2} represent the time varying delays and n_p , n_f. are the varying scaling factors for the position and the force respectively. The position sent by the master to the slave is viewed as a reference x_e for the micromanipulator x_s such that $x_m = n_p x_s$. In the same way, the interaction force with the environment f_e measured by the micro-gripper is sent back to the operator as a reference for the haptic interface such that $f_h = n_f f_e$.

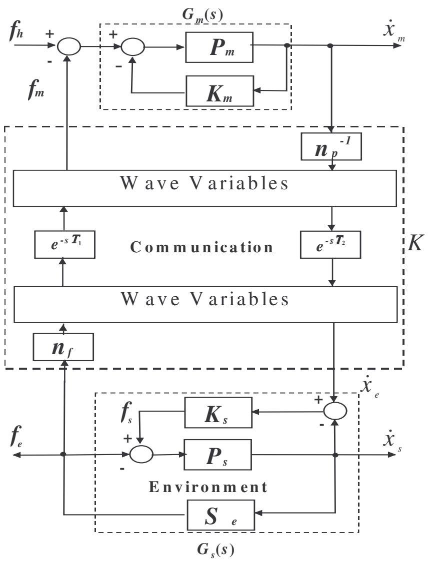


Fig.1. Bilateral architecture for a force reflecting micromanipulator

We consider that the force/position transfer functions of master $P_m(s)$ and slave $P_s(s)$ are given by the following equations :

$$P_m(s) = \frac{1}{m_m s^2 + k_m s + b_m} \qquad P_s(s) = \frac{1}{m_s s^2 + k_s s + b_s} \tag{1}$$

where m_m , m_s are respectively the mass of the master and slave ; k_m , k_s are damping coefficients and b_m, b_s are spring like coefficients. The bilateral architecture of Fig.1 can be viewed as the connection of three parallel blocks G_m, G_s and K. It is assumed that the block G_m defining the master and its controller is passive. Furthermore, the block G_s defining the slave, the controller and the environment ($Z_e=K/s$) is passive, too. In order to prove the passivity of the overall system, it is required to prove the passivity of the communication block K with respect time-delay (T_1, T_2) and scaling effects (n_p, n_f). By using the concept of wave variables [7] and definition of dissipativity [8]. First of all, let us define the power entering the system of communication :

$$P_{in} = \dot{x}_m^T F_m - \dot{x}_e^T F_e \tag{2}$$

where $\dot{x}_m$ and $\dot{x}_e$ are the velocities of the haptic interface and the micro-gripper, respectively. The waves variables ($u_{m,e}; v_{m,e}$) are defined as follows:

$$\begin{cases} u_m = \dfrac{b\dot{x}_m + F_m}{\sqrt{2b}} & u_e = \dfrac{b\dot{x}_e + F_e}{\sqrt{2b}} \\ v_m = \dfrac{b\dot{x}_m - F_m}{\sqrt{2b}} & v_e = \dfrac{b\dot{x}_e - F_e}{\sqrt{2b}} \end{cases} \tag{3}$$

where b is a characteristic wave impedance of the transmission line which effects the overall system behavior as described below. Its choice is crucial since it will be tuned to realize the matching impedance between the communication block and the haptic operator. The return of unexpected waves is then eliminated.

III. A VARYING GAIN CONTROLLER FOR TIME-VARYING DELAYED TELEOPERATION SYSTEM

The objective of the controller is to insure the passivity of the overall system and also to minimize the error between the transmitted position by the master x_m and the slave x_e. In order to cope with the instabilities induced by the time-varying delays, we introduced a modified controller structure initially proposed by Niemeyer [9], Yokokojhi [3] and Lozano [5]. The underlying idea is to introduce adaptive gains α_i between the master wave variables and slave wave variables preserving the tradeoff passivity/performance. The reflected waves can be written as follows:

$$\begin{cases} u_e(t) = \alpha_1 u_m(t - T_1(t)) \\ v_m(t) = \alpha_2 v_e(t - T_2(t)) \end{cases} \tag{4}$$

Following equation (9), we can rewrite the total energy as:

$$\int_0^t P_{in} d\tau = \frac{1}{2}\Big[\int_{t-T_1(t)}^{t} u_m^T u_m d\tau + \int_{t-T_2(t)}^{t} v_e^T v_e d\tau \tag{5}$$

$$-\int_0^{t-T_1(t)} \frac{1 - \dot{T}'_1 - \alpha_1^2}{1 - \dot{T}'_1} u_m^T u_m d\tau - \int_0^{t-T_2(t)} \frac{1 - T'_2 - \alpha_2^2}{1 - T'_2} v_e^T v_e d\tau\Big]$$

The energy is always positive for all delays, if and only if, the gains α_i satisfy the following inequalities:

$$\alpha_i^2 \le 1 - \frac{dT_i}{dt} \qquad \text{for} \qquad i=1,2 \tag{6}$$

We can remark that the values of delays can be different in both directions, the passivity is preserved for all gains α_i satisfying inequalities (6). Nevertheless, the introduction of such gains modifies the waves and can induce a large error between the desired position x_m and the slave position x_e. In order to reduce it, we are searching new conditions for the choice of α_i. The error of position can be written as :

$$\Delta x = x_m(t) - x_e(t) = \frac{1}{\sqrt{2b_{v0}}}\Big[\int_{t-T_1(t)}^{t} u_m(t) d\tau - \int_{t-T_2(t)}^{t} v_e(t) d\tau$$

$$+ \int_0^{t-T_1(t)} \frac{1 - T'_1 - \alpha_1}{1 - \dot{T}_1(\xi)} u_m(t) d\tau - \int_0^{t-T_2(t)} \frac{1 - T'_2 - \alpha_2}{1 - \dot{T}_2(\xi)} v_e(t) d\tau\Big] \tag{7}$$

We can notice that the choice of $\alpha_i = 1 - \dot{T}_i(t)$ leads to an optimal error. Nevertheless, in the case of $\dot{T}_i(t) \geq 0$, , the gains α_i have to be less than $(1-\dot{T}_i(t))^{1/2}$. A judicious choice to ensure the passivity/performance tradeoff is given for $\alpha_i = 1 - \dot{T}_i(t)$. In practice, the derivative value of the time-delay should be measured, continuously, in order to satisfy the adaptive condition. In a first approach, a time-delay estimator based on piecewise-linear model has been experimentally investigated as proposed in [10].

IV. Passivity of the Teleoperation System With Respect to the Scaling factors.

A. Representation of scaling factors in waves space.

In this section, we present the results concerning the passivity of the teleoperation system is in a constrained motion. The aim is to reduce the error between the force measured by the micro-effector f_e and the force fed back to the human operator as a reference f_h. This error depend mainly on the variations of scaling factors. The design objective is to select a force scaling factor to preserve the dynamic similarity and concomitantly preserve the intensive (mechanical) properties that are independent of scale. In the proposed approach, the force scaling factor n_f should be selected on-line depending on (i) the environment of the micromanipulation task and also (ii) on material properties of the manipulated micro-objects. The aim of the controller is so to preserve the passivity of the overall system in spite of a great variability of the scaling factors, which are tuned according to the nature of the task. To solve the problem of variability of the scaling factors in micromanipulation, we analyzed the constraints in the waves space and derive conditions between the parameters.

The scaling factors represented by the gains N_1 and N_2:

$$\begin{cases} \dot{x}_e = N_1 \dot{x}_m \\ f_m = N_2 f_e \end{cases} \tag{8}$$

are illustrated as constants blocks in Fig.4:

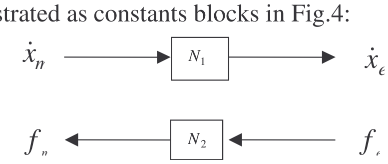


Fig.4: Scaling factors definition.

As every system which is expressed in the power variables $(\dot{x}, F)$ can also be written in terms of the waves variables (u, v), it may be useful to convert dimensional scaling factors from one domain to another. Let us consider the following bilateral controller expressed in the waves space (Fig.3):

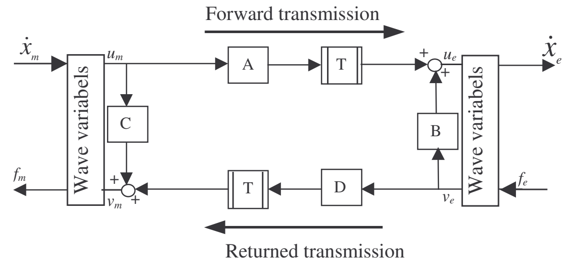


Fig.3: Equivalent four-channel wave system including the delay in the forward and reverse transmission transfer functions and the scaling factors.

where A, B, C, D are transfer functions which have to be specified to ensure passivity as well as transparency in spite of the delays T. According to the equivalent scheme of Fig.3, the bilateral controller can be expressed as follows :

$$\begin{pmatrix} u_e \\ v_m \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \cdot \begin{pmatrix} u_m \\ v_e \end{pmatrix} \tag{9}$$

or

$$\begin{cases} u_e = Au_m + Bv_e \\ v_m = Cu_m + Dv_e \end{cases} \tag{10}$$

By replacing $\dot{x}_e$ and F_e into equation (3) and (8), the transformation matrix in the wave variables domain is expressed as:

$$\begin{aligned} u_e &= \frac{2N_1}{(1+N_1N_2)} u_m + \frac{N_1N_2 - 1}{N_1N_2 + 1} v_e \\ v_m &= \frac{1 - N_1N_2}{1 + N_1N_2} u_m + \frac{2N_2}{1+N_1N_2} v_e \end{aligned} \tag{11}$$

Using parameter identification methods, we obtain the following forms:

$$A = \frac{2N_1}{(1+N_1N_2)} \quad , \quad B = \frac{N_1N_2 - 1}{(1+N_1N_2)}$$
$$C = \frac{1 - N_2N_1}{(1+N_1N_2)} \quad , \quad D = \frac{2N_2}{(1+N_1N_2)} \tag{12}$$

The equivalent waves system with unknown or variable time-delay of Fig.3 is passive with the interconnections A, B, C, D if and only if the following three conditions are satisfied [7]:

$$\begin{cases} |A|^2 + |C|^2 \leq 1 \\ |B|^2 + |D|^2 \leq 1 \\ |A|^2 + |C|^2 + |B|^2 + |D|^2 \leq 1 + (|AD| - |BC|)^2 \end{cases} \tag{13}$$

<u>Lemma 1</u> :

The tele-micromanipulation system preserves its passivity, if and only if the scaling factors are equal ($N_1 = N_2$)

<u>Proof 1</u> **:**

By substituting the scaling factors from (12) into (13), it is possible to redefine the three inequality conditions as explained in [7]. Let us consider now different scaling factors depending on the varying micromanipulator-environment interactions at the micro-scale [11]:

- *Structurally-Dominated Interaction*: The environment is characterized by its structural dynamics. A typical example is the deflection of surface micromachined structures when released from their substrate during micromanipulation. In this case, the scaling factors are $\{ n_p = N \, ; n_f = 1/N^2 \}$. Within the range of scaling parameters the dynamic similarity and intensive properties are preserved [11].

- *Surface-Dominated Interaction*: The micro-handling tasks are also strongly influenced by capillary, electrostatic and van der Waals forces**.** In this case the scaling factors are chosen as **{** $n_p = N$ **;** $n_f = 1/N$ **}.**

<u>Lemma 2 :</u>
In the case of structurally-dominated interactions, the tele-micromanipulation system preserves its passivity by adding filter functions $F_i(s)$*, if and only if the following conditions are satisfied:*

$$\begin{cases} |F_1(s)|^2 \le \dfrac{1}{N^3} \\ |F_2(s)|^2 \le N^3 \\ (N+1)^2(N^3|F_1(s)| \; - |F_2(s)|) \le 4\cdot(|F_1(s)|\cdot|F_2(s)|-1)^2 \end{cases} \tag{14}$$

<u>Proof 2</u> **:**
By adding different filters $F_i(s)$, the equivalent structure in the waves domain can be represented by an equivalent structure defined by :

$$\begin{cases} A = \dfrac{2N^2}{N+1}\cdot F_1(s); \quad C = \dfrac{N-1}{N+1} \\ D = \dfrac{2}{N^2+N}\cdot F_2(s); \quad B = \dfrac{1-N}{1+N} \end{cases} \tag{15}$$

By substituting (15) into (13) , the following inequality conditions verifying those given in (14) are expressed by:

$$\begin{cases} \left|\dfrac{2N^2}{N+1}\cdot F_1(s)\right|^2 + \left|\dfrac{N-1}{N+1}\right|^2 \le 1 \\ \left|\dfrac{1-N}{1+N}\right|^2 + \left|\dfrac{2}{N^2+N}\cdot F_2(s)\right|^2 \le 1 \\ \left|\dfrac{2N}{N+1}\cdot F_1(s)\right|^2 + \left|\dfrac{N-1}{N+1}\right|^2 + \left|\dfrac{1-N}{1+N}\right|^2 + \left|\dfrac{2}{N^2+N}\cdot F_2(s)\right|^2 \le 1+Q' \\ Q' = \left(\left|\dfrac{4N^2F_1(s)F_2(s)}{(1+N)(N^2+N)}\right| + \left|\dfrac{(N-1)^2}{(1+N)^2}\right|\right)^2 \end{cases} \tag{16}$$

<u>Lemma 3 :</u>
In the case of surface-dominated interactions, the tele-micromanipulation system preserves its passivity by adding filter functions $F_i(s)$*, if and only if the following conditions are satisfied:*

$$\begin{cases} |F_1(s)| \le \dfrac{1}{N} \\ |F_2(s)| \le N \\ N^4|F_1(s)|^2 + |F_2(s)|^2 \le N^2(1+|F_1(s)F_2(s)|^2) \end{cases} \tag{17}$$

<u>Proof 3</u> **:**
By adding different filters $F_i(s)$, the equivalent structure in the waves domain can be represented by the equivalent structure defined by:

$$\begin{cases} A = F_1(s)N; \quad C = 0. \\ D = \dfrac{F_2(s)}{N}; \quad B = 0 \end{cases} \tag{18}$$

By substituting (18) into (13) , the following inequality conditions verifying those given in (17) are expressed by:

$$\begin{cases} |F_1(s)N|^2 \le 1 \\ \left|\dfrac{F_2(s)}{N}\right|^2 \le 1 \\ |NF_1(s)|^2 + \left|\dfrac{F_2(s)}{N}\right|^2 \le 1 + |F_1(s)F_2(s)| \end{cases} \tag{19}$$

B. Tracking Error of the Force
The expression of the force tracking error taking into account the scaling force factor n_f is expressed by :

$$\Delta f = f_m - n_f f_e \tag{20}$$

where f_m and f_s are the master and slave forces expressed by:

$$f_m = \sqrt{\frac{b}{2}}(u_m - v_m) \quad ; \quad f_e = \sqrt{\frac{b}{2}}(u_e - v_e) \tag{21}$$

then

$$\Delta f = \sqrt{\frac{b}{2}}(1 - C - n_f A)\cdot u_m - \sqrt{\frac{b}{2}}(D - n_f B + n_f)\cdot v_e \tag{22}$$

In order to reduce the tracking error to zero, the wave variables should verify the following conditions:

$$\lim_{t\to\infty} u_m(t) = \lim_{t\to\infty} v_e(t) = 0 \Rightarrow \lim_{t\to\infty} \Delta f(t) = 0 \tag{23}$$

where

$$\begin{aligned} \Delta f(s) = {} & \sqrt{\frac{b}{2}}(1 - n_f A(s) + C(s))\cdot u_m(s) \\ & - \sqrt{\frac{b}{2}}(n_f + D(s) - n_f B(s))\cdot v_e(s) \end{aligned} \tag{24}$$

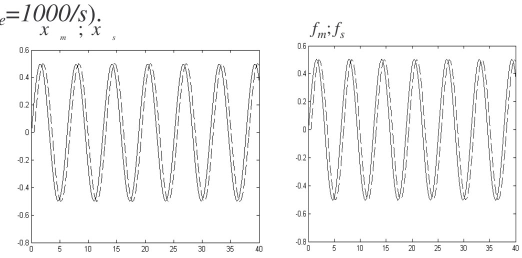
Using the theorem of the final value, the condition (23) allows the minimization of the tracking error such as:

$$\begin{aligned} & \lim_{s\to 0}(1 - C(s) - n_f A(s)) = cst; \\ & \lim_{s\to 0}(n_f + D(s) - n_f B(s)) = cst \end{aligned} \tag{25}$$

V. SIMULATIONS

A. Communication with Time-Delay

The set of simulations of Fig.4 shows the position (Fig.4a) and the force in a free motion (Fig.4b) with a constant time delay of T=1sec using Simulink from Matlab 6.5..The results demonstrate the excellent position and force control tracking of the proposed teleoperation controller under time-delayed teleoperation conditions. To emphasize the delay problem over the internet Fig.5a demonstrates the influence of this parameter on the stability of the controller with an environment (Z_e*=1000/s*).



(a) (b)

Fig.4 : Simulation results of position and force control tracking for a sinusoidal trajectory with a delay of T=1sec. Solid lines (master), broken lines (slave).

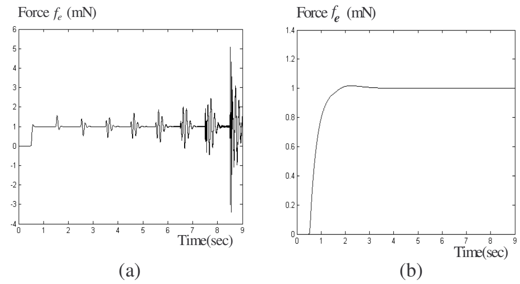


Fig.5 : Variation of slave force f_e for a step of master force f_h taking into consideration a constant delay (T=1sec): (a) multiple wave reflections, and (b) convergence preserved by adding filter $\lambda/(s+\lambda)$.

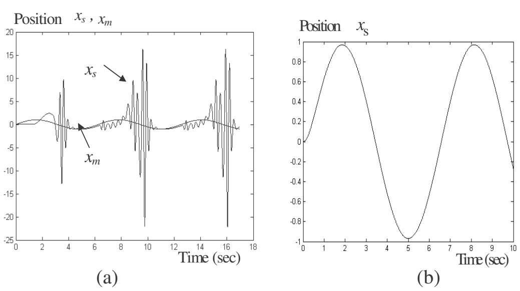


Fig.6: Variation of slave position x_s with a sinusoidal varying time delay (a) without an adaptive gain and (b) with an adaptive gain.

If not dealt with, the delay and the scaling factors might cause multiple wave reflections. Most significantly, reflections at both master and slave side can create internal loops with repeated reflections and thereby oscillatory behavior. The application of a wave filter $\lambda/(s+\lambda)$ with $\lambda = 1/0.3$ reduces strongly the wave reflection within the teleoperator context (Fig.5b). The cutoff frequency of the filter should be selected relative to the delay time. One effect of the reflections is the tendency for oscillations between the two sides, which occur at a frequency of $f_c = 1/2T$. Placing the filter bandwidth near this value will provide strong damping for these oscillations. However, the filter also affects the desired information contained in the wave signals by slowing down micro-teleoperation tasks. Tradeoffs between impedance matching, wave filtering, and adjustments of wave impedance are necessary. When considering a varying time-delay, Fig.6a shows the unstable behavior of the teleoperation system. The position error between the master position x_m and the slave position x_s increases gradually with respect time. By using the adaptive control scheme with a particular value of the varying gain $\alpha_i = 1 - \left|\dot{T}_i(t)\right|$, we have a tradeoff between passivity and performance (Fig.6.b).

B. Influence of Scaling Factors

In the same way, Fig.7 and Fig.8 show the stability of the wave-based controller combining both variation of the force factor and constant (1sec.) or varying time-delay, respectively. It represents the step response of the controllers in the case of *structurally-dominated interaction* and *surface-dominated interaction*. These figures show the stability of the wave-based controller combining both variation of the force factor and variable time-delay. It represents the step response of the controllers for both interactions. Different filter transfer functions, i.e. $\lambda_i / s + \lambda_j$, are inserted in the forward and reverse communication line in order to preserve the passivity of the bilateral controller against variations of position and force scaling factors. These filters are chosen to respect the inequality conditions of (13). In a given environment of micromanipulation, the operator can choose the couple of scaling parameters (n_p, n_f) by adjusting their values in the range of lower and upper bounds given by the passivity domain diagram (Fig.9). The task-based controller $K(n_p,n_f)$ has been synthesized for trading off various performance criteria (force, position) and passivity (delay and scaling).

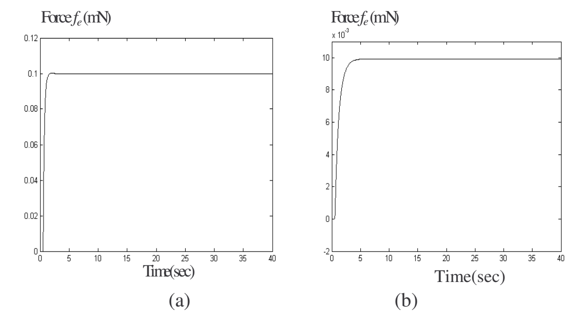


Fig.7: Step response with a time delay of 1sec for (a) $n_p = N$; $n_f = 1/N$ and (b) $n_p = N$; $n_f = 1/N^2$.

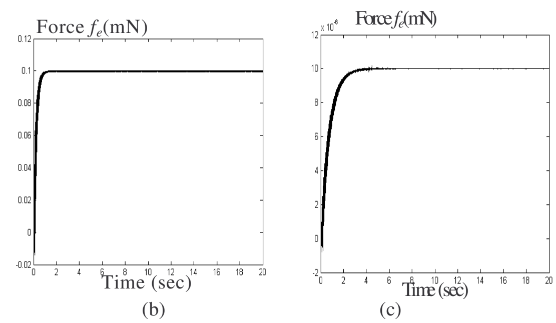


Fig.8: Step response with (a) varying time delay for (b) $n_p = N$; $n_f = 1/N$ and (c) $n_p = N$; $n_f = 1/N^2$.

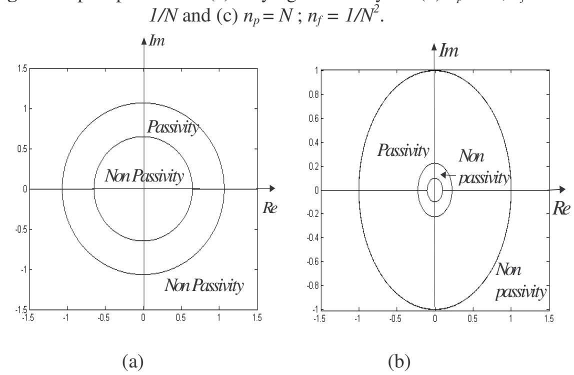


Fig.9: Time domain passivity of scaling factors for (a) structurally-dominated interaction and (b) surface-dominated interaction.

TABLE I : PARAMETERS

Master	$m_m = 1$	k_m=0	b_m=0
Slave	$m_s = 4.88$	k_s=0.512.10^5	b_s=0.232.10^8
Environment	$Z_e = 1000/s$		

VI. Experimental Results

A. Experimental Setup

Fig.10 shows a force-reflecting micromanipulator with a four-degree-of-freedom microgripper used in the experiments. It is called MMOC (Microprehensile Microrobot On Chip). The elementary micro-actuator is a duo-bimorph, a monolithic piezoelectric actuator offering two uncoupled degrees of freedom, i.e. in-plane motion (x,y) and out-of-plane motion (y,z). Due to small size of the gripper, it is not possible to incorporate force sensors at the tip. The solution we selected consisted in using 'remote-located' sensors, such as strain gauges, glued in the position of maximum strain of the gripper (type ESB-020-500 Entran Devices).

Fig.10: Master-slave experimental micromanipulation setup.

The force sensibility is less than one milliNewton. The micro gripper is currently attached to an x-y computer-controlled positioning table, which can be controlled by a 1-dof master manipulator with force feedback at the operator side. The operator observes the microgripper position using a video device and the position is sensed by a high precision linear displacement microsensor (LVDT) with a resolution of 1µm. The experimental setup is developed under Simulink of Matlab 6.5®. with the user interface ControlDesk 2.1® as a master connected to real-time DSP1103 boards. The passive bilateral controller architecture has been implemented and tested

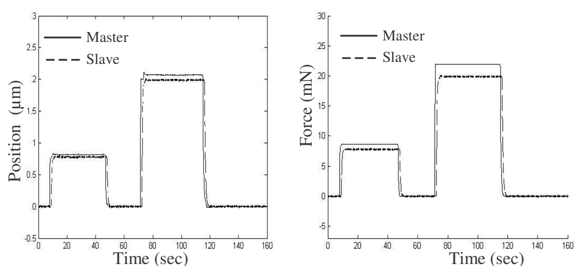


Fig.18: Position and force tracking for passive bilateral controller when n_p=n_f=N=1 and T=1sec.

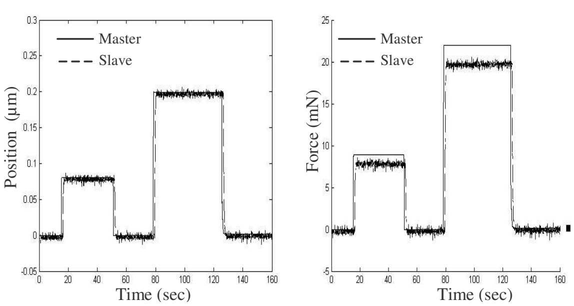
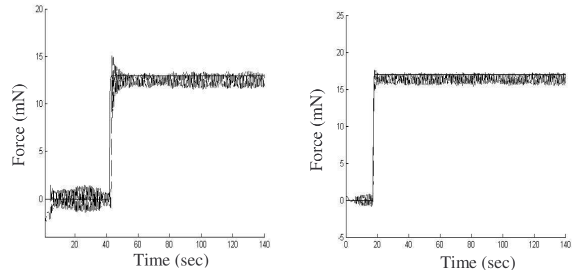


Fig.19: Position and force tracking for passive bilateral controller when n_p=N=10, n_f=1/N=0.1 and T=1sec.

The master and slave position and force tracking profiles are illustrated in Fig.11-12 for different scaling factors and a constant time-delay T=1sec (n_p=n_f=N and n_p=N, n_f =1/N) and Fig.13 force step response for constant (T=1sec) and variable time-delay for $T\in$ [-0.2 ; 0.2]sec in the case of structurally-dominated interaction (n_p=N, n_f =1/N^2). These results shows the good position and force tracking and stability performances.



(a) (b)

Fig.13: Force step response for n_p =N=0.5 ; n_f = $1/N^2$= 4 when (a) T=1sec and (b) with varying time-delay $T\in$ [-0.2;0.2] sec.

VII. CONCLUSION

In this article, we have proposed the design of a bilateral controller for a force reflecting teleoperation system. The proposed approach uses an adaptive controller with two adjustable gains depending directly of the delay shape and duration. To take into consideration the effects due the varying scaling factors, we used a new four-channel structure of impedance filtering the reflective energy excess in the communication line. Several passivity conditions are proposed for design purposes by the optimal choice of filtering structures preserving in this way a good tradeoff between passivity and performances.

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