Experimental Comparative Study of Control Architectures for Haptic Interfaces Including Communication Delays

Bogdan Liacu, Claude Andriot, Didier Dumur, Frédéric Colledani, Silviu Niculescu and Patrick Boucher

Abstract— **The aim of this paper is to present a comparative study of control algorithms for haptic interfaces and virtual environments subject to communication delays. It is well known that the presence of delays deteriorates the overall system performance. More precisely, delays introduce a feeling of viscosity in free motion and reduce the sense of stiffness in case of hard contacts. Six methods in their *basic* form (*classic* Proportional Derivative (PD), PD with local dissipation, PD with passivity observer, PD with passive set-point modulation, wave scattering transform and Smith predictor) are analyzed and compared, using a real-time experimental platform which enables tracking the impact of delays, from the point of view of position tracking error and transparency degree.**

I. INTRODUCTION

Virtual environments have become very popular and are used in many domains, like prototyping (figure 1.a example of prototyping using haptic interfaces and virtual environment [10]), trainings for different devices and assistance in completing difficult tasks (figure 1.b virtual environment used for task assistance/supervision [5], [6]).

Large delays in teleoperation systems are widely considered since several years, aiming at intuitive teleoperation over the Internet. Speaking about haptic systems over the Internet, which are nowadays much more frequently used, the problems encountered in haptic control are very similar.

Comparative studies for teleoperation systems can be found in the literature, like [20], [13]. For the haptic systems, at least one paper [26] compares only three methods (classic PD, PD with passivity observer and wave scattering) in the context of collaborative haptic over the Internet.

The goal of the paper is to present an extended comparison, including the most popular control algorithms (*classic* Proportional Derivative (PD), PD with local dissipation, PD with passivity observer, PD with passive set-point modulation, wave scattering transform and Smith predictor), used in teleoperation systems, applied to haptic systems. The analyzed methods are in their *basic* form, we did not consider special modifications proposed in the literature. In figure 2 we present the general scheme of a haptic system.

Fig. 1. a.Virtual Prototyping. b.Virtual Assistance/Supervision.

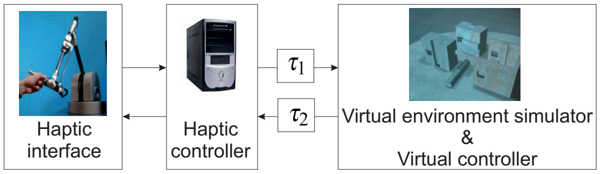

Fig. 2. General Scheme of a Haptic System

The ideal haptic system must have:

- position tracking error as small as possible between the haptic interface and the virtual object,
- high degree of transparency, i.e. in free motion, the force feedback felt at the haptic interface end must be as small as possible and in case of hard contact, a stiff response is desired.

The main problems of such systems are linked to the delays and their effects on stability and transparency. For complex virtual environments, the processing time can increase substantially and can introduce unwanted effects and behaviors. More precisely, in free motion the delay effect can be felt by the viscosity phenomenon (high force feedback felt at the haptic interface end), in the case of a hard contact with the environment, the impact effect will not be stiff, or the most unwanted situation is to loose the system stability due to the delays. The delays must be taken into account and included in the control laws. However, a trade-off between stability, position tracking error and transparency must be always made.

We propose an experimental approach in order to compare the different control structures from a practical point of view. We will use an experimental platform based on the scheme presented in figure 2, with constant time delays ($\tau_1 = \tau_2$). Between the haptic interface controller and the virtual environment controller we will transmit the position in both directions, concept corresponding to position-position

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architecture. To assure a full control of the communication delays and processing time, all the control algorithms (for haptic interface/virtual object) and virtual environment simulations will be run on the same computer.

The rest of the paper is organized as follows: in section II we will present the theoretical background of the most popular control architectures, section III will propose the experimental results and in the end of the paper some conclusions will be drawn.

II. THEORETICAL BACKGROUND

In this section we will briefly present the representative time delay bilateral teleoperation architectures available in the literature.

We will start from the *classical* dynamic (nonlinear) equations of motion for two similar robots in the framework of haptic systems:

$$M_1(x_1)\ddot{x}_1(t)+C_1(x_1,\dot{x}_1)\dot{x}_1=-F_1(t)+F_h(t), \tag{1}$$

$$M_2(x_2)\ddot{x}_2(t)+C_2(x_2,\dot{x}_2)\dot{x}_2=-F_2(t)+F_e(t), \tag{2}$$

where x_1, x_2 are the haptic interface/virtual object position, F_h, F_e are the human/environmental forces, F_1, F_2 are the force control signals, M_1, M_2 are the symmetric and positive-definite inertia matrices, and C_1, C_2 are the Coriolis matrices of the haptic interface and virtual object systems, respectively.

A. Proportional-Derivative (PD) Control

According to the literature [4], [22], [29], proportional-derivative (PD) controllers are largely used in teleoperation systems. For such systems, a very fast response is required and, in most of the cases, they are affected by large communication delays.

Figure 3 presents the general control scheme of a haptic interface and a virtual environment including control.

The main idea is to use two similar PD controllers, one to control the haptic interface and another one for the virtual object. The controller equations are there given as follows:

$$F_1(t)=\underbrace{K_d(\dot{x}_1(t)-\dot{x}_2(t-\tau_2))}_{\text{delayed D-action}}\underbrace{+K_p(x_1(t)-x_2(t-\tau_2))}_{\text{delayed P-action}}, \tag{3}$$

$$F_2(t)=\underbrace{K_d(\dot{x}_2(t)-\dot{x}_1(t-\tau_1))}_{\text{delayed D-action}}\underbrace{+K_p(x_2(t)-x_1(t-\tau_1))}_{\text{delayed P-action}}, \tag{4}$$

where τ_1, τ_2 are the forward and backward finite constant delays and K_p, K_d are the PD control gains.

According to [19], in order to assure a bounded error for position and velocity, the controller's gains must be fixed as follows:

$$K_d^2 > \tau_1\tau_2 K_p^2. \tag{5}$$

Furthermore, under the assumption that the user is no longer moving the haptic interface (the velocity is zero and the position is constant), for achieving an asymptotically convergence to zero of the virtual object velocity and to realize position coordination (between the haptic interface and virtual object), we have the following constraints in choosing the gains:

$$\frac{K_d}{K_p} > \tau_1\tau_2\left(3+\frac{1}{2\varepsilon}\right)+\varepsilon+1, \tag{6}$$

for some $\varepsilon > 0$, more details can be found in [19].

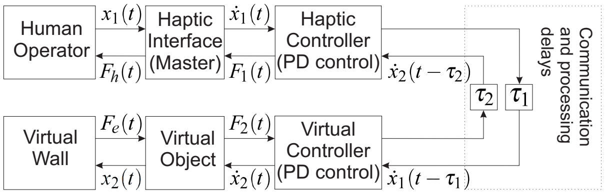

Fig. 3. General PD control scheme for haptic systems.

In terms of transparency, in the case of classic PD control, for one degree of freedom, in steady state the force of the haptic interface can be approximated by the following equation:

$$F_1 \simeq -K_p\tau_2\dot{x}_1. \tag{7}$$

The presence of the term τ_2 in equation (7) demonstrates that the transparency and the system performance are directly linked to time delay. Also a special attention is required to tune the PD gain K_p due its direct influence to the transparency.

B. Proportional-Derivative (PD) control with local dissipation

The main idea of this method is to include an additional term watching on stability. This term is a local dissipation acting in order to maintain the passivity of the system.

A system is said to be passive if and only if:

$$\int_0^t F(\tau)\dot{x}(\tau)d\tau+E(0)\geq 0, \quad \forall t>0, \tag{8}$$

where $\dot{x}$ and F are the variables denoting velocity and force respectively, and $E(0)$ is the energy stored initially in the system at $t=0$. Passivity is also a sufficient condition for stability [14].

The method was proposed by [12] based on the controller passivity concept, Lyapunov-Krasovskii technique for the delayed systems, and Parseval's identity.

In order to achieve coordination between the haptic interface and the virtual object, bilateral force reflection, and energetic passivity of the closed-loop system, the haptic interface and the virtual object control forces $F_1(t), F_2(t)$ from equations (1) and (2) are designed as follows:

$$\begin{aligned}F_1(t)= \;& \underbrace{K_d(\dot{x}_1(t)-\dot{x}_2(t-\tau_2))}_{\text{delayed D-action}}\underbrace{+(-K_{diss}+P_e)\dot{x}_1(t)}_{\text{dissipation}}\\ & \underbrace{+K_p(x_1(t)-x_2(t-\tau_2))}_{\text{delayed P-action}},\end{aligned} \tag{9}$$

$$\begin{aligned}F_2(t)= \;& \underbrace{K_d(\dot{x}_2(t)-\dot{x}_1(t-\tau_1))}_{\text{delayed D-action}}\underbrace{+(-K_{diss}+P_e)\dot{x}_2(t)}_{\text{dissipation}}\\ & \underbrace{+K_p(x_2(t)-x_1(t-\tau_1))}_{\text{delayed P-action}},\end{aligned} \tag{10}$$

where K_{diss} ($K_{diss} = 0.05K_p$) is the dissipation gain to *passify* the delayed D-control action and P_e is an additional damping ensuring coordination between the haptic interface and the virtual object (for more details, see [12]).

C. Proportional-Derivative (PD) control with passivity observer

This method was patented in 2006 by Hannaford et *al.*[8]. The provided method is used for stabilizing a haptic interface of computer controlled virtual-reality or teleoperation systems comprising a robot manipulator. According to the authors, 'stabilizing' means to reduce the sense of vibration in haptic interface.

The energy of the system based on figure 4, is observed using the Passivity Observer (PO) introduced in [25], [24], as follows:

$$E_{obs}(t) = \Delta T \sum_{k=0}^{n} (F(k)\dot{x}(k)), \tag{11}$$

where $E_{obs}(t)$[1] is the real time observed energy with the sign convention represented as in figure 4, and ΔT is the sample time of the system.

The passivity controller (PC) based on the passivity observer, is further built. Among the two possible configurations, only the series connection one is considered, due to the missing of force sensor, see figure 4:

$$F_1(t) = F_1'(t) + \alpha_1(t)\dot{x}_1(t), \tag{12}$$

where $\alpha_1(t)$ is defined as follows:

$$\alpha_1(t) = \begin{cases} \frac{-E_{obs}(t)}{\Delta T \dot{x}_1(t)^2} & if \quad E_{obs} < 0 \\ 0 & \quad\quad E_{obs} \geq 0 \end{cases} \tag{13}$$

In this case, equations (1) and (2) become:

$$\begin{aligned} F_1(t) = \; & \underbrace{K_d(\dot{x}_1(t) - \dot{x}_2(t-\tau_2))}_{\text{delayed D-action}} \\ & \underbrace{+K_p(x_1(t) - x_2(t-\tau_2))}_{\text{delayed P-action}} \underbrace{+\alpha_1(t)\dot{x}_1(t)}_{\text{PC}}, \end{aligned} \tag{14}$$

$$\begin{aligned} F_2(t) = \; & \underbrace{K_d(\dot{x}_2(t) - \dot{x}_1(t-\tau_1))}_{\text{delayed D-action}} \\ & \underbrace{+K_p(x_2(t) - x_1(t-\tau_1))}_{\text{delayed P-action}} \underbrace{+\alpha_2(t)\dot{x}_2(t)}_{\text{PC}}, \end{aligned} \tag{15}$$

where α_1 is the corresponding coefficient for the haptic interface defined in (12) and α_2 is the virtual object coefficient, similarly defined.

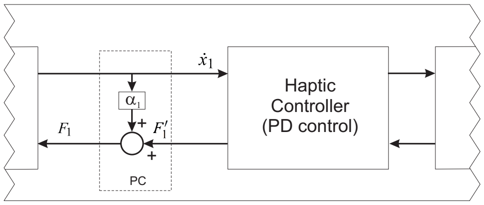

Fig. 4. Passivity Controller

According to [7], a potential problem which may occur is that the forces required to dissipate the generated energy may exceed the actuator limits. This is especially true if velocity happens to be small. A possible solution is to limit the value of α. Another solution could be the limitation of the force generated by the PC, or both in the same time. A detailed study and solution for removing the noisy behavior are proposed in [23]. The solution suggests a method to ignore the produced energy from the velocity sign change and another one to maintain the PC force when the velocity is equal to zero. In [9] it is proposed an exact computation of the maximum value for α:

$$\alpha(t) \leq \frac{m}{(1+d)\Delta T} = \alpha_{max}, \tag{16}$$

where m is the mass of the system, ΔT is the sampling period and $d \in \mathbb{N}$ is the number of round trip[2] delay sampling periods.

Another problem observed by [2] is the accumulation of extra energy due to time delays. This phenomenon makes the system vulnerable to instability because the amount of time needed to have a negative energy is often very large and so the reaction will be too slow. In order to solve this problem, the same paper proposes an energy resetting strategy driven by the following two conditions:

$$f < f_{th}, \quad t > t_{th},$$

where f, t are the current force and time, and f_{th}, t_{th} are the force and time thresholds. The values for the thresholds are chosen by observing the characteristics of the delayed channel (for more details, see [2]).

One of the latest paper [1] presents the problem of position drift. By using the PC, some energy is dissipated and lost. The accumulation of these losses results in a position difference between the two ends. The proposed solution is to generate energy in order to actively compensate the drift as allowed by the passiveness of the communication channel. This technique will be considered in future works.

The PC has several desirable properties for applications including haptic interface control. The PO and PC can both be implemented with simple software in existing haptic interface systems. Energy storage elements in the system do not have to be modeled, only dissipation. Dissipation in the elements outside the PO needs to be identified for optimum performance [7].

D. Proportional-Derivative (PD) control with Passive Set-Position Modulation

Based on the same theory as the previous method (Eq. 8), as reported in [11], this approach has big tolerance to package loss and variable time delays. More precisely, when a data package is lost, the previous set position is maintained. In order to enforce passivity, the control action is

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[1] For the discrete cases, $t : n\Delta T$, where ΔT is sampling time.

[2] Round trip is defined as being the sum of forward and backward delays ($\tau_1 + \tau_2$, in our case, according to figure 3)

restricted before its application, policy that does not possess any singularity in the result.

According to [11], in our case, the passive set-position modulation can be expressed as follows:

$$\begin{aligned}&\min_{\bar{x}_1(t)} \parallel x_1(t)-\bar{x}_1(t) \parallel \\ &\text{subj. } E_1(t)=E_1(t-1)+K_d\dot{x}_1(t-1)^2-\tfrac{1}{2}K_p(-\bar{x}_1(t)+ \\ &\quad +\bar{x}_1(t-1))(2x_1(t)-\bar{x}_1(t)-\bar{x}_1(t-1))\geq 0\end{aligned} \tag{17}$$

$$\begin{aligned}&\min_{\bar{x}_2(t)} \parallel x_2(t)-\bar{x}_2(t) \parallel \\ &\text{subj. } E_2(t)=E_2(t-1)+K_d\dot{x}_2(t-1)^2-\tfrac{1}{2}K_p(-\bar{x}_2(t)+ \\ &\quad +\bar{x}_2(t-1))(2x_2(t)-\bar{x}_2(t)-\bar{x}_2(t-1))\geq 0\end{aligned} \tag{18}$$

where $\bar{x}_1(t)$ and $\bar{x}_2(t)$ represent the modulated set positions for haptic interface and virtual object and E_1, E_2 are the accumulated energies on the haptic and virtual side respectively. With these considerations equations (1) and (2) rewrite as follows:

$$F_1(t)=\underbrace{K_d(\bar{\dot{x}}_1(t)-\dot{x}_2(t-\tau_2))}_{\text{delayed D-action}}\underbrace{+K_p(\bar{x}_1(t)-x_2(t-\tau_2))}_{\text{delayed P-action}}, \tag{19}$$

$$F_2(t)=\underbrace{K_d(\bar{\dot{x}}_2(t)-\dot{x}_1(t-\tau_1))}_{\text{delayed D-action}}\underbrace{+K_p(\bar{x}_2(t)-x_1(t-\tau_1))}_{\text{delayed P-action}}. \tag{20}$$

As mentioned in [11], this method is flexible, local/decentralized, does not involve often-problematic numerical integration/differentiation, and can be easily extended to nonlinear robots. This modulation strategy is also free from the incidental diversion/wave-reflection problem of the scattering/wave-based approaches when the packet-loss is substantial (especially during the hard-contact task) and also from the noisy-behavior/sudden impulsive-force problems of the time-domain passivity control when the robots velocity is slow.

E. Wave-Scattering Transform

Also based on the theory of passivity, wave variables present a modification/extension which creates robustness to arbitrary time delays [16]. The method is applicable to nonlinear systems and can handle unknown models and large uncertainties, thus suited for interaction with real physical environments.

The basic wave transformation relates velocity, force, right and left moving waves [16]. In our case, see figure 5, we will convert $\dot{x}_1$ and $\dot{x}_2$ into u_m and v_s.

The wave variables (u_m, v_s) can be computed from the standard power variables as follows:

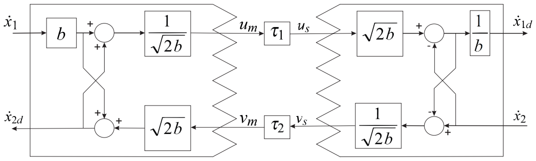

Fig. 5. Wave variables scheme.

$$u_m(t)=\tfrac{b\dot{x}_1(t)+\dot{x}_{2d}(t)}{\sqrt{2b}}, \qquad v_s(t)=\tfrac{\dot{x}_2(t)-b\dot{x}_{1d}(t)}{\sqrt{2b}}, \tag{21}$$

where b is the characteristic wave impedance and may be a positive constant or a symmetric positive definite matrix and $\dot{x}_{1d}$, $\dot{x}_{2d}$ are the delayed outputs after applying the wave scattering transform. The characteristic wave impedance b also assumes the role of a tuning parameter, which can trade off the velocity of motion against the level of forces, and influences many other characteristics. More precisely, increasing the wave impedance will place a larger weight on the velocity compared to the force, making the system appear more damped. When the wave impedance is decreased, force levels are lower, motion is easier and the system appears less damped, for more details, see [16].

This transformation is bijective, so that it is always unique and invertible. No information is lost or gained by encoding the variables in this way. In practice, the wave transformations provide an interface between power and wave variables.

In this case equations (1) and (2) rewrite as follows:

$$F_1(t)=\underbrace{K_d(\dot{x}_1(t)-\dot{x}_{2d}(t))}_{\text{delayed D-action}}\underbrace{+K_p(x_1(t)-x_{2d}(t))}_{\text{delayed P-action}}, \tag{22}$$

$$F_2(t)=\underbrace{K_d(\dot{x}_2(t)-\dot{x}_{1d}(t))}_{\text{delayed D-action}}\underbrace{+K_p(x_2(t)-x_1d(t))}_{\text{delayed P-action}}, \tag{23}$$

where:

$$\begin{aligned}\dot{x}_{1d}(t)&=\tfrac{1}{b}(-\dot{x}_2(t)+\sqrt{2b}u_m(t-\tau_1)),\\ \dot{x}_{2d}(t)&=b\dot{x}_1(t)+\sqrt{2b}v_s(t-\tau_2).\end{aligned} \tag{24}$$

It is well known that this basic wave variables scheme introduces wave-based reflections (see for instance [17]). In the literature many solutions can be found for reducing the reflections, like [18].

In terms of transparency, the wave variables method add an additional term $b/\Delta T$ in steady state and an additional inertia $b\Delta T$ during the motions (for more details, see [15]).

Wave variables provide an alternative information encoding scheme to the standard power variables. The required transformations are extremely simple and preserve all information.

F. Smith Predictor

The Smith predictor control system (figure 6) can predict the objects response and compensate time delays resulting in an improvement of the dynamic characteristic [27]. The objective is to design a controller $\overline{C}$ for the process P so that the closed loop transfer function $\overline{H}$ equals to $He^{-\tau}$ (H represents the closed loop transfer function without delay):

$$\overline{C}=\frac{C(s)}{1+C(s)P(s)(1-e^{-s\tau})}. \tag{25}$$

Figure 7 presents the Smith predictor for the haptic interface corresponding to our system (based on figure 3).

In this case, equations (1) and (2) become:

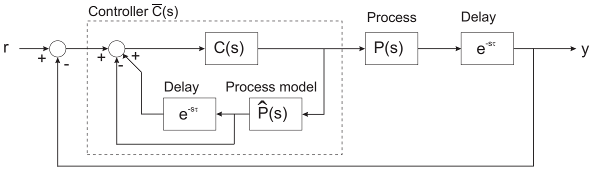

Fig. 6. Smith predictor basic scheme.

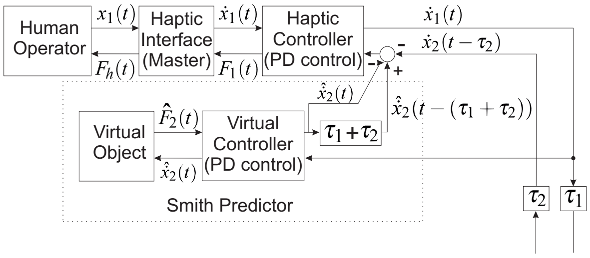

Fig. 7. Smith predictor scheme for haptic interface.

$$F_1(t) = \underbrace{K_d(\dot{x}_1(t)-\dot{x}_2(t-\tau_2)+\hat{\dot{x}}_2(t-(\tau_1+\tau_2))-\hat{\dot{x}}_2(t)}_{\text{delayed D-action}} \underbrace{+K_p(x_1(t)-x_2(t-\tau_2)+\hat{x}_2(t-(\tau_1+\tau_2))-\hat{x}_2(t))}_{\text{delayed P-action}}, \tag{26}$$

$$F_2(t) = \underbrace{K_d(\dot{x}_2(t)-\dot{x}_1(t-\tau_1)+\hat{\dot{x}}_1(t-(\tau_1+\tau_2))-\hat{\dot{x}}_1(t))}_{\text{delayed D-action}} \underbrace{+K_p(x_2(t)-x_1(t-\tau_1)+\hat{x}_1(t-(\tau_1+\tau_2))-\hat{x}_1(t))}_{\text{delayed P-action}}, \tag{27}$$

where $\hat{\dot{x}}_1$, $\hat{x}_1$, $\hat{\dot{x}}_2$, $\hat{x}_2$ represent the estimated velocity and position for haptic interface and virtual object respectively.

According to [3], motion synchronization and invariant local dynamics for distributed interconnected systems can be achieved by using Smith predictor.

Classic Smith predictor needs accurate identity between the compensation model and actual object. When the model has obvious errors, the control quality of Smith control system will become bad, even worse than without predictor [28].

III. ARCHITECTURES ANALYSIS AND COMPARISON

A. Comparison Criteria

We will now analyze each method presented in the previous section, using the following criteria with their corresponding scenarios:

- position tracking error in the case of restricted motion and constant delay, using an optimal tuning in order to have a minimal position tracking error,
- viscosity effect in the case of free motion and constant delay, using an optimal tuning in order to have a minimal position tracking error,
- position tracking error in the case of restricted motion and constant delay, using an optimal tuning in order to have a minimal viscosity effect,
- viscosity effect in the case of free motion and constant delay, using an optimal tuning in order to have a minimal viscosity effect.

B. Experimental setup

In order to assure a full control of the communication delays and processing time, all the control algorithms (for haptic interface/virtual object) and virtual environment simulations will be run on the same computer.

The haptic interface, figure 8, consists of one direct-drive motor and an optical quadrature encoder with 2000 pts/rev (with a gear ratio of 1/12). The controllers and the virtual simulation are running in real time mode (on RTAI Linux) with a sampling time of 1 ms.

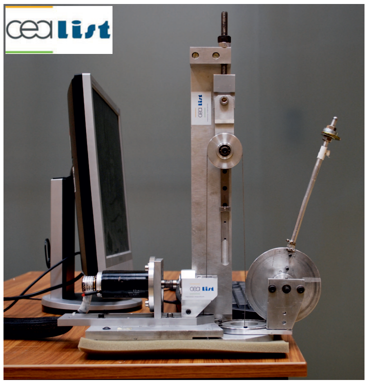

Fig. 8. Experimental Platform

The virtual object is modeled to be similar to the haptic interface ($M_1 = M_2$, $C_1 = C_2$). The virtual wall which results in force environment F_e is defined by the following equation:

$$F_e = K_{wall}(x_2 - x_{wall}) + B_{wall}\dot{x}_2, \tag{28}$$

where $K_{wall} = 20000$ and $B_{wall} = 10$ represent the stiffness and damping used to compute the virtual force environment, x_{wall} is the virtual wall position and x_2, $\dot{x}_2$ are the virtual object position and velocity.

C. Experimental Results

In figure 9 we present the *ideal* system behavior in free and restricted motion, without time delays.

An ideal haptic system must have a *small* position tracking error in restricted motion and an *insignificant* force feedback (low viscosity i.e. high degree of transparency) in free motion.

For our experiments, we have considered a fixed delay $\tau_1 = \tau_2 = 50\ ms$ and a constant human operator force $F_h = 7\ N$ for the restricted motion cases. The delays related to virtual reality simulations were not taken into account. The basic idea is to set up an optimal tuning for restricted motion in order to have a minimal position tracking error (close to the *ideal* case) and then to analyze it for free motion case. Next, the gains will be set up in order to obtain a reduced viscosity (near to the *ideal* case) and then the restricted

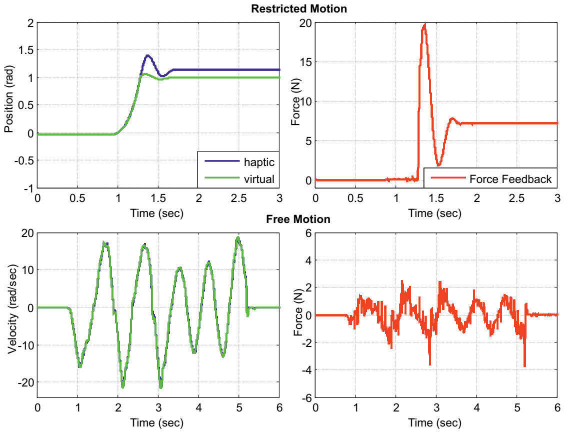

Fig. 9. Ideal Haptic System Behavior.

motion case will be analyzed. Based on the *ideal* behavior, the gains were tuned for the two cases as follows:

- best performance for position tracking error in the case of restricted motion, figures 10 and 11 (free and restricted motion), with:
  - for the first four methods:

$$K_p = 1500, \qquad K_d = 80,$$

  - for the wave-scattering method:

$$K_p = 1000, \qquad K_d = 70, \qquad b = 0.2,$$

  - for the Smith predictor method:

$$K_p = 950, \qquad K_d = 150,$$

- best performance for viscosity in the case of free motion, figures 12 and 14 (free and restricted motion), with:
  - for the first four methods:

$$K_p = 200, \qquad K_d = 15,$$

  - for the wave-scattering method:

$$K_p = 180, \qquad K_d = 15, \qquad b = 0.3,$$

  - for the Smith predictor method:

$$K_p = 250, \qquad K_d = 90.$$

In figure 13 we present the maximum position tracking error and the average force feedback (measured at a speed of 8 rad/sec) for each method and each case.

According to the experimental results, the differences between the methods remain very slight. It is obvious, that for the first five methods the stability is assured, furthermore the passivity observer and the set-point methods provide an additional theoretical guarantee. The Smith predictor method is more sensible in terms of stability. On the other hand,

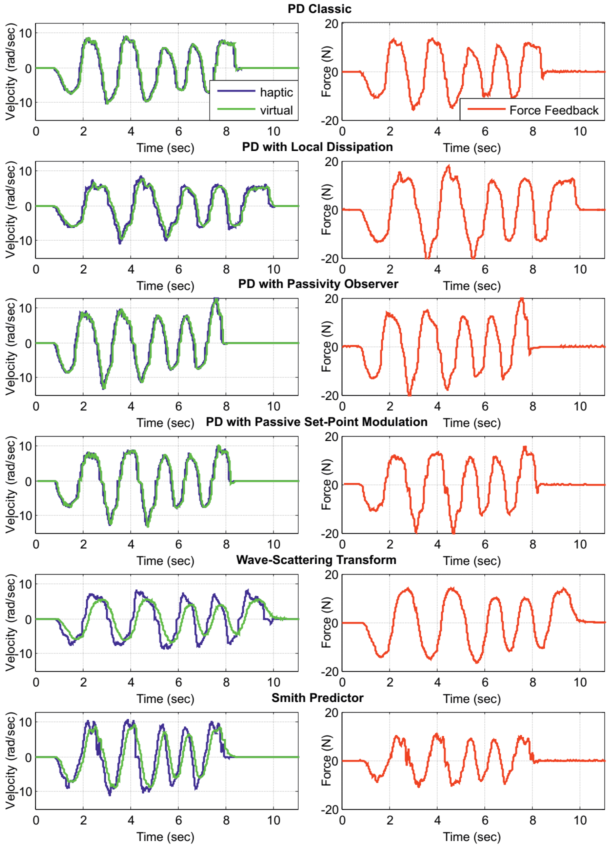

Fig. 10. Optimal error tracking - free motion, 50 ms delay.

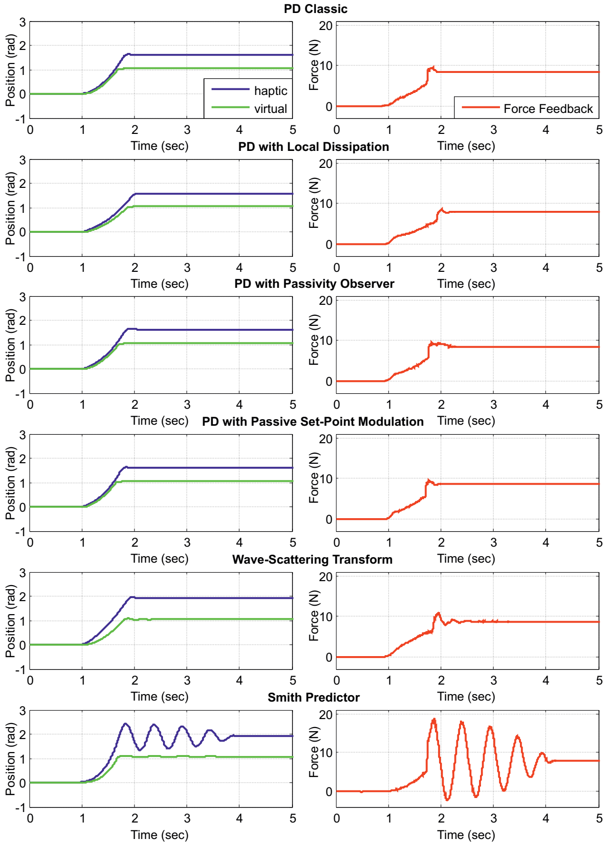

Fig. 11. Optimal error tracking - restricted motion, 50 ms delay.

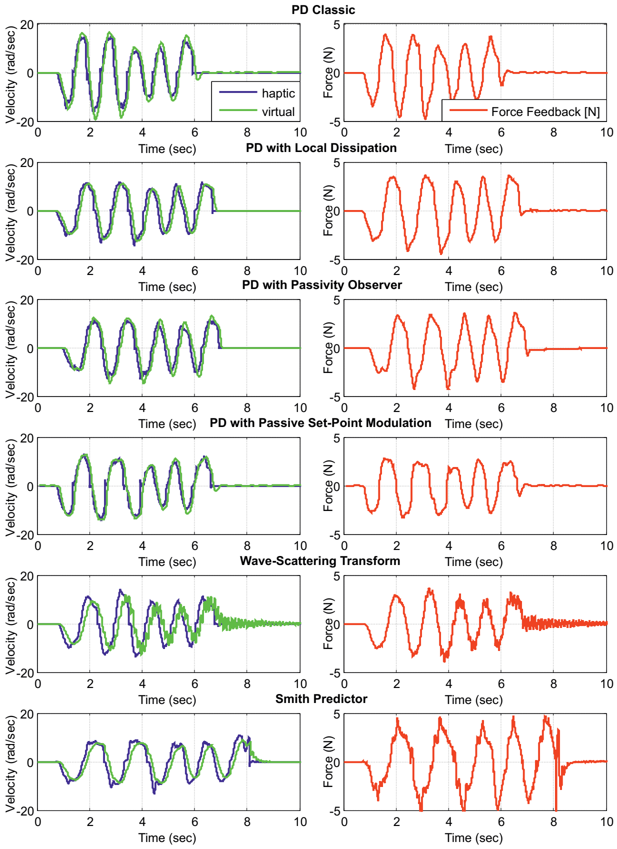

Fig. 12. Optimal viscosity effect - free motion, 50 ms delay.

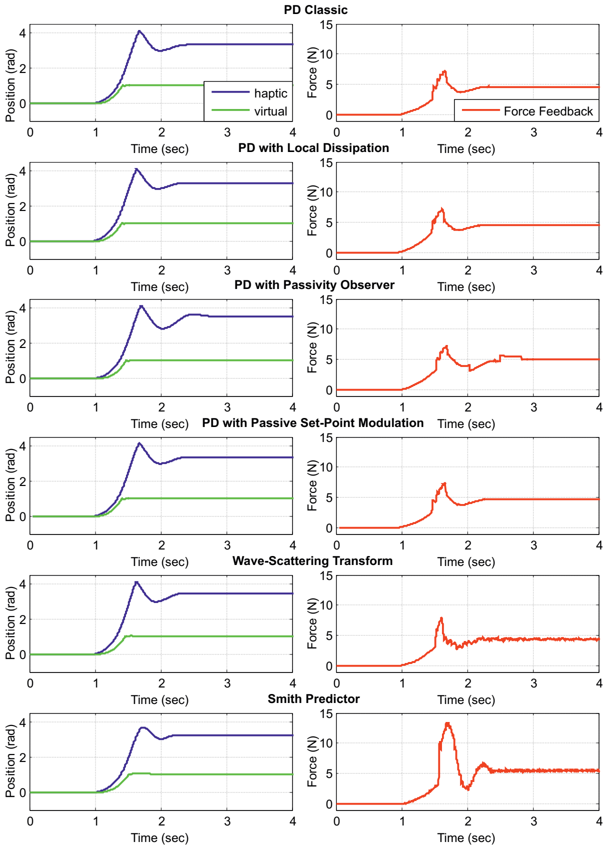

Fig. 14. Optimal viscosity effect - restricted motion, 50 ms delay.

none of these methods can provide high degree of transparency and small position tracking error in the same time. The compromise between transparency and position tracking error is obvious. The presence of time delays deteriorates the system's performances including disturbing effects like viscosity, which is directly linked to time delays.

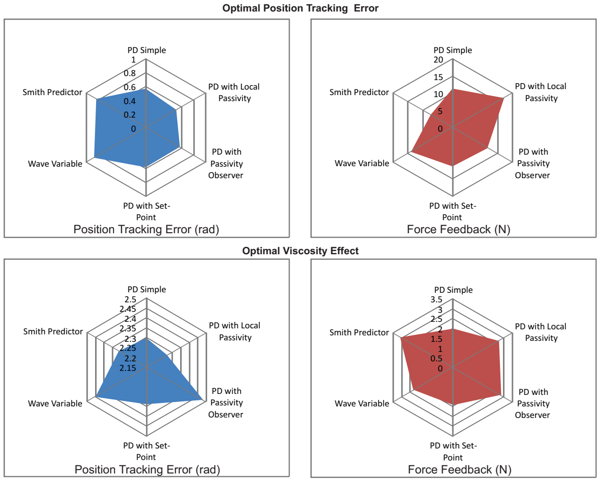

Fig. 13. Position tracking error and force feedback performance in the case of 50 ms delay.

For the first case - optimal tracking error, the best method in terms of position tracking error is the PD control with local dissipation with an error of 0.512 rad, but in free motion the viscosity effect is significant (17.2 N). The best method, from the transparency point of view, is the Smith Predictor, with a force feedback of 7.5 N, but in terms of position tracking error the result is not very good (0.832 rad).

The *best* compromise between transparency and position tracking error is assured by the PD control with set-point method with a position tracking error equal to 0.569 rad and a force feedback of 11.2 N.

For the second case - optimal viscosity effect, which is more significant in the case of haptics (the interest to have a low viscosity effect in free motion and a stiff response in case of hard contact is bigger than to have small position tracking error), the best performance, i.e. the smallest force feedback, is obtained for the PD control with set-point modulation method (1.9 N) and a position tracking error of 2.336 rad. The smallest position tracking error is assured by the PD control with local dissipation (2.271 rad) like in the first case.

The *best* compromise between transparency and position tracking error is assured by the classic PD control with a position tracking error equal to 2.298 rad and a force feedback of 2 N.

It is worth mentioning that some of the methods (wave variables in the second case for free and restricted motion, PD with passivity observer in first case for restricted motion and Smith predictor in the second case for restricted motion) induce significant noise on the responses.

Generally speaking, even if we are able to see small differences between the methods, the optimal tuning for one case will deteriorate the performance for the other one.

IV. CONCLUSIONS

In this paper we have analyzed the most common control methods, used in teleoperation systems, applied to haptics. In haptics, like in teleoperation, a high degree of transparency and a small position tracking error is desired. The two conditions cannot be assured in the same time by none of the presented methods. However, the best experimental results in the haptics context are obtained for the Smith predictor and PD control with set-point modulation method.

In [21] an algorithm to switch between optimal position tracking error and optimal viscosity is proposed with satisfying results.

In future works we will analyze the Smith predictor variants, as a specific control structure or in conjunction with the first five methods which were presented in this paper.

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