Proceedings of the 2002 IEEE
International Symposium on Intelligent Control
Vancouver, Canada • October 27-30, 2002

Master-Model Based Time-delayed Force Feedback Interaction: Experimental Results

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Abstract

This paper extends earlier results on stable haptic and force feedback interaction in the presence of constant and varying time-delay. Although the paper focuses on VE based haptics, results can also apply to teleoperation. The proposed method considers extending our preliminary work where Smith prediction principle has been adapted on delayed haptic feedback interaction. We shall show that this proposed approach is easy to implement and is original since it investigates another way to formulate stable haptic feedback algorithms. It requires to know only the model of the master interface or the haptic display. Stability and robustness analysis are thoroughly discussed. Experimental results and comparison with wave variables are discussed.

1 Introduction

There are many applications which require to feed back haptic cues to human operator: teleoperation, telepresence, virtual reality simulators such as virtual surgery training, driving simulators, etc. Commonly, haptic cues are fed back thanks to an actuated mechatronic device able to constraint the operator desired motion against the applied reaction forces. Contrarily to the vision or auditory human modalities, haptic cues are collected through a direct and dynamic (i.e. active) human contact (touch) with its surrounding environment. In teleoperation and telepresence contexts, haptic informations are collected through a bilateral coupling between the human held or worn haptic display and a remote robotic system. It is able to replicate human desired motions and to collect haptic information during contact or constraint motions. Other applications based on virtual reality techniques, such as haptic feedback surgery training simulators, require also haptic devices to experience haptic interaction between the human operator and virtual environments (VE). This is made thanks to computer haptics algorithms which compute collision detection and subsequent dynamic response motions and forces during contact with virtual objects. Consequently, haptic devices are commonly active actuated mechatronic devices which must be controlled stably to be correctly used and to avoid danger for operator.

In teleoperation technology, the remote executing machine could be far from the operator. Thus transmitted data (desired operator actions or trajectory and sensory feedback informations) could be delayed. Moreover, industry is also attracted by this technology in the frame of virtual prototyping. This extends also to the possibility to work at a distance and to concurrent engineering. Nevertheless, it is well known that a small time delay (experimentally reported to be $\gtrapprox \frac{1}{4}$ sec in teleoperation) may destabilize any conventional–coupled haptic feedback architecture. This is an old problem in teleoperation and many solutions have been proposed to deal with this problem [2][8][12][9]. In addition, solutions developed in the frame of teleoperation have been adapted to VE haptic feedback (i.e. the adaptation consists mostly in a clever discretization of the continuous ones).

In this paper, an original solution derived from Smith prediction [11] is proposed to design stable and transparent controllers for delayed haptic feedback systems. The proposed controller requires only the master model [4]. The solution is proven to be stable and also robust to master device parameters estimation. Simulation and experimental results are convincing and the implementation of the solution in any haptic system is very simple. The other strong point of the solution is that it robust to a constant time delay or a varying time delay.

2 Main result

Before addressing the VE force feedback context, let us recall some generic results used in the proposed solution. Let the figure 1, represent any interconnected pair of systems defined respectively by their time-domain or frequency-domain linear mapping $G_1$and G_2. The external input signals of the interconnected systems are denoted respectively by e_1 and e_2, the out-

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put signals by y_1 and y_2, where as $u_1 = e_1 - y_2$ and $u_2 = e_2 + y_1$ are respectively the controller's signals (or the solutions signals). Eventually, the systems output signals y may be time delayed by respectively τ_1 and τ_2.

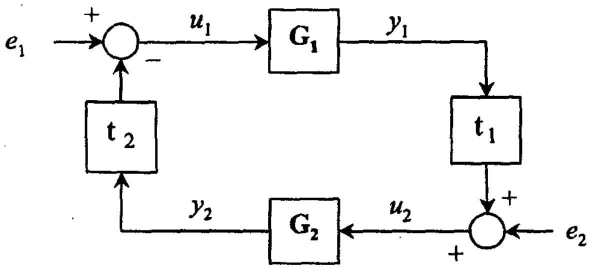

Figure 1: Interconnected systems with time delay.

The process G is said to be passive if

$$\langle y, u \rangle = \int_0^t y(\tau)^T u(\tau) d\tau \geq 0, \forall t > 0.$$

In the control theory dealing with interconnected systems represented in figure 1, when the time delays $\tau_1(t) = \tau_2(t) = 0, \forall t \geq 0$:

Theorem 1 (van der Shaft 96) *If G_1, G_2 are passive then the resulting system with inputs (e_1, e_2) and outputs (y_1, y_2) is also passive, and strictly output passive if both G_1 and G_2 are strictly output passive.*

Proof. see [5] for demonstrations. ■

This passivity property is not guarantied and may be lost when there exist a transmission delays in the closed loop system, that is $\tau_1 \neq 0$ or $\tau_2 \neq 0$.

Theorem 2 *The interconnected delayed system shown in figure 1, can be stabilized by keeping its passivity property, using a process-model based control of either G_1 or G_2, see figure 2.*

Proof. The time-domain equations expressing commands and outputs are as follows:

$$\begin{cases} u_1(t) = e_1(t) - y_2(t - \tau_2(t)) \\ u_2(t) = e_2(t) + y_1(t - \tau_1(t)) + y_{11}(t - \tau_1(t)) - y_{12}(t) \end{cases}$$

where, $y_1(t) = G_1(u_1(t))$, $y_2(t) = G_2(u_2(t))$, $y_{11}(t) = G_1(y_2(t - \tau_2(t)))$ and $y_{12}(t) = G_1(y_2(t))$. Assuming that G_1 is well identified, the second equation can be re-written in the following form:

$$\begin{aligned} u_2(t) = e_2(t) + G_1(e_1(t - \tau_1(t)) \\ -y_2(t - \tau_1(t) - \tau_2(t - \tau_1(t)))) \\ +G_1(y_2(t - \tau_1(t) - \tau_2(t - \tau_1(t)))) \\ -G_1(y_2(t)) \end{aligned}$$

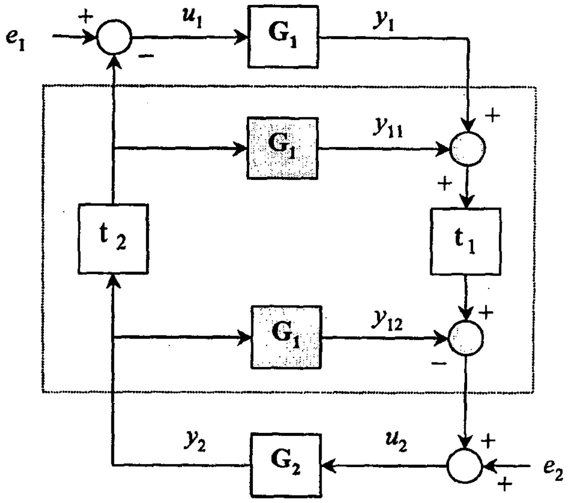

Figure 2: A simple model-based controller to stabilize the interconnected system.

which leads to (since the mapping G is linear):

$$u_2(t) = e_2(t) + G_1(e_1(t - \tau_1(t))) - G_1(y_2(t))$$

which is equivalent to:

$$u_2(t) = e_2(t) + G_1(e_1(t - \tau_1(t)) - y_2(t))$$

This last equation shows that the final resultant system is equivalent to the system of figure 1 with $\tau_1 = \tau_2 = 0$, but with a delayed input $e_1(t - \tau_1(t))$. The passivity of the overall system holds since no hypothesis was made on $e_{1 \text{ and } 2}$ and the passivity property was proved whatever $e_{1 \text{ and } 2}$ are. However we assume that all the causality conditions holds, especially $\tau_{1 \text{ and } 2}(t) < t$ and $\dot{\tau}_{1 \text{ and } 2}(t) < 1$. ■

3 Application to haptic interaction

In a recent previous work [3], the principle of Smith prediction has been adapted for the synthesis of a stable haptic feedback controller to be used with constant and varying time delay.

The originality of the proposed solution is in the kind of prediction of the master part within the remote part. Hence, the developed equations lead to a prediction scheme where only the master model appears and also the estimation of the time delay is necessary. The term "kind of prediction" is used to signify that in fact the proposed solution is not really a prediction since only the master model is required, which means that no prediction of operator behavior or trajectory is needed.

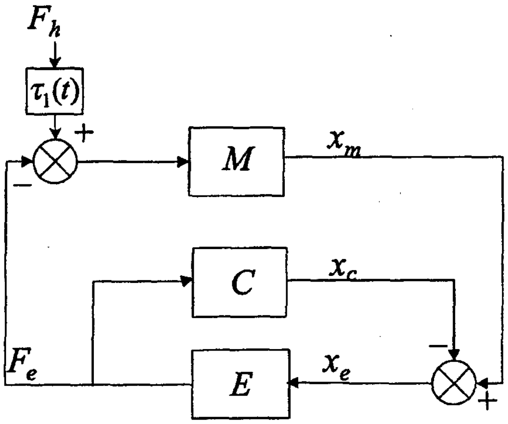

Figure 3: The actual implementation scheme.

where: M is the haptic device transfer function, E is a VE transfer function (assumed continuous with a high sampling frequency), x_m, x_c and x_e are respectively master, virtual coupling and VE positions, F_e is the VE computed force, F_h is the operator applied force on the device, C is the commonly used virtual coupling [1], which guarantee unconditional stability of the haptic interaction system in the absence of time-delay, and $\tau_1(t)$ is upwards time delay.

At the beginning, the controller have been implemented as it is in [4]. But from a practical and a simple observation [3], the structure of the controller made an interesting extension which:

1. avoids the estimation of time-delay, and
2. make a straightforward extension to time-varying time delay.

This is obtained simply as depicted in figure 3. Nevertheless, the new implementation highlights that it is no more necessary to estimate time delay (like in the case of Smith prediction), and more importantly: the behavior of time delay may have no effect on the stability of the system (for more information see [3]).

4 Comparison with wave based approach

Comparing to wave-based approaches, which appear to be a standard solution in time-delayed force reflecting systems, this proposed solution is more transparent to the user (even for important delays, it has been assumed , however, that bilateral control would not be effective under a time delay more than 1 sec, [7] et [6], it seems that when the delay time is longer than about 1 sec, the master model-based approach would be the only solution) since the controller could be designed with no additional corrupting dampers, as engendered from the transformation of force and flux parameters into waves. The price to be paid is in the importance of the position discrepancy between the master and the slave when the contact occurs (here the actual virtual object position) which may be more important in our case comparing (which make one of important future works) to wave-based methods. In fact, in wave-based method, the artificial damping increases with speed (in free motion), which prevent important master-slave position discrepancies, but the inconvenient is the additional felt force which is not directly related to actual remote contact forces, that is to say more stable but less transparent. Moreover, our proposed method is functional for both constant and varying time delay without any change in the controller, whereas wave based passive techniques requires an entire reformulation of the controller or additional control computations, [12] and [8].

The principle of the wave-based approaches is to transform by means of a bijective mapping the flow and effort parameters of the haptic interface and the VE into waves. Let v_m and v_e be respectively the haptic interface and the virtual object speeds (flow) and f_m et f_e be respectively the actual haptic fed force and the VE computed one. The wave mapping is as follow:

$$\begin{aligned} \phi_m &= \tfrac{1}{\sqrt{2b}}(f_m + bv_m) & \qquad \phi_e &= \tfrac{1}{\sqrt{2b}}(f_e - bv_e) \\ \psi_m &= \tfrac{1}{\sqrt{2b}}(f_m - bv_m) & \qquad \psi_e &= \tfrac{1}{\sqrt{2b}}(f_e + bv_e) \end{aligned}$$

ϕ are the incident waves, ψ are the reflected waves, and b is the characteristic impedance associated to the waves (by analogy to the line impedance in network theory). This impedance may affect the behavior of the overall system when it is not well adapted. As stated, this mapping is bijective and may be reversed to produce the system flow and effort parameters from waves, that is:

$$\begin{aligned} f_m &= \sqrt{\tfrac{b}{2}}(\phi_m + \psi_m) & \qquad f_e &= \sqrt{\tfrac{b}{2}}(\phi_e + \psi_e) \\ v_m &= \tfrac{1}{\sqrt{2b}}(\phi_m - \psi_m) & \qquad v_e &= -\tfrac{1}{\sqrt{2b}}(\phi_e - \psi_e) \end{aligned}$$

Similar simulation conditions and parameters were conducted using a wave variable based scheme and our model-based scheme. Obtained simulation results shows, figure 4, that the overall two approaches behaviors are nearly the same. In this case $b = B$, which means that the characteristic waves impedance is equal to the model-based controller damping (or the haptic interface damping including the built-in controller one). As stated before, the transparency of the model-based approach is better but the positions discrepancy (or the static error of the position between the haptic interface point and the virtual object point) is more important in the model-based approach. As suspected, this is due to the fact that the fed force is not nil whatever the contact is not made, this is clearly shown in the figure 4. Increasing b together with B_e leads to a similar force reflection behavior, some oscillations appear. The interpretation for b is in the wave reflection due to the none adapted impedance (as in physical network media), nevertheless, the passivity of the overall system is kept. In what concerns the interpretation for the model-based case is, it has been already mentioned that if the value of $B_e \neq B$ the time-delay term is not canceled from the characteristic equation of the closed loop transfer function. Indeed, passivity is not preserved and stability is compromised.

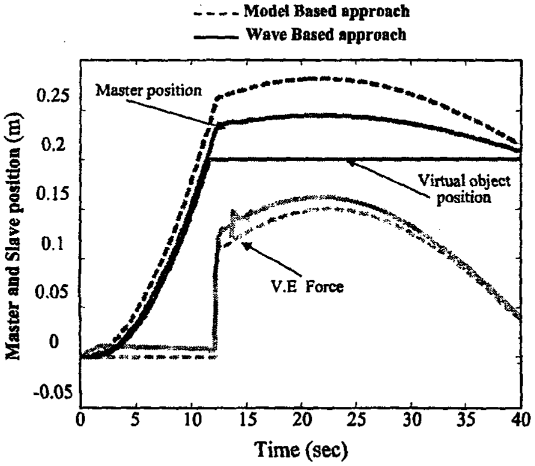

Figure 4: Comparing of simulated wave-based and model-based bahaviors.

The advantages of the proposed method comparing to the wave-based on are: a better fidelity and transparency (specially in the free motion, where control of wave based approach is not zero) of the reflected force, a simple computation of the controllers, extends straightforwardly to varying time delay whereas wave-based approaches present an unstable behavior for which they need further adaptations ([8] and [12]), a position control is possible whereas wave-based method requires velocity.

The drawbacks are: a less conservative method, passivity is lost if the master parameters are not well estimated, a more important master - VE positions discrepancy.

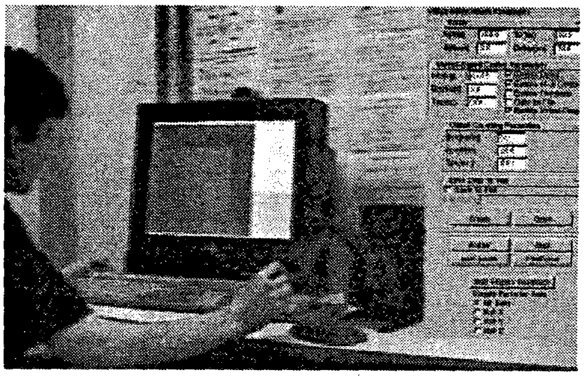

Figure 5: Experimental Setup of the haptic interaction.

5 Experimental results

This section presents simulation and experimental results of the developed controller. The haptic display is a three DOF Phantom actuated arm [10], its process model is taking as apparent mass $\hat{m} = 50g$ and the estimated friction is about $\hat{b} = 3Ns/m$, figure 5. The transfer function of the controllers is discretized using Tustin's method,

$$\hat{M}(s) = \frac{1}{s(\hat{m}s + \hat{b})}\Big|_{s \to \frac{2}{T_e}\left(\frac{z-1}{z+1}\right)} \qquad (1)$$

which preserves the passivity of the mapping. For ease of implementation, discretization of virtual coupling network can be performed using a rectangular integration approximation.

Our virtual environment has as a goal to manipulate a virtual object (a probe) inside the cube, figure 5, where the contact will be performed between the rigid probe and the virtual walls (situated on the X axis in +/-100mm) of stiffness $K_e \in [1000 - 10000]N/m$ and

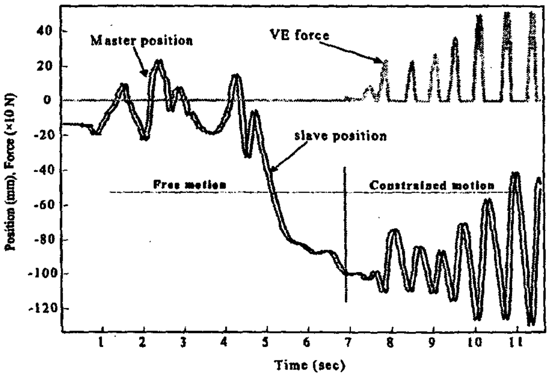

Figure 6: Unstable behavior of the haptic interaction

friction about $B_e = 3Ns/m$ (to signify rigid contact interaction).

We have performed four implementations. First simulation, figure 6, shows the beginning of an unstable behavior of the haptic interaction under a constant time delay, where $T_1 + T_2 = 100ms$.

The next figure 7 gives a stable behavior (under same conditions stated above) when we enable the use of the model based control without error estimation, also the tracking and force of the VE behavior when the operator interacts with a VE K_e. Collision detection and force computation are performed simply and do not cost additional time delay.

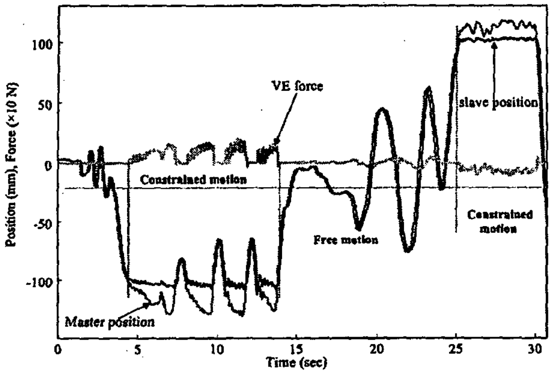

Figure 7: Stability of a delayed virtual contact with a stiff wall and force feedback.

Figure 8 shows another experimental result concerning simulation of a virtual contact under large time delay. The operator apply an arbitrary force F_h which drops the master and probe positions to increase until a contact is made between the probe and the virtual walls. This is done when the virtual probe position reaches ±$100mm$. From this time the local VE controller $C(s)$ guarantees the local stability of the virtual interaction and the calculation of the virtual environment force, which is fed back to the operator. One can notice that when the contact is made, the master velocity v_m drops to zero and the fed force F_e (the controller) increases accordingly to F_h during the contact. The position discrepancy, when the contact is made, is unavoidable whatever is the controller or the approach (unless a very VE or slave plus remote environment prediction is made in the master side), this is due to the undergo physical time-delay. Nevertheless, the virtual probe position x_e is stably maintained by the operator during the whole contact time. We conducted many other simulation cases with multiple hard and viscous contacts that show that the behavior of the force feedback interaction is stable whatever the size of the time delay. Obviously, one must not suspect that functional performances are acceptable for an actual use in the presence of important time delays.

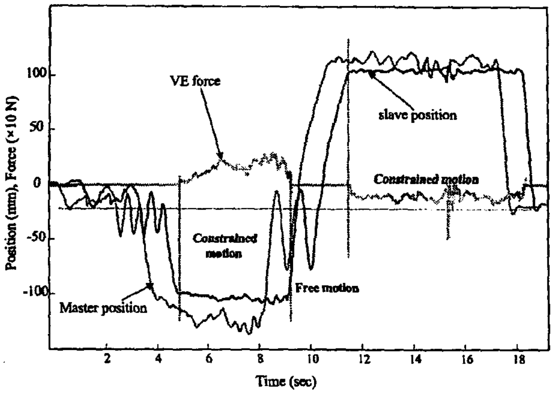

Figure 8: Stabilty of the haptic interaction under large time delays.

The two last figures (9, 10) show robustness results of the above system (which has been detailed in [3]). The first figure 9, the estimated parameters are taken $\hat{m} = 0.2\ kg$ and $\hat{b} = 6\ Nm/s$, we can notice that the behavior of the haptic interaction is still stable and appearance of small vibration.

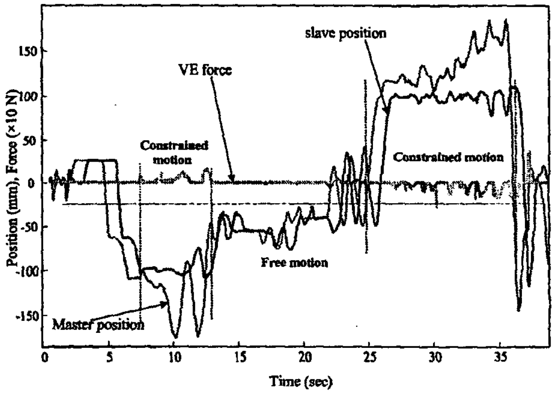

Figure 9: Stability margin due to error in estimation parameters

Figure 10, here the estimated parameters are taken $\hat{m} = 1\ kg$ and $\hat{b} = 8\ Nm/s$, we can show an unstable behavior of the haptic interaction, as proven in theory.

6 Conclusion

This paper presents a master-model based controller to stabilize delayed force feedback systems. The proposed method is based on an astute implementation of a somehow Smith prediction scheme, which requires

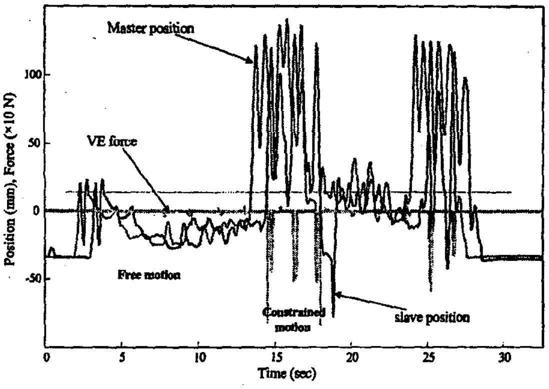

Figure 10: Unstable behavior due to error estimation parameters.

only the haptic device model and do not necessitate the estimation of both (upwards and downwards) delays. The experimental results confirm a stable force reflection from the VE in presence of constant time delays. A robustness analysis of the proposed controller has also been conducted. The error margins that guarantee the stability of fed back forces are found to be wide enough to allow using a linear model of the haptic interface based only on a apparent mass and friction estimation.

Comparing to the wave-based approach, this proposed solution is more transparent to the user (even for important delays) since the controller could be design with no additional corrupting damping, as engendered from the transformation of force and flux parameters into waves. Moreover, the proposed method is functional for both constant and varying time delay without any change in the controller [3], whereas for wave based passive techniques requires an entire reformulation of the controller or additional control computations [12].

Future work will focus on how to improve performances in virtual environment haptics. The idea principle is to predict, within the master site, the behavior of VE feedback force based on computer haptics algorithms, but in this case the upward time delay must be known.

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