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Effect of Transmission Delay on Haptic Perception in Shared Virtual Environments

Hichem ARIOUI

17.1. Introduction

The simultaneous exploitation of force feedback teleoperation systems with simulation and graphic animation, known as virtual reality techniques (VR) techniques, have made it possible to implement shared haptic interaction between multiple remote users in virtual environments [BUR 94]. The remoteness of the operator makes it possible to perform previously difficult and uncommon tasks. In other words, it is easy to gather various experts in a unique virtual model (also called a “synthesis environment”). Conversely, this multi-user implementation inevitably causes transmission delays related to the communication architecture type connecting all human operators or “clients” at the remote site. These problems caused by the transmission latency in force feedback and/or haptic simulation systems are old and have recently become even more complex after the emergence of new communication technologies such as the Internet. This complexity results from fluctuations due to network congestion or information transmission protocol.

Historically, virtual environments have been exploited by teleoperation¹ systems in various remote-programming and predictive visualization architectures when the

1. The word “teleoperation” means principles and techniques that allow the human operator to carry out tasks at a distance from the remote machines location which are under his control. In other words, remote control of robotic tools. One principles is to eliminate the risk

transmission delay made it impossible to perform delayed tasks. Indeed, remote-programming system is an architecture that consists of disabling classic control law based on a bilateral direct coupling principle between master and slave sites. The coupling connecting both sites is replaced by two local control laws.

The concept of remote programming, in particular the idea of using a virtual environment coupled with a force feedback interface, resulted in a multitude of designs for interactive simulation and multimodal-based virtual environment systems. Besides, the conception of force feedback devices has evolved and become more ergonomic and more portable. Thus, in virtual reality, the haptic interface inherits from teleoperation system twice, as is the case for the control law algorithms:

- in haptic simulation, the physical device is based essentially on technology of force feedback master devices (teleoperation);
- coupling algorithms are partially from remote programming, but also dynamic simulations used in graphic animation and the bilateral force reflecting controller.

The applications of haptic rendering in virtual reality concern several fields: interactive surgical simulators, driving and flight simulators, games and distraction, virtual prototyping multi-skills, etc. We should emphasize that in a master/slave system, the concept of remote programming has been proposed as an alternative architecture to overcome the problem of unstable force feedback under the influence of time delay [KHE 97]. From the other side, this concept suffered from a lack of force feedback transparency and poor coherence between the operator's feeling and visual restitutions. Conversely, the classic bilateral force reflecting controls (based on the passivity or prediction principles) offer interesting alternatives, although this proves troublesome in some cases.

This chapter presents an overview of transmission time delay's effect on haptic simulation. On the one hand, we round up the conventional automatic control of such systems to enhance fidelity of force feedback rendering, and on the other hand, suggest tracks for overcoming handicaps of these control laws using the Quality of Service (QoS) techniques in the transmission system protocol.

of dangerous work such as space exploration or the manipulation of toxic substances. To facilitate the various operations of the human operator, teleoperation systems can integrate remote assistance such as graphics visualization, interaction devices or even systems for the planning tasks.

17.2. Haptic simulation in VR applications

A VR application is a computer simulation system in which graphic design is used to create a world that seems realistic. The virtual world is synthesized to be dynamic, responding naturally to a human operator's desired actions (gestures, words or any other external commands). VR involves interactions through multiple sensory channels: vision, touch, smell, taste and hearing.

The concept of virtual reality is more than thirty years old, registered under the USA patent no. 3050870 awarded Morton Heilig for his invention called "Sensorama Simulator". This invention consisted of a 3D computer vision system based on cameras, broadcast stereo sound and wind by using small fans near the operator's head, and had a seat vibrant. Therefore, it was possible to simulate a simple car or motorcycle drive session. Currently, technical progress allows us to make virtual worlds and/or objects within powerful 3D graphics libraries; professional CAD programs are numerous. Interactively, the user can create virtual object models, in particular, textures, space issues and assignment of physical parameters (stiffness, friction, inertia, etc.). All these synthetic features can be felt by the operator using mechatronic devices called "haptic interfaces".

Unlike for visual and auditory modalities, the design of haptic simulation and interfacing in VR applications is particularly delicate, because of its active sense. Designing a device capable of reproducing the user's haptic information accurately (force, pressure, vibration, temperature, etc.) requires some material and a specific design approach. This is different from, for example, vision or hearing and is why the restituted information does not change its physical media (respectively screen or headphones). Achieving a haptic simulation (software and hardware parts) requires active modules capable of feeding back the operator's desired movement or stimulating their haptic sensors.

17.2.1. *Haptic feedback device*

Haptic, from the Greek "*haphe*", means pertaining to the sense of touch (or possibly from the Greek word "*haptesthai*" meaning feel by "contact" or "touch"). It usually distinguishes three sensory modalities:

- kinesthetic sense: this includes the perception of bodily movement and muscular effort;
- tactile sense: this provides information regarding skin contact with objects in the virtual environment (pressure, vibration, roughness, etc.). The finger (specifically the skin) has pressure sensors which give us surface information on the manipulated virtual object;

- thermal sense: this gives information about temperature of the explored virtual object through our finger. In some cases, the thermal effect is used to learn about the nature of the object manipulated.

In VR applications, a haptic feedback system consists of three essential parts:

- human operators: this is the main piece of the systems haptic interaction;
- haptic device, which is composed into three modules:
 - the physical interface or “haptic device”,
 - the computer interface based on algorithms used to simulate the virtual environment dynamics (collisions detection between virtual objects, contact force calculus, numerical integration etc.),
 - the local control box of the device (position and velocity track);
- Virtual Environment (VE): this is a world in which purely computing tasks are performed.

This list can be enhanced by adding “transmission media”. The integration of this component requires fundamental knowledge for a successful haptic simulation, which is based on a communication architecture regardless (i.e. collaborative work distributed on the Internet).

A general architecture for a haptic rendering simulation based VE is represented by Figure 17.1. Several psychophysical studies show that visual feedback is conditional on haptic perception. Therefore, it is important to maintain coherence between visual and haptic feedbacks. This constraint is important for maintaining realistic and natural perception.

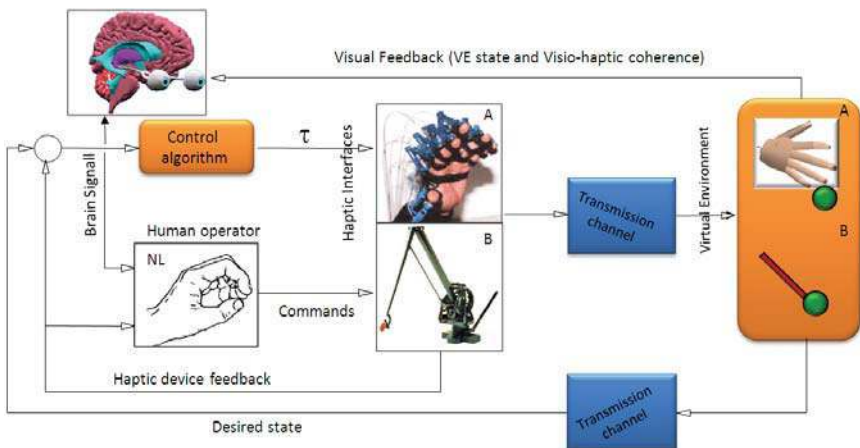


Figure 17.1. A simplistic architecture of a haptic feedback simulation in a VR application

Figure 17.1 illustrates two types of haptic feedback on the hand of the human operator. In order to reconstitute haptic information to the users, a device, directly linked to the operator, is required to exchange haptic information flow between the operator and VE. In terms of mechatronics, several hardware designs are possible. They depend on the haptic application considered, but each application has limitations and constraints. For example, a data skeleton-glove fitted with a 3D Tracker allows control of a virtual hand, using finger movements of the operator, based on the exoskeletons robotics joints (case A in Figure 17.1).

When the application allows it, it is advisable to consider instead a representation of the tool used (case B in Figure 17.1) as a haptic device. The virtual representation (also known as “virtual avatar”) then relates to the device and not the operator’s hand. In this case, the operator manipulates the tool directly.

The whole of haptic simulation can be seen as a system accepting commands from the human nervous system. Indeed, these human orders are reflected by a set of movements imposed by the operator to convey an action within the VE. We call them intentions or guidelines of human actions. The resultant action performed inside the VE is not necessarily similar to that envisaged by the human operator. As for the state of the haptic device, it depends on control law parameters, the operator's intentions and sensorial feedback given by the virtual world response. The desired state of the haptic device can be obtained in two ways:

- either as a direct function of the virtual avatar’s feedback;
- or as a function of the difference between the carried out and desired states.

Generally, force feedback devices are used to generate mechanical impedance in the manner of a dynamic relationship between the effort (force) and flow (speed or position). If we want to represent a mass point manipulation, this device must exert a force proportional to the acceleration on the human operator arm (adding this to the gravitational one), whereas if we simulate deformation of the compressed elastic object, the virtual environment (physical process) will generate a force proportional to the displacement. As far as the hardware of the haptic interface is concerned, there are several specialized designs. Therefore, many of them are an adaptation of master teleoperators or syntaxors used master slave teleoperation system. Thus, these interfaces are designed and conceived with the same technologies as those used for teleoperation systems. These include force feedback interfaces like master arm, joysticks, stylus feedback, etc. In Figure 17.2 below, we see two types of PHANToM™ both developed by two researchers from MIT², Massie and Salisbury [MAS 94, SAL 97], and inspired from many arms in teleoperation.

2. Massachusetts Institute of Technology, Cambridge, Boston, USA.



Figure 17.2. *Two types of SensAble Technologies of PHANToM*

17.2.2. Applications of haptic systems

The areas of haptic feedback system applications in virtual reality are wide-ranging and multiple. Thus, a haptic interface linked to an interactive VE is useful in:

- medical field: for example, the use of a simulator for training surgeons or obstetricians in the appropriate gestures and actions (Figure 17.1A). These systems have the advantage of avoiding experiments on cadavers or real patients and simulate a variety of illnesses, on the one hand through a clinical database and virtual reconstruction modules, and on the other hand, biomechanical models of human muscle tissue;
- piloting and driving complex machines: flight simulators, driving simulators, tank simulators, etc. A subsidiary of Thales or Ford companies specializes, among other things, in this field;
- field of video games: entertainment and educational game eventually distributed on the Internet;
- teleoperation and remote control systems: including remote programming system, which are based on a virtual representation of the remote robot and its environment, and telepresence architectures;
- concurrent engineering and virtual prototyping with multi-users (Figure 17.1B): this implementation can be used for assembly and disassembly operations in automotive industry. As a result, many users with different expertise and located on remote sites can interact together and share the same virtual model.

In recent years, researchers have taken a particular interest in collaborative virtual prototyping and concurrent engineering distributed on the Web. However, a major challenge to tackle before benefiting from all the advantages of a distributed haptic architecture is that of issues caused by transmission delay phenomenon (constant or variable).

17.3. Delayed force feedback systems

Teleoperation systems have been studied extensively since the end of the 1980s. This area is today experiencing a renewal of interest in “Networked Systems”. Indeed, the problems of stability and transparency associated with the presence of delays in communication have not been fully dealt with, the tools available being not yet satisfactory. With the spread of various communication networks and their multiple protocols, the problem of delay has become even more complex due to its variable and/or unknown nature, bringing a significant performance degradation to the whole force feedback system (inconsistency between vision and feeling of force, vibration, etc.), even instability. These fluctuations are primarily caused by congestion phenomenon and may increase because the information transmitted through the network, including transfer characteristics, can be non-deterministic. The contribution of much research in the study of delayed force feedback systems (since the mid-1990s) has attacked the problems of this kind of system with relevant objectives, such as stability and performance (fidelity of force rendering). Some recent results indicate that this field is a fast growing area.

This section presents two fundamentally different approaches from recent literature. The first approach is a purely theoretical approach based on techniques of automatic control whatever the delay (amplitude and variation). The second approach is exclusively based on remote programming, which concerns the separation of the two master/slave sites and the absence of bilateral coupling.

17.3.1. *Automatic control law, solutions and handicaps*

17.3.1.1. *Modeling and control of haptic feedback devices*

The essential objectives and functional constraints of haptic rendering much are akin to those of force feedback systems in teleoperation using a bilateral controller:

- the link coupling the operator, haptic device and VE, should be stable irrespective of the circumstances of practice;
- rendering fidelity haptic must be optimal.

Although various methods are available to model the entire haptic simulation, many authors use models based on the theory of electrical networks. In electronics, the quadrupoles method is particularly well suited to force feedback systems in teleoperation as well as for haptic interactions. It is quite well accepted that for this approach there are analogies between some well-known mechanical and electrical components of an arbitrary network (or system). Therefore, we can draw on the passivity properties for the quadrupoles³ to deduce a stable bilateral control law [LIE 52].

However, these studies are, generally, realized on a remote master-slave system with one degree of freedom with a linear model. If this model helps to understand the essence of the strategies to implement, it may still be difficult to generalize control laws obtained for the multi-axis force feedback devices or for interfaces with more degrees of freedom. Dynamic models of robotic systems (and hence the haptic devices arising there from) are known to be non-linear.

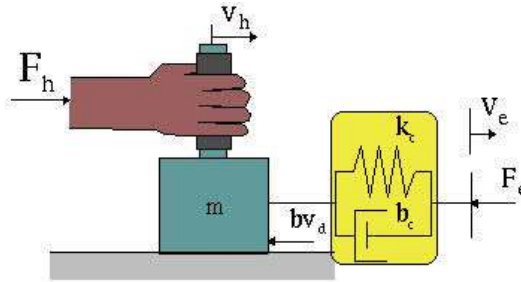


Figure 17.3. Simple representation of a one degree of freedom haptic device⁴ [COL 95]

3. The cascade implementation of passive quadrupole networks (human operator, haptic interface and virtual environment) provides a stable interconnection [SCH 96].

4. Let us take the example of a one degree of freedom haptic device, given by the dynamic equation:

$$m\ddot{x} + b\dot{x} = F_h - F_e \quad [17.1]$$

where m is the apparent mass at the final point of the haptic device, b is the estimated viscous friction of the haptic interface, x, \dot{x}, \ddot{x} are the position, speed and the acceleration of the same final point, F_h, F_e are respectively the human applied force on the haptic interface and the force feedback (control force) resulting from the interaction with the virtual environment. In Figure 17.3, the yellow part represents the local controller on the virtual environment side.

However, haptic devices are characterized by low inertia and low friction, allowing some approximations in the dynamic model (the right part of figure 17.3 is the local controller at the virtual environment side). By taking into account the differences between the master arms in the teleoperation system and those used in virtual reality, it is possible to simplify the device model for a large class of haptic interfaces. In fact, the endpoint of these devices can be considered as an apparent mass/inertia that the operator manipulates in the device workspace, and an apparent friction feedback [COL 95, ADA 98]. Thus, the assumptions described above allow us to take a linear model and study an important number of haptic feedback devices.

17.3.1.2. Force feedback systems control under transmission delay – constant case

In teleoperation, the effect of transmission delay on the stability of force feedback systems has been shown since a 1965 study by Ferrell [FER 65]. Some approaches have experimented with a delay compensation, previously seen as a drawback and evidence of a defective system (Figure 17.4). However, this hypothesis turned out to be false and it was not possible to eliminate the transmission delay from the transfer system regardless of the method used. The solution proposed by Anderson *et al.* in [AND 89] is based on a division of the whole master/slave system into a quadrupole network scheme. The stability of the teleoperator then derives the properties of quadrupole passivity. The approach advocated by Anderson and Spong consists of imposing a transmission channel (quadrupole) perfectly passive. Thus, they determine the bilateral control laws that satisfy the previous condition, this condition coming from the stability of the force feedback system [NIE 97]. The results obtained with this controller, also called a “wave variables” scheme, show that force feedback is stabilized regardless of the constant delay size in the transmission channel. Therefore, the transparency level, in terms of velocity or track position and force feedback, is a lot worse. Indeed, if the human operator wants to explore an area with a certain roughness, this will appear in feedback as a smooth surface due to the filtering applied by this passive approach. Such an approach is only intended for continuous systems. Using bilinear sampling transformations, it is possible to model a discrete system [KOS 96].

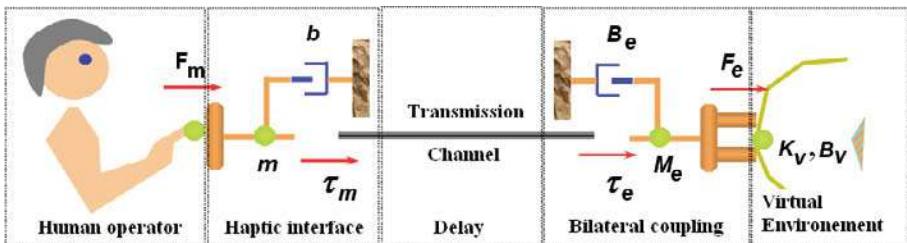


Figure 17.4. Simplified diagram of delayed haptic simulation

To overcome the lack of transparency in such systems due to the controller's passivity, a second group of researchers has opted for predictive methods [ARI 03, SAG 01]. The main feature of the latest techniques is the high quality of the force feedback and coherence with vision modality. Indeed, these last control laws use an estimated model of the haptic interface (or master arm, for a teleoperation system) to stabilize the force feedback under constant delay. In addition, this second class of predictive controllers suffers from a problem of light robustness due to the use of mathematical models of interfaces involving estimation error, which can lead to a degradation of performance, or spread instability through the whole system for large delays.

17.3.1.3. *The variable transmission delay, a more complex issue*

All methods of force feedback stabilization previously mentioned are based on classical bilateral control and have assumed a constant transmission delay. Contemporary communications protocols do not guarantee that condition (constant time delay). The consequence of such a change is that a force/haptic feedback system that is stable in the presence of constant time delays can become unstable when the delay fluctuates, an example being the Internet.

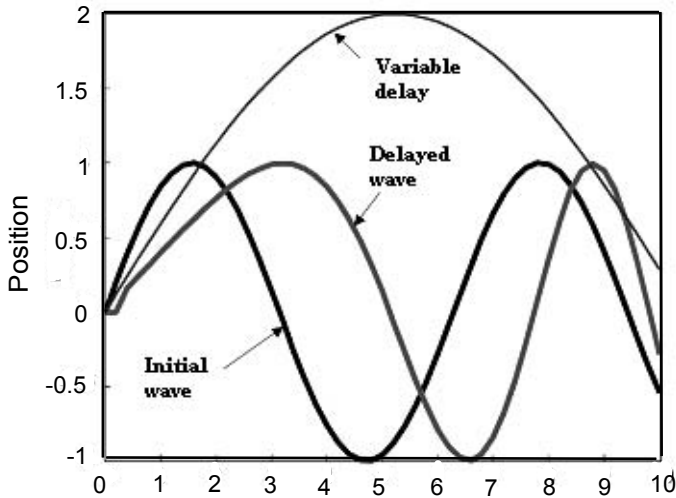


Figure 17.5. *Effect of variable delay on a sinusoidal transmitted wave*

To remedy this problem, an initial idea has been to develop a compensation to the delay variations by adding fictitious delays, called “virtual time delay”, in order to achieve a stabilization problem with constant time delays, for which the classical control approaches are applicable [KOS 96]. This technique, based on the principle

of wave variables, is weakened by major performance degradation in the case of consequent time delays. Other research teams have proposed a transparent pseudo compensation based approaches [NIE 98, YOK 99, YOK 00, HAN 02], controlling the power consumed by the master/slave system to insure passivity of the transmission channel. The primary advantage of these approaches is to ensure system passivity all circumstances (constant or variable time delays) and to limit the consequences of a transient instability, especially when transmissions are abruptly cut-off (blackout phenomenon or large congestion). However, these bilateral control methods ensuring stability under variable delay (challenged by the time delay augmentation; see Figure 17.5) do not improve the fidelity of haptic rendering because they are purely energetic (based on transfer power balance).

On the other hand, predictive approaches are more advantageous due to their high transparency (necessary for simulation-based human perception) and sometimes they not need an adaptation in the case of variable time delay. However, this second class of bilateral controller is only valid for linear haptic devices or with low non-linearity (example of PHANTOM's Pen; see Figure 17.2).

Therefore, while the conventional bilateral control based approaches can give a satisfactory answer to the stability problem, this is still insufficient for the particular issue of haptic fidelity.

17.3.2. Remote programming, solutions and handicaps

Remote programming is a control process specific to teleoperation systems performing under transmission time delay. This control process is unsuited for the haptic simulations in virtual reality. The technique of remote programming was proposed to mitigate the various handicaps of the traditional bilateral control laws between the two master-slave sites, by improving the operator perception of the distant real world by the use of various principles such as predictive visualization, hidden robots, virtual maneuverability guides, etc. In remote programming, the slave robot becomes partially autonomous, executing the programme tasks required by the operator; the intelligent collaboration for monitoring and diagnosis produces its results (sensorial rendering) in a synthetic way to the human operator, which remains the master for determining actions.

Indeed, remote programming is an architecture which consists of enabling the traditional control laws, based on a bilateral coupling principle between the teleoperation station (master side) and the telerobot (slave side). The coupling of the two sites is replaced by two local control loops [KHE 97]. The first loop is situated on the master side, constituted by a master device coupled to a virtual representation of the distant robot and its modeled environment. When the virtual robot is

teleoperated by the main device, the virtual interactions generate synthetic forces which are fed back to the main device in a similar way to a bilateral coupling in force feedback systems. At the same time, macro-instructions (or tasks for the specification of missions) are sent to the distant robot. The second loop is situated on the distant robot side; its role is to ensure autonomy in the execution of the macro-instructions received from the main site. The same reasoning applies to the graphic predictors (proposed before the concept of remote programming). However, the graphic predictors (used in AR) require a visual feedback and a superposition of the virtual image on the video image (or real image). As they were proposed, it was difficult to associate the force or kinesthetic feedback.

The concept of remote programming, in particular the idea of using a VE coupled to a force feedback device, paved the way for a multitude of interactive system architectures and multimode simulation based on VEs. In haptic rendering, these virtual environments became distant for practical reasons of portability. However, the force feedback must be natural (respecting the physics laws), intuitive (acceptable coherence between visual feedback and kinesthetic rendering) and especially stable, in order to eliminate defects caused by communication delays.

17.4. The Quality of Service for a good haptic rendering

The knowledge of the proprioceptive limitations of the haptic sense (or kinesthetic) makes it possible to characterize the necessary conditions, in particular data transfer, for practical use (VEs shared on the network) which can be stable and transparent, whatever the transmitted modality between different clients. More precisely, an ideal perception of the haptic feedback (kinesthetic and/or tactile) imposes a minimum sampling frequency of 1 kHz, due to, amongst other things, the sensitivity of the human skin to small forces (amplitude) or textures (frequency). This update is interpreted by the need for a communication support having a bandwidth with approximately 300 Kbits/second. However, today the majority of communication networks employed by VR systems with force feedback have a sampling rate bordering 20 Hz and a variable delay of transmission reaching 300 ms.

For data transfer at low speed, several methods based on the interpolation, prediction or estimate of the couples position and/or force were proposed to remedy this problem of speed of transfer, but these remain insufficient. Recently, new ideas have emerged for giving assistance to classical control laws, already mentioned

5. In most networked haptic simulations, the contact forces are not exchanged between operators that know that the multimodal virtual environments are represented locally. Only information relating to the transformation matrix for each dynamic objects within the VE is exchanged.

above, in order to improve the perception within the shared virtual environment [MAT 00, BAS 00]. In this recent research, a measure of QoS has been used to quantify the utility and profitability of the haptic feedback (requiring a bandwidth of 1 kHz for a correct operation) in communication networks with several types of architectures.

These studies have shown the possibility of putting in collaboration several operators cooperating intuitively minimizing as much as possible the effect of delay on the stability and haptic perception (evaluation of the felt force in a subjective manner) [MAT 00, BAS 00]. The preliminary results of these experiments have given a first answer on the minimum of necessary properties required as bandwidth size, delay fluctuations, etc.

To do this, the necessary QoS criteria were given to make such haptic simulations feasible, regardless of the communication architecture used. These QoS condition have never been respected by classical control laws and allow a quasi-final resolution of the problem of haptic perception in the presence of transmission time delays.

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