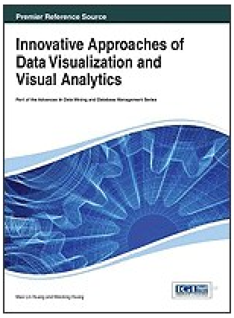

Innovative Approaches of Data Visualization and Visual Analytics

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Chapter 6: Virtual Reality Technologies (Visual, Haptics, and Audio) in Large Datasets Analysis

Bob-Antoine J. Menelas,
University of Quebec at Chicoutimi
Canada

ABSTRACT

With the latest developments in technology, several researchers have integrated other sensorymotor channels in the analysis of scientific datasets. In addition to vision, auditory feedbacks and haptic interactions have been exploited. In this chapter we study how these modalities can contribute to effective analysis processes. Based on psychophysical characteristics of humans the author argues that haptics should be used in order to improve interactions of the user with the dataset to analyze. The author describes a classification that highlights four tasks for which haptics seems to present advantages over vision and audio. Proposed taxonomy is divided into four categories: Select, Locate, Connect and Arrange. Moreover, this work provides a complete view on the contribution of haptics in analysis of scientific datasets.

INTRODUCTION

Analysis of scientific datasets typically involves a set of techniques that aims to transform the raw data into representations understandable by a human user. Following the acquisition of the data starts the analysis process that spans into two distinct stages: transformation and representation.

Raw data are generally defined by a set of points that samples the physical space of the studied phenomenon. Mainly two types of transformations, geometric or topological, can occur on these raw data. They aim to change the sampling or to extract a subset in order to take advantages of algorithms that may offer adequate representations. For example, translations, rotations, or zooming can change the structure of the sampling grid. Other transformations can *a contrario* change the topology of the grid. This can result in converting an irregular grid into a regular grid. Other topological transformations may only affect the sampling of a regular grid (for instance, changing a 3D rectilinear grid to a 3D hexagonal one). Following the data transformation, rendering algorithms are applied in order to provide representations interpretable by a user.

It has been demonstrated that human beings carry remarkable capacities for detection and recognition of patterns by the mean of the visual channel. Based on this, the first works concerning analysis of numerical data triggered interest for exploitation of our visual abilities. Consequently, the process was called visualization. Gershon et al. (1998) and later Zhu et al. (2004) define visualization as a link between the human eye and computers; it helps to identify patterns and extract knowledge from large datasets. Therefore, data should be presented in a way to be easily understandable. According to Ware (2000), visualization aims to build a mental representation, an intellectual understanding of analyzed process or data. Generally, visualization refers to all the resources aiming at reducing the cognitive effort in acquiring knowledge via the visual channel.

Since vision cannot be considered as a predominant sense for human, it is justified to ask whether other modalities, mainly haptic or audio, may play an important role in analysis of large datasets. In fact in the everyday life, humans do not only rely on vision to analyze their surrounding environment since they are rather multimodal. The purpose of this chapter is to discuss the role of not only visual but also haptic and audio in the analysis of scientific datasets. Therefore, this chapter will focus on the use of different sensorimotor modalities in the analysis of scientific datasets.

POTENTIAL OF VR TECHNOLOGIES FOR ANALYSIS OF LARGE DATASETS

First, visualization applications range from non-interactive to command-driven systems. In such systems, commands are sent, processed and then comes the result. However, the need to interact with the system has emerged quickly. For example, one would like to zoom, rotate or filter the data. At this point starts the fusion, the interleaving between the query and the result via an iterative process. From there, data analysis is not only guided by the need for effective presentation of data: there are two main components that are the *presentation* and *interaction*.

At this point, Shneiderman (1996) identifies four main steps for the implementation of effective interaction process: *Overview first, zoom, filter, then details-on-demand*. Recently, Yi et al. (2007) have suggested that the interaction process can be supported through seven types of interaction based on users’ intent while interacting with the system. For several researchers of the field, as part of the Human Computer Interaction (HCI) domain, interactive visualization aims at offering a direct and bidirectional communication between people (users) and the visualization system. Bryson (1996) stated *that the goal is to create the effect of interacting with things, not with pictures of things*. This approach establishes a clear difference between the user and the system: "the user interacts with the system".

Virtual Reality (VR) based-processes adopt a completely different approach in trying to go beyond a simple process of communication between a user and a computer system. The aim is rather to bring the user at the center of the analysis process. In fact, this issue plays a major role in VR technologies that aim at the immersion and presence of the user in a virtual environment. *Immersion* refers to a state of consciousness where the perception of physical reality surrounding the subject is reduced or lost in favor of a totally captivating often artificial environment, one says that the subject is then *present* in this artificial world.

As aarious researchers, we define Virtual Reality as a scientific domain that allows one or more human users to perceive and interact in an immersive, pseudo-natural and in real time with a digital environment called Virtual Environment (VE). This EV can be a copy of reality, but also a simulation of some of its aspects, a symbolic representation of a concept or a phenomenon, or a totally imaginary world (Bideau et al, 2004). Burdea and Coiffet (1994) noted that VR technologies require multisensory interactions and real time rendering in a VE. In the context of the VR-based analysis of large datasets, Loftin et al. (2004) define VR as the use of computer technologies to obtain multisensory rendering and interactions in real time with data, allowing one or more users to occupy, to navigate and to manipulate a computer-generated environment.

By combining all these points of view in the context of analyzing large datasets, for us it seems that VR technologies offer human users the mean to exploit capabilities of their sensorimotor channels (visual, haptics, audio) to pseudo-naturally perceive and interact with the dataset that they want to analyze. Thus, it appears that by the mean of multimodal rendering, VR technologies can allow the improvement of the two main components of user-based analysis of datasets that are *representation* and *interaction*. Moreover, it has been demonstrated that human-like interactions with a computer machine do increase the user efficiency, effectiveness and satisfaction; knowing that multimodality supports human-like interaction, like many others, we support the idea that *multimodal interactions are expected to increase the level of computing accessibility for many categories of users*, (Fikkert et al., 2007; Oviat & Cohen, 2000).

As emphasized by Griffith et al., (2005) having a dataset in a virtual immersive environment creates much better sensory responses to the user when compared to standard visualization systems. One of the primary advantages of using VR for the analysis of large datasets is to improve visual perception. Indeed, it has been shown that an active stereoscopic rendering helps at improving depth perception for distances below 30 meters (Nesbitt, 2003). In addition, the use of display screens, which may have more than seven meters in size, let the user to access a greater amount of information. In the same way, having CAVE-like setups allows the user to perform self-centered movements. Unlike workstations-based situations, the user is able to move, to turn around the object of study in order to benefit from several points of view. LaViola et al., (2009) emphasized that such interactions may be smoother and more efficient (requires less cognitive effort) than those achieved via standard interfaces (keyboard or mouse). Finally, one notes that already in 1996 Bryson (1996) had stated the hypothesis that real-time and intuitive capabilities of VR-based interactions could be exploited for a quick scan of large datasets. He has suggested that the direct manipulation of volume elements is expected to arrive with a more efficient analysis. However, we notice that this possibility is still not established. Recently, Laramee & Kosara, (2007) have stated that a lot of work is still needed in order to arrive with more intuitive interaction methods. Similarly, Zudilova et al. (2008) have highlighted that one of the main obstacles in this area is related to the fact that interfaces that seemed to be intuitive for developers did often proved unnatural for end users. This raises the question of how to get to intuitive interactions.

Knowing that multimodality represents a key factor of VR systems, the way each modality intervenes in an analysis process will be studied in next sections.

ROLE OF EACH MODALITY IN A MULTIMODAL ANALYSIS PROCESS

As most researchers, we agree that modality is directly linked to human senses. We define modality as the form of exchange that can take place between a user and a numerical system. As opposed to a unimodal condition where only one form of communication is possible, several forms of communication are available in a multimodal rendering.

When compared to unimodal rendering, the design of a multimodal rendering requires additional conditions due to interactions that may exist between the various channels. Indeed, it requires that exploitation of different modalities does not oppose one another. Furthermore, it is also desirable that each modality contributes to the achievement of a common goal. Based on such observations, it appears that: *i)* each modality should be exploited for a specific task *ii)* combination of modalities should also address specific tasks. One may note that this conclusion gathers the two points of view generally seen about multimodal rendering.

In the first point of view, multimodality appears as an aggregate of various unimodal rendering having each one its specific characteristics: the Modal Specific Theory proposed in (Friedes, 1974). When analyzing the three main sensory-motor channels of humans, it is obvious that each channel has its own advantages and disadvantages. These differences are not only related to the type of stimuli, but are also due to their spatial, temporal and frequency specificities. Friedes (1974) explains this by the fact that each sensory channel has a unique way of processing information. Because of that, each channel is rather particularly efficient for specific tasks. Visual dominates the perception of spatial information; audio is specialized for temporal processing (Vézien et al., 2009) whereas haptics is particularly adept at sensing movement (Nesbitt, 2000). Based on this, Nesbitt assumes that the perception of information can be provided via three types of metaphors: *spatial*, *temporal* and *direct*. *Spatial metaphors* inform on size, position and structure of objects in space. *Direct metaphors* are associated with the perception of the intrinsic properties of objects (color, volume, hardness, etc.). *Temporal metaphors* reflect temporal changes of the object occurring over time. Then, he associates the three rendering sensory modes (visual, haptics and audio) to the three metaphors defined above. By doing so, he defines the *M-S Taxonomy*, dedicated to multisensory perception, based on a set of nine cases as shown in Table 1. Hence, the design of a multimodal rendering can be seen as the design of appropriated metaphors that could convey information (spatial, direct, or temporal) through a modality (visual, auditory, or haptics). One of the main advantages of this approach is that it provides a clear distinction between the three modalities. Hence, this approach may help to satisfy the first requirement (defined at *i*).

Table 1: Representation of the nine classes of the MS-Taxonomy (Nesbit, 2000)

	Rendering Modes		
	Visual	**Haptics**	**Auditory**
Spatial	spatial visual metaphor	spatial haptic metaphor	spatial auditory metaphor
Direct	direct visual metaphor	direct haptic metaphor	direct auditory metaphor
Temporal	temporal visual metaphor	temporal haptic metaphor	temporal auditory metaphor

In the second point of view, multimodality appears as the result of the combination of several unimodal rendering. The mapping of information into interactive multimodal interfaces has been studied in (Bernsen, 1993). Bowman et al. (2004) define multimodality as the combination of multiple input modalities aiming to provide the user with a richer set of interactions compared to traditional unimodal interface. As input interactions, they state that the combination of input modalities can be divided into six basic types: *complementarity*, *redundancy*, *equivalence*, *specialization*, *concurrency* and *transfer*. For Fikkert et al. (2007), this combination aspect appears as the goal of the multimodal system: *The goal of a multimodal system is, or should be, to integrate complementary modalities in order to combine the strengths of various modalities and overcome their individual weaknesses* (Fikkert et al, 2007). As in the first point of view, one may note that such an observation is particularly adapted to the second requirements (defined at *ii*).

Here, in order to meet the two requirements, these two approaches will be combined. First, the way each modality can contribute to the achievement of a better analysis will be studied. Second, the add value of associating modalities will be analyzed. Regarding the first step, we share the point of view of many researchers that have demonstrated that vision dominates the perception of spatial information whereas audio suits well the perception of temporal information. Hence, we understand that vision and audio should respectively be exploited for presentation of spatial and temporal properties of information. Regarding the haptic modality, the visuo-haptic association and main physiological characteristics of haptic perception will be analyzed, in the following paragraphs, in order to detect how it may contribute to a better analysis of scientific datasets.

HOW CAN HAPTICS CONTRIBUTE TO EFFECTIVE ANALYSIS OF SCIENTIFIC DATASETS

The word haptics comes from the Greek *haptesthai* and means to touch. It is nonetheless used to refer force feedback (based on muscles and joints) and tactile feedback (based on the skin) (Burdea, 1996). In a more general way, it also provides information on proprioception, namely the perception of the relative position of the body parts. Another feature that makes haptic interactions particularly interesting is that they are the only modality that allows sensorimotor interaction. The haptic modality provides a direct access to information related to the nature of objects. It gives information about their weight, hardness or their texture. Over the past two decades, many studies have suggested that one could use haptics to interpret numerical data (haptization). As in visualization, two main approaches are identified: *haptization of information* and *haptization of scientific data*.

Haptization of information concerns the use of haptic feedbacks to access abstract information via the haptic channel instead of the visual one (Menelas & Otis, 2012). This approach proposes alternatives to visual rendering so that people having visual disabilities can also access information. Here, only the analysis of scientific datasets is considered; hence, the *haptization of information* will not be addressed. For more information regarding *haptization of information*, one may refer to a recent state of the art presented in (Paneels & Roberts, 2009).

Haptization of scientific datasets focuses on data resulting from simulations of phenomena closely related to geometry. Knowing that haptics is generally associated with another channel (often visual), it seems more appropriate to talk about *analysis of scientific datasets*. The analysis of scientific datasets is not intended to replace scientific visualization, but rather aims to exploit various sensorimotor channels of human in order to arrive with more effective analysis of complex datasets.

Added Value of the Visual/Haptic Combination in Analysis of Scientific Datasets

In the analysis of scientific datasets, the addition of haptics offers an interfacing far richer than just the visual rendering and more diverse means of communication between the user and the digital environment. In doing so it allows:

- **To Unload the Visual Channel:** In such a case, the haptic feedback helps in replacing the visual channel in the communication between a user and a digital environment. For example, Persson et al. emphasize that the use of haptics for transmitting physico-chemical forces of intermolecular bonds allows presenting more information to the user without risking overloading the visual channel (Persson et al., 2007).
- **To Strengthen the Visual Feedback:** This situation happens when haptics help at emphasizing information already available via the visual channel. Particularly in teleoperation field, works of Basdogan et al. (1998) have showed that the addition of haptic feedback reinforces the sense of presence of users in the remote environment. Similarly, in analyzing medical data, it may be interesting to perceive via the touch sense differences in hardness or temperature between different internal organs (Lundin et al., 2002).
- **To Supplement the Visual Feedback:** In this case, the haptic modality gives access to information that is hardly or not perceptible visually. For example, Lawrence et al. (2000) have used haptics to alert users of the presence of a secondary shock (contained in a bigger one), even if it is not visible.

Beyond relative contributions of its association with the visual channel, haptics has features that seem likely to bring something special to the analysis of scientific datasets. In the next subsection, psychophysical characteristics of haptics will be analyzed in order to point out how they can contribute to better analysis processes.

Psychophysical Characteristics of the Haptic Perception

In everyday life, humans use their senses to perform specific tasks to explore and analyze their environment. Thus, MacLean recalls that touch implies a stronger emotional feeling that vision: *it particularly allows initiation or completion of a task, check the status of an object, or connect physically and/or emotionally with others* (MacLean, 2000). These observations emphasize the necessity to properly use the haptics. In the same way, in analysis of scientific datasets, despite resource constraints (at current state of the technology, haptic interfaces do not exploit one's full potential for tactilo-kinestesic perception [Kahol et al., 2006]), it seems essential for humans to use haptics according to human physiological characteristics. In what follows we briefly point out those that have retained our attention.

As seen previously, *representation* and *interaction* are two major components that can contribute to an effective visualization process. This section aims at analyzing whether physiological characteristics of human could, or not, indicate that haptics presents an advantage over other modalities for improving one or both of these two visualization components.

Regarding the characteristics of haptics, we find that:

- **The Visual Channel Seems to Predominate for Presentation of Information:** For example, von der Heyde et al. have shown that the evaluation of an object's weight could be biased by the visual feedback. With an experiment, they observed that subjects always estimated heavier larger objects, although they were the same weight (von der Heyde et al., 1998). More generally, Welch et al. showed that visual feedbacks dominate the other channels in the spatial perception (Welch et al., 1980). Finally, work led on the pseudo-haptic underlines that a visual feedback can influence the perception of information presented via the haptic channel. As an example, one may cite (Lecuyer et al., 2000) which use a visual feedback to generate a haptic sensation.
- **Haptics is Not Adapted to Memorization or to Recalling:** Despite the fact that haptics is very powerful in discrimination, it should be stressed that it is hardly suited to identification or memorization. As mentioned by MacLean, when sliding our finger on a polished surface, one can easily, thanks to successive comparisons, detect an invisible scratch, but it is much more difficult to remember or to identify a given one (MacLean, 2000).
- **Haptic Perception is Tightly Linked to the Concept of Interaction:** Various studies have evidenced that the perception of information, presented via the haptic channel, requires a specific type of movement named *Exploration Procedure (EP)* (Lederman & Klatzky, 1987; Klatzky & Lederman, 1995). Indeed, the evaluation of a weight requires different vertical movements, while lateral ones are better suited for the perception of a texture. Apart from the perception of a temperature, these EP explain that the perception of information presented via the haptic channel requires and/or involves an interaction.

These observations on physiological characteristics of humans related to haptics suggest that this modality would be more adapted for interaction tasks rather than for the presentation of information. Indeed, haptics does not offer any considerable advantage when compared to visual presentation. In addition, when presenting information through the haptic channel, one would have to face great difficulties to achieve identification as well as memorization of a given haptic feedback. Therefore, we infer that the addition of haptics in analysis process is expected to be optimal if it aims at facilitating and/or improving interaction with the data.

Moreover, the analysis of the add value of the visual/haptic association suggests that haptic interactions can have positive impact on presentation of information. Indeed, haptics can unload, strengthen or supplement the visual feedback. In what follows a taxonomy that aims at identifying how haptics should be used is described in order to improve user's interactions in analysis of scientific datasets. By doing so, methods that can help improving the presentation of information in analysis of scientific datasets will be emphasized.

VISUAL, AUDITORY, AND HAPTIC MODALITIES IN INTERACTION WITH SCIENTIFIC DATASETS

In analyzing work that has, over the past two decades, used vision, audio and haptics in the analysis of scientific datasets, we have defined four interaction techniques that may help at classifying the methods dedicated to analysis of scientific datasets. These interaction techniques are related to four basic tasks: "Select, Locate, Connect and Arrange". For each category besides a description, we also present the visual, auditory and haptic methods that fall within that group.

Select

Selection is a key component in the interaction with virtual environments. Selection allows the user to choose the object of interest among several others. It is a mandatory step in haptic interactions. Contrary to vision or hearing, haptic interactions are direct manipulations (Okamura & Cutkosky, 2001). A selection is hence required for any haptic interaction; it represents the virtual counterpart of the physical contact. In haptic enhanced selection processes, a virtual magnet is frequently simulated at the position of the target of interest. Due to the attractive force, approach toward the point of interest is facilitated and accelerated and the precision of selection is improved. Selection is particularly important in analysis of scientific datasets since it lets the user designate an entity of the dataset that he would like to analyze in detail. The following paragraphs summarize cases where one or more targets (selectable objects) are present in the scene.

Single Target

Regarding single target acquisition, various works have clearly highlighted the benefits of adding force feedback to a purely visual system. In such a condition, a virtual magnet is frequently simulated at the position of the target of interest in order to attract the haptic device. The attraction force can either be constant or function of distance to the target. Evaluations of Keuning (2003) indicate that stronger attractive forces tend to increase accuracy of users.

It was shown in (Hasser et al., 1998) that haptic feedback can improve the speed of task completion. Similar results were observed by Dennerlein & Yang (1999). Their study focused on the add value of an attractive feedback in a point-and-click task. Fifteen adult subjects performed this task 520 times with and without the attractive effect. During this experiment, trajectories imposed to the subjects were random and varied both in terms of direction and distance. Results have firstly shown that the addition of attractive feedback increased the speed of execution, while the time required for the task achievement was significantly reduced (objective assessment). On the other hand, the perception of fatigue and discomfort, measured through a questionnaire (subjective evaluation), were also lowered with the addition of this type of haptic feedback.

In the same way, (Oakley et al., 2000) have used a phantom desktop device for the interaction with a conventional graphic user interface in order to reduce error rate. The experiment aimed at comparing the effects of four types of haptic feedbacks on the usability of a selection task. While the addition of force feedback did not seem to offer an improvement in terms of execution speed of the task, results clearly showed a significant reduction of the number of mistakes.

More recently, Vanacken et al. emphasized that a multisensory rendering was generally preferred by users (subjective opinion) and in many cases it could also accelerate the execution speed of selection tasks (Vanacken et al., 2006). These results were confirmed by Kim and Kwon who examined the impact of a haptic and/or auditory grid in enhancing recognition of ambiguous visual depth cues for position selection in a 3D virtual environment (Kim & Kwon, 2007). During this assessment, four conditions were tested (visual only, grid haptic, sound grid, audio-haptic grid). Results showed that the haptic/auditory grid offered best results. In particular, the errors along the depth axis decreased significantly (nearly by half).

In the same way, Picinali et al. examined whether users were able to integrate information from several sensorimotor channels (haptic and audio) in order to achieve the localization and the selection of single target in a 3D space (Menelas, Picinalli et al., 2009; Picinalli et al., 2010). Realized experiment showed, firstly that an attractive force feedback can easily guide users toward the target. On the other hand, even though the audio channel has a real potential for localization tasks, users have much preferred to use the haptic feedback.

Multiple Targets

Before reviewing works in this area, a brief analysis of difficulties arising from this situation is appropriate. Let us consider Figure 1, by assigning attractive properties to these four targets, the haptic device will be attracted by all targets at the same time. Suppose we want to select the target T_1, with such a situation we are not only attracted by T_1, but also by the three other targets (T_2, T_3 and T_4). This situation can be quite disturbing since it will lead to a deviation from the trajectory to the target T_1 because of unwanted attractions from T_2, T_3 and T_4 (distractors).

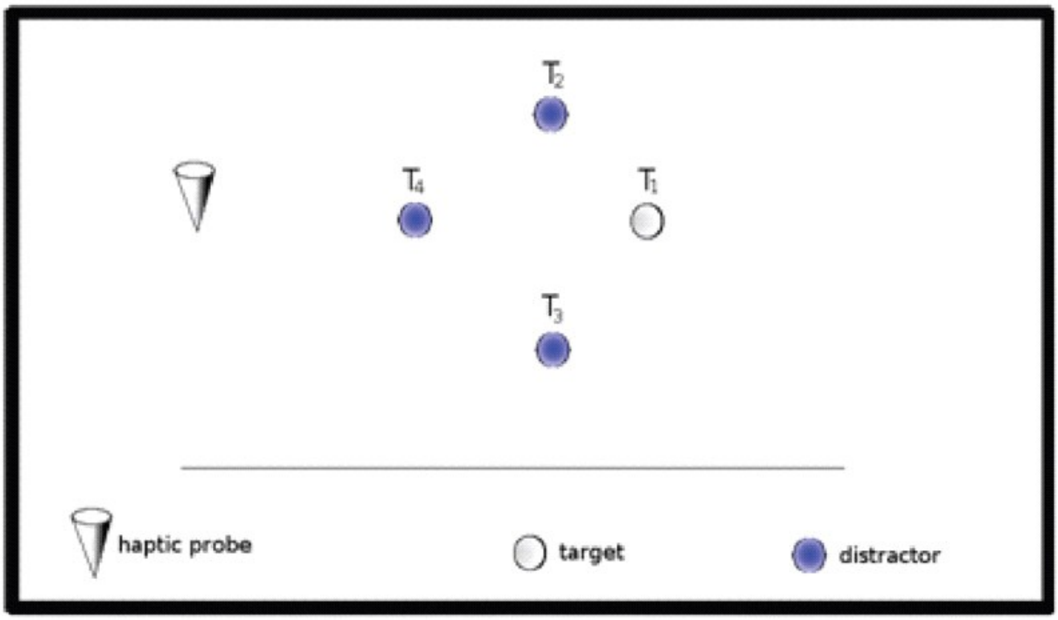

Figure 1: Representation of a situation containing multiple targets

The few studies conducted in the context of environments with multiple targets have led to somewhat contradictory results regarding the addition of haptic feedback. While some tend to say that the haptic feedback is to banish in such an environment, others point out that a correct setting of the attractive force significantly limits the impact of distractors. The main works of this area are summarized below.

Recently, Vanacken et al. (2009) have investigated a multimodal feedback system for target acquisition in dense environments. Tested system haptic as well as auditory feedbacks were exploited to inform the user about the existence of a target in their immediate vicinity. No directional information was provided to the user by the mean of the haptic or the audio channel, evaluations of such a multimodal system did not show any significant improvement of the results when compared to a purely visual system.

A typical situation that involves multiple targets is in interactions with graphical menu interfaces. Evaluations of Dennerlein et al. (2001) in a point-and-click task showed that performances were better with the addition of force feedback even with distracting force fields; however, they noted that speed tended to decrease with the addition of distracters. On the other hand, Wall et al. (2002) highlighted that in the presence of multiple distracters, adding force feedback (a virtual magnet) to a 3D stereoscopic virtual rendering improved subject's accuracy, but did not improve the time taken to reach the target. These results were confirmed by Cockburn and Brewster, (2005) who examined the impact of three types of interactions (audio, vibrotactile and pseudo-haptic) for a task of target selections in a Graphical User Interface (GUI). The auditory interaction was ensured via audio icons (earcones [Brewster et al., 1995]), while the pseudo-haptic feedback was rendered via the dynamic modification of the display control/ratio of the cursor in vicinity of a target. These authors showed in an initial study that all modes of interaction (particularly the pseudo-haptic) tend to decrease the time required for the task completion in the case where the targets were relatively small and isolated. On the other hand, in a second study regarding the selection in a GUI menu, they stress that the addition of these haptic feedbacks could significantly penalize the interaction performances due to the impact of distractors located in the immediate vicinity of the desired target. In the same way, Hwang et al. (2003) have investigated the impact of multiple haptic distracters on the performance of motion-impaired users. Their studies showed that positioning the distracters along the route of the target was detrimental to performance.

In contrast, Oakley et al. (2002) highlighted benefits of an adjusted haptic condition relatively to both visual-only and visual/haptic conditions. In the adjusted condition, in order to decrease the impact of distracters, which are in fact non-desired attracters; their attractive effects are decreased whenever they do not seem to interest the user. Their results indicate that target selection errors are reduced to the same level as in the haptic condition, while speed is not compromised when compared to the visual condition. These results are confirmed in (Menelas et al., 2010), where purely audio haptic feedbacks are proposed for an acquisition task in a multi-target context in a 3D virtual environment. Their study shows that the haptic adjusted condition is relevant for haptic enhanced selection in multi-target context, and also points out the potential offered by audio-haptic rendering for reducing load of the visual channel in selection tasks.

Synthesis

Through this category, the work dealing with the use of haptics in the selection process is reviewed. Situations involving a single target and those where several targets are presented are analyzed. In spite of results, which at first glance appear to be contradictory, detailed analyses have shown that haptics can offer valuable helps in a selection process. It is known that, in analysis of scientific datasets, it may be important to select an entity of interest, typically in order to launch a more detailed analysis (zoom; study the physical characteristics and more). Therefore, we advocate the use of haptic in order to increase the speed of task completion, improve the accuracy and also to reduce the fatigue that such a task can generate.

Locate

This category gathers haptic techniques that are exploited to spatially and/or temporally locate an entity of interest in a dataset. In the haptic enhanced localization, haptics is generally used in order to direct the user toward an entity of interest. In analysis of scientific datasets, this type of interaction counts: the location of areas containing high values, strong currents, as well as the tracking of shock waves, extrema and critical points.

Location of Regions Containing High Values

The location of areas containing high values of a given field (Φ), necessitates the *velocity mapping*. The field value is directly mapped onto to the speed of the haptic device (see Equation 1 [Iwata et al., 1993; Pao & Lawrence, 1998]). While moving in the data volume, the user perceives a viscosity feedback proportional to the field value at the position of the haptic effector. Hence, regions where data values are large appear more viscous to the user. Aviles et al. (1999) and later Van Reimersdahl et al. (2003) reveal that this metaphor is very useful for rapidly scanning a volume in order to identify regions containing high values. Withal, since the generated feedback is directly proportional the speed of the user, this method can be applied for the analysis of a specific point (Aviles at al., 1999; Palmerieus et al., 2007). The force feedback perceived by the user being by definition directly proportional to the speed of haptic device, knowing that the analysis of a specific point requires a very low speed, the force feedback coming from this situation is hence almost null regardless of the field value at the explored point.

(1) $$\vec{F} = \left|\vec{\varphi}\right| \cdot \vec{V}$$

Location of Strong Flows and Vortices

To locate strong flows by mean of haptics, the value of the vector field row Φ is, at each point of the dataset, proportionally (α) conveyed to the user as a force feedback that corresponds to the magnitude and the direction of the local vector, (see Equation 2) (Durbeck et al., 1998).

(2) $$\vec{F} = \alpha \cdot \vec{\varphi}$$

While exploring the flow dataset, the haptic feedback is analogous to the feeling produced when one puts his finger into a flow. Vectors act upon his fingertip, dragging it in the same direction as the local flow field. If the user does not oppose the movement, his hand describes the trajectory of a fluid particle. Yannier et al. (2008) have recently used this method in the analysis of a wind dataset.

Shock Waves Location

Use of haptics for detecting and locating shock waves in the analysis of CFD datasets has been proposed in (Lawrence et al., 2000). Shock waves are characterized by a high gradient, to detect them a haptic feedback proportional to the gradient value at the probe position is sent to the user. In doing so, the user can be alerted on the presence of any secondary shock (even invisible) contained in the main one. This method allows free motion in regions having low gradients ($\rho < \epsilon$: F=0). Within the shock region, the forces applied to the user result in behavior similar to a ball on a hill. The shock surface can only be penetrated from the low-density side ($\rho < \epsilon$) by pushing against the rendered force, hence allowing users to easily understand regions representing high and low density without cluttering the visual display with additional data.

Extrema Location

In the analysis of scientific datasets, it is frequently interesting to locate maxima and minima of a given field. The first use of haptics to this end is the *Topography metaphor* (Pao & Lawrence, 1998). To distinguish maxima and minima of a scalar field, the values are rendered as a surface elevation. Reimersdahl et al. (2003) emphasized that the disadvantage of this method is the lack of information concerning the sign of analyzed scalars. To this end, they rendered positive values by elevations and negative ones with concavities in the virtual surface. A second method related to such detections is the *pseudo-gravity*. At each point of the space, it associates a virtual mass proportional to the value of the field. As a result, with this method: the user's hand is drawn to the highest values of the field.

Critical Points Location

Another method, which can be classified in the same category, was recently presented in (Menelas, Ammi et al., 2009). In this approach, the haptic interaction is restricted to a local environment surrounding the probe position. The haptic as well as the visual feedback are used to translate information related to the activated local environment. For instance, the vibration capabilities of a 6 Degree of Freedom (DoF) device are exploited in order to provide information about the local area explored. Critical points located in the immediate environment of the users are rendered visually by colored spheres and haptically through a sinusoidal vibration. The experiments show that vibration feedbacks reinforce the visual feedback and facilitate the build of a mental map of the analyzed flow field. Instead of an automatic process where points would be discovered at once, the user may at his convenience and on the basis of his expertise, direct the search for critical points to areas of interest. At the same time, the participant can create a mental map of the analyzed flow.

Synthesis

In this category, the use of haptics in the localization of entities or physical properties is discussed. Several cases of study, regarding the CFD domain, have been described. Results shown that haptics plays an important role in user-centered localization processes. In particular, it may complement or reinforce the visual feedback. Moreover, considering that the localization process seems not to require the development of complex strategies (as compared to way finding); we believe that the use of haptic localization process could help at reducing the cognitive load of users during the analysis of scientific datasets. Nevertheless, at current state of the literature much more experimental studies, involving expert users, are still needed.

Connect

This category has a set of techniques that allow the tracking of structures of interest. In some domains, structures located within the datasets (isosurface, streamlines, etc.) may sometimes be very relevant for the understanding of the studied phenomenon. Thanks to the addition of haptic feedbacks, users can easily follow a structure and at the same time, if necessary, can access some local information (value of a field at the explored position) of this structure. With the addition of haptic feedback, the user has an additional channel that may help reinforcing the visual feedback and accessing a greater amount of data (mainly to local information). This category counts work related to *haptic rendering of flow lines* and *haptic rendering of isosurfaces*.

Haptic Rendering of Lines

Haptic rendering of lines has been notably investigated in Fluid Dynamics. These lines are the flowlines (streamlines or pathlines). In this group are denoted:

Torque Nulling: Produce a torque proportional the field magnitude at the end effector position whenever the probe is not aligned with the vector field (Pao & Lawrence, 1998).

Transverse Damping: Facilitates the following up of a streamline by applying on one hand a large viscosity in directions transverse to the field direction and, on the other hand, some forces in the field direction proportional to field magnitude (Pao et al., 1998).

Relative Drag: Lets the user perceive a feedback proportional to the difference between the field value vector and his velocity. If the user does not oppose the force, his hand traces out a streamlines (Pao et al., 1998). In addition to directional information, this method is particularly useful when the haptic device is approaching or receding from the user. Indeed with this method, the depth variations of the flow may be perceived via the kinaesthetic sense. One has to note that such variations are generally hard to perceive through the visual feedback (van Reimersdahl et al, 2003).

Relative Turnaround: To control the movement of the haptic device along a line, the following metaphor is employed. Turning the stylus clockwise results in a movement in direction of the flow, turning it counter clockwise will inverse that direction (van Reimersdahl et al, 2003).

Feature Shift: Haptically conveys the spatial distance between two similar lines, this method renders forces to display the spatial shift. In the proposed method, the haptic device automatically describes one of the lines while being dragging into the direction of the temporarily equivalent point on the other line. The attraction force translates the spatial length between the two points (van Reimersdahl et al, 2003).

Other works of this group have been presented in (Ikits et al., 2003). Their approach relies on haptic constraints to restrict the movement of the user in certain directions by proposing a set of rules defining the movement of the proxy. As an example, to guide the user in a vector field, the proxy is locked along a streamline. More recently, Menelas has exploited an attractive feedback in order to assist a user in the following of a flowline while displaying visually values associated with another field of the explored area (Menelas, 2012).

Haptic Surface Rendering

In medical imaging, isosurfaces are same density regions of a three-dimensional scanner. They may serve for the visualization of internal organs or bones. In fluid mechanics, they offer great opportunities for the study of characteristics contained within a given phenomenon. Haptic rendering methods of isosurfaces are divided into two main categories: "Intermediate representation" and "Direct rendering".

1) Intermediate Representation

Traditional approaches of surface rendering aims at extracting a polygonal approximation of the isosurface using voxel data. Algorithms such as *Marching Cubes* (Lorensen et al., 1987) or *Marching Tetrahedral* (Nielson et al., 1997) are commonly used for the calculation of this intermediate representation. Once this geometrical information is known, haptic feedback is simulated thanks to a collision detection algorithm coupled to a classical penalty based method (Mark et al., 1996). With a penalty method the haptic feedback is rendered by a spring model: $\vec{F} = -K \cdot \vec{X}$ more penetration into the virtual surface $\vec{X}$ results in a larger force feedback. As noted by many authors, using a surface representation provides a stable force feedback. However, because of the computation time required for the surface estimation, such methods do not allow real time changes.

To overcome this limitation, Galean et al. (1991) and later, Korner et al. (1999) have opted for local use of the *Marching Cubes* algorithm. With this method, only voxel data situated in the vicinity of the haptic probe is used to calculate the local surface. With this optimization, real time updating is possible since the surface is generated on the fly. However, there is a direct relation between the computation time and the data count. This tends to restrict the application of such method to non-complex data.

To face this second difficulty, Adachi et al. (1995) have proposed the use of another intermediate representation. In their approach, the local surface is approximated by the mean of a virtual plane (see Figure 2). In order to assume a very fast haptic loop independently to the amount of data, this method updates the virtual plane at a low frequency while maintaining a high update rate for haptic loop. Mark et al. (1996) and later, Chen et al. (2000) have illustrated this model with a haptic rendering method for isosurface without any explicit isosurface extraction (i-e: without any complete polygonal representation).

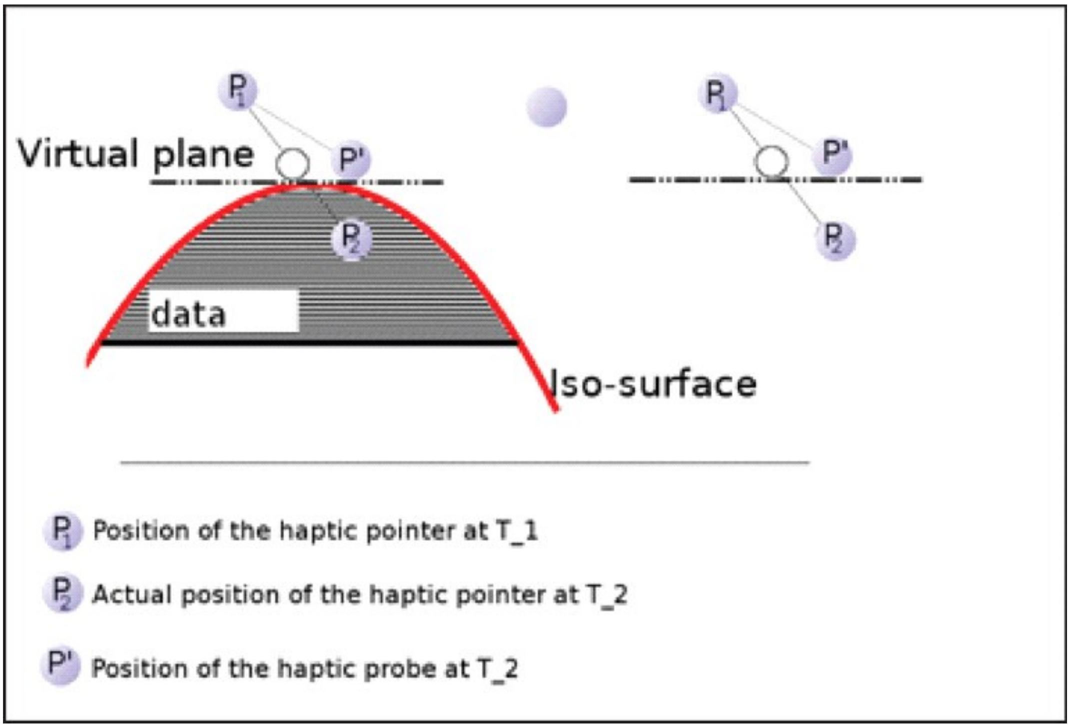

Figure 2: Approximation of an isosurface with a virtual plan

To express the hardness of objects (internal organs or bones) in the medical imaging domain, Lundin et al. (Lundin et al., 2002) have adapted the proxy method (Ruspuni et al., 1997), defined for the surface representation, to volumic datasets. In the proposed approach, the motion of the proxy is controlled by several rules related to the nature (hard, soft) of the data surrounding its position. Low-density regions offer less resistance to the movement of the user. The proxy is indeed able to move more rapidly in such part of the data volume. Thus, the haptic feedback produced with this method does not only render the presence of a virtual isosurface but also provides some relevant information related to the nature this surface. Because of that information, this method is in some cases listed as a 3D rendering method. When using this method, a user can easily distinguish bones from skin or muscles. However, since the proxy is constrained by the local gradient, one has to note that within high gradient data, this virtual surface does not approximate the isosurface.

2) Direct Rendering

A well-known method for direct haptic rendering of isosurfaces has been exposed in (Avila & Sobierajski 1996). The proposed method targets the haptic rendering of an isosurface without any intermediate representation. To simulate the touch of the virtual surface, the force feedback is directly approximated as a difference in the field value. Because of this direct computation (approximation), this method offers a very fast haptic loop. On the other hand, due to this approximation, some unwanted vibrations are observed in regions presenting high frequency data (Fauvet et al., 2007). Indeed in such regions, the strong variations of the field are directly conveyed to the force feedback. These changes represent the vibrations perceived by users. To address this issue, an improvement of this approach has been proposed in (Menelas, Fauvet et al., 2008). A more generic approach was then described in (Menelas, Ammi et al., 2008). In this new solution, rays issued from the probe position are launched in multiple directions (cartesian ones were used in the implemented version) in order to compute the position where the haptic probe would situate if it was not constrained to move on the isosurface. Thereafter the computation of this position, the virtual touch of the isosurface is simulated by the mean of a penalty-based method.

Synthesis

In this category the work addressing the rendering via the touch sense of structures of interest was analyzed. Haptic rendering of flowline and iso-surfaces have been discussed.

Arrange

This category lists techniques where haptics helps to assist users in the spatial arrangement of the elements to be analyzed. The haptic feedback is used to guide the gesture of the user according to some relevant information hidden within the dataset. Such methods have been successfully employed to overcome limitations of traditional docking algorithms. The haptic feedback allows translation of physical and chemical properties of elements to the user involved into the docking process. Through the haptic guidance, a greater amount of information is transmitted to the user without risking the overload of the visual channel. Hou and Sourina noted that the use of haptico-visual molecular-docking systems lets the user to manually explore the conformational molecular space in order to find an optimal conformation faster (Hou & Sourina, 2011).

In (LaiYuen et al., 2005), to assist users in the visualization, manipulation and assembly of molecules in a virtual environment the intermolecular forces were haptically rendered through a 5 DoF haptic device. In such a system, the feasibility in terms of energy and geometry of a ligand to dock or assemble is directly perceived through the haptic channel. The haptic modality is thus used to enlarge the bandwidth between the user and the system. In the same way, in (Persson et al., 2007) a chemical force feedback system has been developed in order to offer a tool that can help students understand the docking protein process. In a semi-immersive environment with stereo graphics, users were able to manipulate the ligand while feeling force feedbacks resulting from the docking process. Experiments point out that the proposed system improves learning speed as well as the understanding of docking processes in terms of the forces involved. In (Ferey et al., 2008), the haptic enhanced reconfiguration capabilities are extended by the means of a bi-manual system. Two proteins are simultaneously handled. While one is manipulated with a tracked 3D mouse, the other is attached to a 6 DoF haptic device that conveys electrostatic and hydrophobic interactions.

DISCUSSION

This work aimed at studying the role of each modality in analysis of scientific datasets. Considering that most researches do agree on the role of visual and audio, this work has focused on exploitation of haptics. After analyzing human sensory characteristics and specifities of the visual/haptic association, we have concluded that to achieve effective analysis processes, it was necessary to use haptics for facilitating interaction with the datasets, since it should also promote presentation of data through other modalities (visual and auditory). In the previous section, we detailed various tasks where haptics seemed to present advantages over other channels through a four-category taxonomy. This section aims at discussing this taxonomy.

To assess the proposed classification, we refer to the evaluation grid proposed in (Beaudoin-Lafond, 2004) while adapting it to our situation. Three criteria are selected: 1.) *the descriptive power:* the ability to describe a significant range of existing methods; 2.) *the evaluative power:* the ability to help assess multiple existing methods; and 3.) *the generative power:* the ability to help the introduction of effective new methods in the analysis process.

Descriptive Power

For each category in the presented taxonomy, all the literature methods that can be classified into it, is listed. In doing so, over 45 methods were reviewed. Although these numbers may seem limited, it is important to emphasize that the use of haptics in analysis of scientific datasets is not so common. In this regard, it is expect that this taxonomy covered most of the existing methods described in the literature.

Evaluative Power

Evaluation refers to the worth and significance of something using criteria against a set of standards. Speaking about evaluation is equivalent to asking the question about the existence of criteria that defines whether a method is more or less suitable for an effective analysis process. Given a method belonging to the proposed classification, seeing that our taxonomy is oriented toward four well-defined tasks, this method is assessable according to the objective of its category. To evaluate a method, one just has to assess whether it offers or not 1) an efficient selection or 2) an efficient location or 3) efficient link (connect) or 4) an efficient arrangement. Since most of these tasks were widely studied in recent years, it may be said that this taxonomy provides a valuable *evaluative power*. Indeed, for a selection, one can assess the time required for achievement of the selection task and the selection accuracy. For a link, one may assess the following-up accuracy and perception of users.

Generative Power

Unlike data-centric taxonomies (Shneiderman, 1996) or those based on low-level actions (Amar et al., 2005), proposed taxonomy is based on high-level actions that are well-known in the world of human computer interaction. In this sense, this classification aims at fulfilling the needs of end users. Hence, two tracks that can lead to the development of new methods are considered.

1. Since the goal of each category is clearly defined, it is believed that this will promote the development of new methods. Indeed, having stated the goal (selection, link, location or arrangement) is the first step towards the development of new methods. Thereafter it will take, depending on user requirements, to design the method that lets to achieve the task.

2. Since identified tasks refer to end-users goals, we argue that developers will be eager to apply existing haptic methods to new areas. However, to take into account the specificities of any new domain, new methods should likely be created. This is what was observed with the haptic rendering of isosurfaces: methods that suited medical data showed some instability with the data from CFD simulation (Fauvet, 2007). To address this problem, a new method, has been proposed (Menelas, Ammi et al., 2008).

Finally, in addition to these three assessment criteria, we would like to emphasize that despite the fact that this taxonomy has been developed from the desire to improve the interaction component of the analysis process, it also includes methods that target the achievement of better data presentation. Throughout the description of each category, different methods that can actually improve the presentation of data were outlined. For the selection group, the work of Menelas et al. (2010) has demonstrated that audio-haptic rendering may be exploited to unload the visual channel for selection a given target in 3D environments containing several others. In the case of localization, Lawrence et al. (2000) highlighted that the proposed haptic interaction could supplement the visual feedback. Similarly in the connect group, Lundin et al. (2002) by controlling the movement of the proxy, come to convey properties related to medical datasets. In arrangement tasks, since it can convey additional information without risking overloading the visual channel, used haptic feedbacks appear as a mean that let to enlarge the bandwidth between a user and the system (Persson et al., 2007).

In the light of these last observations; this taxonomy reminds the interdependence that exists between interaction and presentation components of visualization processes. This analysis is in line with Yi et al. (2007) who recently concluded that these two components are in a symbiotic relationship.

CONCLUSION

In this chapter, the role of VR technologies (visual, haptics and audio) in analysis of scientific datasets was discussed. First, it was identified that interaction and presentation are the two main components of visualization systems. Having observed that multimodality represents the key component of VR systems that may be exploited in analysis of large datasets, two criteria that should be addressed in designing multimodal systems were stated. Thereafter, the manner in which each modality and how combination of several modalities could be exploited in order to arrive with effective analysis processes was analyzed. By doing this, based on physiological characteristics of humans, it was pointed out that haptic interactions should be used in order to improve the interactions of the user. From this, a taxonomy based on interaction tasks where haptics seems to have advantages when compared to other channels was detailed. Identified task are: *Select*, *Locate*, *Connect,* and *Arrange*. Throughout the description of this categorization, a detailed survey of methods of the literature was provided. Finally the descriptive, the evaluative and the generative power of the proposed taxonomy have been discussed.

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KEY TERMS AND DEFINITIONS

Haptics: Haptics is linked to the sense of touch. Nevertheless, the haptic modality refers not only to tactile perception but also to a complex system based on the muscles and joints: it plays a major role in propricoception. In a non-exhaustive manner, it informs on texture, weight of objects as well as their hardness and shape.

Modality: A modality is directly linked to a human sense. We define modality as the form of exchange that can take place between a user and a numerical system. We thus define the visual, the haptic or the audio modality.

Multimodality: As opposed to a unimodal condition where only one form of communication is possible, several forms of communication are available in a multimodal rendering. When compared to unimodal rendering, the design of a multimodal rendering requires additional conditions due to interactions that may exist between the various channels. Indeed, it requires that exploitation of different modalities does not oppose one another. Furthermore, it is also desirable that each modality contributes to the achievement of a common goal.

Multimodal Analysis: As opposed to standard analysis processes of large datasets where only the visual capabilities of human are exploited, in a multimodal analysis several modalities (visual, haptics and or audio) are exploited in order to provide the user with a richer and more natural interface with the data.