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Proposition of new metaphors and techniques for 3D interaction and navigation preserving immersion and facilitating collaboration between distant users

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There are two ways of spreading light:
to be the candle
or the mirror that reflects it.
Edith Wharton.

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Introduction

Virtual Reality (VR) has been recognized as a powerful technology in the human-machine interface field which provides realistic and believable experiences for a user in a virtual world using real-time interaction through multiple sensory channels. Recent progress of the VR technology gives the Computer Supported Collaborative Work (CSCW) a potential and flexible tool of vividly representing data as well as users themselves in collaborative virtual environments. Collaborative Virtual Environments (CVEs) have been defined as computer-based, distributed virtual worlds in which people can meet, communicate and interact with others, with data, 3D objects or artifacts although they may be geometrically far from each other, speak different languages and use heterogeneous computer systems. Therefore, the power of CVEs is not just to simply put people together in a shared virtual world and to connect multiple distant VR systems simultaneously. The success of a CVE is decided by many features: representing multiple users in the virtual world so they can be aware of each other; enabling natural and intuitive interactions between the users, and between them and systems; facilitating immersion of each user; maintaining workflows despite networking problems; facilitating multimodal and real-time communication; and other aspects. The ultimate goal in developing CVEs is to support a smooth collaboration between multiple users which involves considerable communication and negotiation, cooperative and collaborative activities, interaction techniques, and awareness process.

The scientific community has been working in the field of CVEs for decades, but many problems in collaborative techniques for interaction and navigation still remain unsolved. Let's consider an example of a simple collaborative scenario in figure 1. Two users in two different systems are working together in a shared virtual environment. Their task is to co-manipulate a table in the environment. One user on the left of the figure works in a CAVE^{TM} system of four projection walls and a tracking system which gives him the possibility of walking around in the virtual world. He is wearing a pair of active shutter glasses which enables him to see the world in three dimension (3D) and so enhances his level of immersion. He is using a flystick to interact with the elements of the virtual world. The second user on the right of the figure is using a desktop-based system with a keyboard and a mouse. To enhance his level of immersion, a 3D display device and/or a small tracking system can be also installed. Due to the limit of his working system, he cannot move around the virtual world by physically walking as the first user does in a CAVE^{TM} system. Nevertheless, he has access to various controls using the keyboard and the mouse. He also has the support from physical tools such

as tables, chairs, etc., so he can comfortably sit down instead of standing as the first user does.

Figure 1 – Example of a collaborative scenario.

From this example, we discuss two aspects of a collaborative scenario in a virtual world that the designer of the system needs to take into account. The first aspect that is related to the virtual environment tries to answer some following questions:

- How can each user manipulate the elements of the virtual world and how can he perceive the changes of these elements in the world?

- How can each user perceive the presence of the other and what is he doing?

- How can one user and the other move the table together?

- How can the two users share their understanding and activities for a common goal and progress of the task?

The second aspect that the designer needs to study is not only about the different components of the physical world that are necessary in VR systems, but mostly about how the diversity of VR systems can affect the performance of the collaboration. In other words, the main concern in this issue is about how to clear the 'frontier' between the physical and virtual worlds:

- How can the two users who use different interaction devices put the same effect on the virtual objects?

- How can each user still perceive the physical world around him without breaking down his immersion and the feeling of presence in the virtual world?

- How can the two users be aware of some technical problems such as network delays without loosing the continuity of their workflow?

Considering these two aspects into the design of a CVE, we are interested in four main factors including immersion, awareness, communication and naturalness, which takes a major part of the success of a collaborative virtual system. A high level of immersion of a VR system can improve the feeling of presence, which is one of the most important criteria when designing interaction techniques in CVEs. The high level of immersion also helps the user to feel the co-presence with others and to establish a mutual understanding with them. Besides, to facilitate a mutual understanding between collaborators, the awareness factor also takes an important role. If a VR system provides an effective awareness activity, each individual can maintain a situation knowledge of his environment and of others to form a coherent mental picture in directing further perception and anticipating future collaborative events. Another factor that the designer of a CVE needs to consider is the communication channel between collaborators. In a collaborative task, collaborators often work at distance with various system infrastructures and different levels of immersion. Due to this difference, they may have different cognitive models of the shared virtual world and have to spend more time in communication to obtain an agreement about their roles and relationships to complete the task. In addition to the verbal communication channel which is often used in CVEs, other communication channels also have to be studied regarding various spoken languages and heterogeneous system infrastructures. The communication channels to be used need to be intuitive, simple in terms of building a mutual understanding between different collaborators. The fourth factor is the naturalness of a system that has been defined as the interaction fidelity with which the actions performed for a task in a VE corresponds to the actions performed for that task in the real world. Natural interactions may offer a great performance and usability as well as a strong feel of presence for collaborators. In summary, each factor may influence differently but still correlatively the whole performance of an interaction technique in immersive collaborative virtual environments. Considering these aspects, there is always the need of improving and completing interaction techniques in CVEs.

Objectives

From the need of improving and completing interaction techniques in CVEs, in this thesis, we focus on proposing new metaphors for 3D navigation and manipulation techniques to improve the collaboration of multiple users in virtual environments while maintaining their immersion and their awareness. This research began with the following requirements:

1. In CVEs, it is necessary and important to improve interaction techniques as well as communication channels between collaborators while maintaining their level of immersion. Communication channels can be extended to interaction metaphors as indirect and implicit means used to communicate between collaborators.

2. A second part of this research is to study and propose natural interaction techniques in immersive virtual environments. The immersion factor in this study

needs to be taken into account in the design of natural interaction techniques because the same interaction may be found natural or not depending on the level of immersion at each collaborator's site.

3. The last requirement of this research is to propose new metaphors and techniques which enable each collaborator in a CVE to be aware of the whereabouts and the current activities of other collaborators. One also needs to be aware of all the relevant changes of the physical and virtual environments around him.

Dissertation organization

First section has briefly introduced the context as well as some actual challenges that this research addresses. The main objectives which form the basis of this research have been also listed in the previous section. Finally, this introduction chapter has outlined the scope of this dissertation in the field of VR.

Chapter 1 provides an overview of CVEs with different interaction techniques that have been developed to support collaborative navigation and collaborative manipulation. This related work chapter also gives an overview of the four important factors - immersion, awareness, communication, and immersion - which need to be considered when designing a CVE.

Motivated by the need of a natural communication between collaborators in an immersive CVE, specifically for a navigation task, we have developed different solutions for collaborative navigation techniques. These solutions are presented in chapter 2 after a brief overview of collaborative navigation techniques in the literature. In the end of this chapter, the evaluation of our solutions is also detailed.

In chapter 3, from the need of improvement in the efficiency and the ease of use of interaction techniques in immersive virtual environments, we present a new direct manipulation technique which enables users to precisely control 3D objects. This chapter provides a full detail of our manipulation technique and its efficiency as compared to the 6-degree-of-freedom direct manipulation technique in an immersive virtual environment.

In chapter 4, we present an evaluation of some natural metaphors in a specific digital mock-up process application for workstation design. The four factors have been taken into account when we implemented interfaces for different roles in the application. This chapter presents in detail the implementation of this application as well as the result of an experiment that we have conducted to compare the performance of the workstation design process in different operating modes with different interfaces.

Finally, the last chapter presents the conclusions about this work and a discussion on possible future work related to this research.

Chapter 1

Immersive collaborative virtual environments: an overview

Collaborative Virtual Environments (CVEs), as a special kind of systems in Virtual Reality (VR) technology, are designed used for collaborative interactions of multiple users who may be physically located at different sites and be equipped with various devices. As a result, many aspects can affect the performance of their collaboration: level of immersion at each user's site, communication channels, interaction techniques, network reliability, awareness design, and other factors. In order to fulfil the objectives of this research, first and foremost, we study different techniques existing in the literature for the two main interactions usually encountered in CVEs: collaborative navigation and manipulation tasks. Since we focus on proposing new metaphors for three dimensional (3D) interaction techniques to improve the collaboration of multiple users in virtual environments, the four aspects of CVEs - immersion, awareness, communication, and naturalness - are also considered. Note that in this chapter, our aim is not to provide an extensive state-of-the-art about CVEs and the four aspects, but to provide an overview of the research that we consider relevant in the discussed aspects of immersive CVEs.

1.1   Collaboration in virtual reality

Virtual reality has been defined as the technology that involves real-time simulation and interactions through multiple sensory channels (e.g., vision, sound, touch, smell, and taste) in order to provide for users real and/or believable experiences in a virtual way [BL93]. The challenge of VR is hence to make 3D computer-generated objects appear convincingly real in many aspects: appearance, behavior, and more importantly, quality of interactions between objects and users.

To concisely define the characteristics of VR, the three 'I's are used: immersion, interaction and imagination [BL93] (figure 1.1). First, the *immersion* aspect of VR is originally the characteristic that makes the virtuality real and makes a user feel immersed in a virtual environment and be completely separated from the real world.

So far visual aspects implemented using 3D computer graphics are main instruments used to isolate the user's visual senses. Consequently, the immersion characteristic depends a lot on the quality of display devices and of rendering software. However, as the technology for simulating five senses of human beings (i.e., hearing, seeing, feeling, smelling, tasting) steadily progresses, the user will not only be able to see, hear, and feel objects but also smell or taste them in the near future. Second, the *interaction* characteristic is normally considered as a dynamic aspect to help the user not only see, hear or feel virtual objects but also interact with them. By interacting with objects as well as with other people in real time, the user can change the state of a virtual environment, of the objects in it, and so deeply involves himself in the virtual world. Last, a virtual world is often designed to serve a purpose or to offer a specific application because no virtual world would be suitable for all demands. How a virtual world, with all the objects and people in it, behaves and works depends on the *imagination* of its designers. However, in spite of all different designs of virtual worlds, realistic simulation, interaction, and real-time communication are always required.
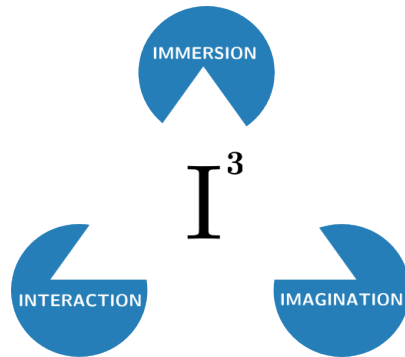
Figure 1.1 – Virtual reality triangle: Immersion-Interaction-Imagination [BL93].

Since VR technology has enormously progressed over these decades, recent advances in this field give the Computer-Supported Collaborative Work (CSCW) a vivid and flexible tool to represent data, objects and multiple users in a shared virtual world for collaboration. In addition, users in the virtual world can share information through communication, and through individual and collaborative interactions with data representations. CVEs have been widely applied in many applications: training simulations, Digital Mock-Up (DMU) and virtual prototyping, design review, scientific data visualization and co-analysis, serious games, e-learning, 3D games, etc. In brief, CVEs have been defined as computed-based, distributed, virtual spaces in which people can meet, communicate and interact with others and with virtual objects [CSM01]. Collaboration in virtual environments is not just to simply put and connect multiple individual VR systems together. The collaboration of multiple users requests many features: multiple users' representations, interaction between user-user and between user-system, immersion, networking, different virtual and real spaces, multimodal and real-time communication, and also other aspects [JDGMT04]. The figure 1.2 represents main factors that can influence collaboration in virtual environments in our opinion.
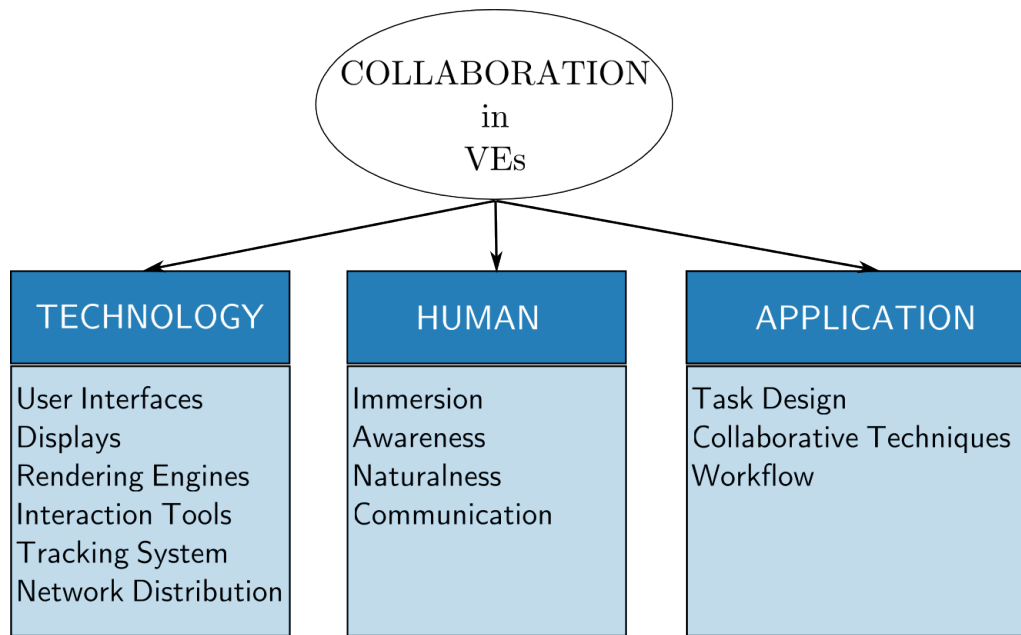
Figure 1.2 – Different factors influence collaboration in virtual environments.

The main goal of developing CVEs is to support a smooth collaboration of multiple users, which considerably involves communication, negotiation, and cooperative and collaborative activities [LMK93]. This goal has to be carried out in a heterogeneous platform of multiple users using different hardware and software setups. We briefly review in the following paragraphs six major problems to solve when implementing a CVE in order to achieve a successful collaboration for multiple users.

1. **Maintaining consistency in a shared virtual environment**
   One of the conditions of sharing a CVE is that all the objects, including 3D objects, data and virtual human representations, need to be exactly in the same state in the shared world for all the users [JDGMT04]. The number of users in a shared virtual world may be changeable. Moreover, during the run-time they may enter the environment after it has been changed from its initial state and they may also leave at any moment. Therefore, the CVE needs to be able to update all the changes of the environment for later comers. More importantly, in collaborative tasks such as cooperative object manipulation tasks, all the changes need to be sent to all the current manipulators in real time to avoid conflicts in controlling objects. This condition mostly requires the system to maintain networking reliability and fast communication protocols.

2. **Maintaining awareness of users**
   A CVE needs to be designed to guarantee that one user can be aware of others' activities at any time via tacit and explicit communication. Dourish and Bellotti [DB92a] state that awareness is an "understanding of the activities of

others, which provides a context for your own activities". Besides, he also needs
to be aware of the changes of the environment in which he is working. Aware-
ness can also relate to activities outside of the current task context where one is
interested in the activities of a collaborator who is not currently present or who
may not be working on the same task [CS98a].

3. **Supporting negotiation and communication**
   Communication has been always considered as an 'instrument' for users to com-
   plete a collaborative work in VR. Communication channels provide for a user a
   possibility of keeping in contact with other people, either by communicating in
   real time in synchronous CVEs, or by leaving notes for others wherever they are
   needed. Communication between them can be explicit (e.g., speaking, writing)
   and implicit (e.g., emotional expression, gestures, postures, visual metaphors).

4. **Supporting data and embodiment representations**
   In order to support collaborative and cooperative activities, one user is virtually
   co-located with others as well as with the information with which they are work-
   ing. Creating data and embodiment representations in the same world help them
   to easily access to the data together with facilities for communication and collab-
   oration. Benford and Mariani [BM95] have proposed the concept of Populated
   Information Terrains (PITs) in which users become a part of the database as is
   the data. In this way, users are explicitly represented or 'embodied' within the
   virtual environment and their presence is not merely implied as a side effect of
   their actions.

5. **Supporting multiple viewpoints**
   Depending on the requirement of collaborative tasks, a CVE can provide different
   points of view on different subtasks for users. If a collaborative task requires
   cooperative activities done through separate and individual subtasks, each user
   retains his own viewpoint(s) to work on different aspects of the task. Additionally,
   the system can support subjective viewpoints to each user on different levels
   of detail and levels of fidelity of the environment [CS98a]. The use of these
   various viewpoints depends on the approach of the designers of the system used
   for communicating and interacting between the users. Besides, in other cases, a
   system can support a What-You-See-Is-What-I-See (WYSIWIS) design [SBF+87]
   by which the users share the same view of a single activity.

6. **Supporting transitions between individual and collective activities**
   A collective task in a CVE includes different individual activities done by multiple
   users to obtain a common goal. Due to this condition, each user needs to be able
   to become an active agent in the virtual world. He can engage in collaborative task
   or go back to individual activities whenever he wants without losing awareness
   of others' activities [CS98a]. Therefore, it is important that each one needs to
   negotiate and share his understanding of collaborative tasks, his activities and
   his own ongoing progress to others.

The interaction in an interactive virtual environment can be categorized into three general tasks: navigation, manipulation and system control [BKLP01, BKLP04, Han97]. Navigation refers to viewpoint manipulation techniques used to move the viewpoint(s) of users and/or to change their parameters such as zoom factor and field of view. Manipulation refers to the interaction techniques of selecting, positioning and rotating objects. System control refers to the techniques of changing the state of the system or the mode of interaction. Since there is no direct involvement of users in system control techniques in a virtual environment, they are out of scope of this thesis. Furthermore, we are interested mainly in collaborative interactions in virtual environments, which will be detailed in section 1.1.1 for collaborative navigation techniques and in section 1.1.2 for cooperation and co-manipulation techniques.

1.1.1 Collaborative navigation and wayfinding

Limited only by the imagination of creators, virtual environments extend their boundaries to a bigger world. However, the physical systems on which virtual environments are implemented still have many limitations such as available space in a CAVE^{TM} system[1], limited field of view of desktop screens or short range of HMD devices. Due to these limitations, navigation techniques are normally necessary for users to move in large-scale 3D environments. As the navigation in the real world, the main goal of navigation techniques is to make the navigation task trivial and more transparent in the whole interaction in a virtual environment. Navigation tasks includes two main sub-tasks: *travel* and *wayfinding*. Travel tasks enable a user to control the position, orientation and zoom factor of his viewpoint [DP01]. Wayfinding tasks enable the user to build a cognitive map in which he can determine where he is, where everything else is and how to get to particular objects or places [DP01, JF97]. Many techniques have been proposed for travel in virtual environments [SFC$^+$10, ZLB$^+$04]: walking-in-place techniques, devices simulating walking, gaze-directed steering, pointing, or torso-directed steering. Wayfinding tasks rely on the user's cognitive map because he must find his way to move around in the environment using this map. In order to build a cognitive map of an environment, spatial knowledge (including landmark, procedural and survey knowledge [THR82]) is normally collected during VE travel tasks. However, due to the potentially large scale of virtual environments as well as the extra degrees of freedom within them whereas there are limited physical constraints, the user easily gets disoriented and lost [BKLP01]. As a consequence, the performance of navigation will be reduced [ETT07] because the user lacks an accurate spatial knowledge of the environment. In order to deal with this difficulty, whilst travel tasks are almost easily done by the user alone, he can get an assistance for wayfinding tasks from other users who share the same environment but have certain advantages in having other viewpoints of the environment.

In order to deal with wayfinding difficulties in VEs, two principal wayfinding supports have been considered: designing VEs to facilitate wayfinding behavior such as

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[1]We use the 'CAVE^{TM} system' term to refer to the generic type of VE system described in [CNSD93]

structural organizations, and proposing wayfinding aids such as maps, landmarks, or navigational cues.

Designing VEs is often extracted from the environmental design principles of urban architects in the real world. Darken and Sibert [DS96] suggested three structural organization principles to provide a structure by which an observer can organize a virtual environment into a spatial hierarchy capable of supporting wayfinding tasks: dividing a large world into distinct small parts, organizing the small parts under logical spatial ordering, and providing frequent directional cues for orientation. When these principles are applied to structured and architectural environments (e.g., urban landscape, buildings), they make it easier for users to construct cognitive maps efficiently [Vin99, DP01]. However, in other applications, such as scientific visualization applications [YO02], or in other kinds of environment, such as in open ocean environments or in forests, it is difficult but still necessary to organize objects in an understandable way and to build semantic connections between them.

Maps are the most used wayfinding aids. By using two kinds of maps (i.e. egocentric maps with 'forward-up' orientation and geocentric maps with 'north-up' orientation [DP01]), users can access to a large amount of information about an environment. However, the map scaling problem of a very large VE and the alignment of the map with this environment can cause high cognitive load for users [BKLP04]. Environment maps can be created in 2D or 3D formats [CV01]. The Worlds-In-Miniature (WIM) metaphor is a technique that augments the immersive display of a virtual environment with its hand-held miniature copy that is like its 3D map [SCP95a]. It is possible to directly navigate on this WIM map by using it to determine and point out where to go next in the VE. Nevertheless, since the environment cannot be seen during this interaction, it limits the spatial knowledge of the virtual environment that the user can gain from the navigation task.

Usually, landmarks or navigational cues are statically implemented *a priori* in a VE. Some examples of these wayfinding aids are architectural cues such as lighting, color, texture; or environmental cues such as horizon, atmospheric perspective [BKLP01]. Landmarks are very powerful cues that make it easier for users to recognize a position within the environment and/or to acquire spatial knowledge. Normally, landmarks are statically implemented *a priori* in the environment but they can also be used as tools. For example, Kim et *al.* [KSCL05] proposed a topic map that contains semantic links between landmarks, which are mostly famous regional points in a VE. This topic map can be applied to the navigation task within the VE as an ontology of subject knowledge representing subjects of the environment (e.g., buildings, its metadata, landmarks), and spatial knowledge representing the structure of the VE. However, it is also limited by the subject knowledge and the spatial knowledge that designers can describe about the environment in the ontology. The more complex and abstract the environment is, the more difficult the description of the ontology is. Additionally, there is another technique for users to discover the environment progressively by retracing their steps [Rud05]. It is called *trail* technique and it describes the path that users had previously followed. Ruddle [Rud05] notes that trails are useful for first-time navigation in a VE, but that eventually trail pollution impedes their utility during subsequent navigation. Accord-

ingly, this approach is only appropriate for a repeated exploration or a search task for a given set of locations.

The way to use these wayfinding aids normally depends on the design of the VE. In addition, they are usually statically configured without users' interaction and are not modifiable at run-time. In a collaborative VE, since navigation and exploration tasks in VEs are not usually considered as the main tasks to achieve, the wayfinding time of one user can be considerably reduced by having the assistance from other users who have other viewpoints of the virtual world or by dividing the users' role in their collaborative task. Therefore, the development of different forms of collaborative navigation techniques aims to enable one exploring user to find his way in a VE without previous travels by getting help from other users. If the helping users have a global and complete view of the VE such as a bird's eye view, 2D or 3D maps [CV01], they can help the exploring user in the VE to easily navigate in the world. One helping user with a global view can guide other exploring users in the world by describing (speaking) routes to take. One solution is that he can choose a pathway to targets and can route the others by trails in the world. An example can be found in [DFNA08] where one user can mark the viewpoints of interest of scientific data as 'anchors' and others can use them as trails to navigate in the world. In the same way, if one user has traveled in a VE, he can leave trails or marks of his experience or his spatial knowledge in the shared environment for later users, for example by putting text marks in it. Other navigation aids have been also used in this case for collaborative navigation such as directional arrows [BRS+12], point light sources [CRS+12, WBL+12], light signal or beacons [NWGM12].

Collaborative exploration can be used in different applications: exploring visualization of scientific data to find points of interest; exploring complex large-scale environments that it takes too much time to build a map for or to set up landmarks; or exploring unstable environments with many dynamic elements that it is difficult to build a representative map at every moment such as training simulators for firefighters or soldiers [BEG+09]. Collaborative navigation can be also useful in collaborative guiding applications (e.g., collaborative visits for museums [Rou04], architectural project reviews, etc.) in which collaborative spoken description is used to guide others in the world. If the users have the same viewpoint, one of them can share his spatial knowledge by leading others the right way from the first-person viewpoint. If the users independently move in a group, they can share the spatial knowledge in the same way using maps or others navigation aids [DR08a].

1.1.2 Collaborative manipulation

Since 3D object manipulation is one of the most major interaction modalities of 3D interactions in VEs, collaborative manipulation techniques were designed to provide a means for multiple users to collaborate in a shared workspace that supports dynamic collaboration over distance and time constraints. Generally, 3D manipulation techniques include three basic tasks (i.e., object selection, object positioning and object rotation [BKLP01]) besides other tasks to change the parameters or proprieties

of objects. In collaborative contexts, the design of collaborative manipulation techniques requires the consideration of how participants should interact with each other in a shared space, in addition to how co-manipulated objects should behave. Collaborative manipulation techniques can be designed by modifying existing 3D interaction techniques or to develop new ones specifically for collaborative manipulation tasks.

As far as collaborative manipulation is concerned, Margery et al. [MAP99] have categorized collaborative manipulations into three levels, depending on how users can act in an environment.

- **Cooperation level 1**: The collaborative system enables users to perceive each other by using avatars to represent them and to communicate between them.

- **Cooperation level 2**: The collaborative system enables users to interact and manipulate objects in the environment individually.

- **Cooperation level 3**: Users can cooperatively manipulate same objects of the environment at the same time. This level can be categorized further into two sub-levels. One sub-level enables two or more users to modify independent properties of an object. The other sub-level enables users to concurrently modify the same or linked properties of an object. The latter sub-level is basically the cooperative manipulation as we discussed in this chapter.

Collaborative manipulation techniques are defined as a set of rules about how multiple users in a shared virtual environment manipulate objects by incorporating individual manipulation operations together [BKLP04]. There are more constraints in cooperative manipulation tasks than in general collaborative manipulation ones because they require that the users need to be able to simultaneously manipulate the same object. The consistency of the shared environment needs to be maintained as the state of the world changes according to activities performed at the users' sites [TK92]. Another problem of cooperative manipulation that needs to be solved is the concurrence of access and rights when multiple users access to the same object at the same time. This problem then leads to another requirement for the behavior of the object in concurrence. How the co-manipulated object behaves depends on the impact of each user's operation affected on the object. Besides these problems, for us, the awareness for two or more users performing a cooperative manipulation task on the same object, the smooth transition between individual and collective activities, and the possibility of manipulating objects by only a single user also need to be carefully considered. The awareness in cooperative manipulation requires that the system represents to all users the operations each user is performing and also their impact on the object and on the environment. In addition, the systems needs to represent to the users possible constraints, limitations and controls they have on the object. The transition between individual and collective activities that is described in [PBF02] is the possibility of changing from individual activities to collective ones without explicit command and interruption in the interactive task. This problem is well connected to the possibility of manipulating objects by a single user because the border of collective and individual activities can be transparent.

We are mostly interested in the highest level of cooperation with concurrent interaction, which includes cooperative manipulation techniques used by multiple users to modify the translation and the orientation of a shared object. Two main approaches have been proposed to deal with cooperative manipulation: separation of Degrees of Freedom (DOFs) of the object and combination of individual actions on the object. The former tends to separate the six DOFs of the object to multiple users. The framework in [PBF02] gives some examples of the DOF separation. One of the examples is that the three dimensions of the translation of the object can be separated by two dimensions controlled by one user and the third one controlled by another user. In another example, one user controls the position of the object and another one controls its orientation. The DOF separation is normally considered as an asymmetric integration approach of cooperative manipulation techniques. The combination approach integrates the actions of all users into a single movement of a shared object. The first solution for the combination is to find the common part of all the users' actions and apply it to the object [BHSS00, RWOS03]. Another solution is to 'average' all the actions of users. One example was the Bent Pick Ray technique by [RHWF06a], in which two (or more) users simultaneously move a shared object using pick rays which are bent to connect to the object (see figure 1.3). The movement of interaction tools that are used to control the pick rays is used to interpolate the rotation and the translation of the object with a weight which reflects the number of the interaction tools. In another study, the SkeweR technique in [DLT06] uses the translation of interaction tools that are used to control 3D cursors according to two control points (or 'crushing points') on the surface of an object to compute its rotation and translation. This techniques especially takes into account the size and the shape of the object when applying the control points of interaction tools on the object. The sole drawback of this technique is that the object cannot be rotated around the axis created by two control points. The 3-Hand technique in [ADL09] enhances the SkeweR technique by adding a third control point, making it possible to have two or three users to simultaneously control an object. The movement of the object is then computed by the movement of its three control points. In brief, unlike the symmetric and asymmetric action integration defined in [RSJ02], this approach is considered as symmetric manipulation not because users need to perform actions the same way at the same time but mostly because users have the same magnitude on the object and they can control it equally.

Other properties of cooperative manipulation are also considered. A virtual environment can be shared between multiple users either at a distance or in a co-located physical world. A co-located collaborative environment depends on the characteristics of the collaborative task and the designers of the system can optimize the communication means to be used when users can have face-to-face communication with all its benefits, e.g., [ABM+97, API+98, SJF09, NM97]. On the other hand, the system needs to establish a projection system that can support multi-users' stereoscopic views as well as special designs for cooperative interactions such as side-by-side or face-to-face interaction techniques. A remote collaborative system is the common case of cooperative interaction in which users can benefit from different system infrastructures at a distance. The major difficulty of a remote collaborative system is how to interpret
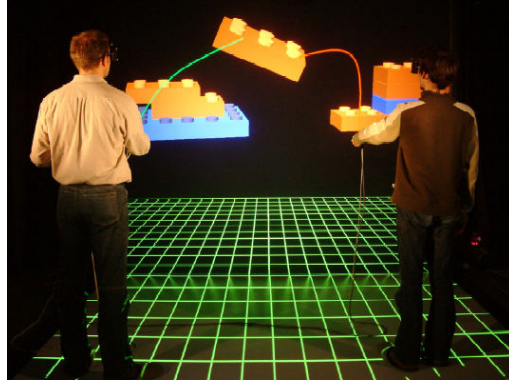
Figure 1.3 – The Bent Pick Ray technique in a cooperative manipulation task [RHWF06a].

and represent the actions of each individual to others and make them aware of all the changes in the environment while they do not see each other directly. Some remote setups of cooperative manipulation can be found in [Bro95, DLT06, FDGS12, PBF02].

In summary, the choice to use a cooperative technique depends on interaction tools used by each user (e.g., homogeneous cooperative technique vs. heterogeneous cooperative technique [PBF02]), requirements of the task, environmental affordance and different expertise of the users.

1.2 Immersion, awareness, communication, and naturalness factors of CVEs

Besides the interaction techniques of navigation and manipulation that take an ultimate role in the whole picture of collaboration in virtual environments, the efficiency and the performance of collaboration tasks are also influenced by other factors of virtual environments such as immersion, awareness, communication, and naturalness. In this section, we briefly review the different aspects of the four preceding factors that we defined: immersion, awareness, communication, and naturalness in collaborative virtual environments.

1.2.1 Immersion in collaborative virtual environments

In the last decade of the 20th century, we have witnessed a blooming success in the virtual reality field when it attracted attention of many researchers, scientists, industrial designers, entertainers, and public. One of the major assets to this success is the ability to immerse users in a virtual world. The remarkable development of 3D stereoscopic displays helps VR designers to bring the third dimension into virtual environments by exploiting the human brain capability to build 3D scenes from depth cues (e.g., motion parallax, stereopsis, perspective, occlusion). It seems that performing a task in a full

immersive environment improves a user's sense of presence and produces a higher level of spatial understanding of the environment than in a desktop environment [ORW06].

While the immersion concept often comes with the presence feeling of a user in an immersive VE, immersion and presence are two different but correlated concepts. Immersion describes the technology that provides stimulus modalities whereas presence in a virtual environment describes a mental state of 'being-there' a user feels while working within the environment [BM07, SS00]. Therefore, immersion can be evaluated by different measures but presence is a subjective feeling of the user at a time and so it depends on state of mind, experience in VEs, and other psychological factors of the user.

It is generally agreed that the level of immersion mostly relates to display apparatus and rendering software of VR systems even though haptic and tactile feedback, 3D auditory channel, and other sensory modalities can take part in the enhancement of the level of immersion. The level of immersion hence depends on several visual factors [BM07], as described in the following paragraphs:

- *Field of view (FOV)* is the size of the visual field in degrees that can be seen at any given moment. The total FOV of the human eye is almost 160° while a Head-Mounted Display (HMD) typically provides a horizontal FOV of 60°, a workbench provides 120° FOV, and the FOV of a CAVE$^{\text{TM}}$ varies from 90° to greater than 180° depending on the distance of the viewer from its projection screens. On the one hand, the 'tunnel vision' effect can happen that introduces immersion decrease if the FOV of a display device is low. On the other hand, a high FOV can produce image distortion and resolution decrease.

- *Field of regard* describes an available FOV of a display device in any given viewing direction. If a display device provides an available field of view at all times, it is considered as a full immersive display [Kje01]. Otherwise, it is considered as a partial immersive display. According to this categorization, although HMDs have a low FOV, they still fully immerse users in virtual environments, allowing them to naturally rotate 360°. Another display system that satisfies this condition is the surrounding display of a 5-side CAVE$^{\text{TM}}$.

- *Display size* and *resolution* parameters take an important role in deciding the quality of the image rendering and the realism its provides to increase the level of immersion. Nowadays, HMDs are broadly used because of their low cost, mobility and less-space constraints compared to other immersive projection systems. Besides considering the advantages, HMD users have to go through some drawbacks such as low resolution, small display size, heavy weight and lack of ability to adjust visual parameters [BDR^{+}02].

- *Stereoscopy* is the first and the most necessary parameter of a display device to provide a high level of immersion. By adding an additional depth cue, VE systems emphasize understanding spatial relationships for immersed users as well as provide an interesting support for natural interactions.

- *Head-based rendering* is based on the actual position and orientation of a user's head for real-time image rendering. Due to this factor, HMDs and immersive projection systems are often used for a single user at one time. This factor also might become a drawback in CVEs when collaborators want to work side-by-side in a shared physical workspace.

- Frame rate, refresh rate and other factors can also influence the level of immersion of a user in an immersive virtual environment.

Besides improving the presence feeling of a user in a VE, the high level of immersion can also affect the ability of the user to interact with objects and with other people in CVEs. A high level of immersion helps the user to feel the co-presence with others and to facilitate mutual understanding between them in a collaborative task [HRBW07]. A large display in an immersive projection system can also help the user to see the VE while maintaining focus on the others and on interaction [GSW01]. In a collaborative task, collaborators often work at a distance with various system infrastructures and different levels of immersion. Due to these differences, they may have different cognitive models of the shared virtual world. Therefore, they have to spend more time in communication to obtain a mutual understanding and so to form an agreement about roles and relationship between them to complete the task [NWZ+05]. It is observed that users in large display systems often take a lead role in a collaborative task [MVSS02, SSUS00]. Narayan et al. in [NWZ+05] have studied the effect of immersion on two-user collaborative task in a VE by using a CAVE^{TM} and a HMD to examine the two immersive factors, stereoscopy and head-based rendering, on task performance. The result indicated that the stereoscopic factor improved the task performance but the head-based rendering had no significant effect on the performance.

In summary, among the diversity of projection devices in the field of virtual reality, the choice of using what kind of projection device is a trade-off between visualization and performance needs versus economic considerations such as cost, space needed, transportability, and so on. CAVE^{TM} systems offer many advantages in terms of large display surfaces, large field of view, and body-centered interaction, which offer high level of immersion and facilitate presence feeling fo users. HMDs, on the other hand, are the most common display devices used in virtual reality, offering complete physical immersion, low cost, mobility despite low FOV, low resolution, and ergonomic issues. In a collaborative context, the level of immersion of a CVE in different VR systems may influence the performance of interaction techniques between collaborators.

1.2.2   Awareness in collaborative virtual environments

When working in a VE, most of the time, a user relies on his situation awareness, along with his knowledge and skills, to achieve his goals. Vidulich et al. [VDVM94] have defined situation awareness as "continuous extraction of environmental information, integration of this information with previous knowledge to form a coherent mental picture in directing further perception and anticipating future events." In other words,

the situation awareness is obtained in a cycle of extracting and integrating the information of the current situation and of the surroundings of a user so he can use it to act accordingly as the situation evolves. The situation awareness is hence a synthesis of both current and past situation information.

In CVEs, situation awareness is extended to groups of individuals with more information to be included in. A collaboration in VEs does not simply start when members of a group begin working together. It starts with their early awareness activities such as using environmental cues to establish a common understanding, knowing who is around and what they are doing, knowing the state of artifacts in the shared workspace, observing other people's gestures and what they are referring to, etc. Therefore, situation awareness in CVEs is defined as having complete knowledge of the environment within which an individual is working and of other people he is working with. When individuals collaborate at a distance, they share a virtual world, which provides common points of reference, but still have their own physical environment. As stated in [SMW04], the situation awareness of each individual about the shared VE and also his own physical environment is mediated by technology. In a global view, either with the information of the virtual environment or with the information of the physical one, the situation awareness in CVEs is classified into three categories: information of the context in which collaborators are working including working (virtual and physical) environments and their common goal; information of other collaborators including their whereabouts, skills, and emotional information; and information of individual and collective tasks and process for coordinating actions (figure 1.4).

From a technical point of view, a VE has to support situation awareness [End95], explicitly and tacitly. Due to the difference in situations at each individual's site, the system needs to provide and maintain a coherent situation awareness for all the individuals. At the same time, there is a limit to which how much situation information is mandatory to be transferred in order to avoid burdening the network. For example, there is no need to explicitly represent the evolution of the current state of the task if all collaborators can see it directly. On the one hand, for a better performance in a collaborative task, the awareness process needs to be achieved without increasing the workload of each collaborator in updating the changes of the world and of others, and in updating the evolution of the task. On the other hand, Gutwin et al. [GG04] states that awareness is knowledge about the state of a particular environment and since the environment changes over time, collaborators must maintain and update their awareness by interacting with the environment.

In the past decades, the awareness process has been designed, implemented and brought into systems, which support shared workspaces such as collaborative writing platforms [DB92b], virtual office environments [SC94], etc. These systems are mostly desktop-based platforms that use video, image, voice and/or text connection for improving the awareness knowledge. In recent times, with the development of virtual reality apparatus and technology, one can be immersed in VEs and experience real-time interactions with virtual elements. These developments can improve the visual, auditory and textual connection as well as propose other options such as haptic feedback, representative embodiment, etc. for a better awareness process. Theses advantages may
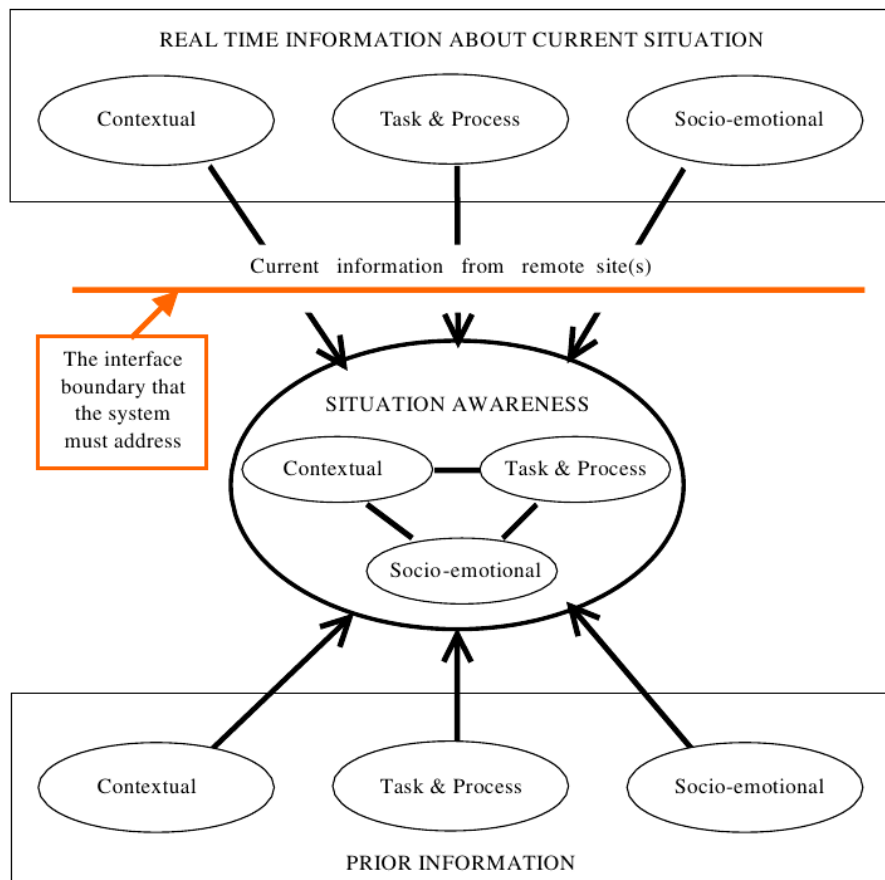
Figure 1.4 – Situation awareness, including the information of working context, of socio-emotional state of collaborators, and of task and process, is obtained from past and current situation information [SMW04].

improve the awareness process without overloading the network with video streaming or may simplify the awareness process by visual interaction metaphors. However, by any means of connection, the collaborative system needs to help each collaborator to answer the next questions: With whom am I working? What is in the virtual world? What is in the physical world around me? What are others doing? What am I doing? Will I be informed if there is a technical problem? An example can be found in the figure 1.5 illustrating the need for situation awareness in collaborative virtual environments. Therefore, in order to figure out in what way collaborative systems need to be designed for improving awareness, we will describe in this section several kinds of awareness including awareness of a VE and its artifacts, of people in it, of ongoing collaborative tasks, of limitations and constraints of the physical environment, and of network delays - the most common technical problem that causes the inconsistency in interactions between collaborators.
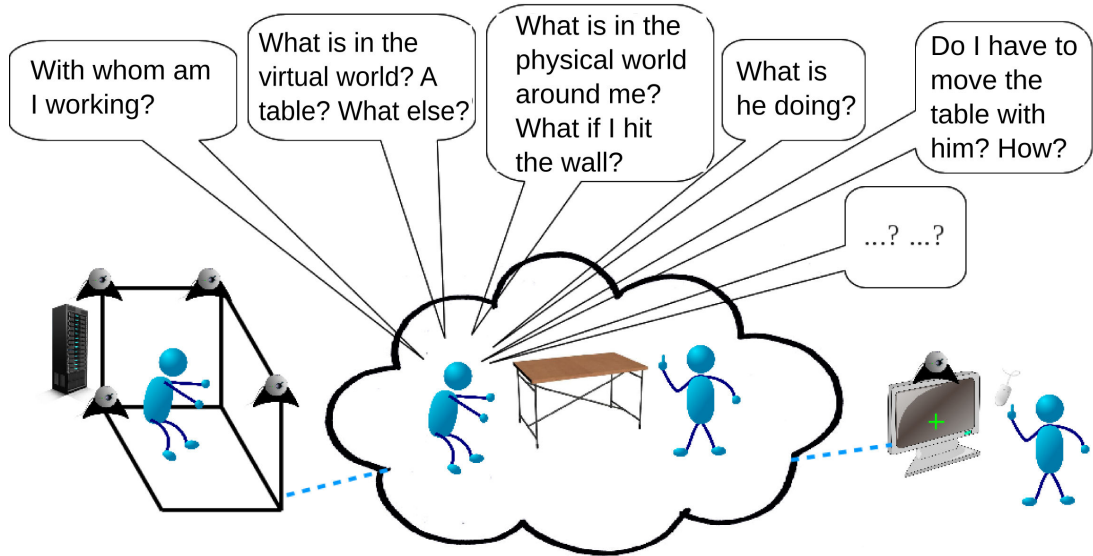
Figure 1.5 – Need for situation awareness in an example of collaborative virtual environments.

1.2.2.1   Awareness of others

The first and most important factor of the user's awareness in a CVE is whom he is working with. All the information about others' presence, their location and their actions and activities needs to be well represented. This awareness involves identifying and locating other users at a particular moment, so it concerns mainly synchronous collaboration.

Awareness of presence is the knowledge about whether there are other users in the same virtual environment and who they are. This awareness of presence can be easily done by representing each user as a recognizable embodiment or avatar. The DIVE system [BF93] uses simple graphical 3D-bodies to show where everyone is in the virtual world. However, representative avatars can be more complex if the realistic requirement is important in CVEs.

Awareness of location covers the knowledge of gaze, view and reach area of other users. Awareness of gaze and view involves understanding the area where a person is looking at and what he can see. Awareness of reach characterizes the knowledge about the area within a person can interact or manipulate artifacts [GG04]. Awareness of presence also implies the awareness of location if these users are working in the same limited 'space': "I know you are there because I can see you". Awareness of location in a narrow space can be improved if the working conditions of each user are explicitly represented. For example, by attaching a 'wire-framed' view frustum [FBHH99] to a user's avatar, others can see the orientation of his/her face and his/her field of view. They can also see where he/she is looking at and which artifacts are possibly seen by him/her. The same idea can be applied to the representation of interaction or

manipulation area to improve the awareness of reach. Based on the limitations and the constraints of control devices (e.g., mouse, flystick, 6 DOF controller, etc.), the interaction area of each user is represented, so the others can understand what he can possibly do. However, a problem may arise when using view frustums as well as explicitly specifying interaction areas to improve the awareness of location. When there are many collaborators working in the same narrow space, the confusion of these 'wire-framed' representations can happen. Additionally, when collaborators work together in a large-scale CVE, the design to improve the awareness of presence and of location is different. The characteristic of this kind of collaborative task does not require the permanent presence of users in the same place or in the field of view. A user can observe others over a map and their small 3D representations in a world in miniature [SCP95b] or in a supplementary view called 'bird's eye view' [DR08b]. This view can provide information about the presence, the position and maybe about the activities of the others. However, this information may be incomplete, especially for the current actions of the others, because its level of detail is low and it makes the perception particularly difficult.

Awareness of actions and activities implies the understanding of what others are doing, either in detail or at a general level. It also includes the knowledge about their intentions and what artifact they are working on [GG04]. In a limited working space, a simple idea of how to represent the others' actions and activities is to show them on the avatar of each user. The more detail in pseudo-humanoid representations there is, the easier it is for others to understand what a user is doing. Depending on the goal of collaborative work, if the users are working together to manipulate or interact with artifacts in the virtual world, a humanoid representing postures or gestures can perfectly show the current actions of each user and so the others can predict his/her intentions and which artifact he is working on. For other applications such as social meetings or teleconferences, the emotional expression and gestures may be important. If they are working in a large-scale CVE, in order to understand the actions of others, another solution can be found in [WSWL02]. The drawback of this approach is that multiple viewpoints can destroy the immersion and the continuity of workflow in the collaboration.

To summarize, awareness of others is the first important step to increase the efficiency of collaborative tasks and reduce errors for collaboration activities. This kind of awareness can be obtained from different perception sources such as visual, auditory, embodiment ones. Therefore, a good design of different factors in the virtual world to improve the awareness of users is important to get closer to an effective collaborative work.

1.2.2.2   Awareness of the virtual environment

We define a virtual environment as an environment that includes all the 3D models, data, information, artifacts and the tools that users use to interact with the environment and with the others. In the literature, many research work have been devoted to improving the awareness of people and their presence in CVEs, but few were interested

in improving the representations of virtual entities for facilitating the perception process and the awareness of the virtual world.

The spatial model of interaction [BBFG94] is one of the earliest work that treated the behaviors of artifacts in the virtual world in the same way as behaviors of 3D embodiments. However, the behavior of artifacts and of 3D embodiments have different properties. A 3D embodiment, which can possibly support the use of gesture and non-verbal cues combined with real-time conversation channels such as auditory and visual ones, can represent the identity of a user and the information about his/her actual whereabouts, actions, activities, etc. [CS98b]. In the virtual world, 3D embodiments can be considered as an active factor while artifact representations are passive ones. Artifact representations may be interpreted as a means to reflect the effect of users' actions onto the environment. By using many advantages of Virtual Reality, developers have many options to represent this effect on artifacts in the virtual world so the interaction of users with artifacts and also the collaboration between different users may become easier and much more effective. An example can be found in [FBHH99] where Fraser et al. used a 'wire-framed' representation of objects to show their current state of 'being moved' differently than the state of 'being pointed'. This representation can help other users distinguish the difference between the grasping and the pointing actions of a user because both grasping and pointing actions are usually done by a similar gesture: extension of the embodiment 'arms'.

Another aspect that needs to be studied is the way object representations or data may or may not remember the actions made on them and show them as a history metadata that can be used as an archive of past actions for later consultations. This aspect is mostly important in asynchronous collaborative work where not all the users connect and work at the same time. This metadata may contain the information about whether the artifact it represents can be manipulated or changed and how. It can also contain all the modifications and information about these modifications are made by whom, where and when. This capability of storing history actions of artifacts may be applied in educational applications of CVEs where course materials, learning contents or other auditory, visual, textual documents, etc. can be archived for all the learners as well as for each individual one.

Access control to artifact representations is also necessary. It defines the possibility of having many access levels of artifacts depending on the authorization level of each user. Access control has been long studied in collaborative systems. In [TAPH05], Tolone et al. have summarized different access control requirements for collaboration and these requirements can be applied in the same way in CVEs. In [CS98b], Churchill et al. states that "one individual may require multiple representations to reflect different aspects of his/her task(s), whilst in other cases different individuals may require tailored representations to provide information specific to their tasks". In the same view, developers need to determine which objects and which properties of them are available and visible to which kind of user. Accordingly, in order to improve the awareness of virtual worlds, the requirement of having different subjective views as well as alternative ones of objects can become necessary and indispensable depending on the nature of each collaborative task.

Information produced by artifacts, either by their internal state or by actions of users when they interact with them, is one of the primary ways that people maintain workspace awareness [GG04]. If the interaction and manipulation process produces minimal feedback, their ability to maintain awareness of virtual environment reduces. This reduction of awareness may become worse when many people try to interact with a same artifact or object. Getting distracted by the action of others, a user may not be aware of the change in the artifact's state and so may not modify his/her actions accordingly. Therefore, effective feedback from artifacts is a key factor to improve the awareness of virtual worlds.

1.2.2.3   Awareness of coordinating actions

We want to discuss in this section an important type of awareness for cooperative manipulation. It is the possibility to make collaborators aware of actual collaborative activities so they can work together with the coordinating actions occurring in the right order and at the right time to complete a task [GG04]. In [Bae93], Robinson et al. states that there are two ways of coordinating actions. The first solution is using explicit communication about how to do the task together. The second way that is using shared materials used in the work process is more efficient but requires people to maintain the awareness of coordinating actions. This awareness enhances the coordination of users because it informs them about the temporal and spatial boundaries of others' actions, and helps them fit the next action in the working process. The awareness of coordinating actions is particularly efficient in continuous actions when people are working with the same objects [GG04].

The cooperative manipulation is a type of collaborative work wherein users manipulate simultaneously the same object. Because this particular activity involves the actions of multiple users on an object at the same time, the awareness of the others' ongoing actions takes an important role in the accomplishment of the collaborative work. Some approaches have been proposed for cooperative object manipulation but not many interaction techniques take into account the awareness aspect. The collaborative pointing technique for colocated multi-user interaction [RHWF06b] allows users to pick up an object simultaneously using pick rays. By bending these pick rays that are normally straight, users can be aware of the change made by their actions on the object and also on the control metaphor (i.e. pick rays). Pinho et al. have proposed some visual metaphors to improve the awareness for cooperative manipulation [PBF08]. In the selection phase, the selected object's color changes when a user points to it. This feature allows another user to know what his/her partner is pointing to. The object's color also changes when the users enter the other phases such as the attachment, positioning and release phases. Because this cooperative manipulation technique combines simultaneous user actions based on the separation of degrees of freedom between two users, the shape and color of the control metaphor (in this case, pointers) change accordingly to each particular manipulation situation, which allows a user to predict the interactive capabilities of his/her partner.

In order to accomplish a successful cooperative manipulation task, each user has to

maintain a continuous awareness of coordinating actions to track, predict and adapt his/her actions with other users. Therefore, some simple but effective metaphors need to be implemented to improve this kind of awareness.

1.2.2.4   Awareness of the physical environment

The awareness of the constraints and limitations of the physical world would be very important when a user is fully immersed within a CVE because his/her feel of presence of the real world can be totally replaced by the feel of presence of the virtual world. This immersion aspect may cause serious collision with hardware parts of the system or more slightly the disturbance and misunderstanding between users during a collaborative work. We will specify how researchers cope with these constraints to make sure that users can be aware of their infrastructure limitations as well as of the others'.

As in most of the virtual reality applications, a physical environment of a collaborative system must be integrated into the virtual one so users can be aware of their own interaction capabilities as well as of the others'. The representation of physical devices can help users to be aware of the working condition of others. They can predict the others' possible actions based on these representations. View frustum representation [FBHH99] is a simple way to show to others about the limited field-of-view of a user and so the capability of his display screen or HMD (e.g., the field-of-view of a HMD is about 50 to 60 degrees and the computer display screen's one is about 90 degrees). In order to visually display a haptic device with a limited workspace in a virtual world in [DLB$^+$05], a semi-transparent sphere that surrounds the manipulated cursor is used to control the force feedback based on the sphere position relatively to the cursor.

The goal is how to benefit greatly from the availability of different infrastructures of users to build an abstract representation of the virtual world. The semantic metaphors and the flexibility of each individual's system make sure that in spite of the difference, the metaphors can make up for the lack of devices or can make users aware of the difference so they can find an effective way to work together. The constraints and limitations of the physical world normally stay transparent so the immersion in virtual environments of users can be guaranteed. The features of the physical world only need to be visible in case of collisions or of the explicit representation of the real world besides the virtual one.

1.2.2.5   Awareness of inconsistency due to network delays

The network delay is one of the main reasons of ineffective collaborations and inconsistency in interactions of collaborators in CVEs. In [VGB99], Vaghi et al. states that "the deployment of CVEs over wide area networks as well as different communication bandwidths increase typical network delays, potentially breaking the consistency between the replicated versions of an environment at the participants' sites". All the information about the activities of all the actual participants, their whereabouts and all the changes that are made to the data and objects in the virtual world need to be

transferred over the network. Therefore, the more complicated the shared environment is and the more people there are in the same world, the more present the increasing network delays are and so is the incoherence of the participants' awareness and actions.

In order to solve this problem, the most evident solution is to reduce the amount of circulating updates and messages on the network [LWG05]. However, if network troubles still arise, the collaboration manager system has to make all users aware of this potential problem. Lamboray et al. [LWG05] have proposed some system features that need to be applied so the network delay effect could be coped by the understanding of users in the virtual world. Depending on the level of trust that each system requires, each feature needs to be considered, so determining which one(s) will be implemented is a compromise between the required level of trust and the system performance. The features such as the prediction capabilities and indication of level of trust associated with the prediction or the calculation of expression and preservation of user's expectations might not be necessary if the system's requirement of the consistency is not too strict.

We want to discuss here some features that may be easy to be implemented and applied in CVEs. These features include the capability of explicit indication of delays with all their characteristics and their effect on the influenced objects or data; and the capability of explicit display of corrections due to discontinuities. Duval et al. [DZ06] present an example (see figure 1.6) of explicit indication of network delays that can be found in a collaborative system. All the possible delays or disconnections due to low-level network problems are detected by sending synchronization messages between different sites in order to coordinate these parallel processes to similarly evolve in each system. If there is a breaking of the real time concept, they choose to let the collaborative task continue by freezing only the parts of the world whose state is uncertain for consistency considerations. The remotely shared objects loose their interactivity as long as the disconnection remains. They use echo objects that represent the state of their associated distant objects and a marker system to inform users about the out-of-date state of shared objects. The problem of this approach is that when a large number of sites are participating to the same collaborative session, there will be many echo objects that maybe 'pollute' the visualization. The solution is then to make sure that there is no more than significant metaphors, which are necessary for indicating the participants about the state of the world and of the other problems concerning network delays. One metaphor can also be used for different indications in different contexts so the redundancy will reduce. Another approach is to create dynamically echoes after the detection of a network problem because the echo objects are not necessarily explicit or available when there is no network problem to be shown. The users are informed about technical problems only when they obviously influence the users' activities. In addition, these network problems can be represented in form of visual, auditory metaphors or other metaphors in the virtual world so the immersion of users is not interrupted.

Developers of CVEs need to find a compromise between the need of representing the network problems because of the unacceptable inconsistency in a collaborative work and the discontinuity and the perturbation it could cause when the goal of almost all VR applications is to totally immerse users in the virtual world.
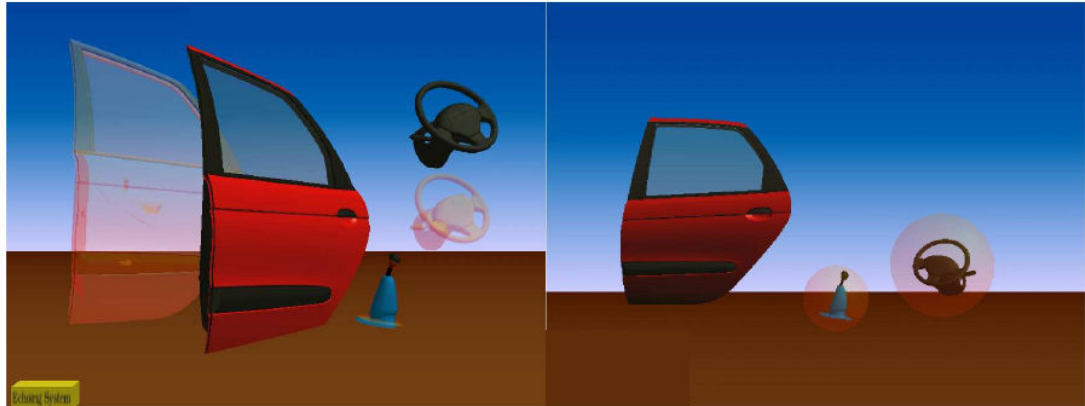
Figure 1.6 – Example of explicit indication of objects that are affected by network delays [DZ06].

In conclusion, in a collaborative virtual environment, the awareness of a user is the up-to-the-moment understanding of the collaborative task to achieve, of the people he is working with, of the shared environment, and of the system infrastructure [GG02]. Since acquiring awareness information by perception process is obvious and simple, and it often happens inside users' head, the design of a CVE for improving the awareness is often not enough considered. However, providing so much information of the virtual world as well as of the physical one does not really help a user to successfully collaborate with others due to information overload. Additionally, the perturbation of information can happen and obscure the main goal of the collaborative work, reducing its efficiency and so compromising the collaboration.

1.2.3 Communication in collaborative virtual environments

A collaborative virtual environment is first and foremost a virtual place wherein people work together on shared artifacts and datasets, and they can exchange information. Communication channels then become 'instruments' for communicating and negotiating with people in order to complete a collaborative task. Communication channels provide for a user a possibility of keeping in contact with other people, either by communicating in real time in synchronous CVEs or by leaving notes for others wherever they are needed. In a collaborative task, users need to negotiate shared understandings of task goals, of task decomposition and sub-task allocation, and of task progress. Therefore, it is important that users can be aware of what has been done and what is currently being done in order to obtain the goal of the collaborative task. In addition, the communication between users can be explicit (e.g., speaking, writing) and implicit (e.g., emotional expressions, gestures, postures, visual metaphors).

The more there are users who participate in a collaborative work, the more various is their peripheral infrastructure. Each user's site may be installed with auditory devices (e.g., headphones, speakers), visual apparatus (e.g., display screens, head-mounted dis-

plays, CAVE^TMs, handheld devices), and input devices (e.g., mouse, keyboard, joystick, flystick, motion detectors). In order to obtain an effective common communication channel, developers of CVE frameworks need to find a general representation of these peripheral devices as well as their limitations, so users can be aware of the difference of communication channels and can choose the right channel to use for communication. We will discuss in this section some major channels of communication and their capabilities and limitations to be used in CVEs. There are audio communication, embodiment and nonverbal communication, text and 3D annotation, and some visual metaphors using for communication and exchange information.

The MASSIVE system [BBFG94] is an example of collaborative virtual systems that supports interaction between users whose equipment has different capabilities. MASSIVE uses graphics embodiments, which have different representations: an audio user has ears, a non-immersive user has a single eye and a text user has the letter "T" embossed on his head (see figure 1.7). These simple visual metaphors allow a user to know how to communicate with others without wasting time to try each communication channel until finding one in common.
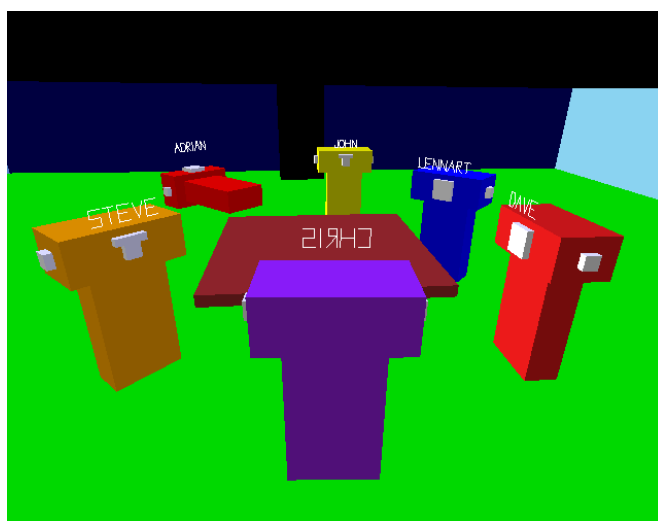

Figure 1.7 – Graphics embodiment of MASSIVE system represent different communication channels of each user in an collaborative virtual environment [BBFG94].

1.2.3.1 Audio communication

Talk is one of the first and most important means of communication in virtual world besides the visual channel [BPO96], especially for social meetings and teleconferences. But is talk solely enough for an effective communication in CVEs? What happens when there is a network delay that influences the quality of the audio channel? If network delays happen, silence in the audio channel could be interpreted differently by each user because of some confusion over whether the origin of the silence is a technical failure or simply the intended silence in talk [BPO96]. The simple approach to deal

with this problem is to add a visual channel and visual metaphors to cope with some problems of consistency in the audio communication of CVEs. This approach allows users to get informed about who is talking or when there is a turn-talking, especially in social meeting or educational applications where the number of users in a shared virtual world becomes important. The whiteboard, conference table, podium entities [BF93] are some typical visual metaphors, which allow users to organize the turn-talking, to get attention to the one who is talking as well as to determine who are listeners.

Audio communication becomes a fast and effective means of communication if it is combined with other communication means or with virtual representations. An avatar for each user with the capabilities of emotional expression and/or gestures and/or postures can be a valuable factor that helps users have a natural communication as it is in the real life. In addition, the audio media can improve the interactions in the virtual world. When the 3D audio signal is rendered according on the position of users in the virtual world by a tracking system, their feeling of presence and immersion in the environment becomes more real. This possibility of 3D audio rendering can be done locally and it depends on the apparatus of each user. Another advantage of the audio channel is that we can use this means not only to communicate to each other, but also to control or manipulate virtual elements or artifacts in the virtual world by using a speech recognition system. This advantage can change the user interfaces designs for CVEs deeply if the speech recognition system is efficient.

Another aspect that needs to be considered is to make the audio channel become a representation or an entity in CVEs. Until now, audio communications via Skype or telephone are normally used as complementary means of communication, and they do not truly become elements or factors in the virtual world that can affect other communication means or can be replaced by them when some problems happen. Therefore, the developers of CVE platforms mainly do not take into account the representation of the communication means. In [BPO96], the virtual representation of talk presence is a 'mouth', which opens when a user's speech exceeds a certain amplitude threshold. As far as we know, there is still no richer and more advantaged representation of audio media in the virtual world. So we can imagine that the different nuances in speaking could be dynamically and automatically interpreted in gestures or emotional expressions or even other visual metaphors so the one without audio channel can globally understand what others are talking about.

1.2.3.2 Embodiment and nonverbal communication

Natural human communication is based on speech, facial expressions, body postures and gestures. In order to obtain a virtual and yet still effectual and natural representation of users in the virtual world, humanoid embodiments or avatars are used as means to improve social interactions and communications in nonverbal aspect. Nonverbal communication signals include gaze, gestures and postures, facial expressions, touch, etc. as well as paralanguage cues such as variations in intonation and voice quality. These nonverbal cues help interlocutors express more feelings or thoughts through the use of their bodies [FMH99, GVCP$^+$99]. Moreover, besides improving the bodily

communication and the natural interaction, a visual embodiment is also used to self represent, to interact with the world and to experience various properties in it. According to [FMH99], the avatar can provide direct representation as well as feedback about the actions, the direction and degree of attention, and the interactive abilities of one specific user to the others at all times. By gaining the understanding and knowledge of their whereabouts and activities, users can develop a strong mutual awareness of the others.

However, Fabri et al. [FMH99] argue that the requirement for the rich representation of users in the virtual world does not necessarily imply the using of realistic avatar. The graphical representation of users in the DIVE system [BBFG94] is very simple and allows the system to detect the possible interactions between users by using the aura, focus and nimbus representations. This representation plays a role as a 'placeholder' of users in space so it does not require a complicated model. 'Blockie' models in the MASSIVE system [BPO96] are also simple because Bowers et al. only wanted to represent some simple gestures such as 'sleeping' state when the user it represents has left his/her machine, 'flapping ears' or 'opening mouth' when the user is listening or speaking. These gestures only inform about the presence or the actual action of the user and not about the emotional expressions or the other complicated behaviors.

In order to make the avatars become more realistically emotional, Guye et al. [GVCP+99] have proposed an interface of different built-in gestures, postures and expressions. The problem of this approach is that users need more time to choose the adequate emotional expressions by panel and this interferes with the continuity of actions in VE just for choosing the right expressions to use. This is also not a natural interaction in CVEs, specifically from the immersion perspective. On the contrary, in [BBL+04], a CVE can render a chosen subset of nonverbal behaviors, filter or amplify that subset of behaviors, or even render nonverbal ones that the user may not have performed. In order to obtain a complicated subset of nonverbal behaviors, nonverbal signals (e.g., eye gaze, facial gestures, body gestures) need to be tracked and then rendered via realistic avatars. The choice of using which kinds of avatar with all the possibilities to express the emotions and feelings is made based on the required social interaction levels in the CVE. However, gestures and postures don't need to be too complicated: for example the smiley icons on a chat messenger are simple but effective to express feelings without slowing down the system and the network transmission for complex graphical avatar and movements. However, if the interaction focuses on social behaviors, the complex graphical avatars can improve the sense of reality and immersion. Moreover, if the collaborative work focuses on 'task-focus' interaction or on a specific collaborative task, the feeling and emotional expression will become less important.

1.2.3.3   Visual metaphors

Visual metaphors for communication are the most important tools of CVEs. 3D virtual environments are first and foremost the world where different abstract or realistic data and models can be created and visualized. By using simple visual metaphors as direct

means of communication in CVEs, users can establish an implicit channel of communication that is easy understand. Visual metaphors also help users get an immediate and direct visual feedback. In addition, not only visual metaphors are used for communication purpose: changing parameters of objects or data in the environments such as color, position, orientation, scale, etc. also provides opportunities for users to express their actions and activities to others.

1.2.3.4   Text and 3D annotation

Although the importance of providing text input and annotation capabilities in virtual interfaces has been recognized, not many research work have been devoted to integrating and manipulating textual data in immersive VEs [BHMN95, HPRB96]. Text and 3D annotation can become powerful tools for communication in a CVE, especially for data visualization and collaborative analysis applications, if the ergonomics aspect for writing or taking notes is improved and if these tools do not degrade the immersion of users. Another advantage of text and 3D annotations is that they are easy to store offline so next time users can access to the same data. This aspect can facilitate asynchronous collaborations between distant users.

Ribarsky et al. [RBOdBvT94] studied how to use text to annotate graphic models in VEs. Notes might take the form of digitized speech or of written text, depending upon the user's needs and preferences. Some textual metaphors such as text or annotation that are texture-mapped onto the walls of a room or of the billboard can become a communication tool to represent information to many users at the same time like in a meeting room. In CVEs, these notes should exist in a visualization space and be directly associated with the part of the visualization to which they apply so the other users can see, access and modify them. Poupyrev et al. [PTW98] have proposed a collection of interface tools that allow users to take notes, annotate documents and input text using a pressured-sensitive graphics tablet, a pen and a handwriting recognition software while still immersed in VEs. This handwriting approach may become a new modality for interaction and communication in immersive CVEs. But using too much devices just for taking notes would 'spoil' the immersion of users and the flexibility of VR interfaces. However, with the development of hand-held devices, this tool can be integrated in a tablet or a smart-phone so users can use it as a supplementary device to explore and work in CVEs. Additionally, the complexity of input devices to produce text in the virtual world can be avoidable by using some graphic metaphors such as a 3D virtual paintbrush or a virtual pen controlled by normal input devices to draw and write without any constraints.

A virtual annotation system by voice input has also been studied as a possible method for the immersive input of text [PTW98]. Voice annotations are represented as a small marker attached to objects, and can be selected later for playback. However, a speech recognition application need to be used to recognize the audio input and then translate it into text for manipulation and editing purpose. This is the main reason why the voice annotations are easy to create but difficult to use.

Some problems arise when using text and 3D annotation in a virtual environment

concerning the limitations of display devices and the integration of text and annotations in the virtual world. A low resolution and a small field-of-view of head-mounted displays normally make it difficult for users to read text in the environment. In a CAVE^{TM}, the field-of-view of the users is expanded as well as the physical motion space. This is the reason why if the system wants to get users to notice the text and annotations in the environment, they need to be attached to the users' position or in their working area. So the integration of these elements need to be designed so they are not disturbing the visualization of users and yet not lost from their sight zone.

Besides the utilization of text and 3D annotations for annotating data, models in the virtual world as well as for communicating between users, synchronously or asynchronously, many CVE platforms integrate the text on menus or pop-up menus to provide for users more controls or options to choose. These menus normally float in the virtual world and can be visually customized if users have control over the level of detail in the visualization and over the kinds of tools employed. This customization process can help users limit graphical structure and means of interaction to retain immersion while still looking on details they think are important. But the problem with pop-up menus in a CVE is the access and display of these menus need to be local so participants do not access to the menus of others and vice versa. On the other hand, we need some metaphors to represent the actual action of selection and controlling over the menus of one participant to the others so they can know what is really going on, especially for the synchronous collaboration in the same shared space.

In conclusion, we have studied different means of communication, which CVEs normally support and exploit. Besides these kinds of communication means, there are still other communication media such as videoconferencing, tactile or haptic feedback, etc., which could help users send some intuitive and effective messages or feedback. In order to cope with the diversity in the peripheral infrastructures of different users' sites, CVE frameworks should at least support and integrate these different kinds of communication means into the system by different representations. The choice of which communication channel to be used would be automatically proposed by frameworks. This choice should be based on the common available means of communication at different interlocutors' sites. It also should be based on the range of communication: it is either a face-to-face communication or a situation where many interlocutors are involved in the same communication process. The problem of data overloading on the network due to the communication signals such as video or audio data might happen. In this case, an alternative communication channel would be proposed. Therefore, a communication manager in CVEs would be necessary for managing and recognizing these possible means of communication, for proposing an appropriate channel of communication for interlocutors without degrading their immersion and their workflow continuity.

1.2.4   Naturalness

Naturalness of a VR system is defined as the interaction fidelity and the objective degree with which the actions performed for a task in a VE correspond to the actions performed

for that task in the real world [BMR12]. Similarly, natural interaction techniques often mimic real world actions with a high level of fidelity. However, due to the constraints and limitations of VR systems such as intrusive display devices, limited interaction devices, the same level of naturalness could not be simply obtained by replicating the actions of the user in the real world into the virtual one.

From the dawn of the development of immersive 3D virtual environments, the idea of reusing and of integrating 2D interfaces into the 3D world has arrived naturally. The 2D interfaces, at first, provide a wide range options of input devices, e.g., keyboards, mice, and other pointing devices, going with various input events such as button press, motion or key press, for fundamental interaction techniques such as menus, icons, clicking, etc. These options offer many possible controls for a user to select, manipulate, navigate and change the state of the virtual world and the objects within it. Later, some applications with hybrid 2D/3D interfaces were conceived and have attained some successes. In the immersive object modeling application of Coninx et al. [CVRF97], 3D interaction techniques are used to make the design of 3D models more intuitive when designers are surrounded by the under-construction objects. In this case, the application makes use of the immersion of 3D VEs to provide another deep perspective for the designers. Nevertheless, they still need classical 2D tools such as menus, dialog boxes, widgets that are particularly helpful for precise manipulations and for editing operations. One of the drawbacks of this solution in integrating 2D / 3D interfaces together, in our opinion, is the disruption of the workflow of the designers, and also of their presence feeling within the virtual world decided by the immersion factor. In another words, the naturalness of the system may degrade because of the intervention of the 2D elements in the 3D world. Another example of integration of 2D interfaces into 3D VEs is to apply 2D metaphors in 3D interaction techniques. The image plane interaction technique [PFC$^+$97] uses 2D projection concept for selection, manipulation of 3D objects, and navigation in immersive VEs. A recognition system is used to identify the hand gestures of the user and then calculate the relative position of his fingers, his eyes's gaze and 3D objects. This calculation provides information to determine the objects to be selected and manipulated. Although using a 2D image-plane concept and so being limited to manipulate objects of various sizes or at a distance, this interaction technique appears natural and intuitive to users as the authors integrate the user' physical body, in this case his hands, as a part of the environment.

One of the naturalness criteria of 3D interaction techniques is that the user must be able to act and behave intuitively in the virtual world, as he would do in the real world. Due to this reason, using hand gestures is often considered in designing natural interaction techniques, especially manipulation techniques, because it is natural for the user to manipulate objects in the physical world using his hands. Moreover, two-handed interactions are also normally preferred over one-handed interaction [Wüt99]. Using two hands helps the user to determine where his hands are at any moment and so to know the distance between them if this factor can affect the interaction performance. However, natural two-handed manipulation have been proved imprecise in immersive VEs compared to supernatural manipulation because the user normally performs fast with two hands and thus imprecisely. The imprecision is also due to the lack of physical

support when the user is working in an immersive VE, making interaction suffer from hand jitter and maybe so-called *Heisenberg effect* - a phenomenon that happens when the user controls a tracked device, a discrete input such as button press event will often disturb the position of the tracker [BWCL01, MAL+10].

In a general approach, researchers try to use body movements and actions of the user to improve level of fidelity of interaction. In navigation tasks, many researchers have compared natural and non-natural navigation techniques and have found that real walking and physical turning might greatly improve spatial orientation and hence wayfinding tasks, thanks to the ability of understanding spatial relationships (e.g., [CGBL98, RKSB13]). Selection and manipulation techniques use virtual hand metaphor as a replica of the real hands to select and manipulate 3D objects directly [BKLP04]. The level of fidelity of the virtual hand metaphor mostly depends on its input devices (e.g., 6 DOF controllers, haptic gloves, Pinch gloves). The virtual hand metaphor using gloves with haptic feedback may make the user feel that he is manipulating objects using his real hands, hence making the human-system interface transparent. These empirical results indicate that natural interactions can offer greater performance and usability and stronger feel of presence for users than supernatural interaction techniques for some tasks.

Nevertheless, despite of unnatural interaction design, many techniques outperform other natural interaction techniques in navigation, selection and manipulation in immersive VEs. McMahan et al. [MAL+10] have evaluated natural interaction techniques in video games and have found that in the racing game Mario Kart Wii, natural techniques cause more errors than supernatural ones. The poor performance of natural techniques is explained because natural interaction often tries to integrate body movements and actions, making the user use large muscle groups and so reducing the speed and precise performance of interaction. Another reason is due to the latency between user input and system feedback, making the action and the perception space of the user not coincide. Therefore, in our opinion, system feedback such as visual feedback is an important factor to improve the involvement of the user in the environment, and thus to increase presence feeling and naturalness accordingly. For example, Figueiredo et al. [FBT93] have used a precise collision detection manager to represent natural behaviour of objects as feedback from the environment to the user, in a way to make him feel that he has a direct interaction with objects. Evaluations that can be found in [PWBI97] have concluded that, generally, supernatural techniques for selection and manipulation tasks obtain a better performance than natural techniques. However, Bowman et al. [BMR12] have argued that despite the poor performance of natural interaction techniques, their naturalness aspect might improve the user's feeling of presence in the virtual world, his understanding of his actions, and his ability to transfer actions he has learned back to the real world. Furthermore, the design of natural user interfaces needs to be considered in interaction fidelity perspective as well as in the context of interaction nature, input devices, and techniques to be used.

In summary, we have observed that in desktop environments, despite of abstract 2D interaction metaphors (e.g., menus, icons, buttons, windows, or desktop metaphors), and of all the limitations of 2D interfaces, users have learned how to use them naturally.

We believe that an important aspect of naturalness of interaction techniques is to improve their intuitiveness and ease of use and ease of understanding. By doing so, a compromise between naturalness requirement and limitations of technology could be found to be applied in interaction techniques that are understandable based on real-world experiences and coherent to the user's assumptions about their purpose. A VR system can make the user feel that he is a part of the virtual world and can be able to manipulate virtual objects directly. The success of a VR system depends on various factors, e.g., immersion, awareness, communication, interaction techniques, etc. and naturalness is only one of the criteria of this success. Due to this fact, naturalness factor sometimes is quite subjectively evaluated as the result of a combination between different factors beside the actual naturalness. Therefore, we need to study further the way to correctly evaluate if a VR system is natural or supernatural and how it influences the whole performance of the system.

1.3   Summary

We have detailed in this chapter an overview of some interaction techniques that have been developed to support collaborative navigation and manipulation in virtual environments. Achieving a well-designed CVE is determined by a smooth collaboration between multiple users even though they may be physically located in different places and be equipped with different devices. As a result, many factors such as awareness, negotiation and communication channels, naturalness, or level of immersion that each user experiences can greatly influence the efficiency and the performance of collaborative tasks. Considering these factors as crucial keys for developing an effective collaborative virtual system, we have identified the following guidelines for the design of collaborative interaction metaphors and techniques:

- Collaborative activities do not completely limit or restrain individual activities. The idea behind the collaboration between multiple users is that a user can get some help from others to do a work together faster and more efficiently. Accordingly, each user can engage in the collaborative task or go back to his own activities whenever he wants without losing awareness of others' activities.

- The system has to maintain awareness of each user about others, about virtual and physical environments, and about current collaborative activities. When working in a virtual environment, a user relies on his situation awareness about his surrounding (virtual and physical) environments, along with his knowledge and skills, to achieve his goals. In a collaborative context, the situation awareness knowledge has been extended to the information about others and about the current collaborative activities.

- The system has to maintain the consistency of the world in a collaborative work. If technical issues happen, the system needs to use some natural metaphors to make all the users aware of the current situation without disrupting their immersion and their workflow.

- Negotiation and communication channels provide for a user a possibility of keeping in contact with others. The negotiation and communication channels can be considered as complementary factors to the situation awareness information to establish a mutual understanding and a cognitive model between multiple users at any time.

- Natural interaction techniques are always appreciated but not obligatory. However, if the design of a CVE is user-centered, the naturalness factor of the CVE is mandatory.

- The design of different interfaces for multiple users needs to take into consideration the role each user is going to play in the whole collaborative scheme. The role of each user is decided not only based on his knowledge and skills but also based on the available apparatus system he is using.

Chapter 2

Enhancing natural collaborative navigation in immersive virtual environments

With the unlimited imagination of humans and useful tools for 3D modeling, many Collaborative Virtual Environments (CVEs) represent such a large space relative to the avatar size, hence navigation is mostly needed to discover virtual worlds and to work within them. How do we know where we are, where everything is in the environment around us, and how to get to particular objects or places? These questions need to be answered whenever we find ourselves in a new environment, a real or a virtual one. In 3D virtual environments, we have to learn from human behavior and human spatial abilities in navigation in the real world and find a way to apply this knowledge into virtual worlds.

Navigation is a fundamental and substantial task for all Virtual Reality (VR) applications as it is in the real world, even if it is not always the main task that a user needs to achieve in a Virtual Environment (VE) [BC07]. Navigation is often considered as a support to another task rather than the main task to complete in a virtual environment. That is the principal reason why navigation techniques, mostly travel techniques, must be simple and intuitive so they involve mainly unconscious cognition and reduce the distraction of the user from his primary task [BKLP04].

In a collaborative context, considering four important factors of an interaction technique, which are immersion, awareness, communication and naturalness, we propose in this chapter three collaborative navigation metaphors, so-called *guiding techniques*: drawing directional arrows, lighting up a path to follow, and orientating a compass to show a direction. These metaphors can be considered as navigation aids that are widely used in travel and navigation tasks and are intuitive, natural and easy to use. We propose using these metaphors as implicit interaction channels for nonverbal communication, simplifying the implementation of a complex module only for communication and information exchange. We have implemented a collaborative system using these three metaphors to achieve navigation tasks. As one of the main objectives of this re-

search is to improve the awareness of collaborators in immersive environments, we have also developed simple visual metaphors for a mutual awareness between collaborators as well as a situation awareness of the physical environment of immersed users. The result of this research has been published in [NFD12, DNF$^+$13, NDF13a, NDF13b].

In this chapter, some collaborative approaches in navigation will be briefly detailed in section 2.1. The three collaborative navigation metaphors will be presented in section 2.2. We will discuss the four considered factors of the design of the collaborative navigation metaphors and of the collaborative navigation system in general in the next section 2.3. An evaluation has been performed to evaluate and also compare the three metaphors in a specific collaborative task with two different roles: an exploring user in an immersive system and a helping user in a desktop system. The result of the evaluation will be presented in the end of this chapter.

2.1 Overview of collaborative navigation techniques

Navigation includes two main tasks: *travel* and *wayfinding*. Travel is simply getting from one point to another within an environment. In a multi-scale virtual environment, he can also change other viewing parameters such as Zoom Factor and Field of View [Han97]. Moreover, in the a collaborative virtual environment, the user could have a possibility of manipulating the viewpoint of others [Fle12] and by doing so, he could make them travel in the world, which is called *passive teleportation*. Travel tasks enable the user to control the position and orientation of his viewpoint [DP01, BKLP04]. Wayfinding tasks enable the user to build a cognitive map in which he can know his location within the environment and the relative location of other elements, and to continually update this map [JF97, DP01].

In the literature, many different techniques have been proposed for travel in VEs [SFC$^+$10, ZLB$^+$04]. By evaluating their effect on cognition, they suggest that for applications where problem solving is important, or where opportunity to train is minimal, then having a large tracked space, in which the user can physically walk around the virtual environment, provides benefits over common virtual travel techniques [ZLB$^+$04]. Indeed, physical walking is the most natural technique that supports intuitive travel and it can help the user to have more spare cognitive capacity to process and encode stimuli [SFC$^+$10]. However, the size of a virtual environment is usually larger than the amount of available walking space, even with big CAVE^{TM}s. As a result, alternative travel techniques have been developed to overcome this limitation such as walking-in-place, devices simulating walking, gaze-directed steering, pointing, or torso-directed steering. In the context of this paper, to get an efficient and simple way of traveling and to improve sense of presence in VE, we combine the physical walking technique to give exploring user (as much as possible) an intuitive travel by using a big CAVE^{TM} with head tracking for position and orientation, and a virtual travel to control the exploring user's position in the VE by using a flystick device.

Wayfinding tasks rely on the exploring user's cognitive map because he must find his way to move using this map. So if he lacks an accurate spatial knowledge about

the environment, the performance of navigation will be reduced [ETT07]. In such large-scale VEs, this problem becomes more serious. In addition, as with navigation in real environment, the exploring user has to navigate the VE many times before he can build a complete cognitive map about this environment, and he may not always want to spend so much effort and time on this task [BC07]. To deal with these problems, many solutions have been proposed such as navigation aids, guidelines that support the user to explore and gain spatial knowledge about VE, e.g., [Vin99, CB04]. Nevertheless, in 3D immersive environments, it is also difficult to give additional navigation aids without interfering with the immersion of the exploring user.

Although collaborative exploration of complex and large-scale VEs is not usually considered the main task to achieve in a collaborative VE, the wayfinding time of the exploring user can be considerably reduced by having the assistance from helping users who can have a global and complete view of the VE such as a bird's eye view. By proposing and evaluating new metaphors dedicated to 3D collaborative interactions, including collaborative exploration, the collaboration between distant users who are sharing a virtual environment can be improved.

Nowadays, common applications of virtual reality as well as of augmented reality support collaborative work: social or action games, scientific applications, etc. With a little help from other collaborators, the user can overcome the difficulty of getting lost in such large and complex virtual space. Collaboration can provide a powerful technique to support the exploring user to deal with lack of spatial knowledge in complex and large-scale VEs. Although Collaborative Virtual Environments (CVEs) have been developed to provide a framework of information sharing and communication [MZP+94, DDS+99, CSM01], collaborative navigation task in such environments has not been largely explored and only limited attention has been devoted to evaluate its efficiency in navigation in VEs.

In order to support collaborative navigation, there are some key features that a CVE should support, including shared context, awareness of others, negotiation and communication, flexible and multiple viewpoints [CSM01]. This is why Peterson et *al.* [PBD01] attempted to design an interface that would facilitate collaborative team navigation because of its benefits of navigation within a team. Many CVE frameworks such as NPS-Net, Dive, Massive, OpenMASK, Spin3D or Collaviz, provide such facilities to share the virtual environment between many users [DF11] By using the collaborative framework Collaviz[1], we can make use of this framework's facilities to share the virtual environment between many users [DDFF10, DF11].

It is essential for navigation in a CVE to support the way of communication between users because it is vital for them to understand what the others are referring to, to be aware of what's happening around them, and also to express their actions. Many developers used verbal conversation as means of communication to accomplish a given common task [HFH+98, YO02]. However, if the users are located in distinct physical domains, even in different countries, language difficulty becomes an obstacle for collaboration to a common goal. So the communication technique for collaboration,

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[1]www.collaviz.org

especially for navigation in CVEs, should be simple, intuitive, efficient and non-verbal. Based upon these points, our primary motive is to develop and to evaluate non-verbal guiding techniques enabling helping users to guide an exploring user toward target places in complex large-scale CVEs.

As navigation aids, some techniques have been proposed such as 'anchors' and a string of blue arrows that connects them or directional arrows [BRS+12], point light sources [CRS+12] or beacons [NWGM12, WBL+12]. Although they are powerful navigation aids, it is usually difficult to apply them for navigation in many kinds of environment. The environment of [BRS+12] is not flexible. It is difficult to modify the helping user's interface because his view and navigation aids are definitively specified. If the VE changes, the interface of the helping user can not be used any more and we have to design a new one.

So according to our best knowledge, there is no complete and evaluated solution to improve the performance, the flexibility, and the ease of use of collaborative navigation in such complex, large-scale CVEs.

2.2   New guiding techniques for collaborative navigation

Many navigation aids and metaphors have been proposed for an efficient navigation task in a collaborative context. Aiming for the same objective, our primary motive is to propose simple, intuitive, and natural interaction metaphors for the collaborative navigation task in immersive virtual environments. Furthermore, since the navigation task mostly involves unconscious activities of users in the world, navigation aids must be dynamic, 'light' in terms of implementation requirement, and may function under various contexts with different purposes if necessary. We would argue that although the three following guiding techniques in the form of navigation aids including arrows, light sources, and compass, may appear simple, they satisfy many requirements of an effective collaborative virtual environments. The navigation aids are presented in this section using a general collaborative navigation scenario in which there are two user with different roles. An exploring user is immersed in a large virtual environment. A helping user who has a global view of the virtual world with more information can help the exploring user to effortlessly navigate in the virtual world using the navigation aids.

2.2.1   Arrows

The first guiding technique is based on directional arrows (see figure 2.1) that are drawn by the helping user to indicate the direction or the path that the exploring user has to follow. The helping user can draw as many directional arrows of different sizes as they want. However, so many directional arrows added within the environment or too big arrows may affect the immersion of the exploring user. As a result, the helping user has to determine when, how and where to put directional arrows to guide efficiently the exploring user. These arrows will disappear after a while. So the helping user is recommended to draw directional arrows within easy reach of the exploring user's visibility zone. By using a dedicated 3D cursor to draw in the view of the helping user,
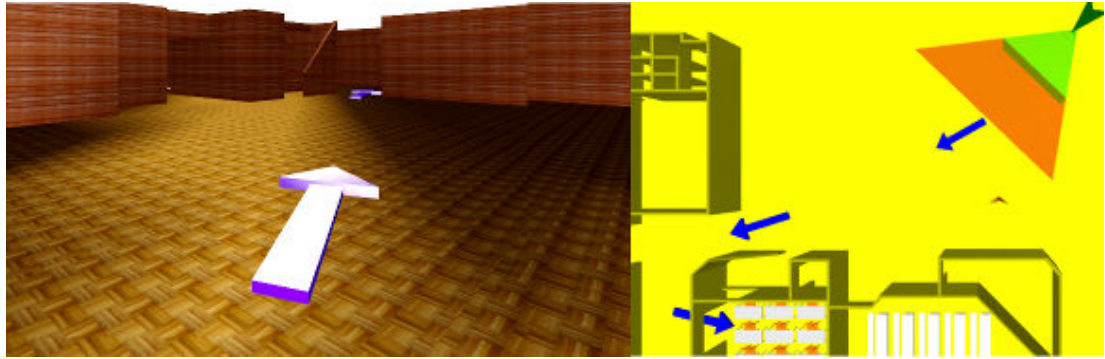
Figure 2.1 – Directional arrows in the exploring user's and the helping user's views.
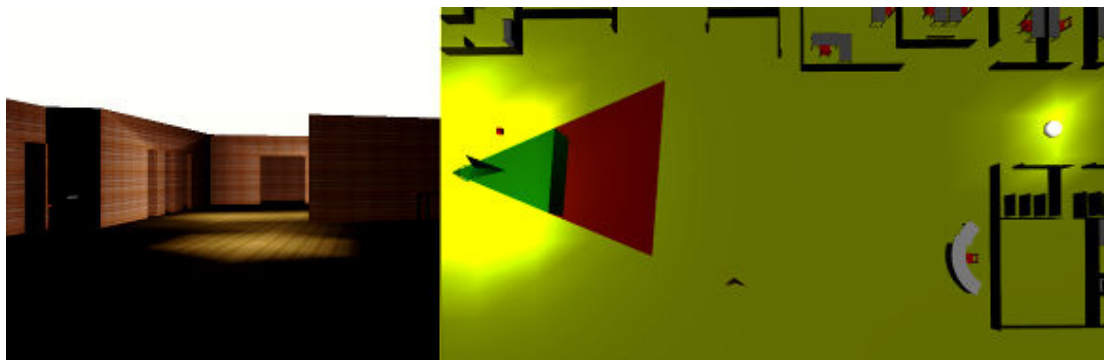

Figure 2.2 – Light source in the exploring user's and the helping user's views.

it improves the ease of use for the helping user and it makes possible to draw arrows at any height and in any 3D direction, so it can facilitate the exploration of multi-floor virtual buildings.

To draw these arrows, the helping user simply has to make a kind of 3D drag'n drop gesture. First he must place the 3D cursor at a position that will be the origin of the arrow, then he has to activate the cursor to create the arrow, and the next moves of the 3D cursor will change the length of the arrow, stretching the arrow between the origin of the arrow and the current position of the 3D cursor. When he estimates that the arrow has a good shape, he can signify to the 3D cursor that the stretching of the arrow is finished. This kind of gesture can be driven by any device that can provide a 3D position and can send events to the 3D cursor, for example an ART Flystick or simply a 2D mouse (with the wheel providing depth values).

From a technical point of view, this 3D cursor able to draw arrows can be brought to a CVE by the helping user when he joins the CVE, so there is nothing to change in the main structure of this CVE and its integrity is guaranteed.

2.2.2   Light source

The second guiding technique is based on a light source used to light up a path to each target object (see figure 2.2). The exploring user cannot see the light source itself but only its effect on objects within the environment. This technique thus depends a lot on the rendering and illumination quality of the exploring user's immersive view. The light source is attached to a support object that can only be seen by the helping user. This helping user controls the light source by moving its support with a 3D cursor and shows up to the exploring user the path he must follow.

It is important to note that when the helping user is using the light source to guide, the available light sources of the building are turned off and that the exploring user has himself a virtual lamp attached to his head to light up the environment around him. Then there are just two light sources, one associated to the exploring user's head and one used to guide him.

Here again, from a technical point of view, this 3D cursor, both the light source attached to the head of the exploring user and the light source used to guide him can be brought to the CVE by the helping user when he joins the CVE, so there are very few things to change in the main structure of the CVE: we just need to be able to put the lights of the CVE off.

2.2.3   Compass

The third guiding technique is based on a compass attached to the position of the exploring user (with an offset), a typical tool to navigate in VEs (see figure 2.3). The compass does not point directly to the target object location, but points to the location of another virtual object that plays the role of the 'north' of this compass, and this object cannot be seen by the exploring user. The helping user can control this 'north' by moving it with a 3D cursor, to show up to the exploring user the path he must follow. So by moving the 'north' of the compass, the helping user can guide the exploring user to pass across hallways, rooms, doors, etc. before reaching the target position. It is thus a simple and powerful tool to guide the exploring user in any VE.

Here again, from a technical point of view, this 3D cursor, both the compass attached to the position of the exploring user and the virtual object serving as the 'north' of the compass can be brought to the CVE by the helping user when he joins the CVE, so, as for the arrow-based guiding technique, there is nothing to change in the main structure of the CVE.

To place the compass at the best possible position relative to the exploring user, it is possible to allow the exploring user to adjust its offset, simply by moving the compass through a 3D interaction. However, this possibility was not offered to our exploring users during the experiment that is presented further in this chapter.
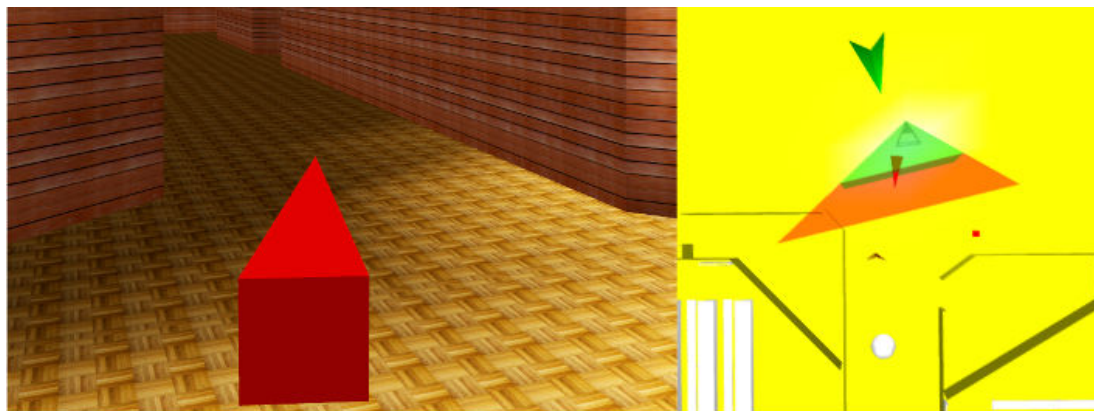
Figure 2.3 – Compass in the exploring user's and the helping user's views.
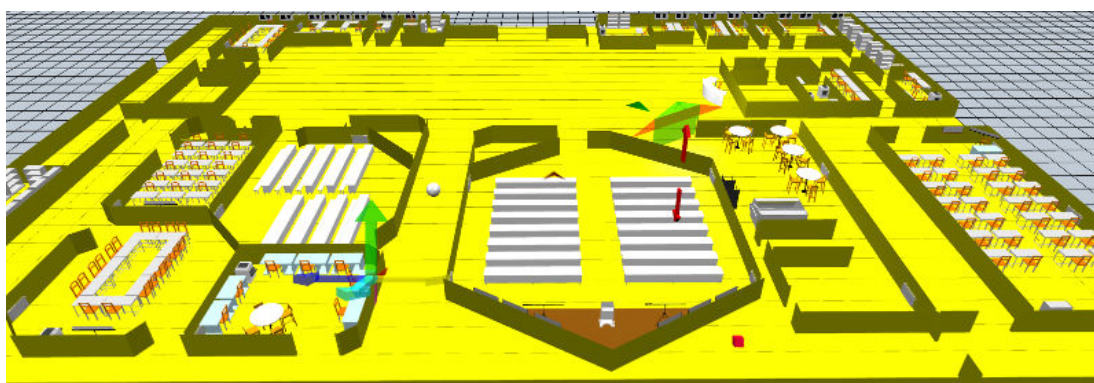

Figure 2.4 – The 3D virtual building from the bird's eye view of the helping user.

2.3 Improving awareness and communication using interaction metaphors in immersive VEs

We focus in section on the awareness and the communication requirements that our interaction metaphors can provide in order to obtain a high performance of collaborative activities between the two users. First, since a collaborative system needs to support different system infrastructures, we are interested in how to represent the limitations of the physical environment to the exploring user, especially when he is working in an immersive system. As in most of the virtual reality applications, the physical environment of a collaborative system must be integrated into the virtual one so the exploring user can be aware of their own interaction capabilities as well as of the others'. Duval et al. [DNF+13] states that the representation of physical devices can describe the spatial relationships between these physical devices and model the users' physical workspace associated to each device. A model for embedding the features of the physical world into the virtual world has been proposed in [FCD+10]. In this model, all the possible workspaces have been described including a motion workspace (the area where the ex-
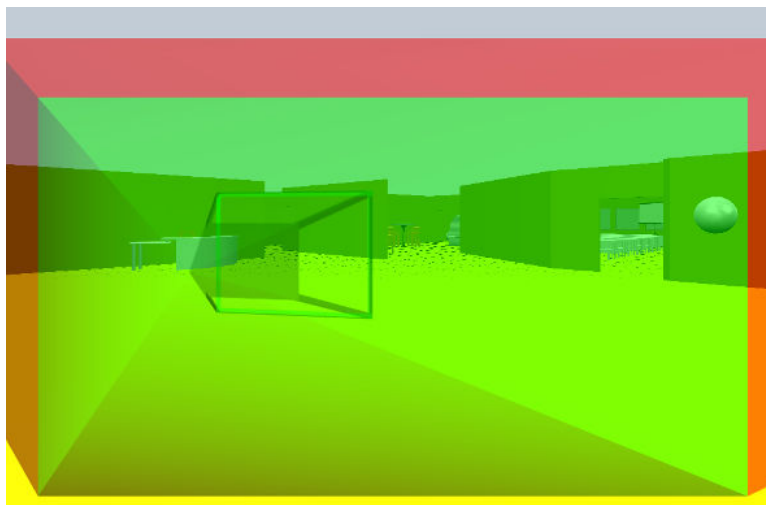
Figure 2.5 – A 'looking over the exploring user's shoulder' view of the helping user.

ploring user can move his body, e.g., in a tracking zone of a CAVE^{TM}, in a zone of maximum wire length of a HMD), a visual workspace (what the user can see through and around a display device), and an interaction workspace (the area where the user can interact by a controller or an input device). Even though these workspaces may not be always visible to users, they help the system developers to implement their collaborative framework without worrying about the changes it could make to the virtual world whenever there is a new physical device added to the system. These workspaces also help precisely define the parameters of physical devices so they can appear in the virtual world and become a part of it. We applied these workspaces into the physical representation of the immersive projection system at the user's site to enhance his awareness of the physical surroundings. In addition, this representation can prevent the collision between the user and the front display screen of the display system. In the tracking zone of a CAVE^{TM}, we have implemented the motion workspace of the user in order to warn him not to hit the real display screen. The system shows a 3D grid that becomes clearer and sharper when the user goes close to the display screen or his hand reaches out close to it as illustrated in figure 2.6. Another representation of this motion workspace to improve the awareness of the user is to darken the virtual world by gradually reducing its brightness intensity when he get closer to the screen (see figure 2.7). These metaphors intuitively represent the intervention of the physical environment in the interaction activities of the user and also its limitations. These metaphors are locally implemented and do not involve in collaborative tasks of distance collaborators. However, it is not complicated to integrate individual physical environments into the whole collaborative scheme, hence augmenting the awareness of each collaborator about the physical limitations of others.

The awareness about the activities of the exploring user and his whereabouts was simply implemented using two pyramids as illustrated in figure 2.8. The green pyramid represents the motion workspace within which the exploring user can naturally walk
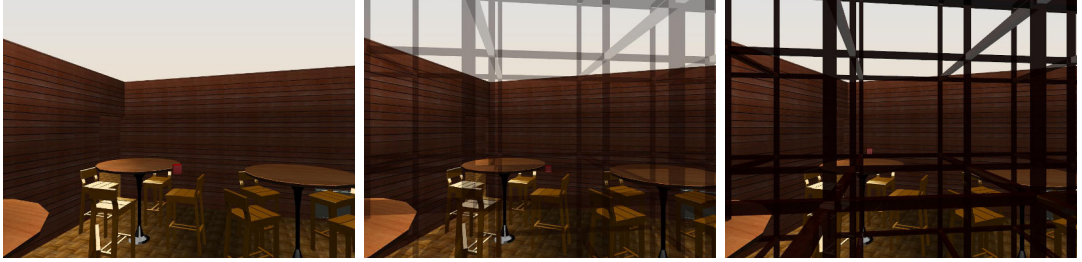
Figure 2.6 – Awareness of the physical environment by using a 3D grid.

Figure 2.7 – Awareness of the physical environment by changing the brightness intensity of the virtual world.

around. The red one shows his interaction workspace within which he can use an interaction tool to manipulate objects. These two workspaces can be seen in a 'god view' or a 'bird's eye view' of the helping user. Thanks to this global view of our multi-scale environment, the helping user knows the current activities of the exploring user and his limits zones at any time and can guide him accordingly in the virtual world. Due to the asymmetric role in the collaborative scenario, the exploring user, on the other hand, does not know the presence of the helping user unless the helping user performs a task, which leaves an effect on the virtual environment such as controlling the compass or moving the light source.

Besides the benefit of the navigation aids as an implicit use for communicating between the users, we also add some color signals as a communication mean for the exploring user or the helping one inform the other of his current state while working together. We use an orange signal for 'waiting' meaning, a red one for 'stopping', and a green one for 'going' meaning. The possibility of expressing a more complicated meaning is limited in this communication mean. Another drawback of this communication approach is that all the two users need to get a common understanding about the regulations or the meaning behind these visual metaphors before they start working together. However, in our opinion, in a simple navigation task, the communication channel does not need to be too complex.
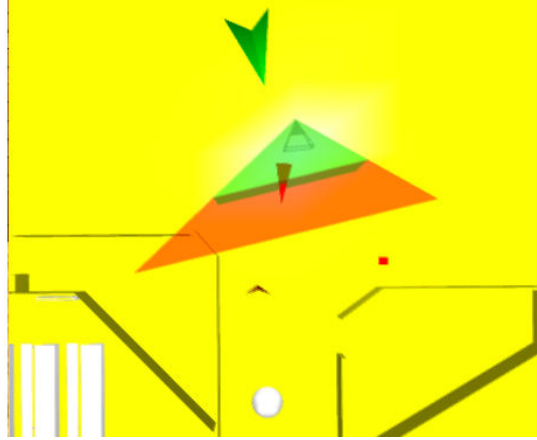
Figure 2.8 – Two pyramids representing the motion workspace and the interaction workspace of an user in an immersive virtual environment.

2.4   Evaluation of the three guiding techniques in a collaborative navigation task

For a complete study of the three navigation aids in a collaborative navigation task, we evaluate and compare these metaphors in a specific scenario in the Collaviz platform. The collaborative navigation task for the evaluation included two separate interfaces for a helping user and an exploring user who had to travel in an unfamiliar large 3D virtual building to find hidden target objects. We have implemented two different interfaces for the two asymmetric users: the exploring user was in an immersive virtual environment with a high level of immersion but less information about the large environment; and the helping user was working on a desktop computer with a low level of immersion but a high access to a global view of the environment with much more detail within it.

2.4.1   Experimental setup

In order to improve the awareness of the helping user about the exploring user, we implemented two principal kinds of views for our helping user: a bird's eye view (see figure 2.4) and a first-person perspective by 'looking over the exploring user's shoulder' (just like a camera attached to the shoulder of the exploring user) (see figure 2.5). By using this technique, the helping user can observe and know what the exploring user is actually doing and can predict his actions and activities. This technique is very useful to improve the awareness of actions and activities for collaborative tasks in large CVEs. The bird's eye view could be considered as a 3D map or a World-In-Miniature [SCP95a]. These views were obtained by choosing some particular points of view: the 'looking over the exploring user's shoulder' view was attached to the point of view of the exploring user and the bird's eye view was obtained by increasing the helping user's scale. Both views were built without any changes to the main structure of the VE, with the same concerns: to guarantee the integrity of the VE, and to offer the possibility to be used

Figure 2.9 – First-person perspective of the exploring user in a CAVE$^{\text{TM}}$.

for any kind of VE.

In order to test these three different navigation aids, we have built a complex, large virtual building (about 2500 m^2) with hallways and many rooms of different sizes filled with furniture objects (e.g., tables, chairs, shelves). These objects were repeatedly used to fill these rooms. It means that each object itself could not be taken as a landmark, and only the way that each room was arranged made it distinct from the others in the building. Besides, the position of objects did not change during the experiment. We used this environment to conduct all the studies described in this paper, with different views from several positions in the VE for a helping user to observe all activities of an exploring user in the immersive system.

The exploring user was immersed in the VE with a first-person perspective (see figure 2.9). He was controlling a flystick to travel in the virtual world and as his head was tracked in a CAVE$^{\text{TM}}$, he was able to move physically to observe objects more carefully in the environment. He was also able to move forward or backward, and to turn right or left by using the joystick of the flystick. The direction of movement by the joystick was where he was looking at. He used some specific buttons of the flystick to pick up target objects or to return to a starting position.

Our system would have made it possible for several helping users to collaborate at the same time with an exploring user. However, in order to simplify the evaluation, there was only one helping user during this experiment for all the exploring users and it was me who played this role. I was in charge of providing the navigation aids always in the same way for each exploring user because I had a good knowledge of the apparition order and positions of targets. I was also the designer of the guiding techniques and was strongly involved in their implementation, their deployment and their testing. So my performance was stable when guiding each exploring user, as I had already improved my skills during the tuning of the experimental setup.

In general, for interaction, the helping user had a 3D cursor to manipulate objects

within the VE, to add navigation aids such as directional arrows, or to control the light source or the 'north' of the compass. The helping user was also able to control the position and orientation of his own viewpoint as well as to change his own scale in the view. It means that he was able to become bigger to have an overall view of the building, or smaller to take a look inside each room to locate the target (but he was not allowed to pick up the target by himself). He was also able to see where was the exploring user at every moment. The interface of the helping user was pure in 3D, although in our experiment he was using a desktop environment. Nevertheless, it would be possible and perfectly adequate for the helping user to use an immersive display system.

In order to locate the next target that the exploring user had to find, the helping user was allowed to move a 3D clipping plane to make a 3D scan of the VE. This scanning tool was also brought into the VE by the helping user. It was generic and as the three guiding techniques that are evaluated in this paper, it guaranteed the integrity of the VE.

The helping user was able to send signals (in our experiment, they were color signals) to the exploring user to inform him about his situation. When the helping user was searching the target object on the map and the exploring user had to wait until the helping user found it, the helping user could send an orange signal. When the exploring user was entering the right room or was following the right way, the helping user could send a green signal. Last, when the exploring user was taking the wrong way, the helping user could send a red signal. These signals could become a communication channel between the users performing a collaborative task.

The hardware setup of the experiment consisted of a big CAVE^{TM} in the shape of an 'L' whose size was 9.60 meters long, 3.10 meters high and 2.88 meters deep. This visual system immersed exploring users in a high-quality visual world and they were using a pair of active shutter glasses. We also used a tracking system to locate the position and the orientation of the exploring user's head. To enable exploring users to manipulate objects in such an environment, we used a tracked flystick as an input device. The helping user worked with a desktop workstation and used a mouse to drive a 3D cursor.

The software setup used for the experiment included Java to write the CVE, Java3D to develop the helping user's views on desktop, jReality to develop the immersive view of the exploring user, and Blender to model the virtual environment.

2.4.2   Task

Task to achieve

Each exploring user of this experiment had to find 12 different positions of target objects represented by small glowing cubes. When the exploring user was picking up the target object, this target was disappearing and a color signal was appearing to tell both users that the target had been reached and that the system had stopped measuring time. Then the exploring user was invited to go back to the starting position for the search

of the next target. By pressing a dedicated button of his flystick, he was teleported back to this starting position. And when both the exploring and the helping user were ready, the target object was reappearing at another position in the environment. During the experiment, each guiding technique was used successively 4 times to find 4 target positions. There was a total of 12 different positions for the three guiding techniques. The 12 targets were always appearing in the same order, and the order of the techniques used for the guiding (A: Arrows, L: Light, C: Compass) was changing after each user, to be one of these 6 configurations: A-L-C, A-C-L, L-A-C, L-C-A, C-A-L, C-L-A. So we were needing a number of subjects that would be multiple of 6 in order to encounter the same number of these 6 configurations.

Measures

In order to evaluate how the three guiding techniques have influenced the efficiency of navigation, we did not count the time it took the helping user to find where was the target position on the map. We just considered the time it took the exploring user to complete the target search task. It included two separate but continuous tasks: a navigation task and a search task. The navigation task was based on the navigation aids added in the environment to find a path from the starting position to the target position. The starting position was always the same for all the target objects and for all the subjects of the experiment. So, for each target, the exploring user moved always from the same starting point and the system measured the time taken to reach the target object. This time was thus measured into the navigation time and the search time. The navigation time was the time taken to navigate from the starting position to the area of 2.5 meters around the target and the search time was the time to search and pick up the target in this area. We used this approach to calculate the time because sometimes the target object was well hidden in the environment, so the exploring user was not able to find it at first glance, and we wanted to make a clear difference between the time taken for the navigation (coming not farther than 2.5 meters from the target) and the time taken for the precise searching and finding of the target. Once the exploring user had entered this zone, the search time was recorded. However, the navigation time was specifically taken into consideration because it was directly representing the performance of navigation aids. The search time was also recorded in order to obtain preliminary data for further studies about efficient and appropriate metaphors for the searching task.

Hypothesis

Our hypotheses predicted that there was no performance differences among the three guiding techniques to help exploring users to navigate in the virtual building. Our assumption was based on the fact that all three guiding techniques provide navigation aids with similar information to indicate directions. For the finding task, we expected users to perform better with the compass than the other aids because it could provide exactly the position of targets.

2.4.3 Subjects

In this study, the designer of the virtual environment played the role of the guiding user. Additionally, there were 18 male and 6 female subjects who served as exploring users. Their age ranged from 21 to 61, averaging at 30.5. There were 13 of them (8 males and 5 females) who had no experience at all in immersive navigation in 3D virtual environments.

2.4.4 Procedure

Before beginning the training phase of the experiment, each subject was verbally instructed about the experiment procedure, the virtual environment and the control devices. He was explained the goal of the experiment to search a target object at different positions by following the navigation aids added in the environment. He was also instructed to pay attention to find the target carefully when he reached the narrow zone around the target because it was not always easy to find it at first glance.

In the training phase, the subject was suggested to navigate freely in the virtual building. When he was feeling at ease with the environment and the control devices, we were beginning the training phase. The subject was given a simple task to complete: he was asked to find his way from a starting point (the entrance of the building) to some target positions with our three different guiding techniques.

In the evaluation phase, the subject was asked to search 12 target positions in the environment by basing on three different guiding techniques.

In the final phase, the subject filled out a short subjective questionnaire concerning his experience of navigating in immersive virtual environments and his opinion about the guiding in general, his preferences for the perturbation, stress, fatigue, intuitiveness, and efficiency of each guiding technique.

2.4.5 Result

Navigation Performance

We focused on the efficiency of the three different guiding techniques when we applied them in the navigation task. So the navigation time was considered as an important measure in this statistical analysis. *P* values of average navigation time of the three techniques were calculated using repeated measures ANOVA and post hoc multiple pairwise comparison (Tukey-Kramer post hoc analysis).

The average navigation time, the average search time and their standard deviations are presented in figure 2.10. For the recorded navigation time, the result revealed a statistically significant difference for the three navigation aids ($F_{(2,285)} = 3.67$, $p = 0.026$). In addition, the Tukey-Kramer post hoc analysis indicated that navigation time in the Light condition (mean = 27.26) was significantly higher than navigation time in the Arrows condition (mean = 22.99) ($p = 0.05$) and Compass condition (mean = 22.97) ($p = 0.05$), while there was no significant difference between Arrows and Compass conditions ($p = 0.99$).
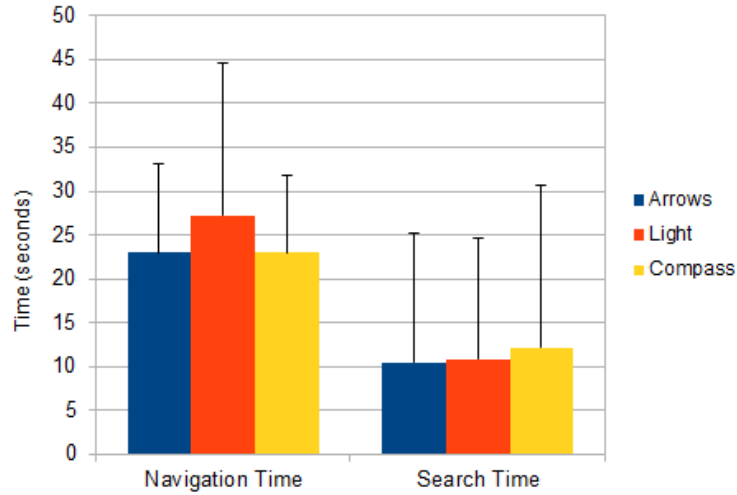
Figure 2.10 – Means and standard deviations of navigation and search time (in seconds) for three guiding techniques.

However, based on the preliminary results of search time, we did not find out about any significant effect of guiding techniques on the recorded search time: for the three guiding techniques ($F(2,285) = 0.29$, $p = 0.74$) as well as for each condition. These results indicated that the effect of the guiding techniques for search time was not statistically significant but this must be confirmed by further studies.

Subjective Estimation

Each user was asked to fill a questionnaire with subjective ratings (using a 7-point Likert scale) for the three techniques according to the following criteria: perturbation, stress, fatigue, intuitiveness, and efficiency. A Friedman test has been performed on the questionnaire and the p-values were showed in table 2.1. Dunn post-hoc analysis showed that the light was rated to be significantly more perturbing, more tiring, and less intuitive and less efficient than the arrows and the compass guiding techniques. Moreover, no significant differences were found between the arrows and the compass guiding techniques on these five subjective ratings. Regarding the subjects' general preference, we found most exploring users preferred to be guided by arrows or by the compass.

2.4.6 Discussion

The results of the navigation performance study showed that the directional arrows and the compass outperformed the light source in navigation task. The low performance of the light source came from the lack of accuracy of light effect on the environment. It might come from the confusion between the guiding light source and the light source

Table 2.1 – Average scores and p-values for five qualitative measures with significant differences shown in bold.

Question	Navigation Aids		
	Arrows	Light	Compass
Perturbation	6.17	4.58	5.67
	p = 0.00054		
Stress	6.29	5.46	6.54
	p = 0.01063		
Fatigue	6.08	4.87	6.41
	p = 0.00011		
Intuitiveness	6.17	4.54	6.20
	p = 0.00010		
Efficiency	5.87	4.46	6.16
	p = 0.00002		

that the exploring user had with him when he was approaching the guiding light source. The light source was also too sensitive to the elements of the environment such as the quality of 3D model of the environment or the rendering and illumination quality of the immersive view as mentioned above. However, we found out that the confusion between the light source to guide and the light source of the exploring user rather affected the search task than the exploration task because this confusion usually happened in a small space such as in a room when the exploring user was surrounded by many different objects.

There were no significant differences among the three guiding techniques in the search task. It can be explained because some of the targets were very easy to find (the exploring user was able to see them as soon as he entered the room where the target was hiding) while some others were very difficult to find (hidden within some furniture in a room). So the final physical approach to the target did not really depend on the navigation aids but rather on the ability of the exploring user to move physically in his surrounding workspace. Further experiments will be needed to have a better evaluation of these guiding techniques for precise search of target.

The subjective results supported the results of navigation performance study in evaluating the efficiency of the arrows and compass aids in collaborative navigation. Most of the subjects found them more intuitive, easy to follow, and efficient to indicate direction than the light source. However, some exploring users found the light source more natural than the other guiding techniques, especially when they were in a big hall or in a long hallway.

Sometimes, in small rooms, not only the light source made the exploring users confused, but also the compass or the directional arrows because they were occluded by the VE (for example, by walls). And for the search task, an exploring user of our experiment found that the compass was a little annoying and confusing when it was near the target because its 'north' was unstable. So some factors such as the quality of

the 3D rendering, the structure of the virtual building, and the size of navigation aids could have a deep impact on navigation and search performances. We need to take them into consideration to improve the performance of collaborative exploration.

The activity of the helping user could also explain some differences between the guiding techniques. Indeed, to guide an exploring user using directional arrows, he simply had to use about 4 or 5 arrows to draw the direction toward each target. With the compass, he just had to put the support object that controlled the compass 'north' at the entrance of the hallway or the room where he wanted the exploring user to enter to and then put it near the target when the exploring user approached it. It was more complicated with the light source because of the confusion between the two light sources. The helping user had to move the light source or make it flicker to get the intention of the exploring user. He also had to choose where to put the light source to make a clear difference between the effect of this guiding light source and those of its own light source in the environment.

Our VR framework enables a helping user to use these guiding techniques in many different platforms: he can be immersed in a CAVE^{TM} with a tracking system or simply be in front of a desktop computer with a mouse. This can facilitate the flexibility of collaborative exploration between distant users who have different working conditions.

2.5 Conclusion

We have presented a set of three collaborative guiding techniques (directional arrows, light source and compass) that enable one or several helping user(s) to guide an exploring user in a complex 3D CVE. In our study, we have evaluated these guiding techniques in the collaborative context with an exploring user and only one helping user. These collaborative guiding techniques can be used in many kinds of 3D CVEs because they do not modify the structure of the environment. Indeed, all the guiding aids are dynamically provided by the helping user through the creation or the manipulation of few dedicated 3D objects that the helping user can bring with him when he joins the CVE. The helping user can also bring with them a generic 3D clipping plane to make a 3D scan of the VE to locate the targets or the places to reach.

An experimental study was conducted to evaluate these three types of guiding techniques for navigation and search in a complex, large-scale building. The results of our experiment showed that these three guiding techniques could reduce wasted time in the wayfinding task because of their simplicity, intuitiveness and efficiency in navigation. Additionally, although the directional arrows and the compass outperformed the light source for the navigation task, several exploring users found the light source guiding technique very natural, and it can probably be combined with the two other guiding techniques.

Considering the naturalness criterion of this research, we have used the navigation aids that are simple, typical, intuitive and natural as ones used in the real world. Due to this characteristic, most of the subjects took part in our experiment as exploring users found the guiding given by the helping user useful and effective. Furthermore,

the navigation aids also carry multiple purposes in the collaborative context when they are used at the same time as a mean to show direction for navigation and a 'channel' used to implicitly communicate between collaborators and to raise the awareness of the exploring user about the helping user. In addition, since the experiment took place in a big CAVE^{TM} for the exploring user in parallel with a desktop system for the helping user, the interaction metaphors also took into account the different levels of immersion of the exploring user and the helping user. Our system provides for the exploring user an early-warning metaphor used to prevent collision between the exploring user and the display system when he is immersed in the virtual world and cannot notice the borders of the physical surroundings with the virtual one.

We have only implemented two asymmetric roles in the collaborative scenario in which the exploring user is immersed in the CAVE^{TM} and the helping user is working in front of a desktop computer. So the interaction tools as well as the manipulation techniques for the two users have been designed considering the difference in principle of the interaction metaphors in immersive and non-immersive environments. In the future, it would be interesting to evaluate the ease of use, the simplicity and the efficiency of our navigation aids from the helping user's point of view when he is immersed in the virtual world himself. In order to perform this evaluation, some appropriate interaction metaphors need to be developed for the helping user working in the immersive environment. Additionally, we also want to study and develop a natural manipulation technique that is more relevant and appropriate to the working conditions that immersive virtual environments normally provide. We will present the result of this research in chapter 3.

Chapter 3

Enhancing direct manipulation in immersive virtual environments

Object manipulation is one of the most essential and important interaction in Virtual Reality (VR). Proposing efficient, easy to use and to integrate, flexible and reusable manipulation techniques has been broadly studied over the past few decades. Due to this reason, the efficiency, the usability, the flexibility and the capability of being used in different manipulation scenarios and being integrated in many VR systems are the most important criteria to evaluate the performance of a 3D manipulation technique.

In this chapter, we focus on direct three dimensions (3D) manipulation technique in immersive virtual environments (VEs). One difficulty working in an immersive virtual environment is to precisely control input devices for accurate work in 3D. The imprecision often caused by hand jitter and *Heisenberg effect* when human beings have difficulties in keeping the hand motionless in a particular position without the help of external devices. A manipulation task for large objects in immersive environment is particularly difficult because of the obstruction of a user's view caused by the objects' large size and of other objects (if there are many) in the same scene during the manipulation [BH97]. Therefore, if the high degree of accuracy is required in a large-object manipulation task in an immersive virtual environment, the manipulation technique needs to be flexible but still efficient at the same time and its design needs to take into account the immersion factor of the manipulation. Solutions can be provided to overcome this issue by constraining the degree of freedom according to the manipulation task [CVRF97].

To address this issue, we propose a 3D manipulation technique, called *7-Handle* technique, based on seven points attached to an object to be manipulated. This technique enables a user to adapt the set of seven points to objects of different sizes and shapes, and to many kinds of manipulation scenarios. We also propose three control modes for the seven handles (including configuring, manipulating, and locking / unlocking modes), which enable the user to lock some parts of the object, an advantage for him when working in an immersive 3D environment. In addition, the principle of this technique enables many users to cooperate the object at the same time. Due to

this reason, it is possible to use this direct manipulation technique in a cooperative manipulation task.

In this chapter, we will first recall some features of the 3D manipulation techniques that are commonly used for object manipulation, especially in immersive virtual environments. In section 3.2, our 7-Handle technique will be extensively detailed. Considering the objective of this research is to study the immersion, naturalness, awareness and communication factors in 3D interaction techniques, section 3.3 will clarify how our manipulation technique copes with these criteria. In the end of this chapter, an experiment whose aim is to evaluate the performance and the ease of use of the 7-Handle technique and the 6 degrees of freedom (DOF) technique for accurate object manipulation in an immersive virtual environment will be presented. The 7-Handle technique as well as the result of this study are published in [NDP14b] and have been demonstrated during the ICAT-EGVE[1] conference [NDP14a] in 2014.

3.1 Overview of direct manipulation techniques

In the literature, traditional 2D toolkit-based interfaces have been extended in many 3D applications [Bie87, Bie90, CMS88]. 3D widgets [CSH$^+$92], especially 3D transformation widgets [Bie87], are one of the most widely used manipulation tools in many Virtual Reality (VR) systems. Most 3D transformation widgets have simple behaviors and few Degrees of Freedom (DOF) to control 3D objects movements. This is due to the fact that while a user would like to be able to use several DOF simultaneously like he usually does in the real world, using too many DOF may make the widgets too difficult to control. Although these widgets may help the user to manipulate objects more accurately in desktop VEs, so far their efficiency in immersive Virtual Environments (VEs) has not been well justified. Besides, the transformation widgets are dedicatedly designed for mouse-and-keyboard-based systems where the user benefits from accurate pointing and direct access to numerous buttons and keyboard shortcuts. Therefore, these metaphors may not be compatible and efficient in immersive VEs where the user uses specific input devices, e.g. flysticks, tracked hands, etc., with limited control options. Furthermore, the manipulation accuracy might be reduced because the user has difficulties in accurately pointing and moving his hands in immersive VEs.

Some other approaches [BH97, PSP99, PBW96, SCP95a] have been proposed to manipulate objects at a distance by creating their miniature models or by expanding the user's virtual arm. These propositions have an advantage for large-object manipulation scenarios: when the user has an overall view of objects or of the whole environment, it is easier for him to know how to move these objects to a particular position and orientation without worrying about obstruction issues. However, one main issue of these approaches is that small movements of the miniature models or of the user's virtual hand from a distance are often magnified in the environment, making accurate positioning difficult. It may be difficult to find a reasonable distance at which the size of objects is not too disturbing and the user can still determine their position. An issue

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[1]http://icategve14.uni-bremen.de/

of the HOMER technique [BH97] is that manipulated objects are taken out of their context: sometimes, it becomes less efficient when the user needs to move an object to a particular position relative to its neighbors.

In order to manipulate objects more accurately and efficiently, PRISM [FK05] has proposed a dynamical adjustment method for the 'control/display' ratio. This ratio determines the relationship between physical hand movements and the movement of manipulated objects, making it less sensitive to the user's hand movements. Switching between precise and direct mode occurs during natural interaction according to the current velocity of the user's hand. Nevertheless, sometimes the user may feel a sense of incompatibility caused by the difference between visual feedback and motor control when the precise mode is active. Osawa [Osa08] has proposed a manipulation technique using two hands (one hand is used for positioning and releasing, and the other hand is used for adjustment control). This technique adds a viewpoint adjustment phase to enlarge the scene when the hand grasping the virtual object is moving slowly. Nevertheless, this adjustment may influence the user's immersion and it may cause fatigue when he manipulates large objects. Additionally, there is no orientation manipulation in this technique, meaning that it is incomplete for an object manipulation technique proposition in general. A rotation adjustment method [OA10] has been proposed later to improve this drawback. The authors separate the object manipulation in three distinct phases: precise position, precise rotation and precise release. But in reality, these three phases should be mixed because it becomes less natural for the user if they are separated. Besides, the difficulty for the user to keep his hands motionless in a particular position in immersive VEs might cause imprecision in the rotation adjustment. In brief, these approaches may be suitable for precise manipulation but the obstruction issue caused by large objects remains unsolved.

Several bi-manual 3D interaction techniques have been proposed to manipulate virtual objects with the two hands of a user [HPPK98]. But only a few of them, such as 'grab-and-carry', 'grab-and-twirl' and 'trackball' techniques [CFH97], enable the user to move and rotate virtual objects. The 'grab-and-carry' technique [CFH97] is a 5-DOF bi-manual symmetric tool that enables the user to carry and turn an object around its center with both hands. Object roll is not supported in this technique because it is not possible to determine rotation around the axis formed by the user's two hands. The 'grab-and-twirl' technique extends the 'grab-and-carry' technique, adding the sixth DOF using either the left hand's roll, the right hand's roll, or a combination of both. The 'trackball' technique is a bi-manual asymmetric tool that enables the user to use the non-dominant hand to move a virtual object while using the dominant hand to rotate this object around its center.

The 3-hand manipulation technique of [ADL09, FDGS12] is more generic and does not need additional aids. This technique determines the position and orientation of virtual objects through the position of three non-aligned manipulation points on a plane. However, this technique is mainly devoted to multi-user collaborative manipulation and it is quite difficult for one user to manipulate objects, unless if it is used with a Reconfigurable Tangible Device [ADL11] called RTD-3. In this last case, the size of the virtual triangle formed by the three manipulation points is limited by the maximal

size of the RTD-3 and it could become less suitable for manipulating large objects.

While there are many propositions of manipulation techniques in the literature, the most used technique is 6-DOF direct manipulation because the others may not be generic, flexible, reusable enough in varying manipulation scenarios and easily integrated in different VR systems. Therefore, we propose the 7-Handle technique, a new manipulation technique that is generic, flexible so the user can choose to adapt this tool to different kinds of manipulation scenarios.

3.2   The 7-Handle technique

The 7-Handle technique consists of seven points attached to the manipulated object. As illustrated in figure 3.1, the three points F_1, F_2 and F_3, called *first-level* handles, are the three vertices of a triangle. The three points S_1, S_2 and S_3, called *second-level* handles, are initially positioned at the midpoints of the three sides of the triangle. Each second-level handle is used to control its two adjacent first-level handles. The combination of one second-level handle and its opposite first-level handle enables a user to control all the three first-level handles at the same time. The last point T, called *third-level* handle, is initially positioned at the centroid of the three first-level handles. The third-level handle can be used as a direct manipulation tool with 6 DOF and is mostly useful in approach phases where the accuracy degree of the manipulation is not predominant.
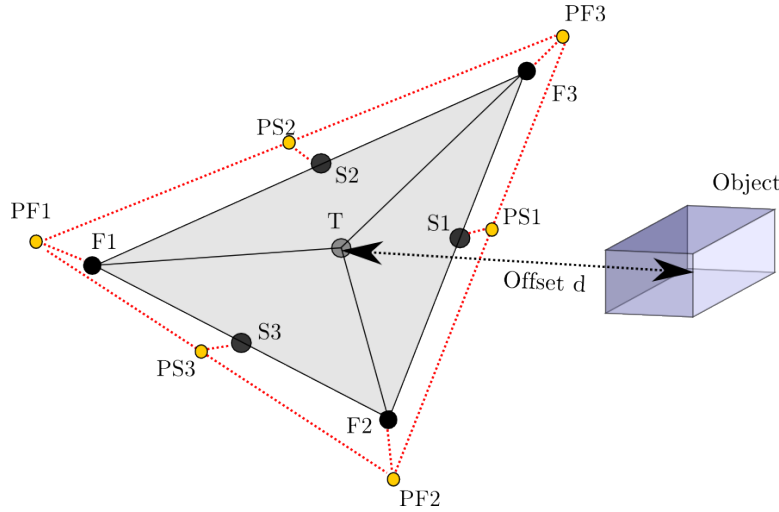

Figure 3.1 – The 7-Handle tool includes three first-level handles F_1, F_2, F_3; three second-level handles S_1, S_2, S_3; a third-level handle T; and six proxy points PF_1, PF_2, PF_3, PS_1, PS_2 and PS_3 of the three first-level and three second-level handles, respectively. The manipulated object is placed at a distance d from the centroid of the 7-Handle tool.

The manipulated object can be positioned from the 7-Handle tool with an offset

distance d, the distance from the barycenter of the object to the centroid of the three first-level handles or to the third-level handle. This offset distance will be used to compute the motion of the object according to the motion of the 7-Handle tool. Most of the time, the motion of the object imitates exactly the motion of the 7-Handle tool. Nevertheless, depending on the offset distance d between the object and the 7-Handle tool, the rotation center of the object may differ from the rotation center of the 7-Handle tool and therefore, the final position of the object is computed by the motion of the 7-Handle tool plus the offset between them. By using the seven handles that have different roles in manipulation tasks and by smoothly coordinating these handles, our technique can improve the accurate manipulation of objects in immersive environments, especially when the user has difficulty in holding his hand motionless in space. Additionally, we separated the handles (as parts of an interaction tool) from the controlled object (as an *interactive object*) [ADA09]. This separation makes our technique more generic, abstract and flexible to manipulate objects in VEs. Due to this feature, we could extend this technique by adding more handles with different roles to control one object, or enable the user to control a group of objects with only one set of seven handles.

In order to improve the usability of our technique, we integrated some visual informative feedback about the state of each handle to inform the user about its availability, its behavior and its functionality. Each handle can be in one of three different states. The first one is the active state when the handle is available and can be grabbed by an interaction tool. The handle is green when it is available and turns bright green when it is grabbed. The second is the inactive state when the handle is controlled or manipulated by other handles. Its position and orientation are computed according to its relation with the other handles to make sure that the shape of the tool does not change during the manipulation task. When a handle is in the inactive state, it appears in a semi-transparent red color and it cannot be grabbed by an interaction tool. The last one is the locked state: the handle is pinned at one place and it cannot be moved unless the user unlocks it. A locked handle is in blue.

We propose three different control modes for the 7-Handle tool, especially for the three first-level handles, including configuring, manipulating, and locking / unlocking modes. The configuring mode aims at making the 7-Handle tool more flexible and efficient to manipulate objects of different sizes and shapes by changing the position of each handle relatively to the manipulated object and so modifying the offset between the object and the 7-Handle tool. The manipulating mode is the main operating mode of the 7-Handle tool: the user uses the tool to modify the position and the orientation of the object. The shape of the tool does not change during a manipulation task. We also provide the locking and unlocking mode when the user wants to pin one or two first-level handles at a place so this (these) handle(s) do(es) not move anymore. These three control modes will be detailed in section 3.2.1, 3.2.2 and 3.2.3.

3.2.1   Configuring the 7-Handle tool

In order to make the 7-Handle tool more flexible and efficient for manipulating objects of different sizes and shapes in many kinds of manipulation scenarios, we propose a configuring mode for all the seven handles, making it possible to change their positions relatively to the object as well as to modify the shape of the tool.

Usually, the first-level handles are recommended to be put near some parts of interest of the 3D model of the manipulated object because later on, when the user manipulates the object, he can easily verify if the part of the object near one of these handles is well placed to the intended position. The adjustment of these first-level handles does not move or rotate the object: it only enables the user to place these handles relatively to the object. After the adjustment of the first-level handles, the offset between their centroid and the barycenter of the object is automatically recomputed to be used in the manipulation phase. The second-level handles are placed at the midpoints of the sides created by the first-level handles. The third-level handle is usually put at the centroid of the triangle created by the three first-level handles. However, the positions of the second-level or third-level handles can also be changed. Since their positions are initially computed from the the first-level handles, they are usually placed inside the object model if the object model has the same barycenter as the one of the tool. Due to this fact, the second-level and third-level handles are sometimes difficult to be seen and reached. Therefore, the user can change the offset of these handles with the object. This adjustment computes an offset between the 'should-be' positions of the second-level and third-level handles and their new positions. This offset will be used in the manipulation phase to update the positions of the second-level and third-level handles in relation to the first-level handles, and vice versa. This offset is initially predefined when the 7-Handle tool is launched and can be modified at run-time by the user.

3.2.2   Locking and unlocking first-level handles

A user can lock one or two first-level handles that is (are) near some parts of the object that are already well positioned. With this possibility, these parts of the object will not move anymore and the user can focus only on other active handles for accurately adjusting the position and orientation of the object. Moreover, if the user finds out that the locked handle(s) misplace(s) the object from its final position, he just needs to unlock this (these) handle(s) and modify the position of this (these) handle(s) again. This locking and unlocking mode are only possible for the three first-level handles.

When one first-level handle is locked, the user can rotate the 7-Handle tool (and also its associated object) around the locked handle. When two first-level handles are locked, the manipulation of the remaining first-level handle enables the user to rotate the object around the side formed by the two locked first-level handles. This manipulation is equivalent to the turntable rotation technique [CFH97]. The manipulation technique in these two cases will be detailed in section 3.2.3.

3.2.3 Manipulating seven handles

Once the reconfiguration has been done, the shape of the tool and the offset between the seven handles and the object remain unchanged during the manipulation. Therefore, in order to represent the shape constraint applied to the handles as well as to represent the actual movement of interaction tools (i.e. the user's hands), we propose to control these handles through *proxy points*. The proxy points are smaller yellow spheres initially hidden inside their associated handles. In figure 3.1, the proxy points PF_1, PF_2, PF_3, PS_1, PS_2 and PS_3 are visually separated from their handles F_1, F_2, F_3, S_1, S_2 and S_3 respectively to help readers have a better look at them. A proxy point can be directly driven by an interaction tool reflecting the intended position that the user wants its associated handle to go. On the other hand, the position of each handle is computed according to the actual position of its proxy point and the shape of the 7-Handle tool. We do not need a proxy point for the third-level handle because the latter can be directly driven by an unconstrained 6-DOF interaction tool. When we talk about controlling a handle, we actually talk about controlling the proxy of this handle. The way each handle moves depends on the position of its proxy point, its own state (active, inactive or locked), the state of its associated handles, and the shape constraint of the triangle. The gap between one handle and its proxy point during the manipulation is made visible by an elastic link and the deformed triangle shape of the tool is shown in semi-transparent yellow. This proxy point comes back to the same position of its associated handle when the user releases it.

Our technique does not limit the number of handles to be manipulated at a time. The user can grab and manipulate one or several handles simultaneously with interaction tools driven by input devices. However, during the manipulation, there are always constraints between handles at different levels. When a handle is currently controlled, its adjacent handles are also indirectly controlled and are not available to be grabbed by interaction tools. Figure 3.2 shows the color change and the availability of each handle in four different manipulation cases when the user uses only the first-level handles to manipulate an object. If one first-level handle is controlled (in bright green color), the third-level handle and the two adjacent second-level ones associated with this first-level handle are simply made inactive (in semi-transparent red color, see figure 3.2.B). When two first-level handles are controlled, all the second-level and third-level handles are inactive and the only handle still available is the remaining first-level one (figure 3.2.C). Last, when all the three first-level handles are controlled, the user now gets an unconstrained 6-DOF manipulation control over the object (figure 3.2.D).

Using the set of seven handles to manipulate an object, the following manipulation scenarios can occur:

1. No locked handle

   (a) *Controlling one first-level handle* (figure 3.3)

   If the proxy point PF_1 is moved to the new position PF_1', the 7-Handle triangle is first rotated $\angle(\overrightarrow{MF_1}, \overrightarrow{MPF_1'})$ degrees around the axis $(M, \overrightarrow{MF_1} \wedge \overrightarrow{MPF_1'})$, and then moved along the vector $\overrightarrow{F_1'PF_1'}$. M is the midpoint of the
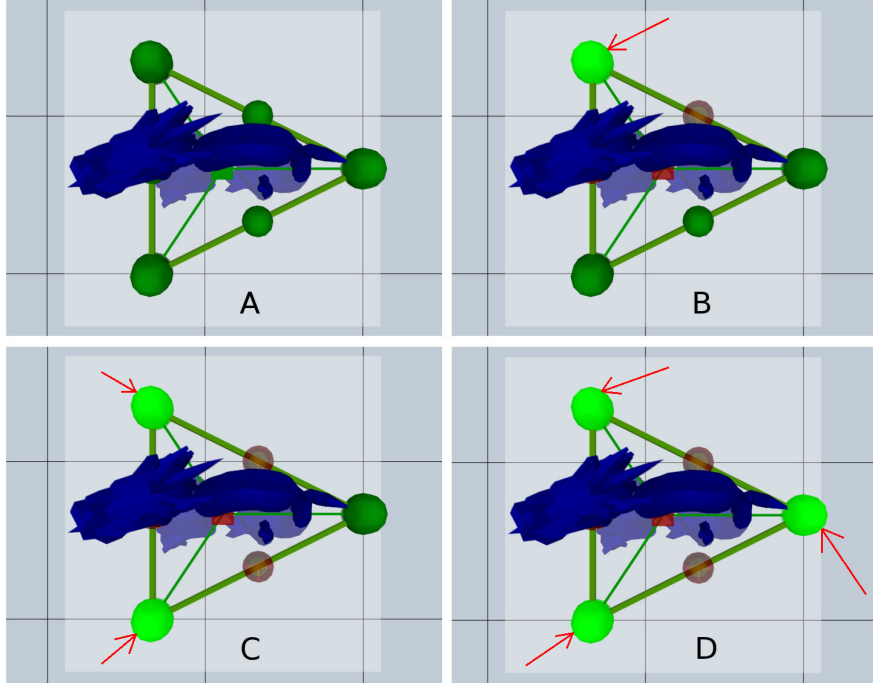
Figure 3.2 – Color representation of handles. The handles change their color to inform their state and their availability to users in the four following manipulation cases (the handles that are controlled are indicated by red arrows):
A: No handle is controlled - B: One first-level handle is controlled - C: Two first-level handles are controlled - D: Three first-level handles are controlled.

side F_2F_3. The $\angle(\overrightarrow{MF_1}, \overrightarrow{MPF_1'})$ denotes the angle between the two vectors $\overrightarrow{MF_1}$ and $\overrightarrow{MPF_1'}$. The axis $(M, \overrightarrow{MF_1} \wedge \overrightarrow{MPF_1'})$ denotes the axis, which is created by the normal vector of the two vectors $\overrightarrow{MF_1}$ and $\overrightarrow{MPF_1'}$ and passes the midpoint M.

(b) *Controlling two first-level handles* (figure 3.4)
   If the proxy points PF_2 and PF_3 are moved to the new positions PF_2' and PF_3', the triangle is first rotated $\angle(\overrightarrow{F_1M}, \overrightarrow{F_1M'})$ degrees around the axis $(M, \overrightarrow{F_2F_3} \wedge \overrightarrow{PF_2'PF_3'})$, and then moved along the vector $\overrightarrow{MM'}$. M is the midpoint of the side F_2F_3, M' of the side $PF_2'PF_3'$.

(c) *Controlling all the three first-level handles* (figure 3.5)
   If all the three first-level handles are grabbed at the same time, the triangle is first rotated α degrees around the axis $(M, \overrightarrow{F_1F_2} \wedge \overrightarrow{F_1F_3})$. M is the centroid of the triangle $F_1F_2F_3$, and M' of the triangle $PF_1'PF_2'PF_3'$. The α is the average of three angles $\angle(\overrightarrow{MF_1}, \overrightarrow{M'PF_1'})$, $\angle(\overrightarrow{MF_2}, \overrightarrow{M'PF_2'})$, and $\angle(\overrightarrow{MF_3}, \overrightarrow{M'PF_3'})$. The triangle is then moved along the vector $\overrightarrow{MM'}$.
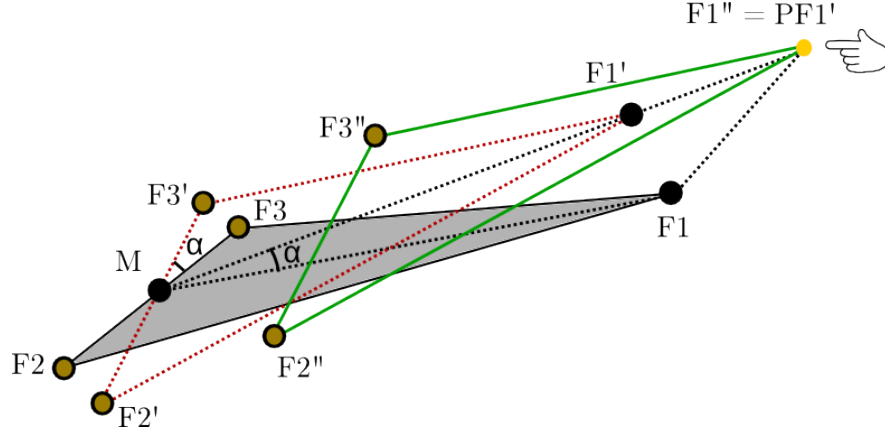
(d) *Controlling one second-level handle*

Figure 3.3 – Movement of the 7-Handle tool when controlling the first-level handle F_1 with no locked handle. The triangle with black sides shows the initial position of the tool, the triangle with red sides shows its intermediate position, and the triangle with green sides shows its final position. This color presentation is applied for the next five figures.
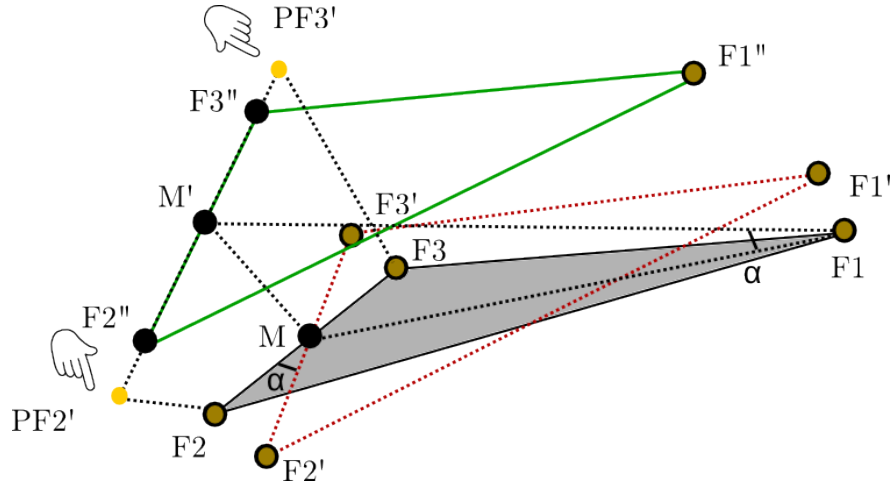

Figure 3.4 – Movement of the 7-Handle tool when controlling the two first-level handles F_2 and F_3 or when controlling the second-level handle $S - 1$ with no locked handle.

> In this case, the behavior of the triangle is the same as in the case of controlling two first-level handles. Instead of grabbing the two first-level handles at the same time, we use the second-level handle to control them.

(e) *Controlling one second-level handle and one opposite first-level handle*
In this case, the behavior of the triangle is the same as in the case of controlling all the three first-level handles.

(f) *Controlling the third-level handle (T)*
If the third-level handle T is driven by a 6-DOF interaction tool, this 7-

Handle tool is equivalent to a direct manipulation technique through a classical 6-DOF interaction metaphor.

2. One locked handle (F_1; F_2; or F_3)

   (a) *Controlling one first-level handle* (figure 3.6)
       Supposing that the first-level handle F_1 is locked at one place and the proxy point PF_2 is moved to the new position PF_2', the triangle is rotated $\angle(\overrightarrow{F_1F_2}, \overrightarrow{F_1PF_2'})$ degrees around the axis $(F_1, \overrightarrow{F_1F_2} \wedge \overrightarrow{F_1F_3})$.

   (b) *Controlling two first-level handles* (figure 3.7)
       If the first-level handle F_1 is locked and the proxy points PF_2 and PF_3 are moved to the new positions PF_2' and PF_3', the triangle is rotated $\angle(\overrightarrow{F_1M}, \overrightarrow{F_1M'})$ degrees around the axis $(F_1, \overrightarrow{F_1F_2} \wedge \overrightarrow{F_1F_3})$. M is the midpoint of the side F_2F_3, M' of the side $PF_2'PF_3'$.

   (c) *Controlling one second-level handle*
       Supposing that the first-level handle F_1 is locked and the opposite second-level handle S_1 is used to control the triangle, its behavior is the same as in the case of controlling the two first-level handles F_2 and F_3 (figure 3.7).

3. Two locked handles (F_1 and F_2; F_1 and F_3; or F_2 and F_3)

   (a) *Controlling one first-level handle* (figure 3.8)
       If two first-level handles F_1 and F_2 are locked, the only available handle that can be grabbed is F_3. The triangle is rotated $\angle(\overrightarrow{MF_3}, \overrightarrow{MPF_3'})$ degrees around the side F_1F_2. M is the midpoint of the side F_1F_2.

3.3   Improving awareness and communication of the 7-Handle technique in immersive virtual environments

We considered the awareness information of a manipulation tool is an important aspect that needs to be implemented. More specifically about the awareness information that an interaction tool can provide, we need to represent the current state of the interaction tool at any moment whether it is controlled or free. In addition, we also need to show all the possible use cases of the interaction tool, which means that the interaction tool has to be intuitive.

Using a color system to simply represent the state of each handle enables us to show the state of the tool and its availability. Figure 3.9 shows the color of the handles when they are not driven by any interaction tool. All the seven handles are green indicating their availability state. In a manipulation mode, the handle being controlled has a brighter green while the handles that are the neighbors of the controlled handle have a red color. In a configuration mode when the user changes the position of one handle relatively to the manipulate object, as illustrated in figure 3.10, la color of the
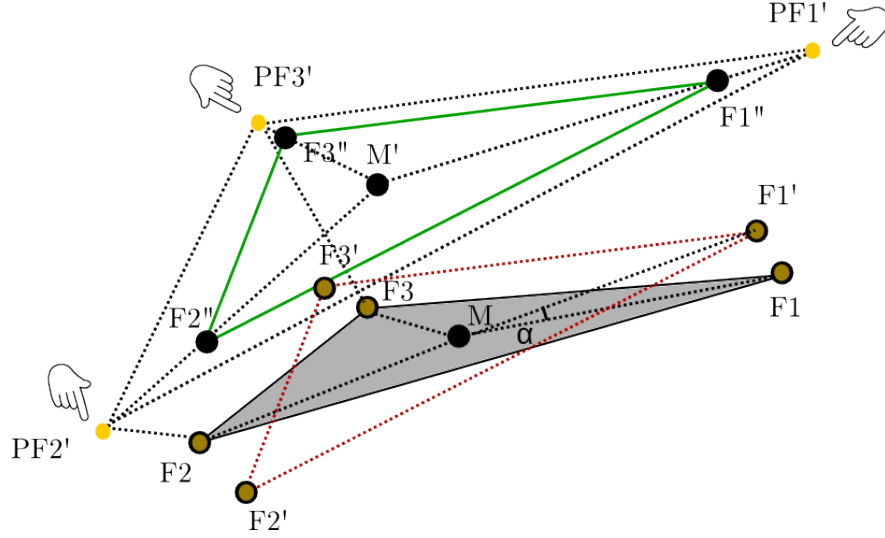
Figure 3.5 – Movement of the 7-Handle tool when controlling all the three first-level handles F_1, F_2 and F_3 with no locked handle.
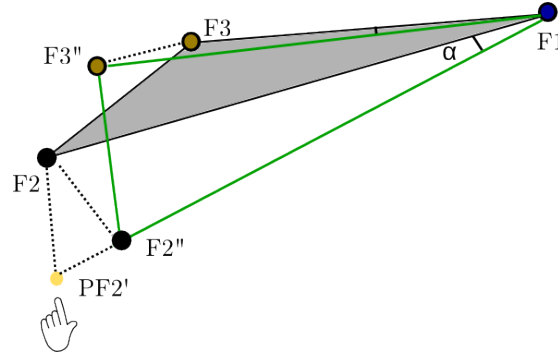

Figure 3.6 – Movement of the 7-Handle tool when controlling the first-level handle F_2 when the first-level handle F_1 is locked.

handle turns translucent light green. The color of its neighbors, on the other hand, is translucent red as an indication about their unavailability because their positions are calculated according to the controlled handle. In addition, the handles in yellow show their immobility state in the configuration mode. Using the same representation, in a locking mode, a first-level handle is represented in blue color as in figure 3.11. The other unlocked handles keep their own color representations as in a manipulation mode. In brief, the change of color of each handle helps the user to recognize the availability and the possible control can be applied in the 7-Handle tool, increasing the awareness of the interaction tool for the user.

In the manipulation mode, we have implemented proxy points as 'mediators' reflecting current movements of an interaction driven by the user (see figure 3.12). These proxy points are implemented to show real-time reactions of the virtual environment
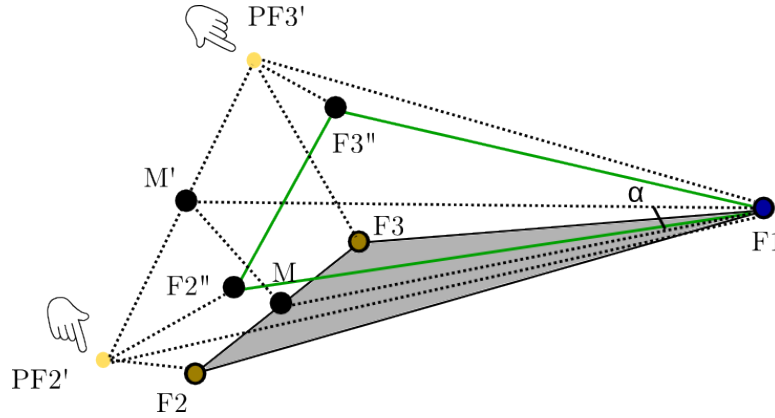
Figure 3.7 – Movement of the 7-Handle tool when controlling the two first-level handles F_2 and F_3 when the first-level handle F_1 is locked.
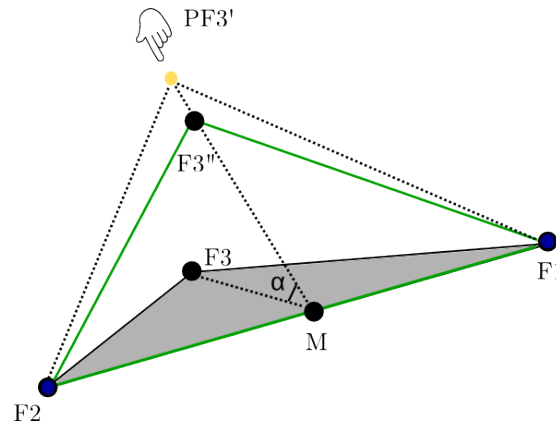

Figure 3.8 – Movement of the 7-Handle tool when controlling the first-level handle F_3 when the two first-level handles F_1 and F_2 are locked.

upon the changes made by the user, making him understand the functionality of the handles. In order to represent the connection between the proxy points and the handles and the movement constraints of the handles, the gap between them is made visible by a yellow elastic link. Furthermore, the feedback given to the user when he releases the interaction device controlling a proxy point and it comes back to its associated handle makes the user be aware of his current actions in the environment. Since our 7-Handle tool does not limit the number of control over the handles, two or three users can cooperatively manipulate the same object. Thanks to the proxy points and the link between them and the handles, a collaborator can perceive current movements of others at any time and so can coordinate his own actions during the manipulation with the others' to complete the task. In a manner of speaking, the 7-Handle tool can be used as a 'communication' mediator for cooperative manipulation.

Our 7-Handle technique, in general, does not appear 'natural' at first to users
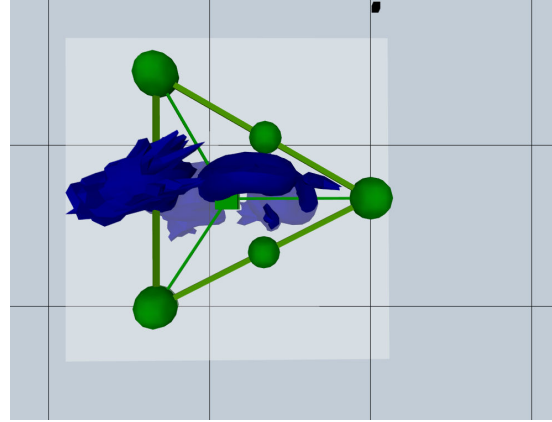
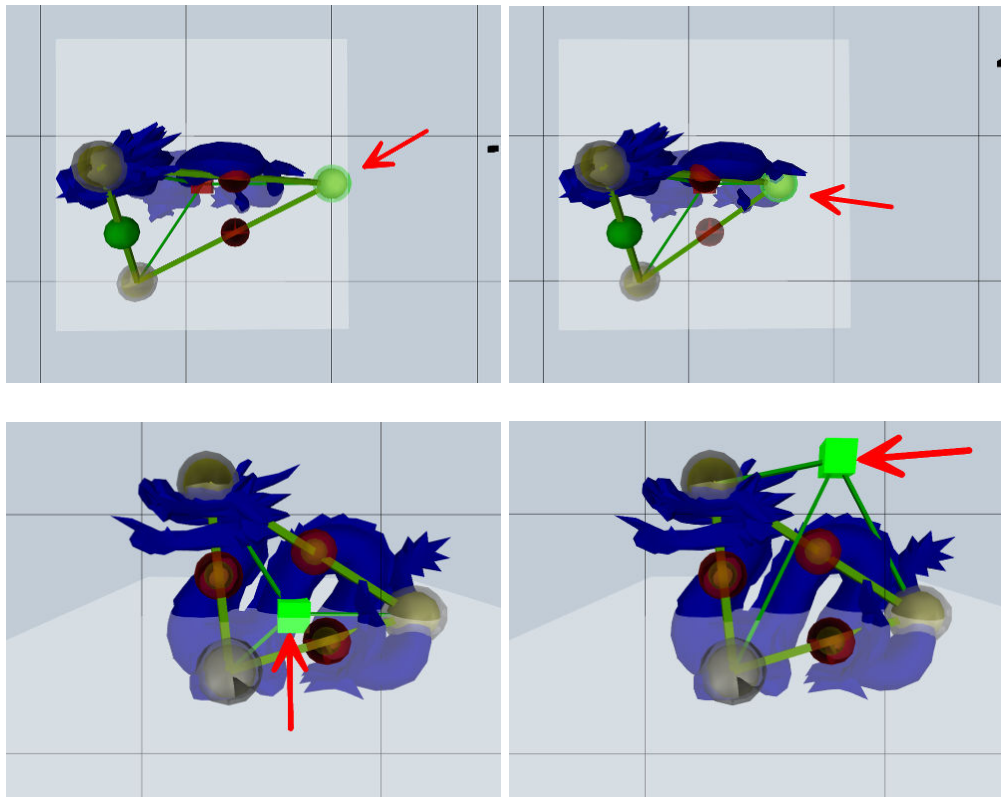Figure 3.9 – Green color of all the seven handles when they are available.

Figure 3.10 – Representation of seven handles' color in configuration mode. Green color of the seven handles in a configuration mode when the first-level handle (top) or the third-level handle (bottom) indicated by a red arrow is moved from its initial position (left) to a new one (right) without changing the position of other handles.
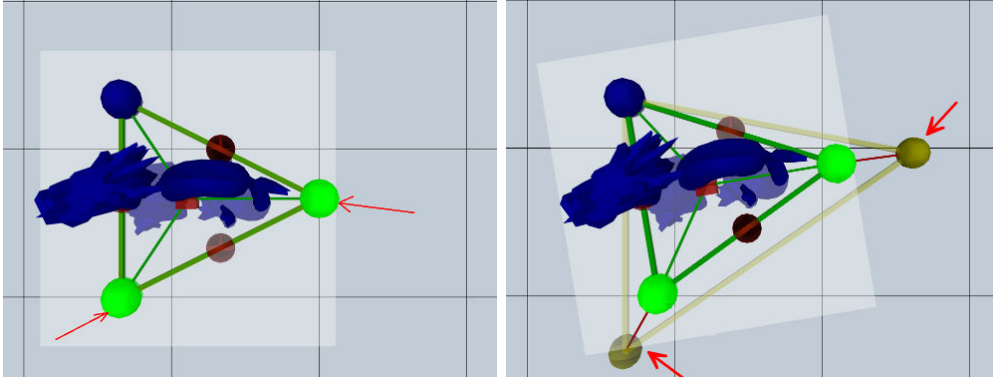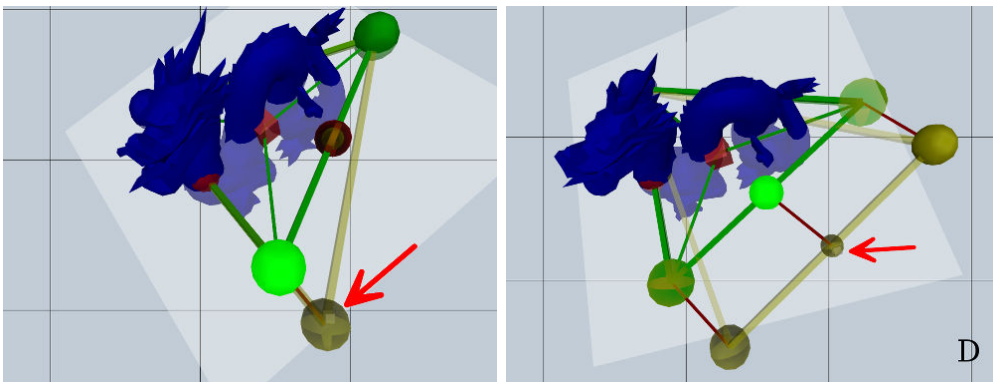
Figure 3.11 – Representation of seven handles' color of seven handles in locking mode. The first-level handle in blue is locked and the other two first-level handles indicated by red arrows in light green are still available and

(a) Controlling first-level handle.   (b) Controlling second-level handle.

Figure 3.12 – Constraints between proxy points and handles.

because from our observation, it takes time for a user to learn how to use the 7-Handle in different manipulation contexts. The three different control modes are not easy to use in the beginning if the user is a novice in 3D manipulation. However, as it happens quite often in the design of manipulation techniques in immersive virtual environments, a trade-off has to be made between the naturalness and the efficiency of the interaction technique. On one hand, if we try to enhance the naturalness aspect of our technique by giving more degrees of freedom for the user in controlling objects, the performance of the manipulation in terms of time might decrease because of the difficulties such as hand jitter or the Heisenberg effect the user might encounter. On the other hand, if we want to obtain a better efficiency, the interaction tool might become supernatural or magic.

3.4 Evaluation of the 7-Handle direct manipulation technique in immersive virtual environments

We have conducted an experiment to evaluate the performance and the ease of use of the 7-Handle and the 6-DOF techniques for accurate manipulation of objects in an immersive virtual environment. In this experiment, we evaluated the interaction between the two factors - the manipulation techniques and the sizes of objects - on the performance of a manipulation task in terms of efficiency and comfort, using discomfort and efficiency metrics described in section 3.4.4. We used discomfort metrics as criteria to evaluate the performance and efficiency of the manipulation techniques because unlike the completion time, the discomfort metrics reflects the effort the user needs to make to work in an immersive virtual environment within which there is a limited number of physical supports, or even not at all.

3.4.1 Context

We used five 3D models of which the size varied from small to large (see Table 3.1). The duplicates of these models, called *target models*, were used to indicate the final position and orientation of the objects. The target models were semi-transparent and in a different color to differentiate themselves with the object models. They could not be grabbed or manipulated by any interaction tool. Each 3D model was positioned 3 meters apart from its corresponding target model. The goal of each manipulation task was to superimpose an object with its target.

We implemented the two manipulation techniques in our system to perform the experiment. The 6-DOF manipulation technique was simply implemented using a 3D cursor driven by a Flystick, enabling the subjects to directly grab and manipulate objects. For the 7-Handle technique, all the three first-level handles were initially positioned near points of interest of each object (points or parts of the object that were remarkable so the subjects can immediately recognize whether or not the object and its target superimposed). We predefined the configuration of the 7-Handle tool because we only measured the completion time of a manipulation task, not including time for preparation. The positions of the three second-level handles and the third-level handle were initially computed according to the first-level handles. Furthermore, although the 7-Handle technique enables users to manipulate objects with two hands, we only used one input device for both the manipulation techniques to guarantee the consistency of the experimental conditions. The subjects therefore used the same Flystick to control a 3D cursor by which they could grab and manipulate the handles. An additional function of this 3D cursor enabled the subjects to lock or unlock the handles.

The hardware setup consisted of a big CAVE$^{\text{TM}}$ of four walls of which the size was 9.60 m long, 3.10 m high and 2.88 m deep. This system used 13 stereoscopic projectors to immerse subjects in a high-quality visual world. The subjects wore a pair of active shutter glasses to see the virtual environment in 3D. We also used an ART (Advanced Realtime Tracking) tracking system with 16 cameras to locate the position and orientation of each immersed subject's head to adapt the scene to his point of view.

Table 3.1 – Size of the 3D models that were used for the experiment.

Object	Length (cm)	Width (cm)	Height (cm)
Cat (T1)	77.0	18.6	50.1
Heron (T2)	64.3	36.5	67.2
Horse (T3)	111.9	23.8	80.0
Dragon (T4)	154.0	52.0	142.0
Camel (T5)	161.0	49.0	165.0

In order to compute the discomfort metrics of the subjects, we used 11 trackers (including trackers for two lower arms, two upper arms, two wrists, two legs, neck, trunk, head) to record their postures during the experiment. These trackers were calibrated for each subject in the beginning of his experimental session and were initiated in the same neutral standing posture for all the subjects (see figure 3.13). The positions of all the trackers were recorded at the frequency of 60 Hz during the experiment and this data was analyzed offline to obtain the mean values of the discomfort metrics.

Figure 3.13 – Setup of our experiment. A subject with 11 position trackers used to record his posture and a Flystick to manipulate the objects (left), and a manipulation scenario of the 7-Handle technique in an immersive virtual environment (right).

3.4.2 Subjects

Subjects of this experiment were recruited among our colleagues in our laboratory and our students. These subjects were volunteering their time and received no reimbursement beyond light refreshments. Twelve subjects (one female and eleven males) aged

from 21 to 31 (mean: 25.9, standard deviation: 3.29) took part in this experiment.

3.4.3 Procedure

Before beginning the training phase, each subject was equipped with the eleven trackers on his body. He was asked not to move the trackers during the manipulation so the discomfort metrics could be consistent and correct for each subject. He was then verbally instructed about the experiment procedure, the virtual environment and the control devices (shutter glasses, flystick). The goal of the experiment was also explained to the subject.

The subject had to pass the training session before beginning his evaluation session. He was given an example object (a dog model of which the size was 75 cm long, 60 cm high and 20.5 cm wide) that was manipulated to its target object twice by the two manipulation techniques. This session enabled the subject to familiarize himself with the manipulation task, the required precision of the manipulation, and the two manipulation techniques.

In the evaluation session, the subject was asked to manipulate five objects using the two techniques (ten manipulation trials in total). Each technique was used by the subject to manipulate five successive objects in the order from small to large ones. The order of the manipulation techniques changed from one subject to another to reduce the order effect of techniques on results and to get a balanced design of all the experimental sessions. The average time of an experimental session for one subject was about 40 minutes.

3.4.4 Discomfort and efficiency metrics

In order to evaluate the two manipulation techniques, we measured the completion time and the two discomfort metrics of each manipulation trial. Each trial consisted in two continuous phases: an approach phase when the manipulated object was moved over a long distance to near its target object, and a refinement phase for an accurate positioning and orientation. A questionnaire and additional comfort estimations were also collected to quantify the satisfaction feedback of the subjects with regard to the considered techniques.

3.4.4.1 Completion time

The completion time is a direct measurement of the efficiency of each technique, as we consider that being quick in a virtual environment means being efficient with the manipulation technique. Moreover, the completion time is a significant discomfort indicator as it affects the fatigue and discomfort of subjects and vice versa. The software we developed automatically recorded the completion time per phase (approach and refinement phases) for each trial.

For each manipulation trial, the software recorded the completion time of the approach phase for each subject to manipulate an object from its initial position into an intermediate zone. The intermediate zone was a sphere of which the radius was 10 cm

and the center was the target object. The object changed its color from green to blue to inform the subject about the ending of the approach phase. The software recorded the completion time of the refinement phase for the subject to manipulate the object from its position in the intermediate zone into its final zone. The final zone was a sphere of which the radius was 1.5 cm and the center was the target object. In addition, another condition of the final position of the object was that the angle difference between the object and its target was not greater than 0.04 radians. The object changed its color from blue to yellow to inform the subject about the ending of the refinement phase that was also the ending of the manipulation trial.

It has been observed that sometimes when a user manipulated an object using the 6-DOF technique, the final position of the object was unintentionally reached and then was immediately gone because he had difficulty in keeping the hand motionless in a particular position. In order to make sure that the recorded completion time of the refinement phase was not affected by this issue, we required that the final situation of each object needed to remain unchanged for at least 3 seconds. So the recorded time of the refinement phase was the total time (from the moment when the completion time for the approach phase was recorded until the moment when the final situation of the object was reached and unchanged for 3 seconds), minus 3 seconds.

3.4.4.2   RULA score

The Rapid Upper Limb Assessment (RULA) score is an indicator of postural discomfort [MC93] used in relation to assessment of physical risk factors in ergonomics. A minimal score of 1 indicates a relatively comfortable posture, whereas a maximal score of 7 indicates a highly uncomfortable posture. From kinematics outputs obtained from the ART tracking system, a processing pipeline described in figure 3.14 computed the RULA score at each frame. This requires that joints angles be obtained from the rotation matrix via a standard inverse kinematics algorithm similar to the one described in [PDD13, PSB+14]. As tracking outputs consisted of both positions and orientations of each segment, the method computed the relative rotation matrix between each body segment. A simple identification of the joint coordinates was performed from these matrices. Finally, successive intermediate RULA scores were computed and gathered. For each phase of each trial, the RULA score was averaged. To compute the final RULA score, adjustments relative to the task properties had to be made. We hypothesized that the 'frequency adjustment' was equal to 1 since trials included repetitive motions. Given that the flystick weigh less than 1 kg, the 'force adjustment' was set to 0.

3.4.4.3   REBA score

The Rapid Entire Body Assessment (REBA) score is an indicator of postural discomfort [HM00] used in relation to assessment of physical risk factors. The REBA score is quite similar to the RULA score, but takes into account the leg postures and is less constraining than the RULA score for a given task. A minimal score of 1 indicates a relatively comfortable posture, whereas a maximal score of 11+ indicates a highly
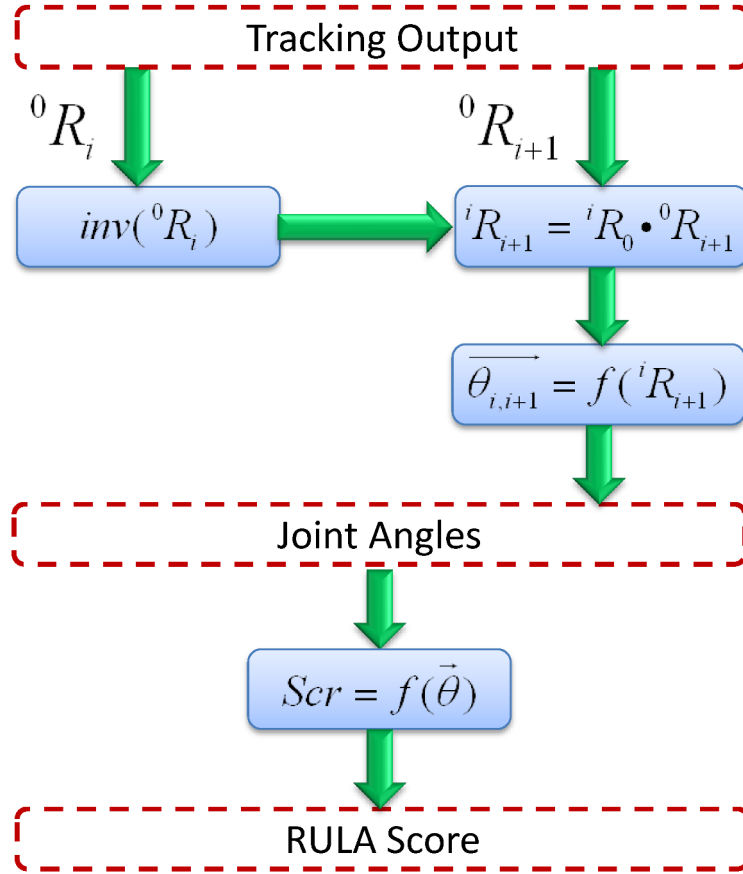
Figure 3.14 – RULA score computation [PSB⁺14]. $^iR_{i+1}$ is the rotation matrix of segment $i + 1$ relative to segment i and $\overrightarrow{\theta_{i,i+1}}$ is the vector containing functional joint angles of the joint between i and $i+1$. ^0R_i matrix is the output of the ART, representing the rotation of the segment i relative to the reference frame 0.

uncomfortable posture. In this experiment, the REBA score was computed in a very similar way as the RULA score. For each phase of each trial, the REBA score was averaged. To compute the final REBA score, adjustments relative to the task properties had to be made. We hypothesized that the 'load score' was equal to 0 as the Flystick weighed less than 1kg. We also hypothesized that the 'activity score' was equal to 2 in any situation as the posture was mainly static and the manipulation involved small range repetitive motions.

3.4.4.4 Rated perceived exertion

Rated Perceived Exertion (RPE), using Borg's CR-10 scale [Bor90] is a reliable subjective indicator of discomfort. It indicates, from 0 (no perceived discomfort) to 10 (nearly

painful task) the task painfulness. We collected RPE score varying from 0 to 10 to describe how hard the subject feel his body is working as a subjective measurement after each manipulation trial.

3.4.4.5   Subjective questionnaire

At the end of the evaluation session, the subjects were asked to fill in a questionnaire with subjective ratings using the 7-point Likert scale for the two manipulation techniques according to the following criteria: intuitiveness, fatigue, ease of use, efficiency and global preference. Some demographic information was also recorded detailing the age, gender and 3D immersion experience of the subjects.

3.4.5   Results

Using the data collected from the experiment, we conducted a statistical analysis to evaluate whether there was an improvement in the manipulation by the 7-Handle technique, compared to the traditional 6-DOF manipulation technique.

3.4.5.1   Competition time

Since we had two different factors (manipulation technique and object size) that could influence the completion time of two continuous phases of a manipulation trial, p-values of the completion time was computed using a two-way ANOVA analysis with repeated measures for balanced design and within-subjects factor to answer the following questions:

- Does the completion time depend on the technique?

- Does the completion time depend on the size of object?

- Does the completion time depend on the technique differently for different sizes of object, and vice versa?

Interaction plots of the completion time of the approach phase (figure 3.15.A) and of the completion time of the refinement phase (figure 3.15.B) were created to display the five size levels on the x-axis (from T1 to T5) and the mean completion time for each technique on the y-axis. We used the univariate repeated-measures two-way ANOVA with Greenhouse-Geisser adjustments if necessary.

For the completion time of the approach phase, the results revealed that there was no evidence of a significant interaction effect between the manipulation technique and the object size factor on the completion time ($F(4, 44) = 1.470$, p-value $= 0.227$). However, in the results of the test for the main effect of the both factors, the object size factor ($F(4, 44) = 4.485$, p-value $= 0.004$) and the manipulation technique factor ($F(1, 11) = 14.769$, p-value $= 0.003$), showed a significantly independent effect on the completion time. In other words, the results showed that the completion time in the
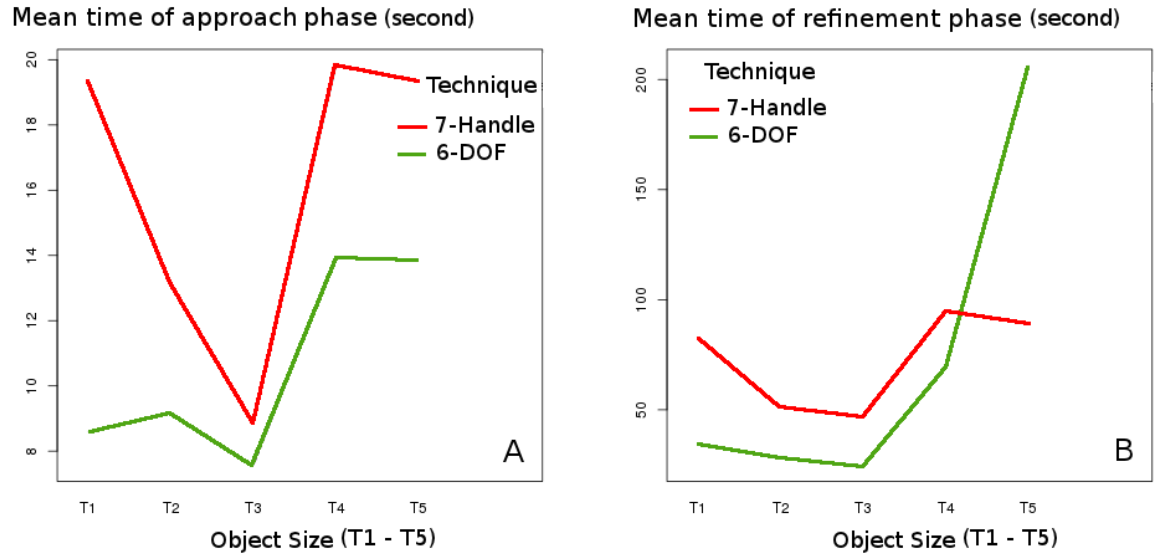
Figure 3.15 – Two interaction plots of the completion time for the approach phase (A) and for the refinement phase (B) for the 7-Handle and the 6-DOF techniques in terms of object size factor.

approach phase of the 7-Hand technique was significantly longer than the completion time of the 6-DOF technique.

For the completion time of the refinement phase, the results showed that there was a significant interaction effect between the manipulation technique and the object size factor on the completion time ($F(4, 44) = 3.899$, p-value = 0.008). Nevertheless, the result of the Mauchly's test for sphericity shows $p < 0.05$, so we could not assume the sphericity and we needed to use Greenhouse-Geisser correction on the number of degrees of freedom of the data. The epsilon of Greenhouse-Geisser is 0.309 and the final result shows a significant interaction effect between the manipulation technique and the object size factor on the completion time of the refinement phase ($F(1.23, 13.61) = 3.899$, p-value = 0.048).

3.4.5.2 Discomfort metrics

We analyzed the RULA, REBA scores and the RPE values using Wilcoxon's signed-rank tests with continuity correction for testing differences between groups when there were two conditions and the same subjects have participated in both conditions (see figure 3.16). The medians of the RPE score on the 7-Handle technique and on the 6-DOF technique were 1 and 2, respectively. The result of the Wilcoxon's signed-rank test showed that there was a significant effect of the manipulation technique on the RPE score: $W = 212$, $Z = -2.5398$, $p = 0.010 < 0.05$, $r = 0.2318$. In other words, the subjects felt that the 6-DOF technique was less comfortable than the 7-Handle
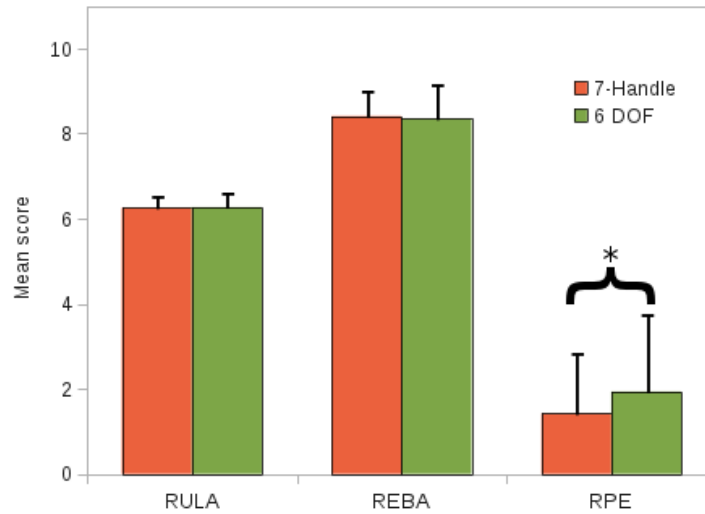
Figure 3.16 – Means of the RULA, REBA, and RPE scores of two manipulation techniques (7-Handle and 6-DOF) and their standard deviations on error bars. (*) There is a significant effect of the manipulations techniques on the RPE mean score.

Table 3.2 – Mean scores and p-values of the subjective data of the first experiment with significant differences shown in bold.

	7-Handle mean	6-DOF mean	p-value
Intuitiveness	5.50	6.50	0.157
Fatigue	**1.66**	**3.33**	**0.019**
Ease of use	5.25	5.08	0.963
Efficiency	**5.92**	**4.58**	**0.034**
Preference	5.66	5.08	0.527

technique. However, we did not find any significant difference on the RULA score of the 7-Handle technique (median = 6.237, mean = 6.255) and the 6-DOF technique (median = 6.337, mean = 6.269): W = 855, Z = -0.4417, p = 0.663 > 0.05, r = 0.0403. We did not find any significant difference either on the REBA score of the 7-Handle technique (median = 8.473, mean = 8.409) and the 6-DOF technique (median = 8.221, mean = 8.347): W = 1027, Z = 0.8245, p = 0.414 > 0.05, r = 0.0752.

3.4.5.3   Subjective questionnaire

A Friedman's test has been performed on the answers of the questionnaire and the p-values are showed in the table 3.2. The results showed that the subjects found that the 7-Handle technique was less tiring and more efficient than the 6-DOF technique. We did not find any other significant differences between the two techniques in terms of intuitiveness, ease of use and global preference.

3.4.6 Discussion

In this experiment, on both the interaction plots of the completion time for the approach phase and for the refinement phase (figure 3.15), we found a 'fall' of the completion time curves for both the 7-Handle technique as well as the 6-DOF technique at the object of average size T_3. This 'fall' was due to the task learning effect. All the subjects manipulated the five objects twice using the two different techniques from the smallest object to the largest one. This order did not change for all the experimental sessions. Usually, the subjects managed to use each technique efficiently to manipulate objects after two trials. However, because of the difficulty of the manipulation when the objects became larger, it took the subjects much longer to complete the manipulation.

The statistical results revealed that there was no significant interaction effect between the manipulation technique and the object size factor on the completion time of the approach phase. However, the main effect of manipulation technique on the completion time was significant: the completion time of the 7-Handle technique in the approach phase was significantly longer than the 6-DOF technique. This can be explained by the fact that in this phase, the subjects usually used the third-level handle to control objects because they would have a 6-DOF manipulation. However, this third-level handle was sometimes difficult to be seen and reached because it was hidden inside the objects. This drawback can be easily solved by adjusting the position of handles relatively to each object so all the handles can be visible and easy to be reached. Another solution is to combine the 6-DOF and the 7-Handle techniques so whenever the user catches objects directly, he will have a 6-DOF control over the objects, otherwise the 7-Handle technique will be applied if he controls the objects by the handles. Besides, the completion time of the approach phase represented a small percentage of the total completion time (mean time of the approach phase = 13.36, mean time of the refinement phase = 72.71).

Regarding the completion time of the refinement phase, the interaction between the manipulation technique and the object size was significant, indicating that the effect of the manipulation technique on the completion time differed when the object was small compared to when it was large. Repeated contrasts on this interaction term revealed that when comparing the difference in the completion time between the two manipulation techniques with the objects of size T_1, T_2, T_3, and T_4, there were no significant differences. However, when comparing the difference between them when manipulating the object of size T_4 with the difference when manipulating the object of size T_5, a significant difference emerged. To sum up, there was a significant interaction between the manipulation technique and the object size factor on the completion time: the completion time for the object of size T_5 (compared to the object of size T_4) of the 7-Handle technique was significantly shorter than the 6-DOF technique. Additionally, there was no significant difference between the two techniques for the objects from the smallest to the near largest size. This result showed the advantage of the 7-Handle tool for manipulating large objects in an immersive environment. If the manipulated object was large, the overall view of the subject was obstructed and so he could not observe all the parts of the object at the same time. Another problem for the 6-DOF

manipulation technique was that when the subject had several DOF simultaneously, a small movement might take the object from its intended position. Usually, the user had difficulty keeping his hand motionless and it was difficult for him to keep the final position of the object unchanged when he released the control of the object. Due to this fact, the final position of the manipulated object was harder to get, especially when manipulating large objects. The 7-Handle technique enabled the subject to locally control the position of each part of the manipulated object without worrying about unintended movements of his hand.

The statistical analysis of the subjective RPE score showed that the subjects felt less comfortable using the 6-DOF technique than using the 7-Handle technique. However, we did not find any significant difference on the RULA score as well as on the REBA score between the two techniques. This result could be explained by the fact that the RULA and REBA scores in the statistical analysis were the mean of the score of a whole manipulation task and therefore the value could be compromised because of the unstable and rapidly changing postures of the subjects. Usually, there is a correlation between the result of the subjective RPE score and the objective discomfort metrics, i.e. RULA and REBA scores [KL12]: if the subjects felt that the 6-DOF technique was less comfortable than the 7-Handle technique, the RULA and REBA scores should be significantly higher for this technique than for the 7-Handle technique. In contrast, we did not find any significant difference between the two techniques in terms of the discomfort metrics. In addition, almost all the RULA and REBA scores were considerably high. This significant measured postural discomfort might represent the great difficulty working in an immersive virtual environment in general where users do not have the support from physical tools such as tables, chairs, etc. Moreover, the unfamiliarity of the subjects with the environment is a well-known factor of motor control alteration [SBSP03, PSB$^+$14]. The lack of visual and physical references as well as the stereoscopic vision result generally in less controlled postures and kinematics [MBZB12, PDS$^+$13] and this result explains partially the high postural discomfort measured in the current study. The difference observed for the RPE score might be explained by the fact that the subjects could control their own body movements more easily with the 7-Handle technique. Using the 7-Handle technique enabled the subjects to manipulate locally each part of the manipulated object due to the arrangement of different handles all over the object, contributing to enhance their familiarity with the manipulation task. Moreover, with the 6-DOF technique, the subjects needed to keep their hand still longer in space and at the same time to pay attention to the whole object to manipulate it efficiently.

Regarding the result of the subjective data, because the subjects did not have to keep their hand motionless in the space in the CAVE$^{\text{TM}}$ for long time, they found the 7-Handle technique was less tiring and more efficient than the 6-DOF technique. Even though we did not find any other significant differences in terms of intuitiveness, ease of use and global preference, in general, the subjects preferred the 6-DOF technique for small objects because it was more natural and intuitive to control them in 6 DOF. However, the 7-Handle technique was more preferred for large objects because this technique enabled the subjects to control the objects more accurately, especially when

the objects obstructed the subjects' view. One drawback of this experiment was that it was designed mostly for right-handed people with average height. One of the subjects had difficulties in manipulating the objects because he was short and left-handed. If the subjects were tall, it was easier for them to manipulate large objects because they could observe all the parts of the objects at the same time. However, we have not yet studied the effect of the subjects' height or left-handedness and right-handedness on the performance of the two manipulation techniques.

3.5   Conclusion

Motivated by the necessity of having a manipulation technique that takes into account the influence of the immersion factor in the whole scheme of manipulation, we have developed the 7-Handle technique, a new manipulation technique for immersive virtual environments. This technique includes seven handles that can be arranged at different parts of virtual objects, enabling an user to manipulate them locally. Our technique also enables the user to adapt his 3D manipulation to different interaction contexts: from moving an object over a long distance to accurately positioning and orienting the object. This advantage is due to the possibility of configuring the set of seven handles to different sizes and shapes of virtual objects, and the possibility of locking and unlocking handles that is useful during the manipulation when the user wants to pin some parts of the object at one place. One drawback of the 7-Handle technique is that it might be difficult to learn how to use it at first. This is due to the fact that each handle has its own function and the way in which each handle takes part in the whole movement of the tool (as well as of the object) will decide the success of the manipulation task.

The statistical results from the experiment showed that the 6-DOF technique was suitable for manipulating small objects because it was easier for the user to control small objects with 6-DOF when he had a whole view of them during the manipulation. However, for manipulating large objects, the 7-Handle technique obtained better results than the 6-DOF technique in terms of completion time, fatigue and efficiency criteria, and RPE score. To conclude, the 7-Handle technique is a new accurate direct manipulation technique for 3D objects in virtual reality environments, especially efficient with large objects. This flexible technique takes into account some difficulties in manipulating virtual objects in immersive virtual environments where usually the user has few physical supports or haptic feedback.

To improve our technique, we could combine the 6-DOF technique with ours by enabling the user to take control of objects in 6 DOF in an easier way. Instead of using the third-level handle to have a 6-DOF control over an object, the user could grab it directly and the 7-Handle tool would become invisible. Our technique could enable the user to configure the set of seven handles in a more dynamic way. He could decide where to initially put the three first-level handles and by triggering an event, these handles could appear at the predefined positions. The position of the higher-level handles could be automatically computed. If the user would find that this tool

would not be necessary anymore, e.g. in the approach phase, because it would be easier to use the 6-DOF manipulation technique, he could make this set of handles be completely invisible in the virtual environment and make it reappear when necessary. The manipulation of the third-level handle could also be improved by combining it with first-level or second-level handles. For example, the third-level point could be the rotation center of the manipulation and the position of first-level or second-level points could be used to determine the rotation factor.

In addition, to completely evaluate the 7-Handle technique, we could study different ways to put the first-level handles of the tool in place and the impact of their position on the efficiency of the manipulation technique. Further experiments of the impact of the shape and size of objects on the manipulation must be also conducted (e.g., evaluating the two manipulation techniques using objects that have the same shape but different sizes, and objects that have the same size but different shapes). These experiments would also provide further results about the impact of learning time of the manipulation techniques on completion time.

Chapter 4

Interaction metaphors for awareness enhancement: application to collaborative ergonomics design in virtual environments

We have seen in previous chapters that for any kind of collaborative task in a virtual environment, either for navigation task or manipulation one, the four factors, i.e. immersion, awareness, communication, and naturalness, prove useful and decisive in acquiring performance efficiency and appreciation from users. In this chapter, in consideration of these factors, we also aim at analyzing the usefulness and efficiency of a 3D collaborative virtual environment (CVE) using interaction metaphors for digital mock-up (DMU) and virtual prototyping process. 3D virtual environments (VEs) help industrial prototyping engineers to design and simulate complex products and validate their designs without building their physical prototypes. Furthermore, to create and validate an industrial design, the engineers need to work with other manufacturing engineers, ergonomics experts, and end-users, in face-to-face or remote collaborative design sessions. CVEs hence have to support different interaction tools and interfaces for several roles in a design session. In addition, an efficient communication channel is a must-have to facilitate a mutual understanding between them. In order to facilitate a 'smooth' collaboration between different users in a collaborative design session, communication means as well as interaction tools and interfaces must be simple, intuitive, natural and easy to use. The level of immersion at the user's site must be taken into account because it affects his ability to interact with objects in the virtual world. Last, as we have already stated in the introduction section of this dissertation, in a collaborative virtual environment, it would be better that the interaction metaphors used in the shared world can be an implicit communication channel. Our aim in this study is to implement and evaluate different communication metaphors into a CVE for

ergonomics design, in terms of immersion, awareness, communication, and naturalness.

4.1 Collaborative virtual environments for virtual prototyping applications

Many applications have been using VR for DMU and virtual prototyping. A collaborative virtual prototyping system (VPS) has been developed at Caterpillar [LD97] supporting remotely collaborative and interactive design review. The participants of this system can share a virtual environment and see each other by video transmissions embedded at their viewpoints. Some virtual prototyping examples for automotive industries were provided in [JP07, DFF$^+$96] to demonstrate how VR is widely used in industry. Figure 4.1 gives an example from an assembly simulation system that helps users to interactively manipulate different elements of a virtual workstation using the direct manipulation technique of virtual hand metaphor or another tool metaphor with constraints.
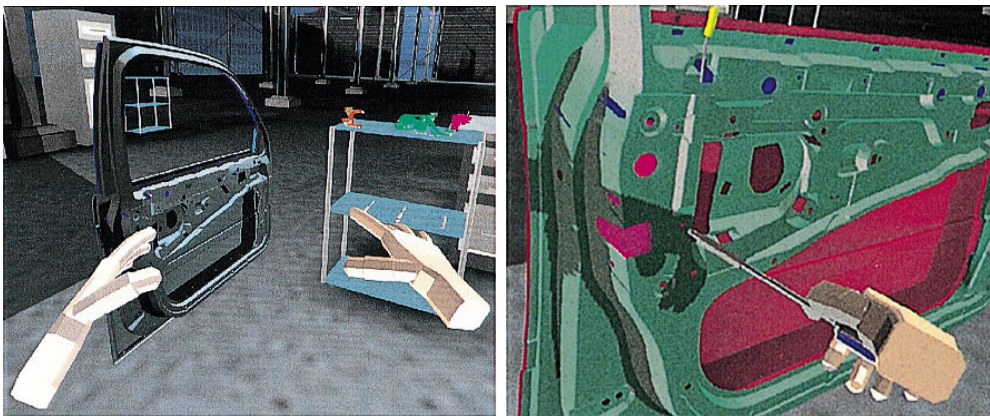
Figure 4.1 – Example of an assembly simulation system from [dSZ99].

Ergonomic evaluation becomes an important factor in virtual prototyping and DMU applications. Ergonomics study aims to integrate human factors in prototyping designs and to help designers and engineers to evaluate the consequences of their prototype design in terms of comfort, safety and effectiveness [CSSJC03, SGG03]. Figure 4.2 from [CSSJC03] shows four possible stages of a workstation design process including two stages of ergonomic analysis in virtual reality. The ergonomic analysis is mostly done using numeric manikins as an intermediate 'instrument' to mimic the working posture of end-users for ergonomics experts [LHÖ07]. Another approach is to record the working posture of an end-user using trackers during a manipulation task and automatically compute postural scores such as RULA (Rapid Upper Limb Assessment) [MC93] and/or REBA (Rapid Entire Body Assessment) [HM00] scores. If we integrate the ergonomic evaluation in real-time into collaborative workstation design systems, the

ergonomics experts can become an important actor in the design process of an assembly line [PDD13]. Figure 4.3 from [PDS+13, PSB+14] represents the ergonomics procedure we used in this chapter to evaluate the ergonomics factor of a collaborative workstation design.
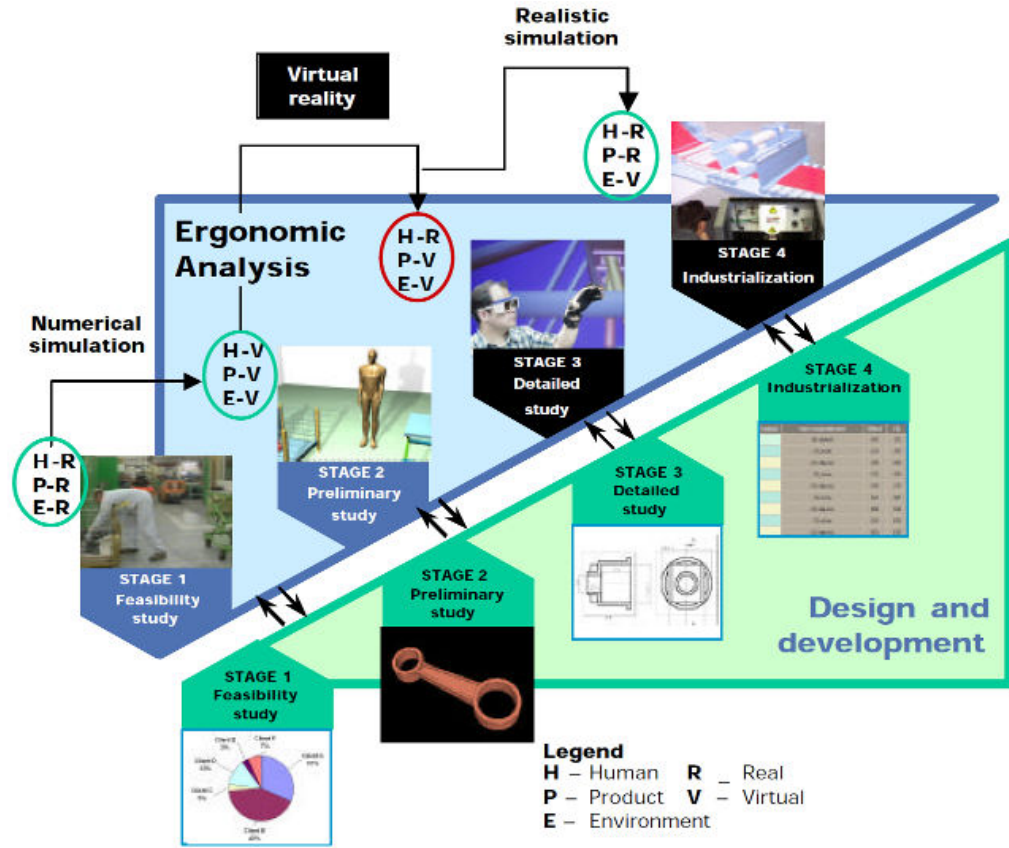

Figure 4.2 – Four stages of an ergonomic methodology applied in a workstation design application from [CSSJC03].

4.2 A use case: collaborative DMU application to workstation design process

Before installing a workstation in an assembly system in real life, its design has to be verified and validated in a DMU application with the participation of different actors: design engineers, ergonomics experts, and end-users. A workstation design is approved after all the related users of the workstation have agreed that the position of all the elements in the workstation satisfies two conditions. The first one is compliance with process specifications coming from the studied assembly system. This condition is verified by design engineers of the workstation design. The second is a good ergonomic
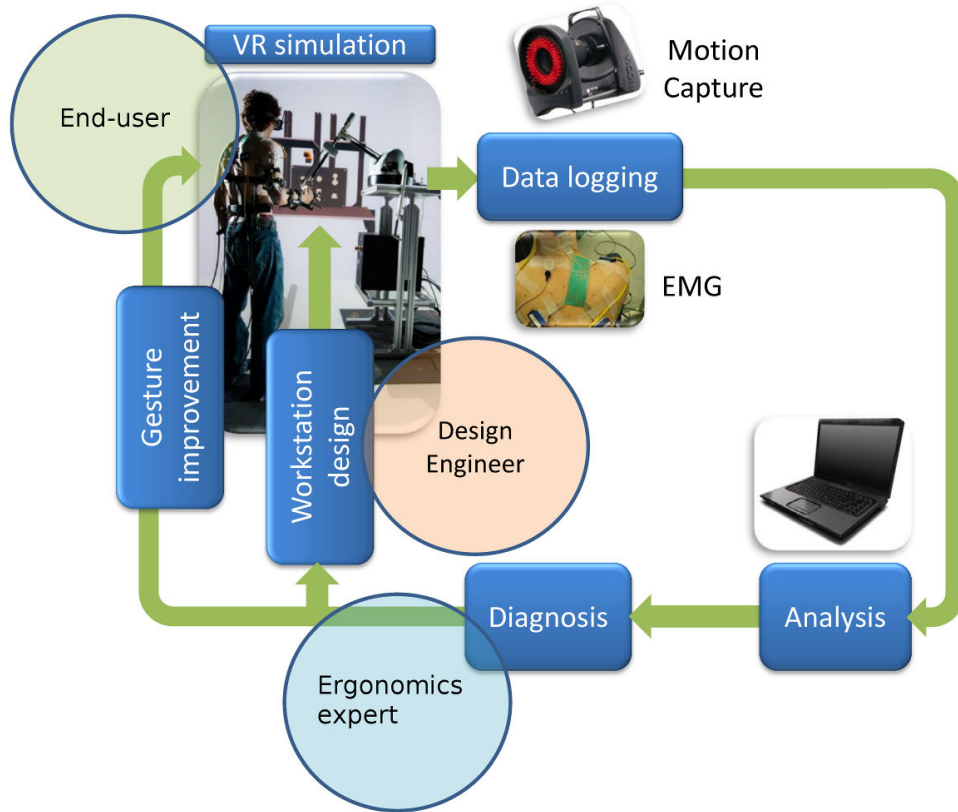
Figure 4.3 – Standard framework for collaborative ergonomic design sessions in VR from [PDS+13, PSB+14]

factor for a long-time working condition, which is examined and measured by ergonomics experts and end-users during the workstation design process. From the necessity of having a collaborative DMU application wherein all the three parties including and engineer, an ergonomics expert and an end-user can work together to verify and to validate a workstation design, we have implemented a simple example of a DMU application using the collaboration platform Collaviz [FDGA10]. In the next section, we will clarify the role of the different actors in the DMU application. In section 4.2.2, two possible operating modes that can happen in the DMU application will be explained. Last, in section 4.2.3, we will describe some interaction metaphors from [PDD14], which have been implemented in the DMU application to improve its naturalness, its immersion, the awareness between different actors, and the communication channel they use.

4.2.1 Different actors in the DMU application to workstation design process

Three main types of actors related in our DMU application have been defined in [PDD13]: design engineers, ergonomics experts, and end-users. In order to simplify the DMU

application as well as to be able to roughly generalize different collaborative DMU applications, we have implemented three interfaces for three actors: a design engineer, an ergonomics expert, and an end-user.

- *End-user* is normally an industrial operator in an assembly system. The end-user is the main subject of the DMU application because he will work in the workstation while taking into consideration gesture recommendations from the ergonomics expert and process recommendations from the design engineer. The gesture recommendations from the ergonomics expert are given regarding to the current physical comfort of the end-user. The process recommendations from the design engineer are given regarding to the current workstation specifications of the workstation design. The end-user then has to find a compromise between his physical comfort and workstation requirements and be able to provide usability recommendations to the design engineer. In our DMU application, the end-user works in an immersive virtual environment whose the first-person interface is illustrated in figure 4.4. Corresponding to each workstation design, a restricted position where the end-user is standing is represented by a round plate in figure 4.4. In other words, each workstation design is evaluated regarding to a specific standing position of the end-user.

- *Design engineer* is the user whose responsibility is to maintain the utility and performance of the workstation prototype. The design engineer, based on usability recommendations given by the end-user and ergonomic recommendations given by the ergonomics expert, can propose to modify some design aspects of the workstation. Since the design engineer may need to verify the whole specification of the workstation, he may need several viewpoints on the workstation during this interactive design phase. For this design engineer, we have implemented a desktop system providing two different viewpoints on the virtual workstation (see figure 4.5a and 4.5b). The design engineer will supervise the end-user working in the virtual workstation and if necessary, will modify the position of some DMU's elements based on the end-user's usability recommendations. We have implemented a simple avatar to represent the current movements of the end-user in real-time using a tracking system in order to facilitate his supervision.

- *Ergonomics expert* is the user who does not directly modify workstation designs but mostly gives gesture recommendations for the end-user and ergonomic recommendations for the design engineer. Accordingly, in our DMU application, we have not implemented a specific interface for the ergonomics expert and his role in the workstation design process is to analyse offline the data resulting from the computation of the ergonomic factors.

In summary, the end-user in the application will be immersed in a virtual environment representing the workstation to design. The design engineer (and the ergonomics expert in an offline analysis) has access to complete data coming from process specifications and the end-user's activities. The ergonomics expert mainly analyses
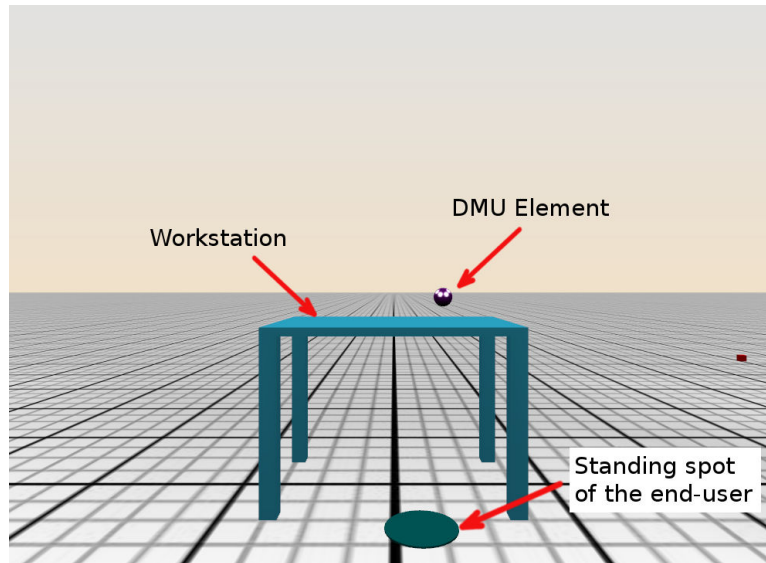
Figure 4.4 – First-person interface of the end-user in our collaborative DMU application.

bio-mechanical parameters of the end-user such as his postures, muscle activities, gaze, etc., whereas the design engineer mostly deals with process indications such as process specifications, possible modifications of the workstation, etc.

4.2.2   Two operating modes in the DMU application

The goal of the three users in the workstation design process is to design a workstation that is a satisfying compromise between the workstation specifications and the physical comfort of the end-user. In other words, in the end, the expected result will be a workstation with all the elements in it that all the three users find adequate. According to the roles of the design engineer and the end-user, and two operating modes proposed in [PDD14], we have implemented the two roles in the framework Collaviz for an evaluation of the efficiency of the two following operating modes.

In the first operating mode, called *direct design mode*, the design engineer takes the main role when he directly modifies the DMU workstation based on the usability recommendations given by the end-user and possibly by the ergonomics expert (see figure 4.6). The end-user will use informative signals such as visual metaphors (e.g., arrows, accessible volumes, etc.) and/or auditory ones to represent usable spaces of the workstation to the design engineer. At the same time, the ergonomics expert can give some advice to the end-user about his working gesture and posture in the workstation and some to the design engineer about the design of the workstation from his ergonomic point of view. Regarding to process constraints of the workstation, the design engineer needs to be able to fully modify the workstation design using appropriate interaction tools. In brief, for the first operating mode, the collaborative DMU application needs to provide appropriate interaction tools enabling the end-user to express his usability
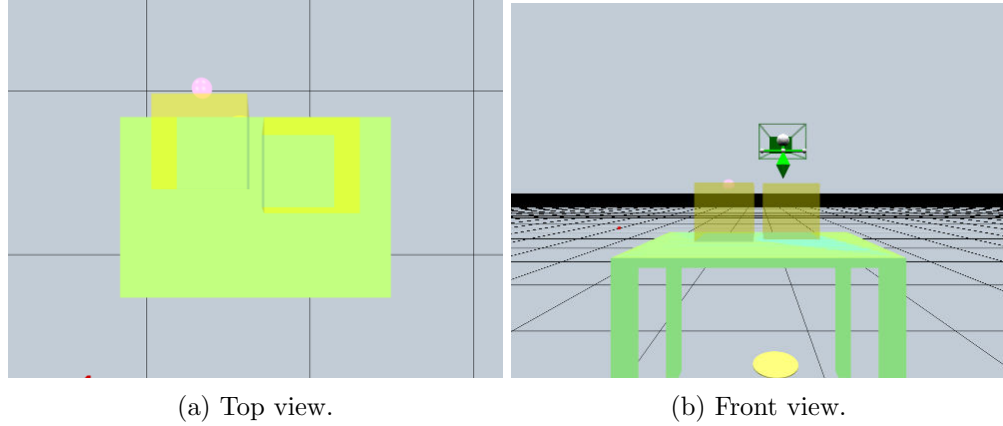
(a) Top view.

(b) Front view.

Figure 4.5 – Two viewpoints of the engineer in our collaborative DMU application.

and availability recommendations to the design engineer, increasing his awareness to the end-user's working conditions. In addition, the system also needs to provide interaction tools enabling the design engineer to change the workstation design, which means enabling the engineer to manipulate the elements of the workstation.

In the second operating mode, called *supervision design mode*, the end-user is the main actor in the workstation design. He will change the workstation by manipulating the elements of the workstation (see figure 4.7). The end-user therefore needs the design engineer to represent workstation specifications for him. The ergonomics expert will take a supporting role as he does in the first operating mode when he proposes gesture recommendations to the end-user during the manipulation and ergonomic advice to the design engineer. The design engineer, in this operating mode, will express the workstation specifications and constraints to the end-user using appropriate interaction tools and then will supervise and validate the work of the end-user.

4.2.3 Interaction metaphors for feedback and interaction

Besides the interaction tools such as a 3D cursor or a virtual hand provided for the end-user and the design engineer to manipulate the elements of the workstation, we need some interaction metaphors for the end-user to express his usability and availability recommendations in the first operating mode, and ones for the design engineer to represent the workstation specifications in the second operating mode. Inspired from the interaction metaphors proposed in [PDD14] and the result we achieved from the research in navigation metaphors in chapter 2, we have used them in our DMU application with some modifications.

In the first operating mode, the end-user needs to express his usability and availability recommendations to the design engineer. We consider the usability and availability recommendations of the end-user is his reachable volume defined as a quarter of a sphere including the space up and in front of him. The reachable volume of the end-user are divided into three zones of level of comfort, a bigger zone envelops a smaller
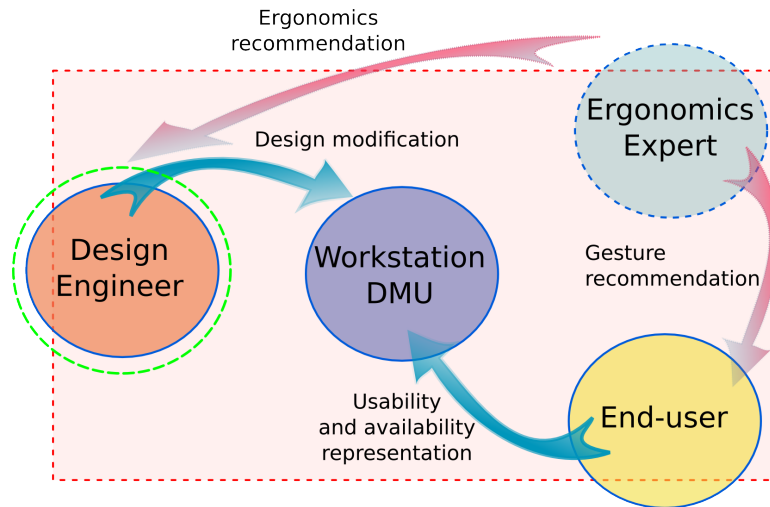
Figure 4.6 – Direct design mode in a collaborative DMU workstation with the design engineer's main role highlighted in green. Figure is directly adapted from [PDD14]
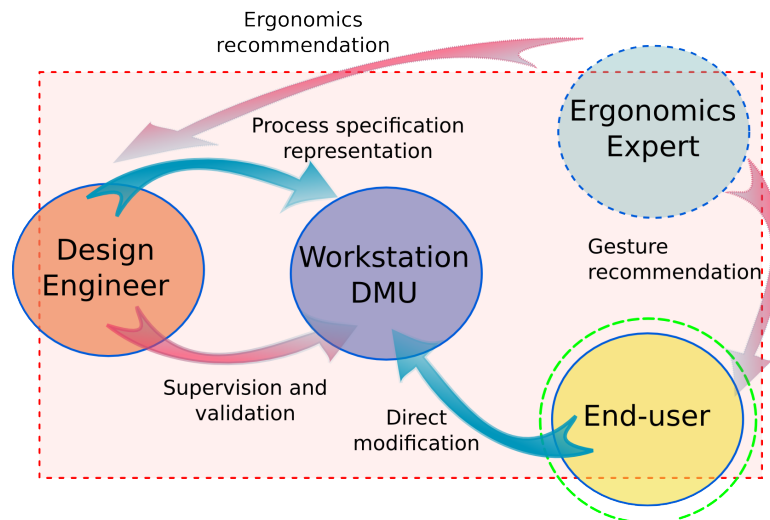.

Figure 4.7 – Supervision design mode in a collaborative DMU workstation with the end-user's main role highlighted in green. Figure is directly adapted from [PDD14]
.

one. The first level zone is closer to him in which he can reach and manipulate a DMU element easily. The larger second-level zone in which he works with little difficulty and discomfort. Last, the largest third-level zone in which he needs to make effort to reach an element. In order to represent these three levels of the reachable zone, three colors are used to encode them as in [PDD14]: green for the first-level zone, yellow for the second-level, and red for the third-level. The end-user can use an interaction tool to

determine or 'draw' his reachable volume. If the end-user works in a CAVE^{TM} with a tracking system, he can use a flystick device[1] to draw his reachable volume by his natural hand gestures as he is using a paintbrush to draw in the air.

As simple as this three-color encoding would seem, after some preliminary studies, we found out that for a better performance, it would be sufficient for the end-user to use only one color to represent his maximum reachable volume. In the viewpoint of the design engineer, he can approximately estimate the comfort volume of the end-user without using three colors representing three adjacent volumes, as we can see in figure 4.8c. Furthermore, in the proposition of [PDD14], the end-user draws his reachable volume using both hands equally as can be seen in figure 4.9. We propose in this study that the end-user uses only one hand because of it would be easier for the end-user if he pays attention to only one interaction tool. The end-user does not need to use both hands unless a bi-manual manipulation technique is required in the application.

In our DMU application, the final working volume of the end-user is calculated based on his reachable volume on a table (an example of a workstation) excluding the dead volumes specified by the design engineer. The reachable volume of the end-user is mostly drawn on the table to provide more information of his usability and availability recommendations to the design engineer who has a top view of the workstation. Besides, the objective of the collaboration is to determine the position of the DMU's elements in the workstation that satisfies the two preceding conditions. In other words, the goal of the workstation design modification is to manipulate the DMU's elements (in our use case one DMU element) into the final working volume of the end-user on the table. Therefore, it would make sense if the design engineer would know the reachable limits of the end-user on the table rather than his limits volume in the air. Nevertheless, our system enables the end-user to draw his reachable zone interactively and freely while standing (see figure 4.8). This information can clearly give the design engineer an idea of the position of the end-user at that moment as well as his reachable volume. Using this color encoding and natural hand gestures for drawing to dynamically describe a spatial volume is a simple but powerful interaction and communication technique to be applied in a collaborative DMU application. Drawn lines could disappear after a while in the virtual environment in order to prevent these lines disturbing manipulation tasks.

In the second operating mode, the design engineer needs some visualisation metaphors to represent workstation recommendations to the end-user and possibly to the ergonomics expert. The workstation specifications, in our use case, are characterized by 'dead volumes' that appear in the workstation. These dead volumes may be the obstacles present in the workstation that the end-user must not access to. The design engineer hence needs interaction metaphors to describe more specifically the dead volumes to the end-user and to express if the modifications made by the end-user in the workstation have a low, medium or high impact on the workstation design. In the same way as in the first operating mode, we use translucent volumes with the three-
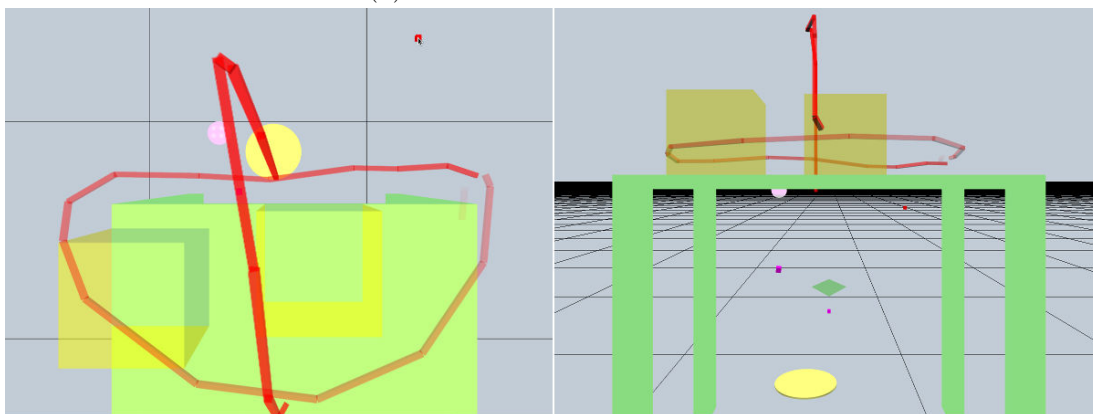
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[1] http://www.ar-tracking.com/products/interaction-devices/flystick2/
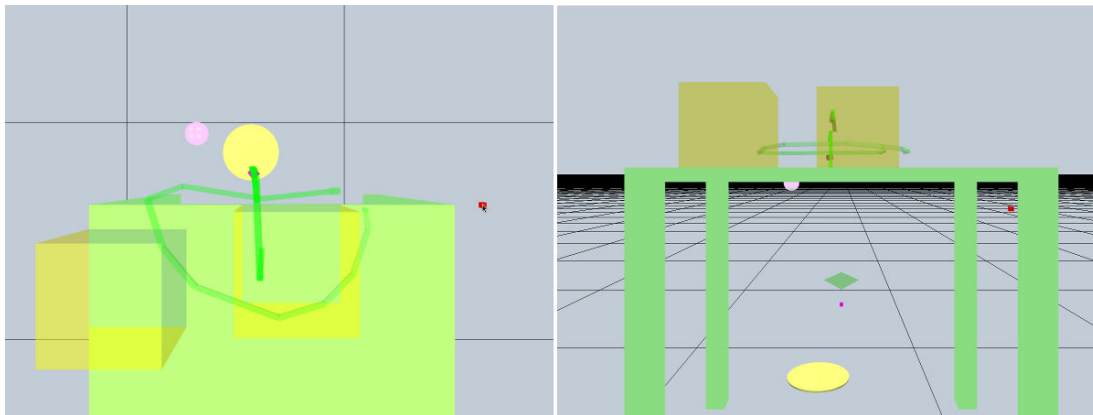
(a) First-level reachable zone.
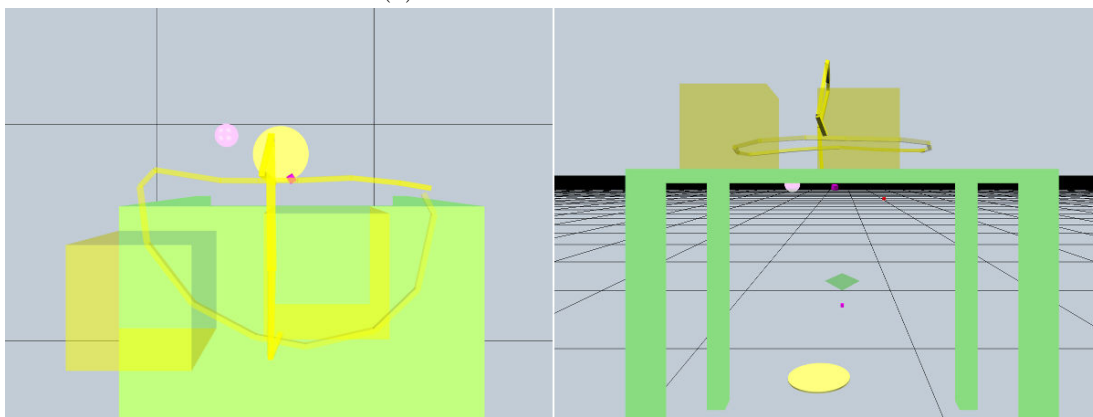
(b) Second-level reachable zone.

(c) Third-level reachable volume.

Figure 4.8 – The end-user draws his reachable volume while standing in a CAVE^{TM} using hand gestures from the top views (left) and front views (right) of the design engineer.
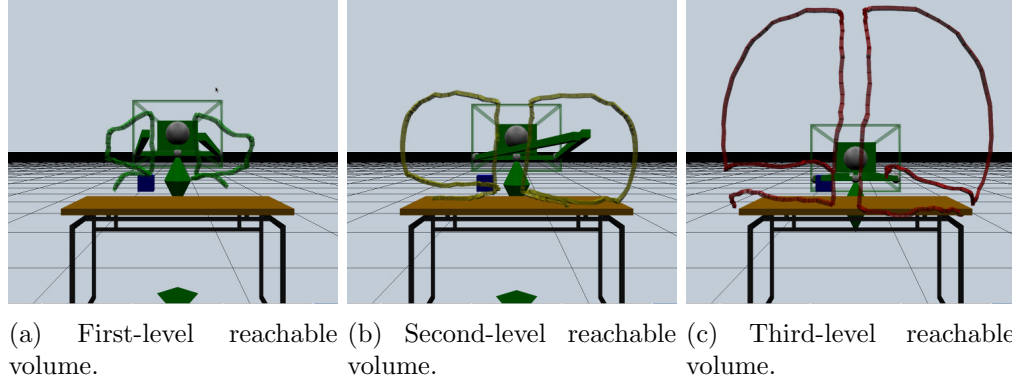
(a) First-level reachable volume.

(b) Second-level reachable volume.

(c) Third-level reachable volume.

Figure 4.9 – The end-user draws his reachable volume using hand gestures [PDD14]

color code metaphor for the design engineer. The design engineer can draw red volumes to indicate the dead zones of the workstation that the end-user cannot trespass. Yellow volumes represent a risk if the end-user works in these zones. Green volumes show safe zones recommended to the end-user (see figure 4.10). The design engineer can remove these volumes once the workstation design process is done or if he wants to redraw them once more. Since the engineer often works in front of a desktop system, we use a simple 3D cursor driven by a mouse. However, it does not mean that our system restricts the engineer to use other interaction tools to draw dead volumes. He can be immersed in a CAVE[TM], or he can wear a HMD device and use different kinds of interaction devices such as a flystick, a Razer Hydra, a Wiimote to perform these interactions.

(a) Design engineer's viewpoint.
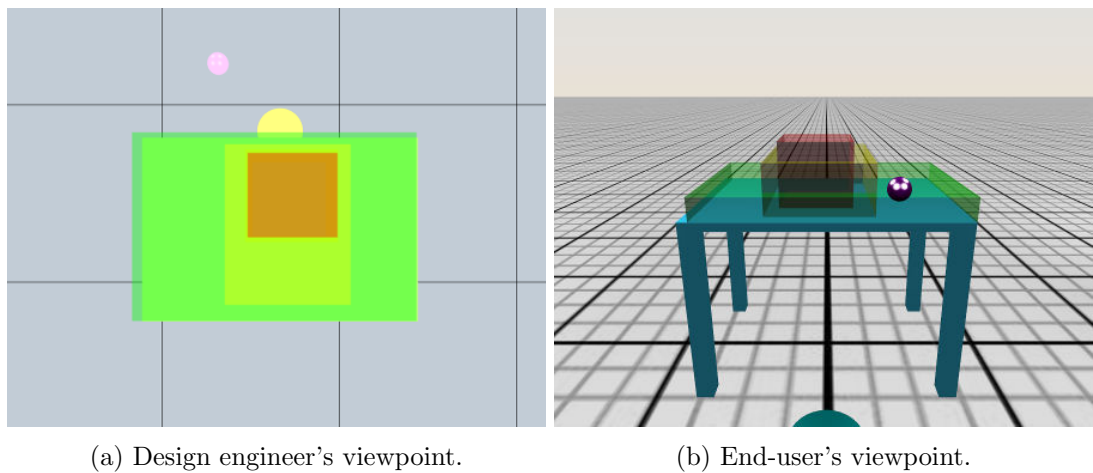
(b) End-user's viewpoint.

Figure 4.10 – Three volumes representing process specification of the workstation drawn by the design engineer. The red volume indicates the dead volume that the end-user cannot touch, the yellow volume shows the zone that the engineer does not want the end-user to trespass, and the green volume represents the safe zone of the workstation.

Considering the four factors (i.e. immersion, awareness, naturalness and commu-

nication channels) that we study in this research, from the preliminary evaluations of
several users after using our DMU application, we can estimate that the interaction
metaphors are natural in terms of expressing the usability and availability recommenda-
tions from the end-user and of describing the workstation specifications from the design
engineer. We have considered the difference in levels immersion of the end-user and the
design engineer in order to develop different interaction tools that are appropriate for
the two operating modes. Furthermore, the interaction metaphors used by the end-user
and the design engineer can be considered as an implicit communication channel for the
two users to express their own working conditions or the workstation design specifica-
tions. We do not need in this case an explicit communication channel such as a verbal
communication line to establish a mutual understanding between the two users. In the
same way, these communication metaphors can increase the awareness process for each
user so he can be aware of the current situation of the other. For the design engineer,
he can observe all the activities of the end-user through his representing avatar. For
the end-user, however, he can only be aware of the design engineer's presence when
the engineer changes the current state of the workstation. We can consider, in this
use case, an asymmetric collaboration between the two users in a workstation design
process.

4.3   Evaluation

As mentioned above, the ultimate goal of the three users in the workstation design
process is to establish a workstation that satisfies its specifications and the physical
comfort of the end-user. In order to achieve this goal, we have developed two possible
operating modes described in section 4.2.2. The aim of this evaluation was to identify
which operating mode, direct design mode or supervision design mode, was the most
efficient and suitable operating mode in the workstation design process. We also aimed
at evaluating the usability of the system from the end-user's point of view based on the
physical discomfort criterion.

4.3.1   Context

In the first operating mode (the direct design mode), we evaluated of the workstation
design process when the design engineer directly modified a DMU element based on the
reachable volume given by the end-user. In order to simplify the evaluation without
losing its interest, in the second operating mode (the supervision design mode), the
end-user controlled the same DMU element based on the information of the worksta-
tion specifications given by the design engineer. We measured the performance of the
manipulation in terms of completion time and distance difference between the final
position of the DMU element and its expected position, which was calculated from the
scene generation module described in next section 4.3.2. The role of the ergonomics ex-
pert in both operating modes was to analyze offline RULA scores (see more information
in section 3.4.4.2) of the end-user. These scores were used to evaluate the physical dis-
comfort criterion of the end-user's postures as he was working with the DMU element

once it was placed in its final position on the table, either by himself or by the design engineer. The result of these scores allows us determine, from the comfort criterion of the end-user, which operating mode provides a better position of the DMU element.

We implemented the two operating modes in our system to perform the experiment. The end-users of the experiment were immersed in a big CAVE^{TM} of four walls of which the size was 9.60 m long, 3.10 m high and 2.88 m deep. This system used 13 stereoscopic projectors to immerse the end-users in a high-quality visual world. They wore a pair of active shutter glasses to see the virtual environment in 3D. We also used an ART (Advanced Realtime Tracking) tracking system with 16 cameras to locate the position and orientation of each immersed end-user's head to adapt the scene to his point of view. The end-users used a Flystick to drive a 3D cursor - an interaction tool to either grab and manipulate the DMU element or draw reachable volumes. The design engineers of the experiment had a simpler interface on a desktop computer with two windows, which provided a top-view and a front-view of the virtual environment. We used a simplified avatar of the end-users in the world to represent their current activities to the design engineers. The engineers used a mouse to drive a 3D cursor to manipulate the DMU element in the direct design mode or to draw dead volumes in the supervision design mode. The engineers were able to remove the dead volumes that they judged to have been unnecessary or badly drawn. The engineers and end-users were not supposed to use verbal communications to exchange information. We have predefined some messages to inform the end-users and the engineers about in which operating mode they were working, when they finished their task in order to record the completion time and the distance difference.

In order to compute the discomfort metrics of the end-users, we used nine trackers (including trackers for two lower arms, two upper arms, two wrists, neck, trunk, and head) to record their postures during the experiment. Due to the difference in height of the end-users, these trackers were calibrated for each end-user at the beginning of his session and were initialized in the same neutral standing posture for all the end-users (see figure 4.11). The positions of these trackers were recorded at the frequency of 60 Hz during the experiment and were analyzed offline later to compute the RULA metrics.

Although we offered for the end-users the three-color code of the interaction metaphors to express different levels of reachable volumes, in this experiment, after a preliminary evaluation, we found out that for a better performance, it would be sufficient for an end-user to use only one color to represent his maximum reachable volume, as explained in 4.2.3. Therefore, we only asked the end-users in our experiment to draw their maximum reachable volumes in green. The same thing was also asked for the engineers to represent only the dead volumes of workstation specifications and the end-users had to estimate themselves the risk and safe zones out of these dead volumes. Figure 4.12 illustrates a reachable volume drawn by an end-user in a CAVE^{TM} and figure 4.13 shows a setup of the engineer's interface in our experiment.
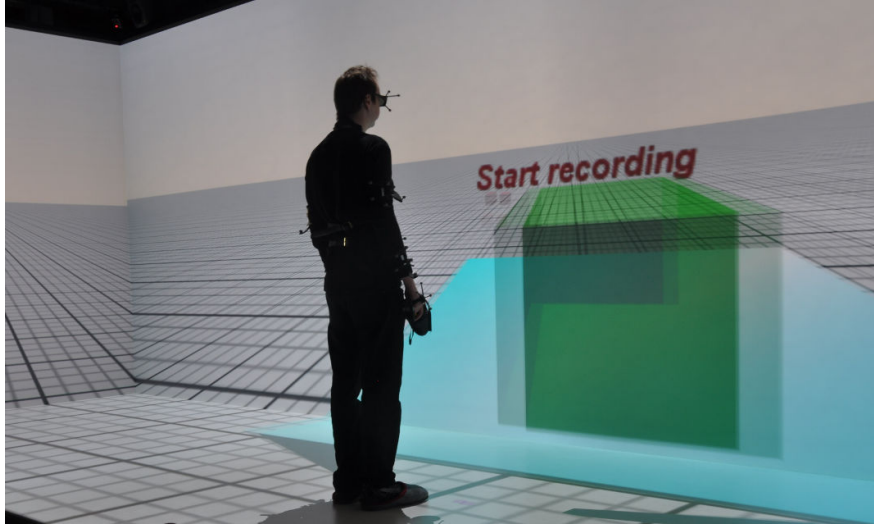
Figure 4.11 – Calibration process of all nine trackers on the end-user's body with the tracking system.
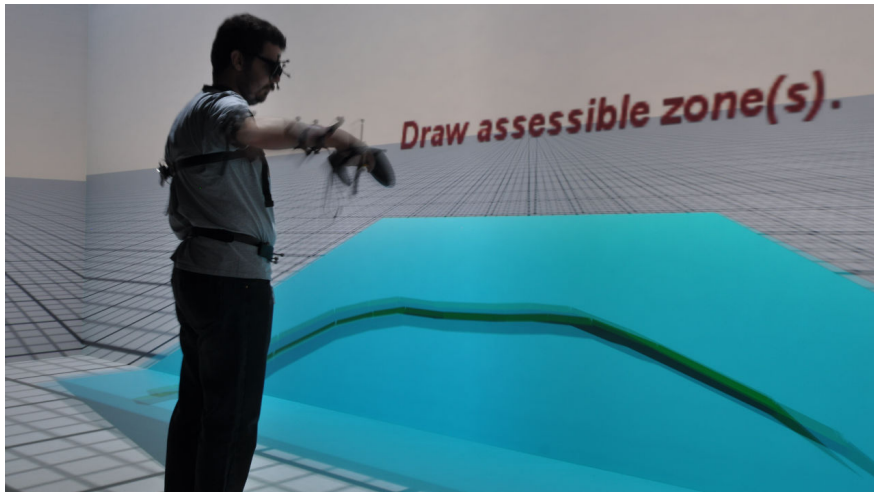

Figure 4.12 – End-user drawing the limits of his reachable volume on the table.

4.3.2   Scene generation

In this section, we will explain how we built different workstation design specifications for our experiment. These specifications have been obtained thanks to a scene generation module that have been implemented by Simon Hilt, an intern in our team, and Charles Pontonnier, our colleague.

In our experiment, we used a table as a common workstation. For each workstation design specification, a DMU element was initially placed at a predefined non-optimal position and therefore, the end-user needed to adopt uncomfortable postures to reach

Figure 4.13 – Interface of the engineer workstation.

and operate it. We examined different parts or volumes of the workstation as illustrated in figure 4.14. Volume U is defined as the reachable space of the end-user at an arranged position P in front of a working volume V. The volume U is specified by the end-user and may be pondered by the ergonomics expert considering to the ergonomics criteria, while the working volume V is determined by the design engineer taking into account process specifications. All the actors in the workstation design process try to find a compromise between the end-user's comfort criteria and the process specifications, which consists in finding an intersection volume $W = U \cap V$ of the reachable volume U and the working volume V. An example of an intersection volume is illustrated in figure 4.15. We used only a cube-shape representation for dead volumes of the working volume. However, the interaction tools of our system can represent different shapes of the dead volumes according to the requirement of the workstation specifications such as spheres, cylinders, or 3D models.

In our use case study, the workstation design specifications for each collaborative scene (we will call it a *scene*) characterized by the position of dead volumes had to be automatically generated. These workstation design specifications had to be unique but comparable in terms of level of difficulty. The level of difficulty of a workstation design specification was decided by the number of dead volumes present in the workstation, their position on the table, and their relative position to the standing position of the end-user. To generate randomized scenes of equivalent difficulty, we assumed that a relevant indicator of difficulty can be extracted from the size and the reachability of the reachable zone of the end-user. This is why we created a difficulty criterion that is a pondered volume of intersection between U and V. The randomized parameters used to generate the scenes were: the dead volumes positions, the end-user's position and the initial position of the DMU element. For a generated scene, we first computed the following pondered volume:
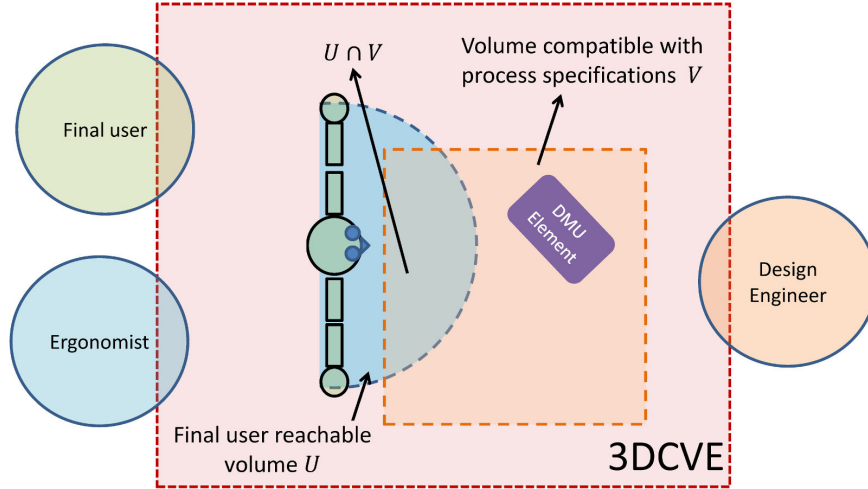
Figure 4.14 – The use case aims at finding a position for an element of the workstation satisfying both constraints: being reachable in a comfortable posture by the end-user (being in volume U and satisfying the process specifications (be in volume V) [PDD14]
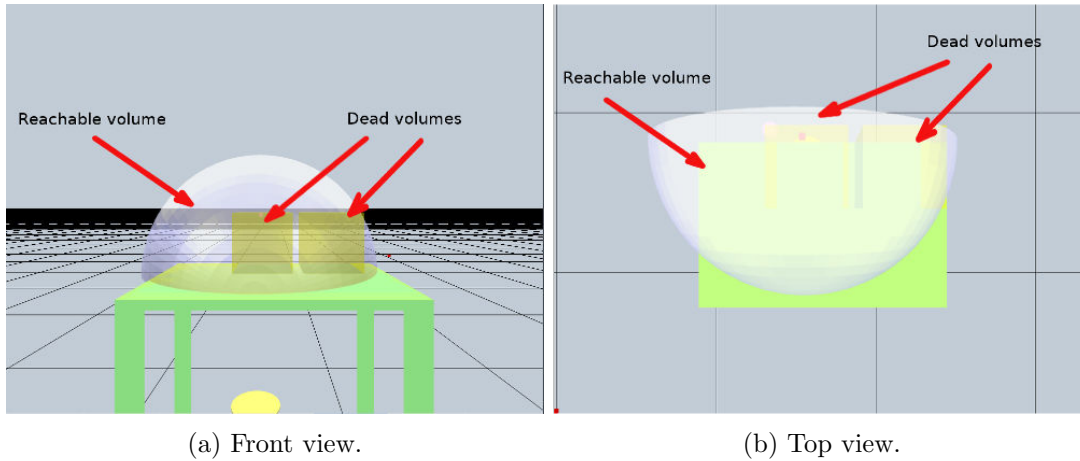.

(a) Front view.   (b) Top view.

Figure 4.15 – Intersection volume W of the reachable volume U of the end-user in form of a quarter of a sphere and the working volume V of the process specifications including an available volume of a rectangular table excluding dead volume(s).

$$W = \sum w_e \cdot r_e \qquad (4.1)$$

Where W is the pondered volume, w_e an elementary element of the volume $U \cap V$, and r_e is the reachability weight associated to this element. r_e was obtained by computing the RULA score for the considered volume w_e, depending on the expected end-user's position and its morphology. The RULA score is an indicator of postural discomfort

[MC93] used in relation to assessment of physical risk factors. The RULA score represents a good indicator of discomfort. A minimal score of 1 indicates a relatively comfortable posture, whereas a maximal score of 7+ indicates a highly uncomfortable posture. Here, only the arm and forearm score were used to assess the final score. Once obtained, the RULA score was used to compute r_e for each elementary volume w_e using the non linear relationship described in figure 4.16. This non linear scale was used to penalize the high RULA scores obtained in some ill generated scenes. The product $w_e \cdot r_e$ was finally summed on the complete $U \cap V$ volume to obtain W.
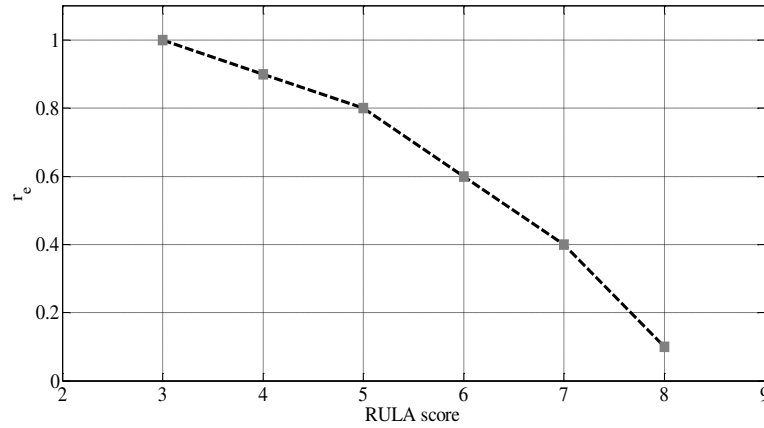

Figure 4.16 – Non-linear relationship between the RULA score and r_e. This was designed to penalize and discard the scenes with a poor amount of easily reachable volume.

Once obtained W, the difficulty of the scenes was pondered by adjusting the initial position of the element to place. We used the NIOSH method to assess the difficulty of placement of the element [WPAGF93]. The NIOSH equation was initially developed to rate a lifting task between two positions. We used it at a constant weight to adjust the distance between the initial point and the center of the $U \cap V$ intersection volume, to compute the W^* difficulty score of the scenes.

Finally W^* was used to gather the scenes by difficulty. From a representative set of scenes, we chose two levels of difficulty that led to a relative easiness of resolution and a sufficient challenge, corresponding to the scenes with one or two dead volumes. Then, a large set of '1 dead volume' or '2 dead volumes' scenes was generated for each considered morphology, and only 12 scenes by level of difficulty were kept from the initial set for each morphology, guaranteeing for each subject a different set of scenes.

We have generated six categories of manipulation tasks for both operating modes based on the height of subjects (see Table 4.1). In each category, we have generated 32 different scenes (16 scenes with one dead volume, and 16 scenes with two dead volumes). The selection process of these scenes in each category was arbitrary. In total, we have created 96 scenes with one dead volume and 96 scenes with two dead volumes, which were completely different but equal in terms of level of difficulty. In these scenes, the distance between the initial position of the DMU element and its expected position was

(a) One dead volume.   (b) Two dead volumes.
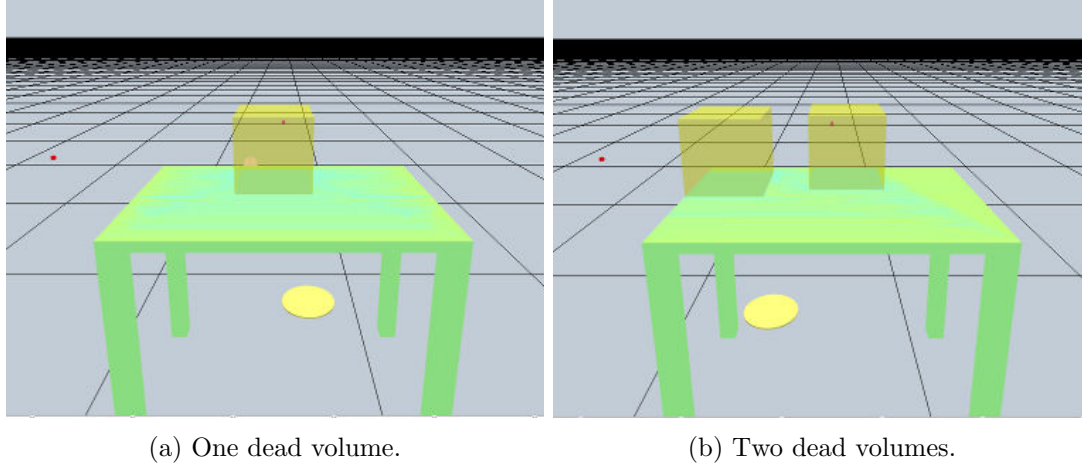
Figure 4.17 – Level of difficulty of a workstation design was described as the number of the dead volumes exist on it according to process specifications.

also approximately equal from scene to scene.

Table 4.1 – Categories of generated scenes for both operating modes of the experiment were calculated based on the average height of each group of subjects.

Category	Height Range (cm)	Average Height (cm)
Cat. 1	156 - 160	158
Cat. 2	161 - 165	163
Cat. 3	166 - 170	168
Cat. 4	171 - 175	173
Cat. 5	176 - 180	178
Cat. 6	higher than 180	183

For each session of our experiment, two subjects played an end-user role and an engineer role. In detail, 12 scenes were chosen for two operating modes from a 32-scene category regarding the height of each end-user: three scenes for the direct design mode with one dead volume, three for the direct design mode with two dead volumes, three for the supervision design mode with one dead volume, and three for the supervision design mode with two dead volumes. We arbitrarily chose 12 scenes from a pool of 32 scenes in order to avoid the influence of a specific scene on the final results. Six scenes, including three scenes with one dead volume and three with two dead volumes, were used in the first operating mode, i.e. in direct design mode. Six other scenes, including three scenes with one dead volume and three with two dead volumes, were used in the second operating mode, i.e. in supervision design mode. The 12 scenes were totally arbitrarily ordered in each session in terms of level of difficult and operating mode to be performed. Once they had finished 12 scenes of the two operating modes, they exchanged their role and performed 12 new scenes chosen from a 32-scene pool

Table 4.2 – Within-subjects factors of our experiment.

Factors	Levels	Description
Difficulty	1 dead volume 2 dead volumes	See figure 4.17a See figure 4.17b
Operating mode	Direct design mode Supervision design mode	Engineer active - end-user passive Engineer passive - end-user active

according to the height of the new end-user.

4.3.3 Population

The subjects of our experiment were recruited among our colleagues in our laboratory and our students. These subjects were volunteering their time and received no reimbursement beyond light refreshments. Sixteen subjects (one female and fifteen males) aged from 20 to 30 took part in this experiment (average: 24.8, standard deviation: 2.83). Their height average was 179 cm and varied from 161 to 190 cm (standard deviation: 8.54). Most of the subjects had experience in 3D virtual worlds but not specifically in immersive environments (average: 4.67 in a 7-point Likert scale from 1 to 7). Since two subjects participated in an experiment session and then exchanged their role, we have had 32 data sets in total for statistical analysis.

4.3.4 Procedure

Before beginning the training phase, two subjects of one session were verbally instructed about the experiment procedure, the two interfaces (the immersive interface for the end-user and the desktop one for the engineer) and the interaction tools and controls (flystick, mouse and keyboard). The goal of the experiment and the requirements of the two different operating modes and two levels of difficulty were also explained to them. One of the subjects was first equipped with the nine trackers on his body. These trackers were firmly put on his body so that during the manipulation they stayed firmly in place and then the discomfort metrics would be consistent and correct for each subject. The calibration was done each time a new end-user was equipped with the trackers.

The training phase was done each time with four scenes (one one-dead-volume scene and one two-dead-volume scene for the direct design mode, one two-dead-volume scene and one two-dead-volume scene for the supervision design mode), which were chosen

arbitrarily from the scenes pool for the end-user. This session enabled the end-user and the engineer to familiarize themselves with the manipulation of the DMU element, the drawing of reachable volumes and of dead volumes.

In the evaluation session, twelve scenes were loaded one after another to both the end-user and the engineer. A message would appear on the screen of the engineer and in front of the end-user in the immersive environment to inform them the current scene was for the direct design mode or for the supervision design mode. A signal would be given to both subjects to indicate the start of a manipulation task. The task finished when both the end-user and the engineer agreed on the final position of the DMU element and validated it. The end-user was then asked to put his hands on the DMU element for three seconds for recording the position of all the trackers on his body (see figure 4.18). They had to exchange the role in the last part of the session. The training and the evaluation phases were also carried out in the same way as in the first part of the session. The average time of an experimental session for two subjects was about 60 minutes.
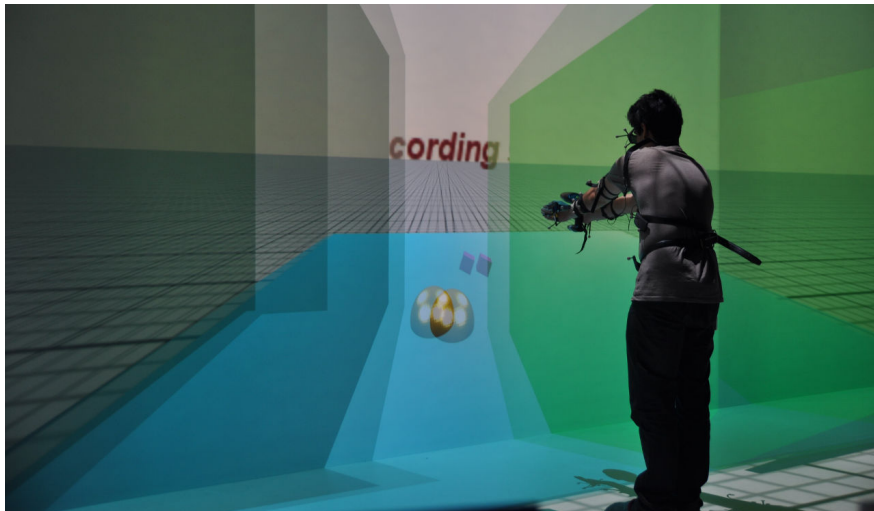

Figure 4.18 – End-user putting his hands on the DMU element for three seconds to record the position of all the trackers on his body. The RULA scores will be computed from this data.

4.3.5   Efficiency and discomfort measurement

In order to identify the most efficient resolution method between the direct design mode and the supervision design mode we presented in the last sections, we measured the completion time and the distance between the expected position of the DMU element on the table and its final position in each task. We also aimed at evaluate the usability of the system from the end-user's and the ergonomics expert's point of view using the postural scores RULA.

The completion time is a direct measurement of the efficiency of each operating mode. The time was started by our system technician when both the end-user and the engineer were ready. The final completion time was recorded when both of them agreed and validated the final position of the element. The efficiency of each operating mode also was estimated using the distance between the expected position and the final position of the DMU element. The expected position was computed for our scene generation engine based on the position of the end-user and the position of the dead volume(s) in the workstation. We only took into account the distance computed using the coordinates x and y projected on the table plane. The difference in the z coordinate did not make any significance if we considered the working scenarios in the real life.

The discomfort measurement was computed using the Rapid Upper Limb Assessment (RULA) scores as we did in section 3.4.4.2. In order to obtain a correct discomfort measurement, we recorded the position and orientation of the trackers' outputs on the end-user's upper body as he was trying to grab the element with both hands only in three seconds without making any movement. The postural RULA scores were then computed from these data.

In the end of each experimental session for two subjects, both of them answered a questionnaire about a general comparison of the two roles in the two operating modes as well as the simplicity, difficulty, and similarity of the scenes. Some demographic information was also recorded detailing the age, gender, height, weight and 3D experience of the subjects.

4.3.6 Results

Using the data collected from the experiment, we conducted a statistical analysis to evaluate the most efficient resolution operating mode in a collaborative workstation design DMU.
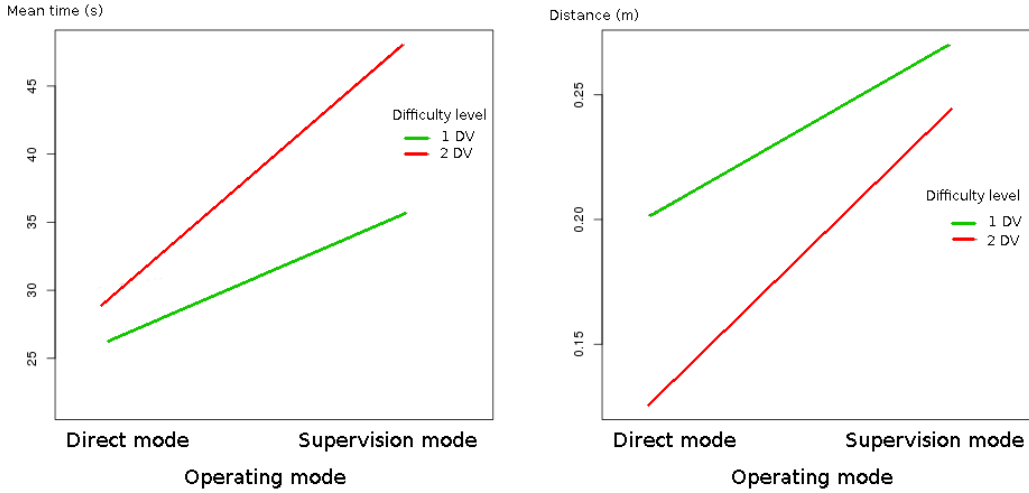
4.3.6.1 Completion time and distance difference

We studied two factors in our experiment: the two operating modes (i.e. the direct design mode and the supervision design mode), and the level of difficulty that was differentiated by the number of dead volumes in each scene, on the completion time and the distance criteria. We computed the p-values of the time and the distance using a two-way ANOVA analysis with repeated-measures for balanced design and within-subject factor to answer the following questions:

- Do the time and the distance difference results depend on the operating mode?

- Do the time and the distance difference results depend on the level of difficulty?

- Do the time and the distance difference results depends on the operating mode differently for different levels of difficulty, and vice versa?

Figure 4.19 showed the interaction plots of the completion time and of the distance difference on the two operating modes with two different levels of difficulty. The result

revealed that there was a significant interaction effect between the level of difficulty and the operating mode factors on the completion time ($F(1,47) = 5.876$, p-value = 0.019). However, we could not find any evidence of a significant interaction effect between the level of difficulty factor and the operating mode factor on the distance value ($F(1,47) = 0.1493$, p-value = 0.7009). The results of the test for the main effect of both factors also showed no significantly independent effect on the distance value (the result of the level of difficulty factor: $F(1,47) = 2.188$, p-value = 0.146, the result of the operating mode: $F(1,47) = 0.038$, p-value = 0.846).

(a) Interaction plot of the completion time.   (b) Interaction plot of the distance difference.

Figure 4.19 – Interaction plots of the completion time (left) in second and of the distance difference (right) in meter .

4.3.6.2   Discomfort metrics

We analysed the RULA score using the univariate repeated-measures two-way ANOVA with Greenhouse-Geisser adjustments if necessary. Figure 4.20 represented the interaction plots of the RULA scores on the two operating modes with two different levels of difficulty. We found a significant interaction effect between the level of difficulty factor and the operating mode factor on the RULA score ($F(1,47) = 9.5507$, p-value = 0.003).

4.3.6.3   Subjective questionnaire

We have collected 16 data sets for the questionnaire from 16 subjects in our experiment. Table 4.3 and figure 4.21 summarized the mean and standard deviation values of the first part of the questionnaire. They represented a general evaluation of our experiment on the 7-point Likert scale (from 1 to 7) in terms of level of difficulty of the scenes (Difficulty), the complexity of the end-user and the design engineer roles (Complexity),
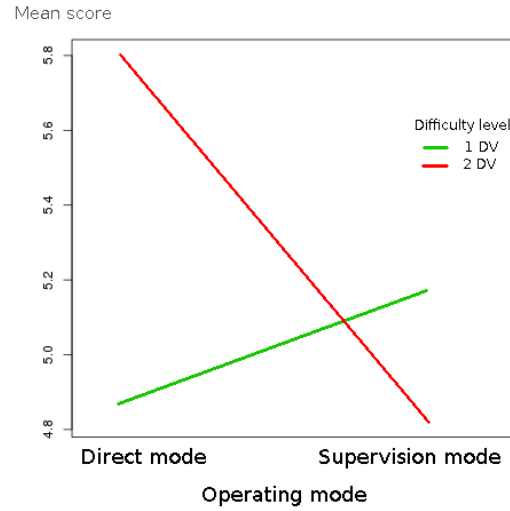
Figure 4.20 – Interaction plots of the RULA scores.

the adaptability of the interaction metaphors (Adaptability), and the difference between scenes (Difference). From the results, we could conclude that the subjects found the scenes used in the experiment were easy to solve and the two roles they played were simple. We had a high appreciation from the subjects about the adaptability of the interaction metaphors. Last, the scenes we used in the experiment were not perceived as very similar one to another.

Table 4.3 – Mean and standard deviation values of the general evaluation of the experiment set-up on the 7-point Likert scale.

	General evaluation			
	Difficulty	Complexity	Adaptability	Difference
Mean	2.00	2.50	5.31	3.56
Std	0.89	1.46	1.01	1.55

The second part of the questionnaire represented a general comparison between the two roles in terms of comfort, intuitiveness, fatigue, naturalness, and efficiency (from -3.5 for the engineer to 3.5 for the end-user) as illustrated in table 4.4 and in figure 4.22. From the results, we could conclude that the subjects found the end-user role was much more intuitive and natural than the engineer role. The other criteria (comfort, fatigue, efficiency) did not show much difference between the two roles.
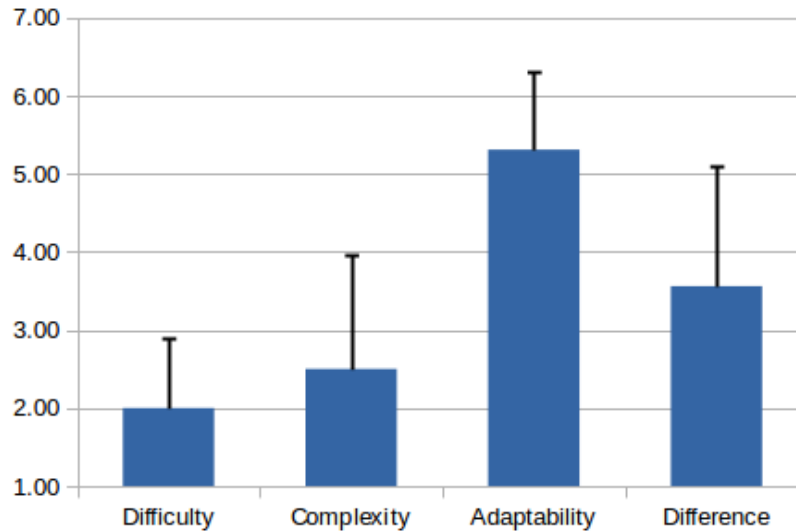
Figure 4.21 – General evaluation of the experiment set-up.

Table 4.4 – Mean and standard deviation values of the subjective comparison between the engineer role and the end-user role (from -3 for the engineer role to 3 for the end-user role).

	Comfort	Intuitiveness	Fatigue	Naturalness	Efficiency
Mean	0.37	2.25	0.68	1.68	0.93
Std	2.30	0.86	1.58	1.62	2.17

4.3.7   Discussion

Completion time

The statistical results revealed that there was a significant interaction effect between the level of difficulty factor and the operating mode on the completion time. It meant that if the engineer who controlled the DMU element in the direct design mode, it did not matter if there was one or two dead volumes in the working station: the completion time was approximately equal. This result could be easily explained by the fact that in the direct design mode, it was the engineer who manipulated the element from its initial position to the final position where he thought that the end-user could reach element. This manipulation was not affected by the complexity of the workstation design specifications because we did not use a physics engine for collision detection during the manipulation task of the design engineer.

In the supervision design mode, when the engineer had to draw dead volume(s) for the end-user, the more dead volumes he had to draw, the longer the time it took for
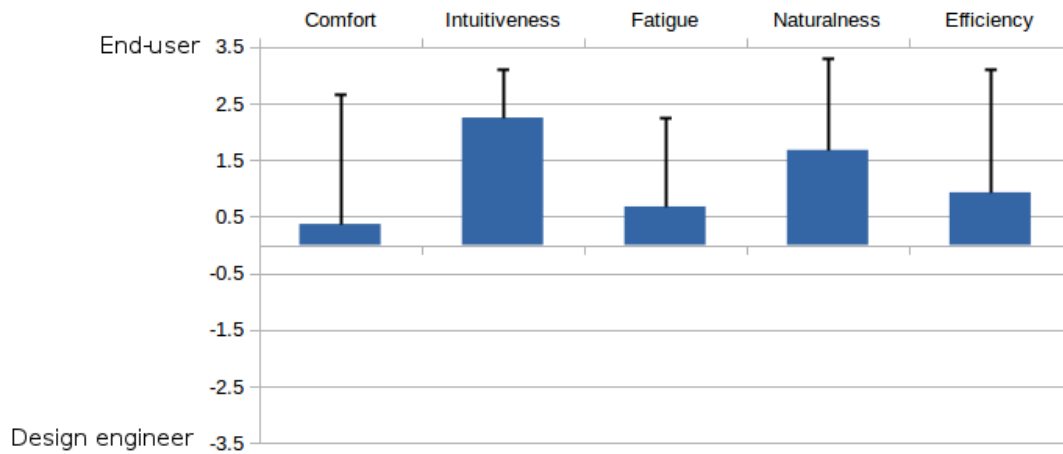
Figure 4.22 – Subjective comparison between the engineer role and the end-user role (from -3 for the engineer role to 3 for the end-user role).

both the end-user and the design engineer to complete the manipulation task. Consequently, the time it took for both the end-user and the engineer to complete a task in a complex workstation with two dead volumes was clearly longer than in a one-deadvolume workstation design (mean = 39.14, std = 19.49 and mean = 26.76, std = 8.03 accordingly). From this result, we can conclude that it was considerably faster if the engineer directly manipulated the DMU element because he had a global and complete view of the workstation design specifications and he did not need to describe these specifications to the end-user.

Distance difference

We considered the distance difference between the expected position and the final position of the element in the workstation as an important measurement to evaluate because it represents the accuracy of manipulation tasks. We found no evidence of a significant interaction effect between the level of difficulty and the operating mode factors on the distance difference value. The results of the test for the main effect of the operating mode and the level of difficulty did not revealed either any significantly independent effect on the distance difference value.

In our experiment, the expected position of the DMU element was calculated as an optimized position, which maximized the comfort of the end-user and satisfied workstation design specifications. However, the distance difference was a subtle measurement, especially in the level of difficulty with one dead zone. In this situation, the end-user and also the engineer had many potential places to put the element on the table out of the dead volume. Due to this reason, the mean value of the distance difference in the first-level difficulty was quite greater than the second-level difficulty although this

conclusion was not significantly confirmed by the statistical analysis.

RULA score

Regarding the results of the RULA score, we obtained a considerably high interaction between the two factors (i.e. level of difficulty and operating mode) on the RULA postural scores. In the direct design mode when the engineer controlled the DMU element, if there was only one dead volume, the engineer tried to put the element as close as possible to the end-user. However, in the second-level condition of difficulty, the engineer might not be able to correctly estimate the posture the end-user needed to make to reach the element where he put it. Due to this reason, the discomfort RULA score was greatly high compared to the score in other conditions. The postural discomfort was reduced in the same second-level difficulty but this time it was the end-user who manipulated the element. Because of the limited available volume for working, in the second-level difficulty condition, the end-user always tried to put the element in narrow places in order to be able to reach it easily. However, in our opinion, this conclusion could not be generalized because in our experiment, the subjects in the engineer role drew dead volume(s) in the position where they were regarding workstation design specifications. They did not consider the different levels of risks using three-color code that we have presented in section 4.2.3. If the end-user put the element too close to dead volume(s), the risk in the working process might arise. It would be a compromise to be found when the engineer represents the dead volumes using different colors to correctly express the limits of each volume.

Subjective questionnaire

Regarding the result of the subjective data, the subjects of the experiment thought that they had to solve different scenes whereas their level of difficulty was similar from one to another. We have then successfully restricted the possible learning effect of our experiment when the subjects worked on different scenes in the whole session. Another positive result that we obtained from the experiment is the high appreciation from the subjects about the adaptability of the interaction metaphors. They found them adaptable for an end-user and a design engineer working efficiently in workstation design processes.

The design of the interaction metaphors as well as the interface for the end-user role in an immersive virtual environment tend to make him more comfortable in the workstation design. This could lead to the fact that the end-user in our workstation design application is a more natural role, answering to proprioceptive constraints and involving the end-user's body in the workstation. On the other hand, the design engineer role is more technical, dealing with exteroceptive constraints and disconnecting the design engineer from his own representation in the collaborative workstation design. Consequently, the end-user role was much more intuitive and natural than the design engineer role. Therefore, most of the next improvements must focus on the design engineer role in order to make it more natural and easier to use.

In summary, on the one hand, if we consider the completion time as the most important aspect to achieve when the end-user and the engineer work collaboratively in a workstation design process, the engineer would be the one who should control the element instead of the end-user because he knows the workstation design more specifically than the end-user and he has not to describe the workstation design specifications to the end-user either. On the other hand, if we consider the comfort of the end-user in the workstation design as the main criterion to evaluate the performance of a DMU process, it would be better if the one who controls the element is the end-user. He has a real view of the workstation design from the first-person viewpoint and he can find a good spot to put the element regarding to his postural comfort.

4.4   Conclusion

We have implemented and evaluated two interaction metaphors into a DMU application with a specific purpose. After taking into account different aspects of a collaborative workstation in an immersive virtual environment including the difference in level of immersion, awareness process, communication, and naturalness, we have adapted and improved these metaphors in order to achieve a better performance.

More specifically, we have evaluated two interaction metaphors used for workstation design process in a collaborative DMU application. We have implemented two different interfaces for two roles in a workstation design process including a design engineer and an end-user. The design engineer had a desktop interface that provided multiple viewpoints and interaction tools to control the DMU's elements. The end-user was working in an immersive projection system with a high level of immersion and natural interaction techniques to facilitate a first-person viewpoint and to simulate the real workstation condition. Due to the two specific interfaces for the design engineer and the end-user, we have modified some interaction metaphors that have been proposed in [PDD14], making them simpler, more relevant and natural to our collaborative DMU application.

From our experiment, we have come to some conclusions concerning the collaborative workstation design. The statistical analysis of the data of the evaluation has revealed that in the direct design mode, the efficiency of the workstation design process was better achieved. On the other hand, if it was the design engineer who controlled the DMU element, the collaborative task was done faster than in the supervision design mode wherein the end-user controlled the element. On the other hand, we obtained a better comfort metrics of the end-user in the supervision design mode. It meant that if it was the end-user who controlled the DMU element, the element would be well placed, increasing the comfort criteria of the considered workstation design. Moreover, from the subjective questionnaire of the evaluation, the subjects of our experiment found that the interaction metaphor used by the end-user in the supervision design mode was more intuitive and easy to understand and use. The manipulation technique that was used in the immersive virtual environment for the end-user was also simple and natural. The task of the design engineer was more complicated because it required some

experience of working in 3D applications such as 3D modeling software. Nevertheless, both interaction metaphors were appreciated by our subjects. In general, they found them natural, intuitive, and efficient when working together in a collaborative virtual environment.

In the future, the role of an ergonomics expert would be dynamically added to the system along with his own interaction tools so he could change the workstation design and the working flow from the ergonomic requirements. In addition, the next improvement in our application must focus on the interface of the design engineer in order to make the interaction between design engineer - system as well design engineer - end-user more natural and easier to use. Moreover, the influence of different levels of immersion on the whole performance of the workstation design process could be verified. This could be done by implementing an interface for the design user with a higher level of immersion. The question would be that the efficiency of the workstation design process would stay still if we change the level of immersion of the design engineer.

Conclusion

This research is concerned with the design and evaluation of new interaction metaphors and techniques for navigation and manipulation in immersive collaborative virtual environments. This work has been organized around four factors that are very important for collaborative virtual environments: immersion, awareness, communication, and naturalness. These four factors are the main ones to consider when designing interaction techniques in collaborative virtual environments.

The immersion factor in a collaborative virtual environment may influence the whole scheme of collaboration between multiple users depending on the level of immersion at each user's site. A high level of immersion helps a user to feel the co-presence from others and to easily establish a mutual understanding with them. If the level of immersion is different from one site to another, an agreement about roles and working relationships can be formed between them. Therefore, due to a wide display-system-setup diversity, the developer of a collaborative interaction technique needs to take into account the difference in level of immersion into its design.

The second factor is the awareness of the user about his surrounding (virtual and physical) environments, about other users' whereabouts, and about coordinating activities. The awareness knowledge of the user is vital in a collaborative task because how is the user going to act and perform the task completely depends on his past and present situation awareness knowledge. The richer the awareness information is provided by the system, the easier it is for the user to work in a group of users with different viewpoints, interaction tools, understanding grounds, and different goals.

Since a verbal communication channel is easily implemented in virtual environments nowadays, the communication factor is often forgotten in the core design of an interaction technique. In our opinion, a communication channel between users must be also established to exchange information through implicit and tacit means: effects of the users' activities on the environment, state of interaction tools, or feedback of the system responding to the users' activities. The communication and awareness can be correlatively studied, considered as 'instruments' to complete collaborative tasks [ND14].

The naturalness aspect of an interaction metaphor or technique is the last but not least factor that must be taken into consideration. While dealing with the constraints and limitations of virtual reality systems, the designers of a collaborative virtual environment often attempt to 'bring' all possible actions of users in the real world into the virtual one. This is due to the fact that the intuitiveness, simplicity, ease of use of natural interaction techniques facilitate the interaction of users in the virtual world.

Contributions

Considering the influence of the four preceding factors in collaborative virtual envir-
onments, this research consists in studying, proposing and evaluating new metaphors
and techniques for 3D navigation and manipulation in a collaborative context.

In the first part of this research regarding interaction techniques for 3D collaborative
navigation, we have proposed a set of three navigation metaphors (or so-called guiding
techniques, including drawing directional arrows, lighting up path to follow, orientating
a compass to show a direction) [NFD12, NDF13a, NDF13b]. These techniques can be
dynamically implemented and used without constraints in any 3D virtual environments.
An experimental study has been done to evaluate these metaphors in a large complex 3D
virtual world. The result of the experiment has revealed that these guiding techniques
could reduce wasted time for an exploring user to build a cognitive map while travelling
in a large complex 3D virtual environment. We have studied the difference in level of
immersion between users into our design and thus have proposed an asymmetric working
relationship between them. The users with low level of immersion but full access to a
global and complete viewpoint of the virtual environment can help other users with high
level of immersion but limited access to the information of the environment to navigate
within it. Accompanying these navigation metaphors are some metaphors (e.g., using
a 3D grid, changing the brightness intensity of the virtual world) developed to improve
the awareness of the collaborator in an immersive virtual world [DNF+13]. These
awareness metaphors are not limitedly used in a collaborative exploration context, but
also can be easily applied for any immersive virtual environment. In the same way, a
set of color-code signals were also proposed to raise the awareness between users and
to exchange information about the state of their current activities. Furthermore, the
navigation metaphors can be used as a means to show direction of navigation, thus
being considered as an implicit communication channel in the collaborative task. From
a subjective evaluation from the subjects of our experiment, they found our metaphors
of navigation aids, of awareness and of communication, natural, simple, and intuitive
because these metaphors were inspired from the real world.

In the second part of this dissertation, our research focuses on the necessity of hav-
ing an efficient direct manipulation technique in immersive virtual environments. It is
very important for the design of a direct manipulation technique extensively dealing
with the difficulties the user encounters in immersive projection systems. The hand
jitter and Heisenberg effects happen making the manipulation imprecise. Our direct
manipulation technique, called 7-Handle technique including a set of seven handles,
has solved this imprecision issue by dividing the number of degrees of freedom (DOF)
of an object into fewer DOF of each handle. Our manipulation technique provides for
the user the capability of partially controlling the object, making the manipulation
of large objects easier in immersive virtual environments. In addition, our technique
offers the possibility of cooperative manipulation between users, improving its usability
in different manipulation contexts. We use a set of color metaphors assigned to handles
to represent their state and their availability, enriching the awareness information of
the interaction technique to the user. We have also implemented proxy points, a set of

representing 'mediators' used to reflect the current movement of the user's hand (and of others' if in the cooperative context) and at the same time to represent the constraints between handles of the interaction technique. Thanks to these proxy points, the user can perceive his current activities (and the others' activities if in the cooperative context) and how the manipulation tool responds to his control. The implicit and tacit communication channel in our manipulation technique is combined with the awareness improvement design. In the naturalness aspect, the subjects of our study did not find our technique natural at first because it took time for them to learn how to efficiently control the 7-Handle in different contexts. However, once they had learned how to use it, they came to appreciate the flexibility of our technique and the high precision they can obtain for manipulating objects in immersive virtual environments. This 7-Handle technique and the result of our study are reported in [NDP14b] and have been demonstrated during the ICAT-EGVE 2014 conference [NDP14a].

In the last part of this dissertation, we have studied how to adapt two interaction metaphors proposed in [PDD13, PDD14] into a specific collaborative use case - a digital mock-up application - considering the four preceding factors. From the necessity of having an optimal immersion for the whole system and natural interactions between two users, i.e. an end-user and a design engineer, we have implemented an asymmetric setup in terms of immersion for them. Indeed, the end-user was immersed in a CAVE^{TM} system with a first-person's interface because it was important for a workstation design that the ergonomic factor was examined when the end-user worked in a virtual workstation as he did in the real one in a long-time condition. Moreover, using the tracking system of a CAVE^{TM} could help an ergonomics experts to measure some ergonomic metrics from the end-user's working posture such as RULA and/or REBA scores. On the other hand, since the design engineer often works with desktop interface and uses designing applications such as computer-aided design (CAD) software, it would be natural if he had different viewpoints of the shared workstation with appropriate interaction tools and multiple control options. Concerning the awareness and communication factors, they were implemented through communication metaphors between the end-user and the design engineer. From the previous work of this research, we have developed some effective implicit communication metaphors. We have then applied them into this collaborative workstation context by modifying some existent communication metaphors, making them simpler, more relevant and natural, and fitting in our collaborative DMU application. Additionally, an avatar was also implemented to virtually represent the end-user in real-time, making it easier for the design-engineer to observe and be aware of all the activities of the end-user. The use of a simple avatar therefore naturally enhanced the awareness of the design engineer about the end-user in the shared environment. Last, the naturalness of the interaction metaphors that we used in our DMU application were highly rated by the subjects of our experiment, especially for the end-user role. Indeed, we have considered the naturalness factor as the most important aspect when designing the interface for the end-user. The end-user could use natural interaction metaphors such as hand gestures using effective interaction tools while working in an immersive virtual environment. He was also able to intensely involve himself in the workstation design considering his own postural comfort.

Future work

Our research focuses on proposing and evaluating new interaction metaphors and techniques for 3D navigation and manipulation while preserving immersion and facilitating the collaboration between multiple users. In the future, we still need to continue to fully and extensively evaluate these new metaphors and techniques.

For the new navigation metaphors in the collaborative exploration context, we have only implemented an asymmetric relationship between the users: one or several users with a low level of immersion help an exploring user with a higher level of immersion to explore a large and complex virtual world. It would be interesting to further evaluate the ease of use, the simplicity, and the efficiency of our navigation metaphors if the helping users were also immersed in the virtual world. In order to perform this evaluation, some appropriate interaction metaphors must be developed to be adaptable to the new working condition of the helping users, even though the navigation aids would stay the same. Additionally, from our empirical study, we found some limitations of these navigation aids such as the occlusion of arrows and compass in the first-person's viewpoint in an immersive display system, which somehow disrupts the immersion and the workflow of the exploring user. In the future, these navigation metaphors should be improved to overcome their limitations.

Our direct manipulation 7-Handle technique still needs further improvements and evaluations. In an immersive virtual environment, the empirical study showed that our manipulation technique did not outperform the 'classical' 6-DOF manipulation technique in the manipulation task of small objects. This is due to the fact that it was easier for the user to control small objects with 6 DOF if he has a global view of them during the manipulation. Due to this reason, we could combine the 6-DOF technique with ours so users can have more options of control in different manipulation contexts. Our technique could still be improved by providing a more dynamic way of configuring the set of seven handles and a possibility of hiding this 7-Handle tool if necessary. We consider this improvement important because when working in an immersive virtual environment, the better feeling of presence the user gets and the more natural the virtual world appears to him when the less present (artificial) interaction tools are in the world. In addition, to completely evaluate the 7-Handle technique by different criteria, further experiments of the impact of the shape and size of objects in the manipulation performance must be conducted. Furthermore, we would evaluate and compare the performance of our manipulation technique in different levels of immersion: when the user is immersed in a CAVE$^{\text{TM}}$ system, wears a HMD device, or works on a desktop computer. His feeling of presence under these conditions also must be studied more extensively.

From the use case of chapter 4, as in the collaborative exploring task or the direction manipulation technique, the same question must be asked is if we enhance the immersion condition for one of the users with a low level of immersion, is that whether or not the efficiency and the performance of the workstation design process would stay the same. Additionally, in the next step, we must focus on the improvement of the design engineer's interface in order to provide a more natural interaction between design en-

gineer - system and design engineer - end-user. Last, in order to enrich the utility of our application, in the future, the role of an ergonomics expert would be dynamically added along with his own interaction tools so he could change the workstation design and the working flow in real-time.

For a bigger picture of natural interaction techniques for collaborative virtual environments in consideration of the immersion and naturalness preservation, there are still many questions and problems, which have not been answered and solved. We would further investigate the priority order in which the four main factors (immersion, awareness, communication, and naturalness) would be considered the most important for a given collaborative navigation and manipulation context. Another problem that we would study is the question of how the presence of a user in the collaborative virtual environment would be perceived by others. In our collaborative scenarios, the relationship between different users is often asymmetric: one user is aware of all the activities of the others but not conversely, unless when the first user wants to make an impact on the world. This problem could be extended to another one: if we replace one user by an artificial agent, would the other users still perceive the same presence?

Publications

- **Journal Paper and Refereed Conference Papers**

    1. *A New Direct Manipulation Technique for Immersive 3D Virtual Environments*
       Thi Thuong Huyen Nguyen, Thierry Duval, Charles Pontonnier, in Proceedings of the 24th International Conference on Artificial Reality and Telexistence and the 19th Eurographics Symposium on Virtual Environments (ICAT-EGVE), p. 67-74, Bremen Germany, December 2014.

    2. *Improving Awareness for 3D Virtual Collaboration by Embedding the Features of Users' Physical Environments and by Augmenting Interaction Tools with Cognitive Feedback Cues*
       Thierry Duval, Thi Thuong Huyen Nguyen, Cédric Fleury, Alain Chauffaut, Georges Dumont, Valérie Gouranton, in Journal on Multimodal User Interfaces (JMUI), Vol 8, p. 1-11, December 2013.

    3. *A Survey on Communication and Awareness in Collaborative Virtual Environments*
       Thi Thuong Huyen Nguyen, Thierry Duval, in Proceedings of IEEE International Workshop on Collaborative Virtual Environments (3DCVE), p. 1-8, Minnesota US, March 2014.

    4. *Guiding Techniques for Collaborative Exploration in Multi-Scale Shared Virtual Environments*
       Thi Thuong Huyen Nguyen, Thierry Duval, Cédric Fleury, in Proceedings of the International Conference on Computer Graphics Theory and Applications (GRAPP), p. 327-336, Barcelone Spain, February 2013.

    5. *Embedding the Features of the Users' Physical Environments to Improve the Feeling of Presence in Collaborative Virtual Environments*
       Thierry Duval, Thi Thuong Huyen Nguyen, Cédric Fleury, Alain Chauffaut, Georges Dumont, Valérie Gouranton, in Proceedings of the International Conference on Cognitive Infocommunications (CogInfoCom), p. 243-248, Kosice Slovakia, December 2012.

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- **Posters and Demonstration Papers**

  1. *Demonstration of the γ-Handle Technique*
     Thi Thuong Huyen Nguyen, Thierry Duval, Charles Pontonnier, in Proceedings of the 24th International Conference on Artificial Reality and Telexistence and the 19th Eurographics Symposium on Virtual Environments (ICAT-EGVE), p. 21-22, Bremen Germany, December 2014.

  2. *Demonstration of Guiding Techniques for Collaborative Exploration in Multi-Scale Shared Virtual Environments*
     Thi Thuong Huyen Nguyen, Thierry Duval, Cédric Fleury, Demonstrations de la conférence francophones sur l'Interaction Homme - Machine (IHM), p. 1-2, Bordeaux France, November 2013.

  3. *3-Point++: a new Technique for 3D Manipulation of Virtual Objects*
     Thi Thuong Huyen Nguyen, Thierry Duval, in Proceedings of IEEE Symposium on 3D User Interfaces (3DUI), p. 165-166, Florida US, March 2013.

  4. *Collaborative Exploration in a Multi-Scale Shared Virtual Environment*
     Thi Thuong Huyen Nguyen, Cédric Fleury, Thierry Duval, in Proceedings of IEEE Symposium on 3D User Interfaces, p. 181-182, California US, March 2012.

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Proposition de nouvelles techniques d'interaction 3D et de navigation 3D préservant l'immersion de l'utilisateur et facilitant la collaboration entre utilisateurs distants

Résumé du manuscrit

Thi Thuong Huyen NGUYEN

1.   Introduction

Les développements récents de la réalité virtuelle font du travail collaboratif assisté par ordinateur un outil prometteur et flexible. Il est en effet aujourd'hui possible, de représenter les données ainsi que les utilisateurs eux-mêmes de manière vivante dans les environnements virtuels collaboratifs (EVC). Les EVC se définissent comme des mondes virtuels distribués, générés par ordinateur, dans lesquels les utilisateurs peuvent se rencontrer, communiquer et interagir entre eux, mais aussi avec des données et des objets 3D. Les utilisateurs peuvent être éloignés physiquement, parler des langues différentes et utiliser des systèmes informatiques hétérogènes tout en collaborant malgré tout au sein d'un EVC. L'objectif principal des EVC est de proposer une collaboration fluide entre plusieurs utilisateurs. Ceci implique de prendre en charge un nombre considérable d'échanges, de communications et de négociations mais également de permettre des activités collaboratives. Par ailleurs, il est nécessaire de proposer des techniques d'interaction ainsi que des moyens pour bien prendre conscience de tout ce qui se passe dans l'environnement.

Afin de préserver ces différents aspects dans la conception des EVC, nous nous intéressons à quatre facteurs essentiels : l'immersion, la conscience, la communication et l'intuitivité. Ces facteurs sont déterminants pour le succès des systèmes virtuels collaboratifs. Un haut niveau d'immersion peut aider un utilisateur à percevoir la présence des autres utilisateurs et à facilite la mise en place d'une compréhension mutuelle. De plus, un système d'EVC doit fournir un support efficace pour que l'utilisateur ait conscience de tout ce qui se passe dans son environnement, des activités des autres ainsi que des activités collaboratives en cous. Par ailleurs, grâce à la richesse de l'information qui supporte la prise de conscience, les utilisateurs doivent pouvoir collaborer facilement entre eux même s'ils ont des points de vue différents, des outils d'interaction variés ou encore des rôles et des objectifs différents. Un autre facteur à considérer est la communication entre des utilisateurs. En plus de la communication verbale, qui est souvent utilisée dans des EVC mais reste problématique en raison des différences de langues parlés, des chaînes de communication

implicites peuvent être mise en place ou elles peuvent être représentées par des métaphores et techniques d'interaction. Ces métaphores de communication doivent être intuitives et simples pour faciliter la compréhension mutuelle entre les utilisateurs. L'aspect naturel des techniques d'interactions se mesure à la fidélité de l'interaction qui s'assure que les actions effectuées dans le virtuel correspondent à l'action équivalentes effectuée dans le réel. Des interactions plus naturelles sont, pour l'utilisateur, plus performantes, plus utilisables et elles améliorent son sentiment de présence.

2. Objectifs de la thèse

En tenant compte des quatre facteurs cités plus haut, nous proposons et évaluons de nouvelles métaphores pour la navigation et la manipulation afin d'améliorer et d'enrichir les techniques d'interactions dans les EVC. Cette recherche a été réalisée en prenant en compte les points importants suivants :

- Dans des EVC, il est nécessaire d'améliorer les techniques d'interaction et de communication entre des utilisateurs tout en préservant leur niveau d'immersion. Le concept de chaînes de communication peut être étendu à l'utilisation des métaphores d'interaction car elles sont des moyens de communication indirects mais implicites entre des utilisateurs.

- Les techniques d'interaction proposées doivent être le plus naturel possible. De plus, le facteur d'immersion est pris en compte dans la conception des techniques d'interaction naturelles car la même interaction peut être évaluée naturelle ou pas en fonction de niveau d'immersion chez chaque utilisateur.

- Les nouvelles technique et métaphores proposées doivent permettre à chaque utilisateur d'un EVC d'être au courant des activités des autres ainsi que des changements de l'environnement virtuel mais aussi de son environnement réel.

3. Proposition de nouvelles métaphores pour la navigation collaborative dans des environnements virtuels immersifs

La navigation est une tâche fondamentale et conséquente pour toutes les applications de réalité virtuelle tout comme dans le monde réel [Burigat et al., 2007]. Cependant, la navigation est souvent un support à une autre tâche plutôt qu'une tâche en soi. Pour cette raison, les techniques de navigation se doivent d'être simples et intuitives de façon à n'impliquer que des processus cognitifs inconscients et non contrôlés par l'utilisateur. Dans un contexte collaboratif, le temps consacré pour s'orienter dans le monde peut être réduit considérablement grâce à l'assistance d'un autre utilisateur

qui a une vue globale et complète du monde.

Nous avons proposé dans ces travaux de recherche, trois métaphores de navigation collaborative : indiquer un chemin en dessinant des flèches, illuminer un chemin à suivre et orienter une boussole pour montrer une direction (cf. figure 1). Ces métaphores de navigation sont considérées comme naturelles car elles sont utilisées de manière éprouvée dans la réalité comme des outils de navigation et d'exploration.
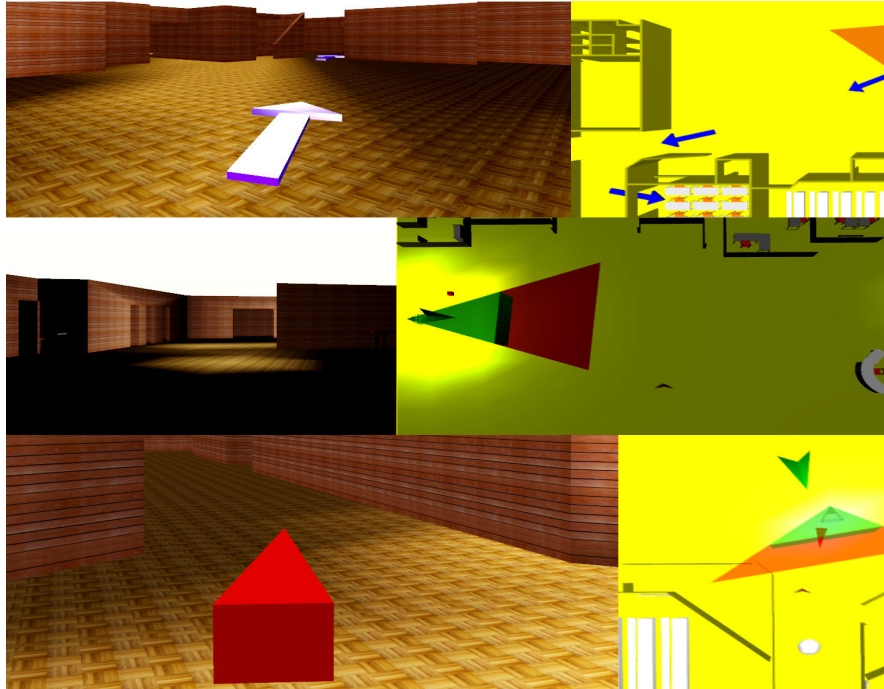

Figure 1: Trois métaphores de navigation collaborative : flèches directionnelles, source de lumière et boussole.

Nous avons également proposé des métaphores de communication non-verbale utilisant des signaux de couleurs pour échanger des informations et des états du système. De plus, afin d'améliorer la prise de conscience de l'environnement physique par l'utilisateur dans le monde virtuel immersif, nous avons implémenté des métaphores de prise de conscience pour prévenir l'utilisateur s'il se trouve à une distance seuil des écrans de projection (cf. figure 2).

Nous avons mené une expérimentation pour évaluer la performance des trois types de métaphores de navigation dans un environnement virtuel étendu et complexe. Deux rôles différents ont été asymétriquement implémentés : un utilisateur qui explore le monde virtuel et un autre utilisateur qui est devant un ordinateur avec une vue global de l'environnement. Nos résultats révèlent que ces métaphores réduisent considérablement le temps passé à chercher un chemin dans des contextes d'exploration collaborative. De plus, ces métaphores de navigation, de

communication, et de prise de conscience peuvent être implémentées dynamiquement et utilisées directement dans n'importe quels environnements.
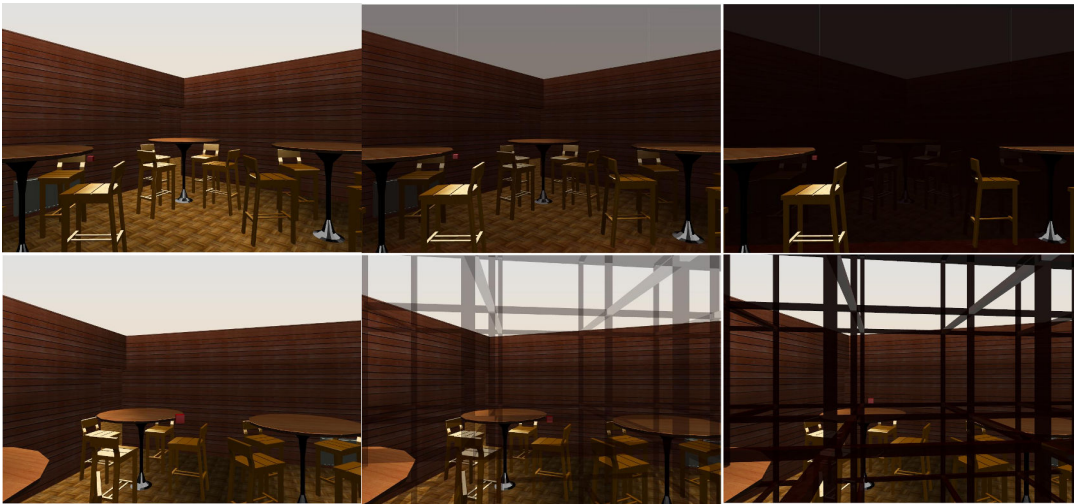

Figure 2: Deux métaphores d'awareness pour prévenir l'utilisateur la possibilité d'avoir une collision avec les écrans de projection : réduction de l'intensité de la lumière (haut) et affichage d'une grille 3D.

4. Proposition de nouvelle technique de manipulation dans des environnements virtuels immersifs

La manipulation d'objet 3D est l'une des interactions les plus importante et essentielle dans les EVC. L'objectif de ces travaux est de proposer une nouvelle technique de manipulation directe dédiée aux environnements virtuels immersifs. Une des difficultés pour un utilisateur qui travaille dans une monde immersif est de contrôler précisément et exactement les objets qui l'entourent. Des imprécisions qui proviennent des tremblements de main de l'utilisateur et de l'effet Heisenberg quand il n'y pas de support physique dans le monde virtuel. Une autre difficulté résulte de l'occlusion des objets dans la scène immersive quand leur taille est grande. En conséquence, la manipulation de grands objets dans l'environnement immersif est particulièrement difficile.

Afin de résoudre ces problèmes, nous avons développé une technique de manipulation qui utilise sept points de contrôle : trois points au premier niveau F1, F2, F3 et trois points au deuxième niveau S1, S2, S3 ainsi qu'un point au troisième niveau T (cf. figure 3). En réduisant le nombre de degrés de liberté de l'objet manipulé à l'aide de ces points de contrôle, notre technique permet à l'utilisateur de contrôler partiellement l'objet, rendant ainsi la manipulation d'objets volumineux plus aisée. Nous avons développé différents modes de contrôle pour l'ensemble des points comme la configuration, le verrouillage et le déverrouillage des points de contrôle et leur manipulation.

Dans le mode de configuration, l'utilisateur peut changer la position relative d'un point de

contrôle par rapport aux autres et par rapport à l'objet à manipuler. Ces positions relatives sont enregistrées et sont utilisées plus tard pour calculer la position de l'objet en fonction de la position des points de contrôle. Ce mode de configuration permet à l'utilisateur d'adapter la forme de notre outil de manipulation en fonction de la forme et de la taille de l'objet à manipuler.

Le mode de verrouillage qui est appliqué aux points de contrôle du premier niveau permet à l'utilisateur de verrouiller une partie de l'objet qui a été préalablement correctement position. Cette partie ne bouge plus après le verrouillage et cela facilite la manipulation d'autres parties de l'objet qui ne sont pas encore correctement positionnées. Quand un point de contrôle est verrouillé, l'utilisateur peut tourner l'objet autour de ce point (cf. figure 4). Si deux points de contrôle sont verrouillés, l'utilisateur peut tourner l'objet autour du côté formée par ces deux points.

Dans le mode de manipulation, en fonction de la position relative entre les points de contrôle et de l'état de chaque point (verrouillé ou libre), la position de l'objet est calculée à partir de la position du barycentre des sept points. Pour représenter le mouvement effectif des mains de l'utilisateur et les contraintes de l'outil, nous avons implémenté un ensemble de points de proximité qui sont attachés aux points de contrôle. Ils sont guidés par un dispositif interactif.
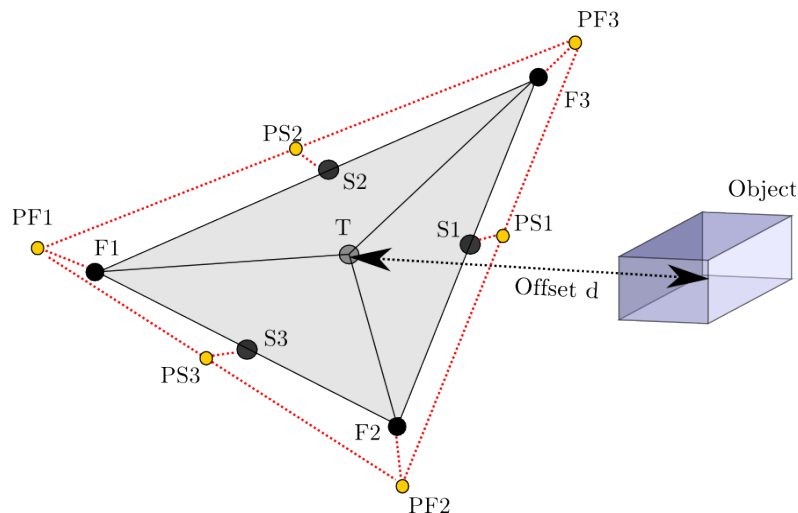

Figure 3: Ensemble de sept points de contrôle de notre outil de manipulation F1, F2, F3, S1, S2, S2, T

Le mouvement de chaque point de contrôle est donc fixé par la position de son point de proximité, par la forme de l'outil et par l'état de ses points de contrôle voisins (cf. figure 5). L'écart entre le point de contrôle et son proxy est représenté par un lien élastique.
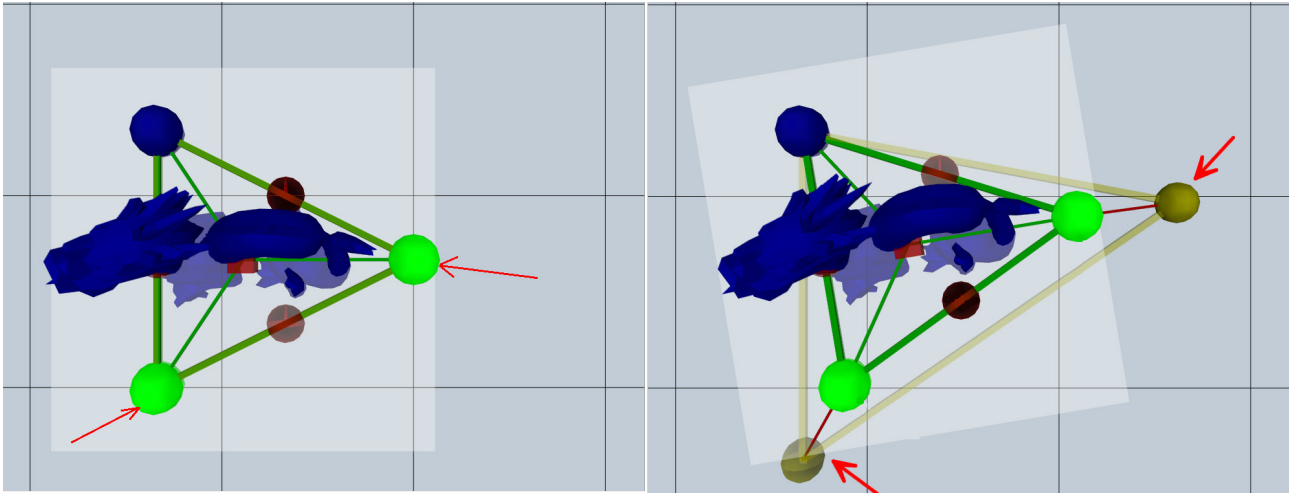
Figure 4: Manipulation de l'objet quand un point de contrôle au premier niveau est verrouillé (point bleu)
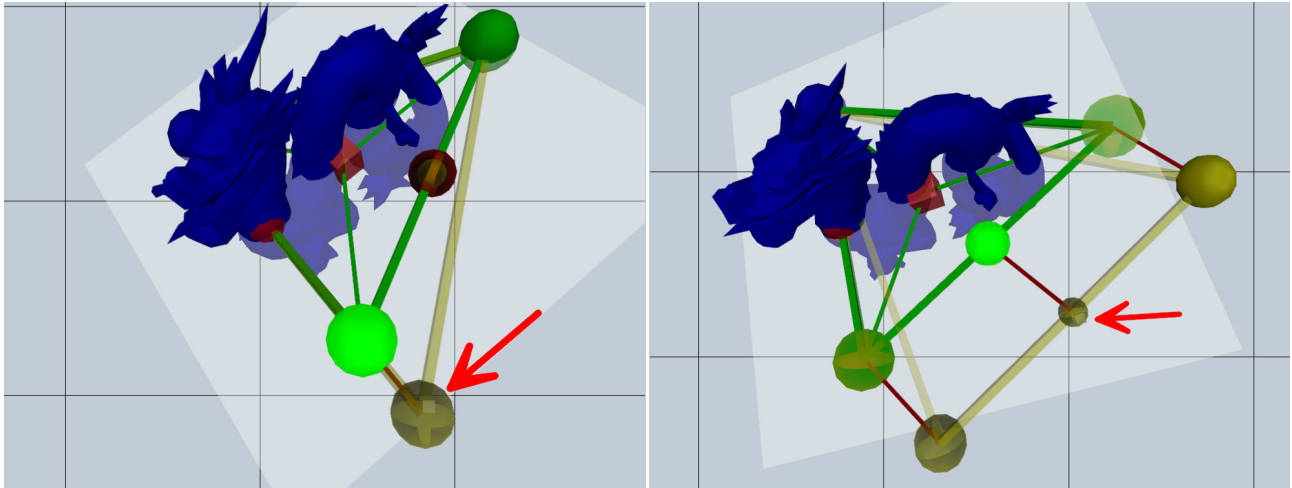

Figure 5: Manipulation d'un point de contrôle au premier niveau (gauche) et d'un autre au deuxième niveau (droit). Les points jaunes sont des proxies et des points verts ou rouges sont des points de contrôle.

Pour améliorer l'aspect de retour visuel renforcer l'awareness de l'utilisateur sur l'état de l'outil, nous avons utilisé un ensemble des couleurs pour représenter l'état de chaque point de contrôle. Quand le point de contrôle n'est pas contrôlé, il est vert pour montrer sa disponibilité. Si ce point devient rouge, il est contrôlé par un des ses voisins et sa position est déterminée par le calcul entre la forme de l'outil et la position actuel de ses voisins. Enfin, s'il est bleu, il est verrouillé et l'utilisateur ne peut pas le changer sa position. En plus, grâce aux proxies et le lien entre ces proxies avec des points de contrôle, l'utilisateur peut reconnaître la fonctionnalité et la possibilité de contrôle de l'outil dans chaque situation de manipulation. Le retour visuel permet aussi à l'utilisateur de reconnaître ses actions actuelles dans l'environnement. Puisque nous ne limitons pas le nombre de contrôles qui peut être effectué en même temps sur l'outil, deux ou trois utilisateurs peuvent

manipuler l'objet en collaboration. Dans ce cas, grâce à le retour visuel de l'état de l'outil, un utilisateur peut percevoir les mouvements actuels des autres et peut donc coopérer ses actions pour compléter la tâche. Dans une certaine manière, notre outil peut être utilisé comme un médiateur de communication pour la manipulation collaborative.

Nous avons mené une expérimentation pour évaluer et comparer la performance et la facilité d'utilisation de notre outil en comparaison avec la technique de 6 degrés de liberté (DDL). La performance et la facilité de ces deux techniques sont comparées en termes de la taille des objets à manipuler. Le résultat a montré que notre technique a prouvé plus efficace pour de grands objets en termes du temps à compléter les tâches, la fatigue et l'efficacité.

5. Métaphores d'interactions pour l'amélioration de l'awareness : application à la conception collaborative de l'ergonomie dans des environnements virtuels

Nous avons proposé plus haut des métaphores pour la navigation et la manipulation qui permettent d'améliorer l'immersion, la prise de conscience, la communication et l'aspect naturel des techniques d'interaction dans l'EVC immersifs. À partir des résultats obtenus, nous avons réalisé, dans cette partie de recherche, une implémentation et une évaluation des différentes métaphores dans un contexte collaboratif spécifique : une application de conception et d'aménagement de poste de travail industriel. Il y a trois types d'utilisateurs dans l'application de conception de poste de travail : un utilisateur final, un ingénieur de conception et un expert en ergonomie. Afin d'avoir un niveau d'immersion optimal et des interactions naturelles entre des utilisateurs, nous avons implémenté une configuration de système asymétrique pour chaque utilisateur. Chacun pouvait utiliser quelque métaphores de communication implicites qui étaient simples, naturelles, et pertinentes dans notre contexte collaborative.

L'utilisateur final travaille dans un monde virtuel immersif en prenant en compte des recommandations de design de poste de travail qui viennent de l'ingénieur et des recommandations de postures qui viennent de l'expert en ergonomie. L'utilisateur doit donc trouver une compromise entre les exigences du design et son confort physique dans le contexte de longues séances de travail. La raison pour laquelle nous avons immergé l'utilisateur dans un système immersive CAVE avec une vue subjective à la première personne était qu'il est important d'examiner le facteur ergonomique d'un design de poste de travail quand l'utilisateur final travail dedans comme il fait dans la réalité. En plus, en utilisant des systèmes de tracking du système CAVE, l'expert en ergonomie peut mesurer quelques paramètres ergonomiques du posture de travail de l'utilisateur comme des scores RULA / REBA. Nous avons implémenté une métaphore de communication pour

l'utilisateur qui lui permet de dessiner à l'ingénieur son volume accessible (on son zone de confort) dans un design de poste de travail (cf. figure 6).

En revanche, nous avons constaté que dans la réalité, l'ingénieur travaille souvent sur des ordinateurs et utilise des applications de conception comme CAD. C'est la raison pour la quelle nous avons implémenté des points de vue différents de l'environnement partagé avec des outils d'interaction appropriés (cf. figure 7). Nous avons représenté l'utilisateur final en un avatar simple pour montrer ses activités actuelles à l'ingénieur. Cette représentation facilite la prise de conscience de l'ingénieur sur toutes les activités de l'utilisateur en temps réel. Cependant, l'interface basé sur ordinateur permet aussi à l'ingénieur d'exprimer des spécifications de poste de travail utilisant trois couleurs différentes pour montrer des zones de sécurité et de dangers à l'utilisateur. La figure 8 représente trois simple zones de sécurité : l'accès au zone rouge restreinte, l'accès au zone jaune peut poser un problème et l'accès au zone vert est illimité.
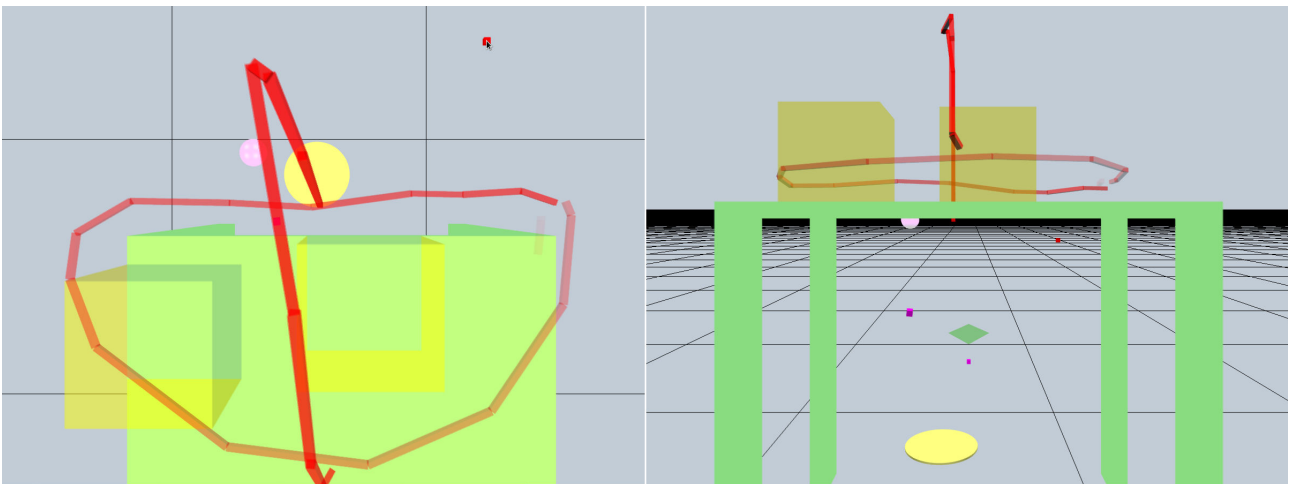

Figure 6: Un volume accessible dessiné par l'utilisateur dans le monde immersive utilisant un dispositif interactif de 6 degrés de liberté.

Ces deux métaphores de communication pour l'utilisateur et l'ingénieur sont utilisées deux mode d'opération. Le premier mode permet à l'utilisateur d'utiliser sa métaphore de communication pour dessiner son volume accessible et en se basant sur cette information, l'ingénieur peut manipuler un objet vers cette zone. Le deuxième mode permet à l'ingénieur d'utiliser sa métaphore de communication pour dessiner des zones de danger à éviter pour que l'utilisateur puisse manipuler l'objet hors ces zones. Le résultat a montré que l'aspect naturel des métaphores de communication étaient fortement appréciés par les participants de l'expérimentation, surtout pour le rôle de l'utilisateur final. En effet, nous avons considéré le facteur naturel le plus important dans la

conception de l'interface pour l'utilisateur. L'utilisateur peut utiliser des gestes de la main pour dessiner des zones accessibles dans un environnement immersif. Il peut s'intégrer lui-même dans le poste de travail pour estimer son zone le confort.
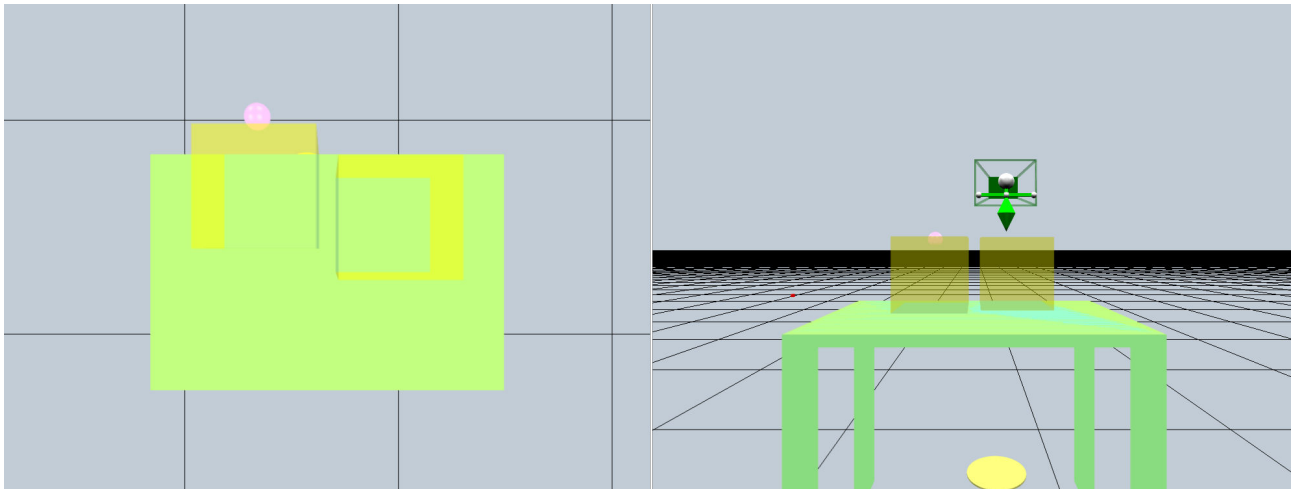

Figure 7: Deux points de vue de l'utilisateur sur un poste de travail
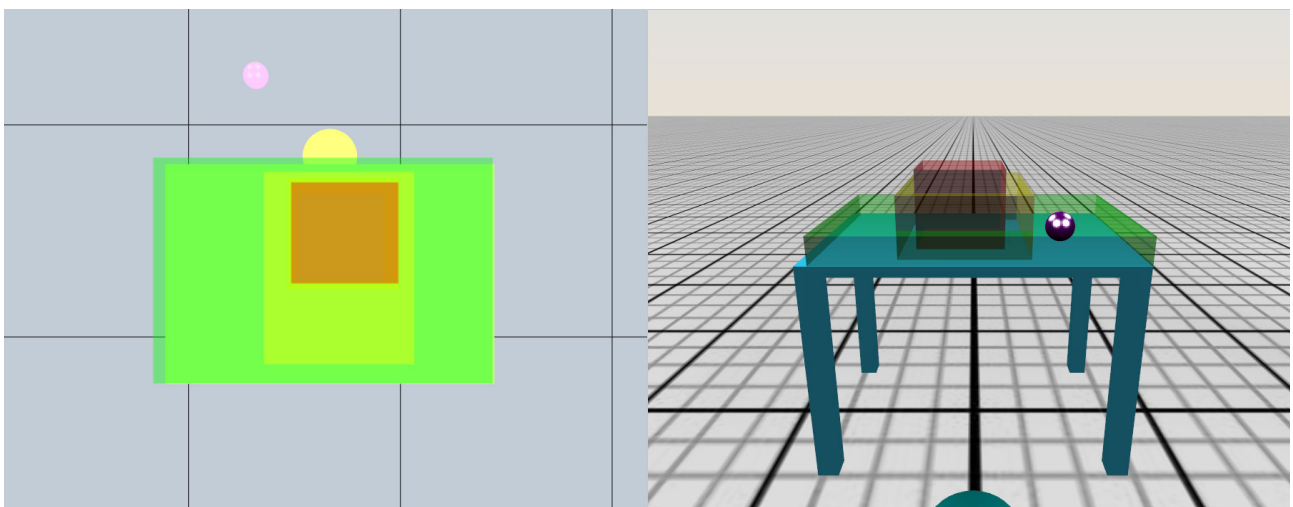

Figure 8: Exemple de représentation de trois zones de sécurité en cubes selon les spécifications de poste de travail

6. Conclusion et perspectives

Nous avons étudié dans ce travail quatre aspects qui sont les plus importants dans la conception d'une métaphore ou technique d'interaction dans un environnement collaboratif immersif. Ils sont l'immersion, la prise de conscience, la communication, et l'aspect naturel des interactions. Nous avons proposé trois métaphores de navigation collaborative pour qu'un utilisateur puisse aider un

autre qui n'a pas d'une connaissance complète de l'environnement. Une technique de manipulation direct a été également proposé pour faciliter la manipulation précise dans un environnement immersif où il n'y a pas assez de supports physiques. Nous avons aussi évalué une application de conception de poste de travail en implémentant et améliorant quelques métaphores de communication.

Dans le futur, plusieurs évaluations et expérimentations seraient nécessaires à mener pour évaluer à fond nos nouvelles techniques. Nous devrions étudier l'influence de l'aspect d'immersion sur la performance et l'efficacité de la collaboration quand nous mettrions en haut niveau l'aspect immersif pour des utilisateurs qui n'étaient pas immersif avant. Nous étudierions l'ordre de priorité dans lequel quel facteur serait considéré comme le plus important dans un spécifique contexte d'interaction. Un autre problème que nous étudierions serait comment la présence d'un utilisateur dans un environnement virtuel collaborative serait perçu par les autres. Dans nos scénarios de collaboration, la relation entre différents utilisateurs est souvent asymétrique : un utilisateur peut prendre de conscience de toutes les activités des autres, mais pas à l'inverse. Si on remplacerait un utilisateur par un agent virtuel, percevraient-ils les autres utilisateurs le changement ?

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Titre de la thèse:
Proposition de nouvelles techniques d'interaction 3D et de navigation 3D préservant l'immersion de l'utilisateur et facilitant la collaboration entre utilisateurs distants

Nom Prénom de l'auteur : NGUYEN THI THUONG HUYEN

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- Monsieur HACHET Martin
- Monsieur KUHLEN Torsten
- Monsieur DUMONT Georges
- Monsieur MESTRE Daniel
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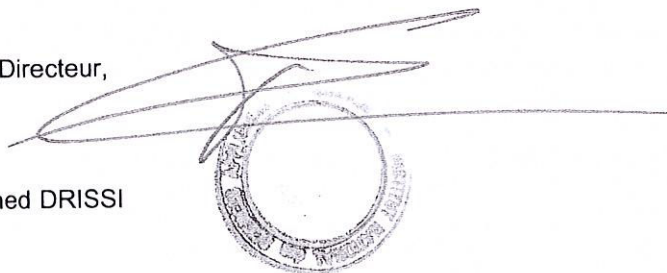~~Thèse pouvant être reproduite après corrections suggérées~~

Fait à Rennes, le 20 Novembre 2014

Signature du président de jury

Le Directeur,

M'hamed DRISSI

Résumé

Les développements récents de la réalité virtuelle font du travail collaboratif assisté par ordinateur un outil prometteur et flexible. Il est en effet aujourd'hui possible, de représenter les données ainsi que les utilisateurs eux-mêmes de manière vivante dans les environnements virtuels collaboratifs (EVC). Les EVC se définissent comme des mondes virtuels distribués, générés par ordinateur, dans lesquels les utilisateurs peuvent se rencontrer, communiquer et interagir entre eux, mais aussi avec des données et des objets 3D. Les utilisateurs peuvent être éloignés physiquement, parler des langues différentes et utiliser des systèmes informatiques hétérogènes tout en collaborant malgré tout au sein d'un EVC. L'objectif principal des EVC est de proposer une collaboration fluide entre plusieurs utilisateurs. Ceci implique de prendre en charge un nombre considérable d'échanges, de communications et de négociations mais également de permettre des activités collaboratives. Par ailleurs, il est nécessaire de proposer des techniques d'interaction ainsi que des moyens pour bien prendre conscience de tout ce qui se passe dans l'environnement.

Afin de préserver ces différents aspects dans la conception des EVC, nous nous intéressons à quatre facteurs essentiels : l'immersion, la conscience, la communication et l'intuitivité. Ces facteurs sont déterminants pour le succès des systèmes virtuels collaboratifs. En tenant compte des quatre facteurs cités ci-dessus, nous proposons et évaluons de nouvelles métaphores pour la navigation et la manipulation afin d'améliorer et d'enrichir les techniques d'interactions dans les EVC.

Premièrement, nous proposons et évaluons un ensemble de trois métaphores de navigation pour explorer un environnement à plusieurs : indiquer un chemin en dessinant des flèches, illuminer un chemin à suivre et orienter une boussole pour montrer une direction. Ces métaphores peuvent être implémentées dynamiquement et utilisées directement dans n'importe quels environnements. Nos résultats révèlent que ces métaphores de navigation réduisent considérablement le temps passé à chercher un chemin dans des contextes d'exploration collaborative. Par ailleurs, nous avons développé une technique de manipulation directe dédiée aux environnements virtuels immersifs. Cette technique, qui utilise sept points de contrôle, affranchit l'utilisateur de plusieurs difficultés souvent rencontrées telles que le tremblement de la main ou l'effet Heisenberg lors de la manipulation d'objets 3D dans un système de projection immersive. En réduisant le nombre de degrés de liberté de l'objet manipulé à l'aide de point de contrôle, notre technique permet à l'utilisateur de contrôler partiellement l'objet, rendant ainsi la manipulation d'objets volumineux plus aisée.

Enfin, nous avons implémenté et évalué deux métaphores d'interaction dans une application de conception et d'aménagement de poste de travail industriel. En tenant compte des quatre facteurs cités ci-dessus, nous avons implémenté une application de conception de poste de travail pour trois principaux types d'utilisateurs : un utilisateur final, un ingénieur et un expert en ergonomie. Afin d'avoir un niveau d'immersion optimal et des interactions naturelles entre des utilisateurs, nous avons implémenté une configuration de système asymétrique pour chaque utilisateur. Chacun pouvait utiliser quelque métaphores de communication implicites qui étaient simples, naturelles, et pertinentes dans notre contexte collaborative.

Abstract

Recent progress of the virtual reality technology gives the computer supported collaborative work a potential and flexible tool of vividly representing data as well as users themselves in collaborative virtual environments. Collaborative virtual environments have been defined as computer-based, distributed virtual worlds in which people can meet, communicate and interact with others, with data and 3D objects. People may be geometrically far from each other, speak different languages and use heterogeneous computer systems. The ultimate goal in developing collaborative virtual environments is to support a smooth collaboration between multiple users which involves considerable communication and negotiation, cooperative and collaborative activities, interaction techniques, and awareness process.

Considering these aspects into the design of a collaborative virtual environment, we are interested in four main factors, including immersion, awareness, communication and naturalness. These factors greatly determine the success of a collaborative virtual system. From the need of improving and completing interaction techniques in CVEs considering the four preceding factors, in this research we propose and evaluate new metaphors for 3D navigation and manipulation techniques.

The first contribution of this research is to propose and evaluate a set of three navigation metaphors in a collaborative exploration context, including drawing directional arrows, lighting up path to follow, and orientating a compass to show a direction. These navigation metaphors can be dynamically implemented and used without constraints in any 3D virtual environments. The empirical result of our experiment revealed that these navigation metaphors considerably reduced wasted time in a wayfinding task of a collaborative exploring scenario.

We have developed, in the second part of this research, a direct manipulation technique in immersive virtual environments. This manipulation technique deals with some difficulties the user often encounters such as hand jitter or Heisenberg effects while manipulating 3D objects in immersive projection systems. By dividing the number of degrees of freedom of the manipulated object into each handle of our tool, our technique enables a user to partially control the object, making the manipulation of large objects easier in immersive virtual environments.

The last contribution of this research is the implementation and evaluation of two interaction metaphors in a digital mock-up application. Taking into account the four factors including immersion, awareness, communication and naturalness, we have built a workstation design application for three main users: an end-user, a design engineer and an ergonomics expert. In order to have an optimal immersion for the whole application and natural interaction between them, we have implemented an asymmetric system setup at each user's site. Each user could use some implicit communication metaphors which were simple, natural and still relevant in our collaborative context.