Empty Museum. An Immersive and Walkable VRML2 Environment.

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ABSTRACT
This paper describes a new system for experimentation of three-dimensional, virtual reality (VR) environments, based on the creation of an immersive and walkable space we have named Empty Museum. The user can walk physically and freely around this virtual, three-dimensional space, without any wire connections and while observing multimedia contents included into the same area. Work has consisted on the design of the hardware and controlling software for this immersive space, but also on the creation of an application that allows the user to visualize any type of VRML 2.0 content in this VR hall, enabling us to create various animated and interactive worlds. These experimental worlds have served, on one hand, to analyze the user's response to new forms of interaction occurring in the virtual, walkable space, and on the other, to discern new forms of creating contents that can derive from the use of real space as part of the actual interface.

Categories and Subject Descriptors
I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism – *Virtual Reality*; I.3.6 [**Computer Graphics**]: Methodology and Techniques – *Interaction Techniques.* H.5.1; [**Information Interfaces and Presentation**]: Multimedia Information Systems – *Artificial, augmented and virtual realities*; [**Information Interfaces and Presentation**]: H.5.2 User Interfaces – *Input devices and strategies, interaction styles.*

General Terms
Design, Experimentation, Human Factors, Theory.

Keywords
Virtual Worlds, Wireless, Wearable Computing, Mobile Computing, Direct Interaction.

1. INTRODUCTION
In recent years, the term "immersive applied to experimentation with virtual spaces has acquired the meaning of "surrounding" in the sense of "all that surrounds the spectator . For a virtual setting to be considered as such, the user must, at all time, find the expected image that would correspond to the virtual surrounding environment, regardless of the direction looked at.

Until now, "immersion" in a environment of these characteristics has not gone much further. The sensation of three-dimensionality could be increased with the use of stereoscopic image and spatialized sound. However, the natural way of experimenting space as humans know it, i.e. observing while moving through it in any direction, made it necessary to use hardly believable metaphors [1]. That is, putting into the user's hands a joystick, mouse or other similar type of interface that enabled a control of direction, and asking the person to pretend to be driving around a virtual setting in an imaginary car or by means of other external forms of propulsion.

The necessary use of the imagination to perceive the metaphor of the vehicle as something real takes away all naturalness and, consequently, much of the reality to the experience of the exploration. To experiment a space in the real world, it is necessary to move through it, understanding by movement not only the motion in itself, but also the kinaesthetic sensation of perceiving one's own body in movement, given that the interpretation of one's own movement facilitates the comprehension of the scale of what surrounds us.

The action of exploring requires a personal rhythm of movement, which differentiates it from the action of travelling. In the latter, the objective is to arrive to a certain point and any variations in the movement are secondary to the perception of the actual journey in itself and, therefore, to the finality of the movement. Yet, in the exploration of space, i.e. when observing a cathedral or a museum, it is necessary for the spectator to decide the rhythm of the movement, the pauses, the accelerations, when to move faster or slower, when to browse or move sidewards, turn or go back. The simulation of all the possible forms of movement by using a metaphor and a device such as a joystick is very difficult, specially considering that movement is usually limited to two modes, i.e. standstill and forward at a constant speed, generally with an abrupt and non gradual transit from one state to the other.

The reason for using the metaphor of the vehicle is no other than the dependence on the physical location of the computer that generates the images, that remains static while simulating the movement. Until now, the complexity of the process of visualizing three-dimensional environments required the use of computers with high graphics performance, which were not very movable. This limitation has been overcome with the arrival of portable computers with high graphics performance. Another technological constraint was occasioned by the volume, weight and power supply needs of the HMD (Head Mounted Display). This is no longer a problem since the existence of small, light-weight, battery operated systems, i.e. Glasstron or similar. Another obstacle to be overcome was the restriction to movement occasioned by the cables that connected the user to the 6 degrees of freedom (DOF) tracking system. This tracking system has a fixed element that acts as a position reference and cannot move around with the user. However, in the market there are now some alternatives i.e. Intersense IS600 Mark2 that allow you to obtain the position in space of a small, light-weight, wireless and battery-operated sensor. This makes it possible to finally relieve the user from the eternal umbilical chord that traditionally connected him or her to the VR engine.

We found various systems now using this new approach, i.e. MARS by the Columbia University [4][7][8] and the one developed by Cybercompanion [2], that allow the user to walk freely without connection to a fixed computer, while displaying the 3D contents. Other approaches, i.e. Archeoguide [3], apply the characteristics of this new generation of wireless systems to outdoor environments of augmented reality.

We present here the architectural and design issues we worked on to implement a wireless VR system equipped with high resolution graphics and compliant with authoring tools and a data format that allows the user to view multimedia contents in three-dimensional environments.

The idea is to use real space as one of the elements in the motion interface and as part of the actual virtual space. This, without doubt, facilitates the experimentation of synthetic, architectonic-type spaces, already worked with in the examples of systems previously mentioned. However, the fundamental contribution of this new approach is to open the way to the use of a new form of contents, where the experience of the visit goes further than simple contemplation. Although there is still much to do, we have started to study the parameters associated to the perception of one's own movement and worked on new forms of interaction with the virtual contents, based on the location of the observer.

2. SYSTEM DESIGN

The system here described was planned as an extension to systems previously developed by the authors for different purposes and based on HMD. During the handling of these systems, two significant attitudes were repeatedly observed in the users.

In the first place, there was a tendency of starting to walk with the HMD on, while observing the environments, action that was limited by the short cable that connected the user to the station that generated the VR images. Although the system had 6 DOF trackers that detected position and orientation, the sensors were wired to a heavy and cumbersome electronic unit that made movement difficult. For this reason, the 6 DOF were left in 3, as the user was limited to observing all around, without moving from the initial position.

Secondly, we noticed the difficulty of the users to learn to handle "artificial movement systems (i.e. mouse-based) even when very elementary. Certain movements became very complicated; just think, for example, in having to move back two paces, duck, turn around, move sidewards in a circle or just vary the speed. The simple fact of being able to look in one direction while moving in another was confusing. The alternative of eliminating this possibility, so movement could only take place in the direction you were looking in, though less confusing, set such limitations that made the system completely unnatural and very awkward regarding freedom of movement.

Parting from these premises that totally invalidated the systems that were available until then, work started on a new paradigm to eliminate these constraints and reach a new dimension in the experience of virtual space exploration: the use of movement in real space as the interface for motion in virtual space. We next describe the problems encountered and the decisions made regarding design during the conception of both the physical system and the software architecture for the Empty Museum.

2.1 Hardware Architecture

For the physical construction of the VR system we sought for commercial "off the shelf elements that could be integrated satisfactorily to meet the requirements observed. This allowed us to build an acceptably light and comfortable system in a short time and with low costs.

We will start with a division of the system in two blocks: the mobile devices that will be carried by the user and the fixed devices that will be separated from the user.

Our main objective was the construction of a wireless system, though it was also desirable for the devices carried by the user to be comfortable, light-weighted and manageable. A balance had to be found between the components to be included in the portable system and those to be included in the fixed system.

The portable system must at least include the visualization screen, mounted on a structure as light and comfortable as possible. For this reason we chose Sony's Glasstron, for being a much lighter device than conventional HMD. During testing, one of the users received a telephone call and held a conversation of approximately 15 minutes without taking the HMD off. Other testers used the device for more than 45 minutes non-stop, without showing any signs of weariness, demonstrating we had found an acceptably comfortable system to use. In technical aspects, Glasstron offered satisfactory visualization quality and the possibility of being battery-operated, essential in this application. Possibly the main disadvantage was the reduced field of view, which, at first glance might provide a poorer sense of immersion than other HMD. However, as objectives were mainly aimed at the user's freedom of movement, the Glasstron turned out to be the best option and the overall sense of immersion obtained was clearly greater than those of other systems with a larger field of view, i.e. the V6 or V8 of Virtual Research. Another aspect considered during the selection was the possibility of using the see-through screens to mix the virtual image with the real background scene, of great use in future applications of MR (Mixed Reality).

Another fundamental element is the computer in charge of generating the images. It was discussed whether to place it in the fixed unit or in the portable unit, connected to the HMD. The first option presented the advantages of being able to use any computer without weight or size restrictions. Moreover, it avoided the user having to carry its weight. However, this made it necessary to use a wireless system to communicate with the user's screen, a transmitter/receiver unit for the audio and video signals. As the motion capture sensors would also probably have to be connected to the computer and situated on the user's head and as laptops with very high graphics performance had now appeared on the market (integrating GeForce chips from nVidia), we decided to place the computer in a backpack carried by the user. This avoided many problems and facilitated the construction of the system and of future extensions, by connecting further devices to the portable computer carried on the user's back.

The tracking system needed 6 DOF, to detect at all time the user's position and orientation. Although orientation can be tracked using autonomous, gyroscope-based systems connected to the portable computer, position tracking always needs an external reference framework to be able to locate the specific co-ordinates of a sensor. For this reason we sought a system that in some way detached the mobile sensors from the external reference. The IS-600 of Intersense offers 3 DOF (position) for the wireless, battery-operated sensors (Sonidiscs). The position is obtained through an electronic unit connected to the device that acts as a position reference (X-Bar), that communicates through infrared light and ultrasounds with the wireless sensors [5]. The electronic unit was connected to a fixed computer that, through a wireless network (IEEE 802.11b), transmits the data to the portable computer carried by the user (Figure 1).

The other 3 DOF (orientation) could not be obtained from the IS-600, as the sensors it uses (InertiaCube) would need to be physically connected to the heavy electronic unit and to the X-Bars (typically assembled on the ceiling). Moreover, the possibility of connecting the autonomous system to the portable computer would avoid the additional latency corresponding to the transmission through the wireless network, improving the response time of the visualisation and consequently, the user's sense of immersion. We tried diverse gyroscope-based systems from different manufacturers with little success. Some caused abrupt changes in the orientation, others accumulated errors until all correspondence between real and virtual space was totally lost and the user was notably confused. Finally, the InertiaCube2 of Intersense proved to be the product that provided the best results. It uses a hybrid gyroscopic, magnetic and inertial system that reaches a great stability in the lecture of the orientation. Regardless of not being very precise, the error obtained does not accumulate as in other systems. This sensor connects to the laptop's serial port and uses the same battery as the Glasstron, although power supply can also be obtained from the laptop's USB port. It is very possible that in the near future a USB version of this system will appear on the market.

Therefore, the final design of the first Empty Museum prototype placed the rendering computer in the mobile unit carried by the user, and communication with the tracking system was conducted through a wireless network. The diagram of Figure 1 depicts the components and connections between them. This system provides the user with an autonomous system (not limited by the presence of the traditional umbilical cable connected to the VR engine) so he or she can walk freely in a space of up to 8x8 metres, sufficient, as we shall see, to display spaces which are even larger.

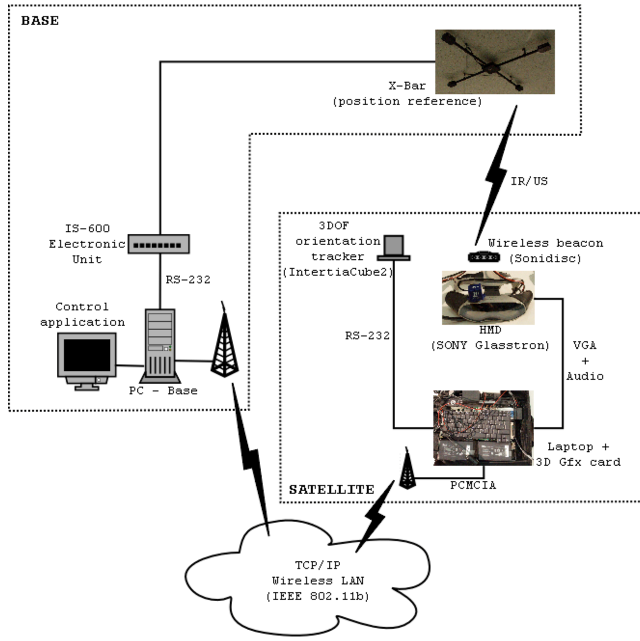

Figure 1. Diagram of the system blocks.

2.2 Software Design

Once we had the adequate, perfectly integrated hardware, to be able to display varieties of three-dimensional contents, it was necessary to develop a software able to manage complex worlds with all their characteristics of animation and interaction, and simultaneously, manage the tracking devices and control the system as a whole.

The system's software architecture is composed of two applications, corresponding to the fixed-mobile division explained in the previous section (see Figure 1): a controlling application that is run on the fixed PC, that manages the wireless tracking system (*base*), and a visualization application that is run on the laptop carried by the user (*satellite*).

The base application monitors the connections of the satellites present in the system and allows the operator to view the condition of these satellites, disconnect them, calibrate their tracking devices, assign virtual worlds to them, etc.

The satellite application continuously receives data of its position from the base through the wireless network and of its orientation from the gyroscopic/inertial/magnetic system. From this data, it generates, in every moment, the image corresponding to the position of the user's head. This image is displayed on the HMD screen.

2.2.1 Definition of the Worlds: VRML 2.0

For the construction of the contents of the virtual worlds we adopted the VRML 2.0 format, for its versatility, that, apart from defining the scenegraph with geometry, materials, textures, lighting, etc., permits the incorporation of spatialized 3D sound, animations, videos and behaviours controlled by sensors of proximity, touch, visibility, etc. In general, it provides a great potential for interaction and combination of multimedia elements.

Using this format also makes it possible to build worlds with authoring tools i.e. CosmoWorlds. To interpret the VRML 2.0 information, a viewer was developed based on the kernel of the open source library OpenVRML [10], which was adapted to this specific application and new features were added.

2.2.2 *Empty Museum Software Architecture*

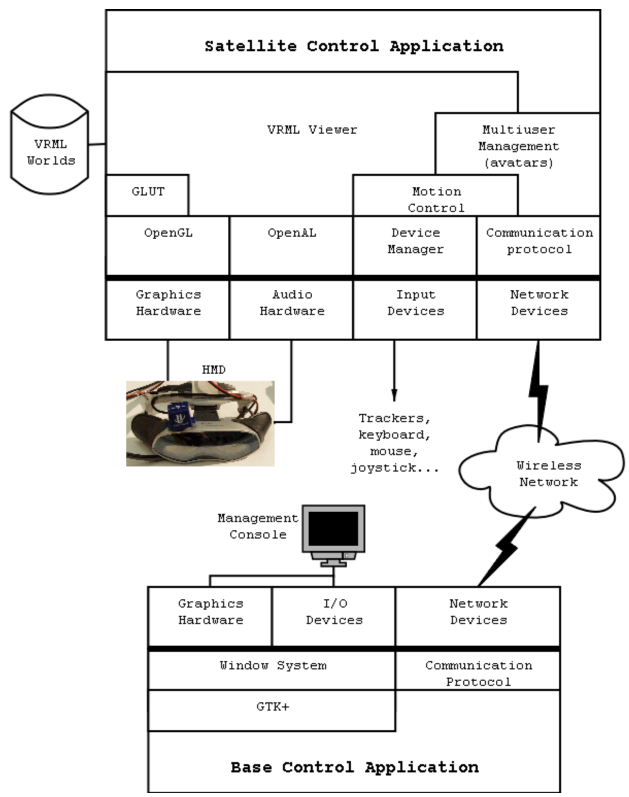

Figure 2. Software architecture of the Empty Museum.

An important aspect during the development was the software's portability. For this reason we used standard libraries and APIs, avoiding, when possible, closed or proprietary formats or dependence on particular platforms. This way, the programmes are prepared to work under Win32 or Linux systems. The software was written in C++ language and OpenGL as the API for the graphics hardware. Spatialized sound was implemented using the OpenAL library [9]. For the development of the controlling application's interface, we used the GTK+ library [6].

Even when the actual implementation of the system uses a specific hardware, the software has been designed and developed in a modular way and is thus completely configurable. It could be adapted to use combinations of different devices without making changes in the programs. The configuration files used are defined in a XML language and we developed graphical tools to generate them. The software architecture of the system is illustrated in Figure 2.

2.2.3 *Multi-user Spaces. Communications Subsystem*

The Empty Museum is not limited to one user in the same space. As the tracking system can manage various sensors simultaneously, it has multi-user capacity.

The software was developed so that various users could visit the same or different virtual worlds at the same time, in the same real/virtual space. The users can optionally see each other as an avatar, which is a VRML model included in the definition of the virtual world and which moves associated to the corresponding user's position.

The protocol used in the communications system is based on TCP/IP. A general outline of its working is illustrated in Figure 3.

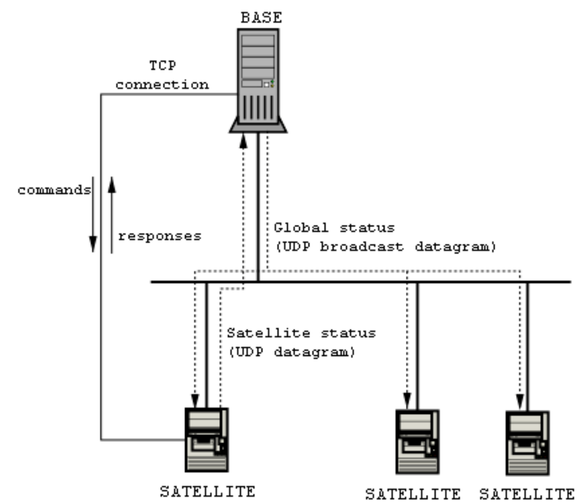

Figure 3. Multi-user communications system.

3. HYBRID SPACE

The user of the Empty Museum experiments space in a double manner. On one hand, the space as what he or she knows as such, with known dimensions, in a real area the person is conscience of being in (Figure 4). On the other hand, in that same space there are virtual objects. Not only does the user see and accept these as inserted in the space, as happens in the augmented reality systems, but is also able to experiment their size in relation to him or herself through parallax and movement around, nearer and away from them. The actual virtual space (not the objects inserted in it) is, therefore, as genuine as the actual real space, inasmuch as it has its same properties. As a user, you see yourself immerse in a hybrid space in which it is easy to move around and observe the objects. The real space thus becomes part of the interface.

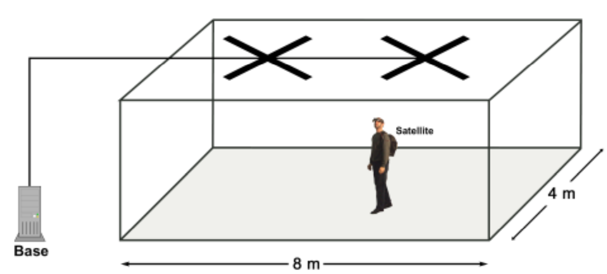

Figure 4. Structure of the Hybrid Space in the Empty Museum for a 4 x 8 m configuration.

The dimensions of both spaces can, however, be different in size, and this difference can be manipulated by introducing a scale factor in the movement. This way, we can lodge a large virtual space into a much smaller dimensioned real space. The user moves around, taking steps that can cover various metres of the virtual space, giving a sensation of very fast movement that is surprisingly not unpleasant. On the contrary, the testers described it as natural and fluent. This allows us to display great virtual spaces in a small room. When experimenting with an example of architectonic space (Figure 5), we displayed the inside of a building more than 30m long in an Empty Museum of only 8m long.

For worlds that are much larger or complex, we have also experimented with the “teleport chamber metaphor, as described later on.

4. INTERACTION WITHOUT CURSOR. EXPERIMENTAL WORLDS.

To make it possible for the user to interact with the different variety of contents in the Empty Museum, we decided to look for a form of communication between the user and the system that avoided the use of accessory elements i.e. cursors, keyboards or other similar devices. For this first stage of development, we decided to approach the problem from the opposite perspective, that is, designing contents to interact with the user simply through his or her location in the virtual space. With this new approach in mind, we designed various experimental worlds to test different established levels of interaction and dynamism.

4.1 Level 0. Only Visitable Space. Architectonic World.

In this level we frame the first experimental world. It consists on an architectonic interior, that can be visited but in which no event is produced and no response is made to the user’s movement.

Interaction is restricted to walking around and observing the interior space. The user can observe from any point of view, simply by moving around. It is a good starting point as a first contact with the Empty Museum.

Figure 5. Interior architectonic space.

4.2 Level 1. Animated Space. Sea Museum.

The user appears in a marine setting, just above the water surface. There are seagulls in the air, crying out and flying around in circles, boats sailing, dolphins swimming and jumping out of the water... The user can dive underwater to see more objects.

When the user ducks, he or she can then see the submarine world. There is a certain surprise when the user finds what he or she would expect to see: shoals of fish, seaweed, a shipwreck... Vision becomes misty and the echoes of the sea depths can be heard, together with the sounds of the dolphins that swim past nearby.

Figure 6. Sea Museum. Surface and immersion.

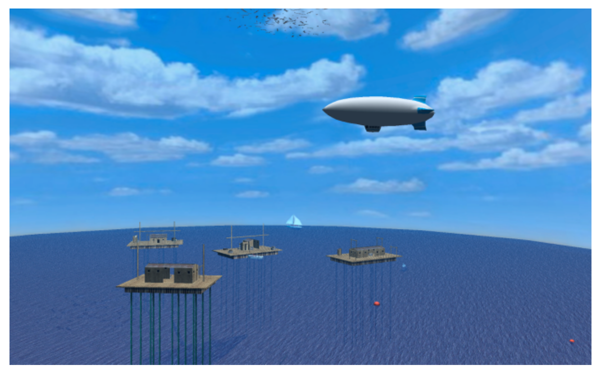

Figure 7. Sea Museum. Example of entry view of the user.

It is a much more dynamic world that in the previous case, as it includes spatialized sound and animations that the user can discover by exploring the different corners of this world. The user passes from the surface to the underwater world in a natural way, as would happen if he or she were really in that space at a giant scale.

4.3 Level 2. Interactive Space. Persistent Changes. Museum of Sacred Art.

This world is inspired in the Romanesque music, sculpture and architecture. The user appears in a hall where there are signs that make reference to certain medieval instruments portrayed in the Portico of Glory of the Cathedral of Santiago de Compostela. When drawing near to any of the signs, an image of the sculpture of the musician corresponding to the instrument named in the label descends towards the user and a three-dimensional model of the actual instrument emerges from the previous image and its music begins to sound. This allows the user to contemplate the instrument while listening to its sound.

The user walks around all the world’s areas of exhibition, observing the different instruments that, once displayed, remain visible or “already activated . The individuals that tested the

Empty Museum were surprised by the persistence of these changes, indicating their astonishment for having being able to permanently modify the aspect of the virtual world by their intervention. The persistence of the changes provides more realism to the experience, given that it is an attribute of the things in the real world.

Thus, this world advances one more step regarding the level of interaction with the user, in the sense that the elements in the world react towards the user's movements. Various proximity sensors (see Figure 9) activate the animations and sounds.

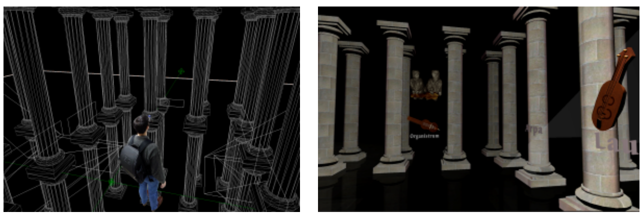

Figure 8. Museum of Sacred Art. Location and view of the user.

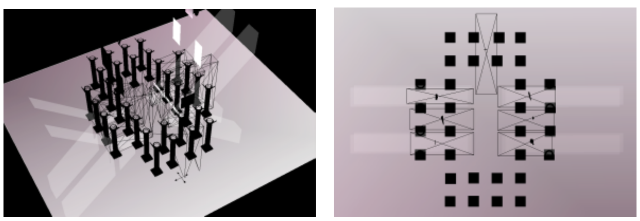

Figure 9. Location of the proximity sensors.

4.4 Level 3. Highly Interactive Space. Persistent and Non-Persistent Changes. Toy World.

The user appears inside a room full of toys, which are activated when drawing near to them. This way, he or she can start the electric train going, open a large chest from which little tin soldiers start marching out, make the jack in the box spring out (Figure 13) or view a film projected in a toy cinema, among other activities.

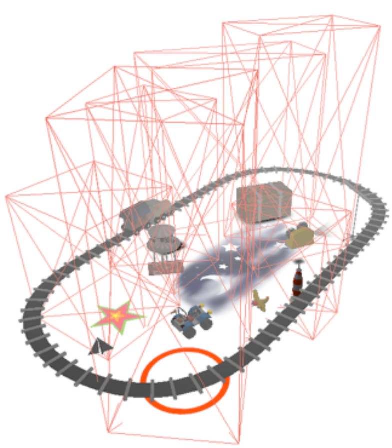

Figure 10. Toy World. Object sensors.

Figure 11. Toy World. Location and view of the user.

4.5 Level 4. Teleporting.Worlds in Other Worlds. The Art Gallery.

The user starts out in a surrealist art gallery that displays two paintings (Figure 12). When walking through them, as Alice through the looking glass, the user appears in a moving, three-dimensional version of the painting, as if looking into the artist's mind. In one of the corners of this dream world there is a white cylinder that metaphorically represents a teleport cabin. When the user has finished examining the imaginary world, he or she can walk into the cylinder and be teleported back to the art gallery, where the experience can be repeated with the other painting.

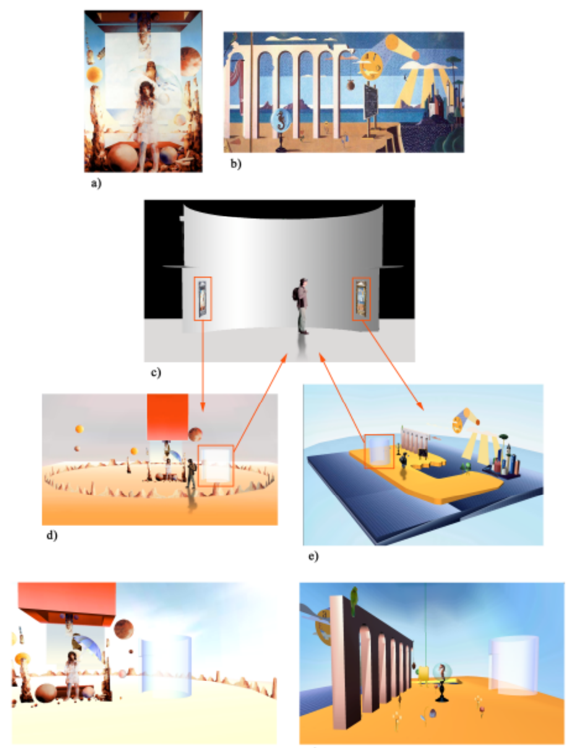

Figure 12. The Art Gallery: a) Original painting by Xaime Quessada. b) Original painting by Urbano Lugris. c) Art gallery with the paintings exhibited. (The arrows indicate the location of the teleport elements and their destination). d) View of the user inside Quessada's painting. e) The user inside Lugris' painting. f) View of the user inside Quessada's painting. g) View of the user inside Lugris' painting.

This world includes a new characteristic, i.e. the inclusion of various worlds inside one same world. The user can be teleported from one to another very easily, based on a concept between hyperlink, since it acts as a link between two elements of information, and teleport chamber, given that it is perceived and works as such. The users accept this type of movement between worlds as natural and very easy.

5. PERCEPTION IN THE WALKABLE VIRTUAL SPACE

We can define reality as the cognitive interpretation of what we perceive, that is, the interpretation of the information an individual receives from the surrounding environment through his or her senses. Therefore, to make a person feel immerse in a reality that is different from the real, physical world, you must fill that person's senses with information of the virtual world you want to introduce him or her into. If you only stimulate some of the senses in this direction, the user will be receiving information from two different environments simultaneously, allowing him or her to distinguish which one is real and which virtual. The more senses you artificially stimulate, the more the user becomes immersed in the virtual world.

As indicated earlier, the major difference between this and previously described systems of virtual space experimentation is the extraordinary contribution that real movement inside the room has to the sense of realism of the virtual space. This is because, when you move, your own kinaesthetic and vestibular systems provide you with information that corresponds to what you are seeing, and to this we add the traditional stimulation of visual and auditory senses. All users that tested the Empty Museum confirmed that the sense of immersion was greater than that obtained by any other traditional VR system, including CAVE.

This sensation can be observed from the outside, through the expressions and gestures of the user who is exploring the worlds. It is frequent to see the person moving to avoid obstacles, even though these are virtual and do not present any physical adversity or obstruction, i.e. the pillars of a virtual building. Backward movements can also be observed before animations of objects that are potentially dangerous, i.e. to avoid collision with a virtual toy car that is chasing around the floor, or a startled jump back in surprise. (Figure 13).

A shared comment among people observing Empty Museum users is that part of the entertainment is to watch the users' reactions, seeing to what point he or she becomes involved in the virtual world.

Figure 13. Interaction with the virtual objects.

Sound plays an important role, given that the spatialization of the different noises generates a sound landscape inside the room, which changes according to the user's position. This way, the user can locate objects of interest through their sounds or produce emotions of anxiety or alarm before threatening noises. In this sense, we must point out the enormous potentiality of the Empty Museum as an audio-based spatial training system.

6. CONCLUSIONS

In this paper we have described how we built a wireless, multi-user VR system using "off the shelf elements. This system solves great part of the constraints found in the conventional VR systems in which the user is connected to a computer through a cable. We have also outlined the characteristics of a new paradigm for three-dimensional navigation through virtual worlds and started to study this paradigm's potentiality.

The system has been tested and assessed by users with and without technical knowledge on VR. From the results of these tests we can conclude that the users' approval has been very good.

The sense of immersion is clearly superior to that reached in preceding systems with reduced mobility. The fact of being able to move and interact as in the real world allows the users to explore the space immediately, without technical skills and without receiving previous instruction on how the system works. Moreover, feedback through the kinaesthetic and vestibular senses introduces the user into the world with a level of immersion that cannot be achieved in any other way. This avoids rejection from the users and makes them very efficient in the use of the system, with a practically null learning curve.

The restrictions of previous paradigms of movement in three-dimensional environments (clumsiness, slowness, impossibility of certain movements, etc.) disappear, offering the user good movement abilities and a capacity of reaction incomparable with any other device or metaphor for simulating movement. The possible size restriction owing to real space dimensions is reduced, if not eliminated, with the possibility of scaling the movement. This allows us to walk around spaces that are much larger than the real physical space available, with acceptably good perceptual results. For larger, more complex spaces, we have also successfully tried out the "teleport chamber metaphor as a means of transition between different worlds or between areas in one same world.

The described system not only improves the way of exploring conventional 3D worlds, but is also a new way of focussing the design of virtual spaces and VR applications. It opens a new field of research in spatial perception and interaction through the user's own movement, position or viewpoint.

The integration of the Empty Museum with the VRML 2.0 format enables the generation of new multimedia contents. The result of this union of walkability with multimedia is a further advance in VR systems.

7. FUTURE LINES OF RESEARCH

The most immediate extension of the developed prototype is to facilitate the user other possibilities of interacting with the environment, other that through own location or movement, as long as it is using natural forms that conserve the system's philosophy and does not reduce the sense of immersion. Among the more interesting ways of interaction we can mention interfaces using gestures, conversational interfaces or the use of the line of vision as pointer for selecting elements in the virtual world.

Another aspect to study is the combination of hybrid space with real objects in a MR system, whether based on transparent HMD or through the use of a mini video camera attached to the HMD.

One of the most interesting applications of the Empty Museum on which we are actually working on is the so-called *Art V-Space*. Inside a 3D world, the user can create works of art from nothingness, with the simple gestures of his or her hands, using them as different instruments or tools. Apart from the basically 2D arts, i.e. sketching and painting, the system adapts excellently to others i.e. architecture, sculpture or music, offering a promising potentiality for the creation of new means and contents.

A line of research that can be combined with the previous is that of multi-user spaces. The interaction with other users for the exchange of information, for the joint creation inside the Art V-Space (for example, creating music between various artists), for co-operative work (CSCW) or simply for entertaining applications, offers new possibilities in this environment. Also, due to the Empty Museum's flexible architecture, users can share the same virtual space without sharing the same real space, enabling a form of telepresence and completely immersive, three-dimensional interaction between users located in distant places.

8. ACKNOWLEDGMENTS

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