Virtual Environment and Sensori-Motor Activities: Visualization

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ABSTRACT

The levels of immersion and presence felt by users in a Virtual Environment (VE) are very important factors that dictate the quality of the Virtual Reality (VR) experience. Sensori-motor systems, both hardware and software, are the components of a VR system that contribute to generate the VEs and to create the feeling of *being there*. This paper reviews the different visualization hardware/software components that are at the heart of a VR system and provides means for assessing their performance in the context of various applications. Because of its historical and functional importance in the field of VR, visualization hardware is reviewed first (HMDs, VRDs, stereo glasses, CRT, LCD monitors and Plasma displays...). Then, a list of the most important insights, which should be addressed when designing and assembling a VR system, are discussed. Finally, visualization software is covered in the context of the available hardware components.

Keywords

Virtual Environment - Virtual Reality – Visualization Hardware – Visualization Software.

1. INTRODUCTION

The design of a Virtual Environment (VE) depends *strongly* on the desired application and on the related human factors, especially on the paradigm of user-interaction with the virtual objects. In a VE, the user receives information through several sensorial interfaces (visual, auditory, haptic…). [Popescu92] demonstrated the suitability of a multi-modal interaction model for describing the human-computer interaction in VEs. While the simplest VE configuration considers only visual interfaces, the need for increased immersion drives the designers towards the integration of additional communication modalities.

While being focused primarily on technology development, research in Virtual Reality (VR) is now mainly application-driven. The initial focus on technology was necessary in order to allow for the design of complex applications. While VR environments were initially oriented mainly towards military simulation and training, the development of new technologies triggered the birth of new application fields, such as medicine (including anxiety disorders, pain distraction, ankle rehabilitation), education, engineering, retail (virtual shopping), entertainment etc. Moreover, testing the technologies in a particular application context brings a strong feedback to hardware design. Furthermore, immersion is a fundamental concept in VR, but there are practical applications where semi-immersive devices are more efficient than fully immersive VEs.

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2. VISUALIZATION HARDWARE

Several types of visualization systems are available for graphics rendering of VEs: VR helmets, conventional displays (Cathode Ray Tube monitors - CRTs or Liquid Crystal Displays - LCDs), stereo glasses which allow stereoscopic vision, projection systems, and other immersive rooms (including CAVEs). Some systems require a device for tracking the user's position and orientation (especially VR helmets and CAVEs) and powerful image generation systems.

When choosing a given display technology, many requirements and constraints need to be taken into account such as: support of stereo vision, immersion and presence levels, motion tracking, refresh rate of the display, image resolution, colour and brightness, size of the field of view (FOV), motion representation, quality, cost, comfort, and ergonomics and health issues.

In the following sections, an overview is presented of the most important hardware technologies for visualization currently available on the market for VR and Augmented Reality (AR)[1] applications. A more complete and thor-

[1] In VR applications, many approximations can be made without decreasing the quality of immersion since all

oughly review is done in [Laurendeau03]. Several parameters must be considered when choosing visualization hardware and it is difficult to select one specific parameter, or a combination of parameters, that should lead this choice.

2.1 Head Mounted Displays (HMDs)

HMDs are well-known for providing maximum visual immersion since, when combined with a head tracking system and a fast image generation system, they can cover a 360° FOV (horizontal and vertical) relative to the orientation of the head. HMDs also provide excellent support for stereoscopic vision by using a separate display for each eye.

There is a host of different HMD technologies currently available on the market. Prices spread from a few hundred dollars to hundred of thousands of dollars. The Cy-visor from [Daeyang] E&C (Figure 1a), which provides a wide FOV, is among the category of low-cost HMDs (*cost<1K$*). Figure 1b shows higher performance HMDs (*1K$<cost<10K$*), the Hi-Res900 system from Daeyang E&C / [Cybermind] with support for audio and tracking and the iReality's CyberEye CE-200 from [iReality.comInc.]. Many systems are available in this price range. The top-level price category of HMDs (*10K$<cost<50K$*) aims applications for VR experts. Such devices are very often specifically targeting military applications as shown on Figure 1c – the Proview XL35/XL50 and the Proview SO35/SL35 from [KaiserElectroOptics]). The most expensive HMDs (*cost>50K$*), the Gemin-Eye 2 and Gemin-Eye 3 (Figure 1d) are sold by [CAE].

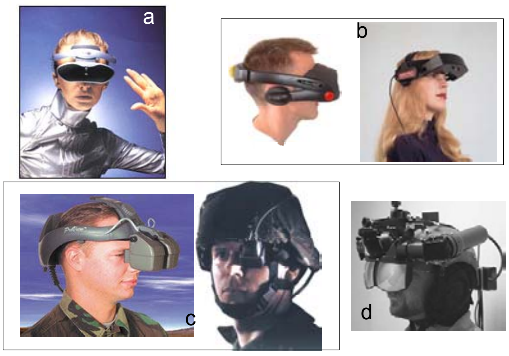

Figure 1: HMDs at different prices

Although the cost of HMDs is often the most important factor driving the choice of a specific technology, other important factors such as resolution, FOV, optical system, support for stereo, support for AR, support for motion tracking (very important), support for integrating audio information, and user comfort (which involves aspects such as size, weight, cable connections, and tuning parameters) need to be considered.

2.2 Virtual Retinal Displays (VRDs)

VRDs may be considered as a special type of HMD but offer many distinctive features that make them very interesting for AR applications. VRDs project images directly on the retina using a laser beam.

VRDs allow the user to look at the real world and at the displayed information simultaneously. This technology is thus useful for wearable computing since people can use the device while performing their regular activities (such as walking in the streets or shopping).

[MicroVisionInc.] is the unchallenged leader in commercializing VRD technology. The company already owns such a large number of patents that it almost blocks all competition. It currently produces the Nomad personal display system models of VRD for AR applications. As shown on Figure 2, the Nomad generates very bright monochrome graphics and text.

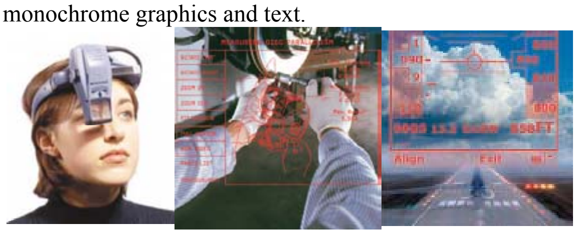

Figure 2: MicroVision's Nomad System and examples of AR applications using this system

Research is very active in the field of retinal display technology since one of the most important challenges still remains to achieve tracking of the user's eye in order to generate the right point of view in good registration with real world content. The Human Interface Technology Lab at University of Washington is carrying out research on new VRD prototypes as well as on the design of an optical tracking system that can be combined with the VRD [Chinthammit01].

In addition to the issues that must be addressed with all types of displays, issues more specific to HMD and VRD technologies also need to be considered in the VR and AR contexts: (1) support for stereovision, (2) immersion, FOV, resolution, alignment of optical system, and collimation, (3) adjustment of collimation distance, (4) elimination of the vestibular conflict, and (5) lag between the tracking system and the generated display.

2.3 Stereo Glasses

Even though stereo glasses are not display systems *per se*, it is relevant to cover this type of equipment at this point in the survey since glasses are used by many types of visualization systems, ranging from small CRT monitors and LCD panels, to large projection screens (with front or rear projection), immersive theatres, desks, or CAVEs.

Two types of stereo glasses can be found on the market: (*i)* active stereo glasses or shutter glasses (see Figure 3a), and (*ii)* passive stereo glasses based on colour filters or polarized filters (see Figure 3b).

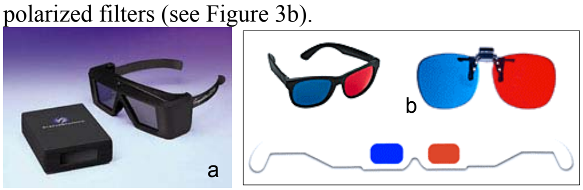

Figure 3: a- CrystalEyes shutter glasses with synchronization box by [StereoGraphics] and b– Different models of anaglyph glasses

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components are synthetic and the user can compensate for the missing details and slower response time of the system. In AR applications, such approximations and slow response times cannot be tolerated and high performance head motion and object trackers are needed in order to create the illusion of virtual objects coexisting with real world objects.

2.4 Monitors

2.4.1 CRT

CRT monitors (including television sets) are still the most commonly used visualization devices, mainly because they come as the default display available on computers and game consoles. CRT monitors can be easily adapted for supporting stereo. They offer a wide variety of resolution formats but do not cover a large FOV and limit the position of the user as well as the number of viewers. Several technologies are available for 3D visualization using CRTs: active stereo with shutter glasses is by far the most widespread technology, videowalls (see Figure 4)…

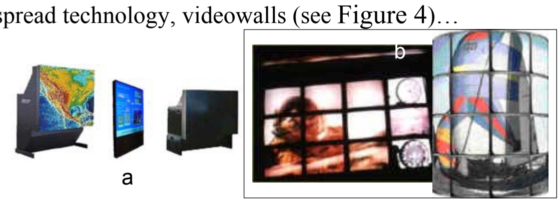

Figure 4: a- [HARP] Visual Communication and b- [Commtech] MultiMedia Videowalls

CRT monitors are well suited for most office and home applications, but they present many problems for industrial and outdoor applications. Most CRTs are not well suited for mobile applications and environments subjected to high vibration levels. Unless panels are used to block or reduce outdoor light, the display can be affected by unwanted reflections. CRTs are sensitive to magnetic fields and monitors also produce magnetic interference. Magnetic shielding can be applied to a certain extent for reducing magnetic interference, but it will never be possible to eliminate this effect completely. Because of the scanning process of the electron beam on the surface of the screen, flicker effects can cause user fatigue.

Technologies such as HMDs, VRDs, organic LEDs and LCDs can help to avoid these problems. It is thus very important to be aware of the environmental conditions associated with a specific application before choosing a display technology.

2.4.2 LCD and Plasma

With a significant drop in prices over the last years, digital display devices, such as LCD displays, are becoming more popular for personal computer systems and it is expected that they will replace current CRT screens in the near future. The main advantage of LCD displays is that they occupy much less room than CRTs. The increase in accessibility and popularity of LCD technology is also true for VR and AR applications and innovative technologies have been developed to adapt conventional LCDs for stereoscopic viewing.

Contrary to LCD displays, plasma displays, although they share most of the characteristics of LCDs, are still very expensive and are dedicated for high-end applications. Plasma screens are larger than LCDs (up to 50 inches) and provide excellent contrast and brightness. These features make them perfect for large audiences, even under normal room lighting conditions. Except for their price, plasma displays are currently considered as being the best display technology available on the market.

LCD displays cannot achieve refresh rates as high as conventional CRTs do mostly because of the internal circuitry that is needed to interface with the video signal source. Slow refresh rates prevent LCD displays from being used in stereo applications using shutter glasses, although stereovision can still be achieved by other means. Another limitation of LCD monitors is their poor image quality for resolutions other than the native resolution of the LCD array. Fortunately, the native resolution of current LCDs is often enough to meet most applications.

The very precise positioning of LCD or Plasma pixels, combined with the use of a digital connection (DVI link) to the graphics rendering hardware, allows special masks (polarizing, holographic or prismatic) to be aligned with high accuracy on the surface of the screen.

2.4.3 Autostereoscopic

Autostereoscopic displays (see Figure 5) are an excellent alternative for producing stereo images using standard LCDs or plasma screens. Autostereoscopic systems can generate stereo images that can be viewed without special glasses. The basic principle of autostereoscopic displays consists in applying a thin (lenticular, holographic or prismatic) mask on top of the screen (LCD or plasma). The mask deflects the light projected on the screen differently for adjacent columns which, when observed by the viewer, are perceived as the two images of a stereo pair. However, image resolution in stereoscopic mode is half its value in monoscopic mode. The advantage with autostereoscopic displays is that standard screens can be easily converted to stereo displays, even for conventional laptops.

Due to patents and intellectual property issues, each vendor has developed his own technology for generating autostereoscopic displays.

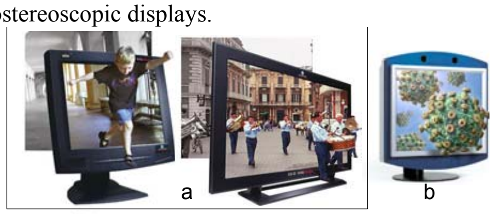

Figure 5: a- Stereographics' lentilar autostereoscopic technology. 18" monitor at 6K$ and 42" plasma screen at 15K$ and b- [SeeRealTechnologies] system with embedded tracking system

Autostereoscopic displays can be combined with a tracking system for tracking the viewer's head or, more specifically, the viewer's eyes, and thus compensate for changes in position and distance with respect to the display. This also allows the viewer to see around objects. Because the main feature of autostereoscopic displays is to relieve the user from wearing glasses, a passive vision system is recommended as an eye- tracking device.

Autostereoscopic display technology is very promising. However, it is still difficult to decide which approach (lenticular masks, holographic masks, etc.) is best suited for VR applications. One thing is common to almost all available systems: depth information is generated at the expense of decreased image resolution and lower image brightness. Furthermore, even though the viewer is relieved from wearing glasses or helmets, his freedom of motion in front of the display is restricted.

It is important to note that most autostereoscopic displays require special 3D drivers in order to support unconventional pixel mappings. Supporting multi-view displays (exploiting slanted lenticular masks, prismatic masks, or wavelength filters) may become difficult from the hardware point of view.

Based on the different technologies that have been reviewed for generating stereo images, it is clear that LCD and plasma autostereoscopic displays should become very popular for desktop VR, because they are cheap and only impose minor upgrades of current computer screens (on laptop computers).

2.5 Holographic & Volumetric Displays

Futuristic (and expensive) devices, such as holographic displays and volumetric displays, are now available on the market. However, most of these devices are still under development. Although both types of devices produce the same result (a "ghost" object floating in 3D space), they are based on very different principles. While holographic displays send stereoscopic images to the viewer in order to create the perception of depth, volumetric displays project the image of an object in space, so different viewers can observe it from different vantage points [Lloyd02].

2.6 Projection Systems

There is a wide variety of projection-based displays, some with only one projection surface, others with several surfaces. Each projection surface may allow monoscopic or stereoscopic viewing by one or many users. The projection surface can be planar or non-planar (cylindrical, spherical, conical and domes). Systems can use several projectors in order to create large-size environments or for increasing resolution. Finally, the physical assembly of the projection surfaces may vary according to the application. Projection systems include CAVEs, immersive desks, panoramic displays, and simulation cabins. Three projection technologies are currently available: *(i)* CRT projectors, *(ii)* LCD projectors and *(iii)* Digital Light Processing (DLP) projectors, which are among the most recent technologies to appear on the market.

2.6.1 CRT Projectors

CRT projectors are the most commonly used devices for VR applications, mostly because they can achieve refresh rates (120Hz) that are required for active stereo. For VR applications, it is recommended to use a fast green phosphor for avoiding ghost effects.

All CRT-based colour projection systems use three separate CRTs and accompanying optical systems that need to be calibrated for achieving good colour convergence. The calibration process of these projectors is a tedious task. CRT projectors are also bulky and heavy hardware components that are not well suited for mobile VR, LCDs being more lightweight for such applications. Although CRT projectors have better contrast ratios, more pure black and white levels than LCDs and DLPs, image brightness is not very high and they must operate in low ambient light conditions for achieving good performance.

Despite these comments, CRT-based systems still offer advantages over the concurrent LCD and DLP technologies. For instance, CRTs have a lower dark level that shows better performance for edge blending and multiple projector applications (CAVEs, immersive theatres and mosaic displays). CRT projectors can achieve a wide range of native resolutions and refresh rates. They produce less audio noise and heat than LCDs or DLPs projectors, which need a high power lamp and a noisy cooling system. CRTs being analog devices, it is rather easy to design circuits for compensating image distortion.

Several vendors offer CRT-based projection systems for VR applications: [Barco], [Mitsubishi], [Sony], [VirtualDynamics], [ChristieDigital] and [VideoDisplayCorporation].

2.6.2 LCD Projectors

LCD projectors have the ability to produce brighter images than CRT-based systems. Since they can generate the three basic colours using the same optical path, there is no need for compensating convergence or calibrating the optical system. LCD projectors are small and light hardware components and are cheaper than CRTs. These features make them well adapted for mobile VR applications.

As mentioned earlier, LCD projectors use a high power lamp (typically 300 to 400 watts) and need a noisy cooling system (fan). The lamp, which can cost between 500$ to 1000$, usually needs to be replaced after 2000 hours of operation. This makes LCD-based projectors expensive with respect to maintenance.

Contrary to CRTs, LCD systems achieve good performance only at their native image resolution and do not offer much flexibility for compensating distortion. Consequently, the projectors must be assembled with care and must project images on flat surfaces (unless special lenses and mirrors are used).

Finally, LCD projectors produce linearly polarized light, a feature that can be exploited by passive stereo systems. For instance, [Barco] is able to make LCD projectors function with passive stereo based on linear polarization. [ChristieDigital] also sells an integrated dual LCD projector system (LX33) for passive stereo (linear polarization). However, for several other LCD projectors, the polarization's orientation cannot be controlled or made compatible easily with conventional polarized glasses. Most LCD projectors are not compatible with the increasingly popular passive stereo based on the circular polarization, because they already produce a linearly polarized light.

2.6.3 DLP Projectors

The DLP technology has been invented and developed by Texas Instruments [DLPTechnology]. DLPs are basically micro-mirrors that are switched at a very high frequency so as to control light reflection. Colour images are obtained by using red, green and blue filters. The original DLP engine was a single electronic chip that was generating the three basic colours (Red, Green, Blue) sequentially by using a rotating disk with three colour filters. The second and third generations of DLPs use a 3-chip engine and generate the three basic colours separately. This 3-chip technology achieves better performance with respect to colour generation than the first design. It also achieves faster refresh rates and supports active stereo with shutter glasses.

Even though they are more expensive than LCDs, DLP projectors offer several advantages for VR applications. As is the case with LCDs, DLPs were formerly affected by pixelization problems (or screen-door effects), but these problems have been eliminated on most recent projection systems. DLP projectors produce higher image brightness than LCDs and do not produce polarized light, which makes them suitable for stereo systems using any type of polarization filters (linear and circular).

As for LCDs, DLP projectors formerly had a refresh rate that was too low to achieve active stereovision. However, more recent projectors, such as [Barco]'s Galaxy projector, feature a 110Hz refresh rate, a performance that is adequate for achieving active and/or passive stereo. [ChristieDigital] also manufactures high-speed DLP projectors that are compatible with active stereo applications.

For several stereo applications using DLPs, two projectors and polarized filters are combined. [Bourke02] explains how such a dual projection system can be assembled and used. The setup does require projectors with high refresh rates and a LP350-model or the more recent LP530 from [Infocus] can be used.

[ChristieDigital] and [VideoDisplayCorporation] also sell similar DLP projectors for VR applications.

The Gemini package from [Barco] is a turnkey solution for circular polarization systems using two DLP projectors. Gemini integrates a DUET II active to passive stereo converter box that allows one computer equipped with a stereo card to drive the two projectors.

2.6.4 Immersive walls

Immersive walls are the simplest projection-based systems that can be assembled and used for VR applications. They are comprised of a projector, mirror and projection surface. Rear projection systems are preferred over front projection systems since occlusion caused by users standing in front of the wall can be avoided. The display can be combined with a motion tracking system and stereo glasses. The geometry of the system being simple, complex image generation hardware is not required.

An immersive theatre can be built by combining two or more square surfaces with common edges in order to cover a wider field of view and thus create a better immersion experience. It is also possible, using an additional projector and mirror, to project part of the display on the floor to improve the quality of immersion further. An L-shaped setup such as [Barco]'s TAN Holospace is an instance of such an immersive theatre (see Figure 6).

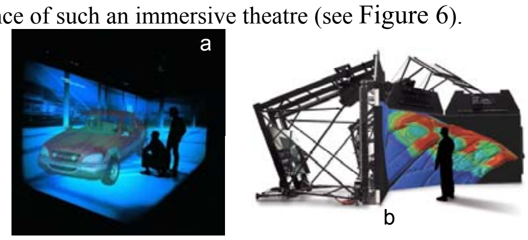

Figure 6: a- Barco&TAN's Holospace and b- Barco's MoVE Immersive Theatre

[Barco] and [Fakespace] both offer reconfigurable systems that can be used as immersive theatres.

The idea of combining more than one wall can be expanded to multiple surround walls. The purpose is to achieve a wider field of view and to allow viewers to move or turn their head, thus providing an even better immersion experience than single wall systems.

Recently acquired by Fakespace, [Mechdyne] offers surround-screen visualization systems that can be equipped with two, three, four, five, or six projection surfaces for creating VR environments for cooperative work applications.

2.6.5 Immersive Rooms

2.6.5.1 CAVE

The CAVE acronym means "CAVE Automatic Virtual Environment". It is a projection based VR system developed at the Electronic Visualization Lab (EVL) at the University of Illinois in Chicago. CAVEs consist in a particular arrangement of 4 to 6 walls, generally about 3m (10ft) wide. Rear projection is used in order to prevent shadows from the VR participants. A front projection may however be used for the floor surface. Shortly after the first CAVE was built at EVL, a second CAVE was built by the National Center for Supercomputing Applications (NCSA) at the University of Illinois (see Figure 7a). This CAVE is used by NCSA's Visualization and VEs Group to conduct various types of research in the fields of VR and scientific visualization. It is now a commercial product sold by Fakespace Systems. Several other commercial products (and custom systems) based on the CAVE are being implemented all around the world.

With HMDs, CAVEs are probably among the best immersion devices available on the market. The main advantage with CAVEs is the relative freedom of motion that is given to the viewer, the eyewear and the tracking system for the stereoscopic display being lighter and less obtrusive than for HMDs. In comparison, CAVEs can be used for many hours while HMDs period of continuous use do not exceed 30 minutes. A CAVE also allows several users to share the same immersive experience.

The main disadvantage with CAVEs is their high cost. A CAVE can cost typically between 100K$ and 250K$ per wall. High performance image generation systems, such as Onyx supercomputers from Silicon Graphics, are needed. CAVEs also require a lot of room and/or a specially designed building. Maintenance is very expensive since the system needs to be calibrated frequently.

Health issues are less important for CAVEs than for HMDs since the user can move easily and perceive images more naturally. Users may still experience fatigue (mainly eyestrain problems) caused by wearing stereo glasses.

Compared to HMDs, CAVEs do not require that an accurate tracking system be used since graphics rendering does not need to be synchronized with head motion. Head tracking is mostly used so as to allow the user to change his vantage point and to look around objects in the scene. Being relatively immune to the (motion tracking) lag problems, the CAVE environment has less chance to cause motion sickness and other vestibular diseases.

2.6.5.2 VR Cube

The 6-wall setup, also called the "Cube", is the "ultimate CAVE", because it allows full visual immersion. The PDC VR-Cube (see Figure 7b) built by the German manufacturer TAN (now a division of Barco) for the Center for Parallel Computers is an instance of such a system. The Cube requires more room than a 4-wall setup since front projection can no longer be used for the floor screen. A two- or even three-story high room is required for installing the full system. The floor projection surface must be designed for rear projection but still be rigid enough to support the weight of the users. Another important issue is the design of the frame supporting the VR-Cube. When a magnetic system is used for tracking the user's head motion, the material of the frame shall not interfere with the signals emitted by the tracker. A wooden structure must be used and must be sturdy enough to support the cube, projection systems, mirrors, and other components. Finally, a door is also needed to access the cube without affecting the projection system. The simplest way to access the cube is to allow one wall to move on wooden hinges.

Figure 7: a- NCSA'sCAVEs and b– VR-Cube

2.6.6 Immersive Desks

For a wide range of applications, full-body immersion is not required and achieving arm and hand immersion in a workbench-style environment is enough. For instance, a medical application for surgery training for which all action is focused near and around the operating table may only require a workbench immersive environment. Workbenches can also be very useful for visualizing maps and digital terrain models. Immersive workbenches are special projection systems that have the shape of a table and onto which stereoscopic images can be projected. Some L-shaped configurations with two intersecting surfaces also prove useful. Even though it is simpler than a CAVE, an immersive workbench still requires 3D glasses and a tracking system [Barco] (see Figure 8a-b) [Fakespace] (see Figure 8c) [Trimension].

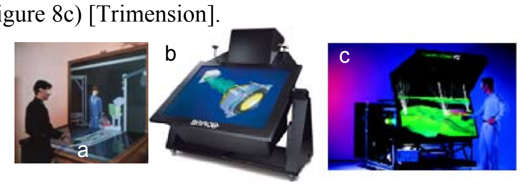

Figure 8: a- Barco&TAN's Holobench, b– Barco's Baron Immersive Table and c– [Fakespace]'s Immersadesk R2

2.6.7 Domes

Some companies have developed self-supporting structures, which can be used as projection surfaces with very wide FOV. Multiple projectors are needed to cover the full area of the screen while maintaining good resolution. Projection systems can support domes, partial domes and mosaic displays, because such systems share common features with flight simulators (see Figure 9 for examples).

3. SELECTING HARDWARE FOR A VR APPLICATION

Selecting hardware components for a specific VR application is a complex process. A "one solution fits all applications" recipe does not exist and many issues must be considered such as the compatibility between hardware and software, system integration, etc. The most important insights into the different issues, which should be addressed when designing and assembling a VR system, are discussed below.

3.1 Cost

Large displays and powerful image generation systems are very expensive devices. Hence, PC-based image generation systems and low-cost display technologies should be considered for systems that are submitted to tight budgetary constraints. One way of reducing system cost is to buy components separately (display, screen, tracking systems, audio…) and perform in-house integration. This assumes that trained technical staff is available to spend a significant amount of time on the integration task. When in-house integration is not possible, companies such as Fakespace and Barco sell turnkey systems and offer support for installing and starting up the system. However, significant overhead cost must be provided for in the budget. It is thus of paramount importance to define the system requirements very carefully for the application at hand before choosing between an in-house solution and a turnkey solution.

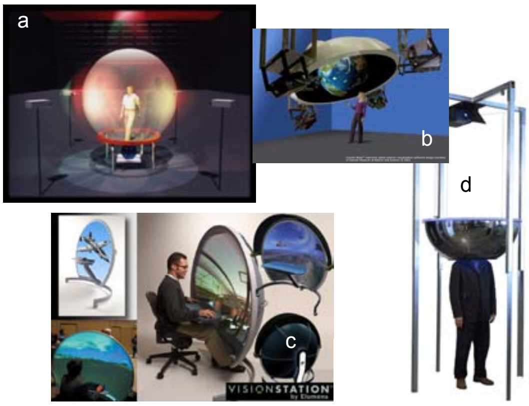

Figure 9: a- VR-Systems [Cybersphere], b- [Trimension]'s Mini V-Dome, c- [Elumens]' VisionStation and d- the [Panoscope] from the Laboratoire de muséographie, Université de Montréal

3.2 Type of Application

The VR application is also an important issue to take into account before choosing a visualization technology. Systems for training surgeons do not impose the same constraints on the visualization hardware that combat training or molecular analysis do. An immersive workbench is an excellent choice for medical surgery training or command and control operation planning but is a poor environment for combat training for which VR helmets or CAVEs are a much better solution. Desktop VR (CRT with stereo glasses or autostereoscopic LCD display) may be an excellent environment for inspecting and manipulating objects.

Several simulator setups integrating specific control interfaces are needed for specialized training applications such as driving a car or piloting an airplane. Other applications require lightweight and portable equipment, while still other applications require large displays that can only be installed as permanent infrastructures.

Selecting the best display format for a specific application is not always obvious even when budget and integration constraints are not taken into account!

3.3 System integration and compatibility

As for all engineering design projects, component (hardware and software) compatibility and system integration issues should be addressed early in the selection process. The application itself may impose that specific software modules or device drivers be used which puts constraints on the type of computer and operating system (PC or SGI platform for instance). PCs cannot drive multiple-display systems often found in CAVEs, while SGI engines or PC-based clusters can. A specific graphics-rendering card may be imposed by the selected display technology. For instance, there is no standard for stereo support by HMDs. Some HMDs supporting stereo use a specific video signal specification that only a few graphics rendering cards can provide. An electromagnetic head tracking system may not be adequate because of the presence of metallic objects in the environment (air-conditioning ducts, optical benches or even steel beams in the building) or because of magnetic interference (such as the interference caused by fans in the air conditioning system, magnetic resonance imaging equipment, etc.). These are only a few parameters that need to be considered in a VR visualization design process.

3.4 Audience

The type and size of audience for which a VR visualization system is built is a very important factor to consider. First, a clear distinction must be made between VR *participants* and VR *spectators*. VR participants usually need to interact with the system by using different interfaces and trackers, while spectators are more passive and need only to watch the same images as the participants.

Several applications involving collaborative work require that all the participants be located in the same room and watch the same display. When this is the case, it is important to decide whether all participants must share the same view or if a different view has to be generated for each user. In general, for CAVEs and other stereoscopic systems, only one participant is tracked and all other participants share his point of view. In order to generate a FOV that is different for all participants while sharing the same display, autostereoscopic displays and volumetric displays must be used. When the number of participants is small, it may be possible to track each participant and project distinct images for each one but this implies the use of sophisticated and expensive setups. For instance, Barco's Virtual Surgery Table supports 2 participants having their own point of view.

For large audiences, composite screens such as video walls may be used but, in this case, users' motion is very limited. CAVEs, HMDs, and simulation cabins are generally not adapted for large audiences. Another way to satisfy more participants is to replicate the display system, which also increases the system cost!

3.5 Scaling and object size

For applications such as surgery training, it may be necessary to work with real scale objects, for other applications (observation of digital terrain models or analysis of molecules), scaling the environment may not cause significant problems for the quality of immersion. Depending on the typical size of objects, the scale factor that can be applied to these objects in the VR world, and the fraction of the object that needs to be seen, a different display volume may be required.

3.6 Work envelope

An important aspect of a display system is to consider how much the participant is allowed to move and interact with the virtual scene. Actual display systems offer a very limited working envelope because of the intrinsic size of the display and the limited range of tracking devices (including tethers). For several applications, a limited working envelope may be acceptable, because a person or viewer can stay in a seat or stand at the same location. For the other applications involving a lot of motion and displacements in a large volume, very few solutions do exist. For example, it is not yet easy to allow someone to walk in a VR world for long distances unless a treadmill or other type of locomotion interface is used.

Although a relatively limited working envelope is needed for most VR applications, it is always recommended to use wireless and non-obtrusive devices (tracking system, shutter glasses and other I/O devices).

4. VISUALIZATION SOFTWARE

The field of graphics rendering engines is evolving rapidly and new engines become available while others become obsolete in a short amount of time. Consequently, a wide selection of engines can be found on the market. In order to limit the extent of the survey to the engines showing the most potential for development and exploitation in VR applications, only those, which have proven relevant performance and durability, are discussed. This does not mean that engines not listed in this paper do not show potential for development but rather that these engines are still too recent to be of interest for being used in a full-scale VR application.

4.1 Evaluation Criteria

Because of the large number of engines that are available, and because of the wide range of functionality and performance that they offer, it is of paramount importance to define a set of criteria on which an objective comparison can be made between the various commercial products and academic implementations. These criteria shall be stringent enough to allow the selection of the engines that are best suited for a given VR application. In this survey, the graphics rendering engines were evaluated and classified according to the following set of criteria: 1- supported computer platform; 2- supported programming language; 3- cost; 4- supported file formats and database; 5- special features and characteristics; 6- base layer; 7- type and nature of documentation and customer support; 8- adopted rendering method; and 9- CAD tools for designing VEs and associated databases.

4.2 Available Products

4.2.1 Cg (C for Graphics)

Cg is a language for programming GPUs. It is the best way to take advantage of today's GPUs across multiple platforms and Application Programming Interfaces (APIs). Supporting DirectX as well as OpenGL environments, the compiler allows developers to create advanced visual effects for today's programmable GPUs from [nVidia] and other vendors. In short, Cg will do for GPUs what "C" and "C++" does for CPUs. Cg is leading the convergence of film and real-time rendering.

4.2.2 Open Scene Graph [OpenSceneGraph]

The Open Scene Graph is a portable, high-level graphics toolkit for the development of high performance graphics applications such as flight simulators, games, VR environments, or scientific visualization. Providing an object-oriented framework on top of OpenGL, it frees the developer from implementing and optimizing low-level graphics calls, and provides many additional utilities for rapid development of graphics applications.

4.2.3 Intrinsic Alchemy [VicariousVisionInc.]

Intrinsic Alchemy is a high-performance software platform for delivering real-time 3D applications across multiple systems. Intrinsic Alchemy is a comprehensive development and run-time environment that offers game programmers the best of both worlds--peak performance on each hardware device combined with remarkable flexibility and ease-of-use. By hand-tuning each implementation for the target device, Intrinsic Alchemy exposes the unique hardware features of each hardware design and creates a consistent development framework.

With an innovative architecture, advanced real-time rendering techniques, support for leading third-party tools and modules, and easy integration with the developer's own tools and code, Intrinsic Alchemy frees developers to focus on creating great games.

4.2.4 Java3D [Sun]

Developers can easily incorporate high-quality, scalable, platform-independent 3D graphics into Java technology-based applications and applets. The Java 3D API provides a set of object-oriented interfaces that support a simple, high-level programming model. This enables developers to build, render, and control the behaviour of 3D objects and visual environments. By leveraging the inherent strengths of the Java language, Java3D technology extends the concept of "Write Once, Run Anywhere" to 3D graphics applications.

4.2.5 OpenGL Performer [SGI]

OpenGL Performer is a powerful and comprehensive programming interface for developers creating real-time visual simulation and other professional performance-oriented 3D graphics applications. The toolkit simplifies development of applications used for visual simulation, simulation-based design, VR, interactive entertainment, broadcast video, architectural walk-through, and computer aided design.

4.2.6 Visualization Toolkit (VTK)

VTK, [KitwareInc.], is an open source, freely available software system for 3D computer graphics, image processing, and visualization.

4.2.7 WorldToolkit (WTK)

WTK, [Sense8], is a portable, cross-platform development system for building high-performance, real-time, integrated 3D applications for scientific and commercial use. WTK has the function library and end-user productivity tools that are needed to create, manage, and commercialize custom applications. The high-level API allows applications to be quickly prototyped, developed, and configured as required. WTK also supports network-based distributed simulations and an array of interface devices, such as HMDs, trackers, and navigation controllers.

5. CONCLUSION

This paper focuses on the description of academic and commercial technology related to visualization hardware/software components as a part of VR systems that contribute to generate VEs. This paper addresses the practical needs of a potential VE designer, providing sets of evaluation criteria for an application-tailored selection of the currently available VR hardware and software products.

While conducting this survey, innovative visualization technologies have demonstrated a high potential of being used in future VR systems. Volumetric displays and (flexible and transparent) organic LED displays are among the most promising technologies. Improvement to VRDs, motion tracking devices, AR systems and finally, mobile computing devices (wireless networks and portable or wearable computers) are also to appear in the near future.

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