CAVE: An Emerging Immersive Technology - A Review

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***Abstract*— Currently, the CAVE (Cave Automatic Virtual Environment) systems are one of the best virtual reality (VR) immersive devices available for portraying the virtual environment. The CAVE gives the illusion of being surrounded by a fictional world, providing a fully interactive, scientific visualization. The CAVE systems can provide a completely new dimension to scientific experimentation as well as entertainment. At the same time, the CAVE systems are a work-in-progress, with CAVE2 having improvements to reduce the complexity, high costs, and cumbersome hardware required by the original CAVE systems. In this paper, we give a system overview of the CAVE systems, its applications and enhancements.**

Keywords— CAVE; CAVE 2; Immersive Virtual Reality; Tracking System; Versions of CAVE; Applications of CAVE;

I. INTRODUCTION

Virtual environments provide stereoscopic head-tracked displays that allow users to perceive three-dimensional structures of the data being analyzed. Researchers who need to control, drive or interact with their scientific data have found this unique feature to be extremely useful. Creating a convincing sense of immersion demands very high degrees of performance at all levels of hardware and software used [19].

The name "CAVE" is a recursive acronym (CAVE Automatic Virtual Environment). The CAVE was researched and developed by the Electronic Visualization Laboratory, at the University of Illinois at Chicago as a tool for scientific visualization. Since its premiere at the 1992 SIGGRAPH conference, the CAVE has achieved international recognition as the pinnacle of immersive virtual reality system technology, providing a compelling display environment for science, engineering, and art. The goals that motivated the design of the CAVE were to produce a virtual reality environment that was suitable for scientific research and to provide a user interface to steer high performance computing applications running on remote supercomputers[17]. The CAVE produces a sense of immersion by surrounding a user with wrap-around screens on which images are rear-projected in stereo on the walls and down-projected in stereo onto the floor. To perceive stereo users wear three-dimensional shutter glasses[17]. The CAVE2 Hybrid Reality Environment represent the intersection of best-in-class display walls and virtual reality environments, enabling researchers to analyze high resolution 2D and 3D data through a unified visualization instrument[12].

II. PRACTICAL REQUIREMENTS

A. Accessibility, immersion and portability

Visual immersion needs specific and expensive hardware such as Head Mounted displays (HMDs) suffer from small field of view and user gets isolated from the real and virtual worlds. Multi-user specialty is a major advantage of CAVE systems, besides presenting a wider field of view, and allows persons to be physically within the virtual environment [21]. Users can develop applications in 3D that can be ported or handled on immersive devices after simplifying software development and debugging [16]. The framework is not only multi-platform but also multi-device that can seamlessly access mobile devices as well as CAVE systems.

B. Robustness and application deployment ability

The framework should be compact and robust enough to reduce external dependencies, conflicts and sizes.

C. Completeness and Cost-effectiveness

Virtual reality requires many things simultaneously from 3D models to tools to create graphic user interfaces. The graphic engine features a simple but complete graphic user friendliness interface system offering the same functionalities on PC and CAVE systems [16].

D. Modern and updated

The graphic engine of immersive devices like CAVE requires regular updates as well as open architecture allowing an easy integration of new elements and features when necessary.

E. Virtual Reality aware

The field of virtual reality often needs specific devices, like HMDs, CAVEs, or haptic devices. The required framework should support a series of functionalities to

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directly use this hardware or to simplify their interfacing. For example, stereographic rendering is directly supported on CAVE and can be easily activated on a PC to output images to a head-mounted display.

III. System Overview (Literature survey)

The CAVE system consists of the following components:

A. Audio System

In the 1990s, 3D visuals were accompanied by directional sound only. In order to incorporate 3D audio, Head Related Transfer Function (HRTF) was used but only a single user could be tracked at any given time. This was a disadvantage for multi-user system like CAVE [6].

To get over this disadvantage and to enhance the audio-visual experience, various audio engines were developed. One of these audio engines was developed by Virtual Reality Laboratory (VRLab), of the Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland, which features spatial audio positioning through the OpenAL API, audio streaming from .wav and .org files, as well as DSP effects through Creative EAX 2.0[19]. It is easy and straight-forward to add audio sources to scene graph and is robust too.

AUDIENCE (Audio Immersion Experience in the CAVERNA digital) [7] is another project which helps to implement flexible and scalable multichannel spatial audio solutions for this CAVE environment. It provides visual and auditory immersion experience for more than one user inside the CAVE.

B. Video System

CAVE video system is an inside out surround 3D video presentation that uses window presentation. The ascension position sensor attached to the Stereographic Crystal Eyes' stereo shutter glasses returns values on which the correct perspective and stereo projections are based. With a resolution of 1024x768 or 1280x492 pixels per screen, each screen updates at 96Hz or 120Hz respectively[8] .

On each wall two off-axis projections are displayed. Shutter glasses allow displaying different images to each eye. This is done by synchronizing the rate of alternating openings to the screen update rate [8]. Due to this a viewer wearing a shutter glasses experiences a 3D illusion. In order to display two images as one 3D image the screen update rate is cut into half while generating a stereo image. Thus, with a 120 Hz screen update rate, the total image has a maximum screen update rate of 60 Hz. Depending on the viewer from the projection screens, the panoramic view of cave can be varied from 90˚ to greater than 180˚. The direct viewing field of the frame design for the stereo glasses provide a view of about 100˚ [6]. The resolution and update rate can be improved with some design changes to the CAVE's current visual specifications. The user would wear passive crossed polarizer with matching polarizer on the corresponding projector so as to restore stereovision without shutter glasses.

C. CAVE Callibration

Static position errors in the magnetic tracker can be corrected using a calibration procedure. The distortion of magnetic field due to the metal structure can be avoided by making use of austenitic stainless steel which is non-magnetic and has low conductivity. The outputs obtained from custom-built ultrasonic measuring system and positions reported by magnetic tracker are compared and then a look-up table is created, and is used to interpolate corrected values [19].

Despite an accurate calibration of their convergence an unavoidable misalignment will be produced from projecting images projected by two separate projectors. This problem can be resolved by means of calibration software. The concept of this software is to let user draw an accurate shape manually following the screen borders and then this shape can be used as polygon to render images into. The OpenGL frame buffer [7] object extension is used to perform a high resolution (1024x1024 pixels) render-to-texture by the CAVE. To fit the display shape, this texture is then mapped onto the previously adapted polygon. We can also use a grid with movable control points to improve image superposition for stereo rendering. The deformations caused by the beamers being physically projecting from the points can be avoided by matching control points of the grids projected from the two projectors. Moreover, this calibration solution also solved a problem due to unequal pixel sizes on the CAVE walls because of different distances between the projectors and the displays [21]. Here, the earlier concept of an accurate match of the render to shapes is accompanied by anti-aliasing technique which caused this problem to disappear. Therefore, a continuous image on different walls with great immersion experience is achieved which is further improved by stereographic rendering.

D. Stereographic Rendering

The basic requirement of stereographic rendering is the generation of two images and their display at same time. One computed for right eye and one computed for left eye. CRT projectors with high refresh rate featuring up to 120Hz as refresh frequency are used by top level solutions. Using shutter glasses, this system can display a maximum of 60 images per second per eye [8]. A professional graphic card including a synchronization output for shutter glasses will drive the video projector. And according to the vertical synchronization of display, this output changes the polarity of shutter glasses. This professional graphic cards and high quality projectors are very expensive and require periodic servicing.

There can be a situation where large numbers of viewer are present in a CAVE system at the same time and since the shutter glasses are fragile and are in low amount, we can opt for an old style blue and red glasses stereographic system. Stereographic rendering adds depth information to the surrounding image and thus improves immersion [6]. But while user is moving, to avoid break in presence the perspective referential should be accordingly displayed.

E. Tracking System

1. *Camera and vision based algorithm to track markers located on the user's head:*

All the necessary functions treat the video information in real time and extract 3D position and orientation of predefined markers are provided by the open source library ARToolkit [8]. The tracking accuracy was degraded due to frequency changing markers' illumination. A solution for this problem is to place a light bulb inside a small cube covered with markers fixed on the user's head, creating some kind of head worn lantern with semi transparent markers on the sides, to keep their luminosity constant and independent from the brightness of the images rendered on the CAVE walls.

2. *Magnetic tracking system:*

For an electromagnetic tracker operating at 60Hz sampling frequency for a dual sensor configuration with ascension flock of birds, six degrees of freedom is used to track head and hand position. To perform the correct stereo calculations for a user, the eyes of the user are located using his/her head position [6]. To allow the viewer to interact with the virtual environment, the CAVE's second position sensor is used.

3. *Optical tracking system with active markers using multiple viewpoints:*

Great accuracy around a few millimeters in positioning is provided by this system so as to get the perfect result for applications where multiple people can be present in CAVE at the same time and interact freely without loss of immersive experience. The reference points for converting sensor spatial coordinates can be easily matched by aligning the three laser dots on a reference grid displayed on the walls and the floor.

F. Graphics Engine Of CAVE Systems

3D graphics software for the platforms of CAVE system is limited and difficult to find. Many projects adapted standard PC engines to fit into a network architecture to satisfy a CAVE installation[9]. Initially developed by the Electronic Visualization Laboratory at the University of Illinois,
CAVElib is a powerful complete API for developing applications using SID(Spatially Immersive Devices0 devices with multi-platform support and requiring less efforts from the user. CAVElib[5] works directly on a of immersive devices like CAVEs, ImmersaDesks ,RealtyCenters,etc.Unfortunately, CAVElib function is limited by very expensive licenses and lack of support for mobility.

Due to the multi-core approach used in CAVE frameworks ,multi-workstation libraries are also used to simplify rendering on clustered machines, like WireGL using off the shelf PCs connected with a high-speed network to provide a scalable rendering architecture. Chromium is a software derived from WireGL allowing rendering on multiple screens. Both Chromium[4] and WireGL come as an OpenGL driver automatically distributing graphics calls over the different cluster machines.

IV. VERSIONS OF CAVE

CAVE systems differ in size and characteristics, ranging from small-sized environment to very large scale frameworks for public exhibitions and entertainment [15]. Modern CAVEs can be roughly divided into three categories: professional solutions sold by specialists of Virtual Reality equipment, very inexpensive home solutions made with common materials, and intermediary architectures aiming at the quality of professional solutions.

A. Professional Solutions

Interest in CAVEs and Spatially Immersive Devices (SIDs) has risen since their invention and is today transferred into commercial products like BARCO and VRCO. Despite the large amount of development in this direction, professional solutions are still extremely expensive [21].

Most of the CAVE installations are based on a cluster/multi-core approach, to spread rendering over many machines. It is also possible today to bypass the complex network and synchronization work by using a unique PC with a multi-GPU card expansion or SLI architecture. Models like NVidia, QuadroPlex series allow the creation of a stereographic four-sided CAVE as used in πCAVE[20], which has a rectangular parallelepiped configuration with a large width one of the characteristic features of the CAVE system. The large volume of πCAVE allows several people to stand on the floor at the same time, without any mutual occlusion of the screen views in the room. There are also completely different approaches using spheres instead of boxes to build up immersive CAVE-like environments[3] using a rotating sphere wherein the user can walk by standing still at his/her place and watching images projected on the spherical surrounding display.

The StarCAVE[13] supports fully-tracked VR immersion (360◦ look-around capability) for 1 prime user and several observers and consists of bright, high-resolution, high-contrast visuals, and lifelike immersive ambient auditory experience, dynamically scaled to arbitrary virtual scenes, for one or more listeners. It provides a platform to explore and evaluate multiple approaches to immersive audio experience and sonification of scientific data in certain visualization contexts.

B. Home-made, alternate solutions

Reduced versions of CAVE systems, with fewer walls or even which are transportable exist. One of them is the V-CAVE (made with just two walls, hence the name V-CAVE, because the two screens form the letter *v*) [9]. Some variants are also installed on plastic tubular frames that can be assembled and disassembled, making a compact portable version of a CAVE system.

Wall displays can be considered as a single-wall version of CAVE but less expensive and much easier to build and manage. Wall displays have the advantage of being very easy to setup, requiring less space, and not requiring any complex calibration of neither the projectors, nor multi-PC rendering. Some wall displays use a multi-projector approach to improve the resolution of the screen, which requires a more sophisticated and finer calibration system to correctly align and provide seamless continuity over the portions of the display covered by more than one projector[11]. Some of them are also movable, similar to a V-CAVE, like the stereographic system presented in [6]. Unfortunately, most of these cost efficient solutions, implement only a subset of the features of a full CAVE system[1], with less sides, inferior resolution, and poor rendering quality.

C. Low-cost solutions

Sauter, in [10] describes a low-cost CAVE solution based on generic Windows and Macintosh computers[10]. The HIVE (in Hanover) is also a low-cost implementation of a small three-wall CAVE setup made at less cost. HIVE-like systems are among today's less expensive approaches to build a multi-side virtual display with the usually low budget available for education [1]. Unfortunately, such systems usually are transitioned into very small environments with fewer walls and poorer quality when compared to other more expensive but also superior solutions.

V. APPLICATIONS

A. CavePainting

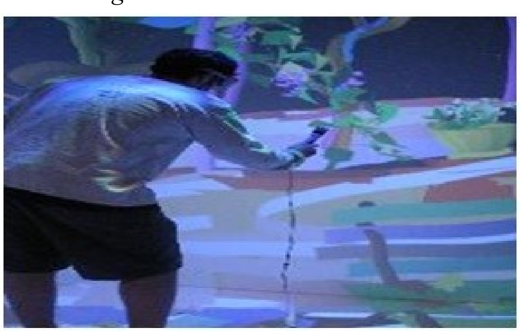

Fig. 1. CavePainting: Painting using CAVE technology

This is an artistic medium that uses a 3D analog of 2D brushstrokes to create 3D works of art in an immersive virtual reality CAVE environment[16]. These 3-dimensional marks are a fluid, highly flexible visual language that is brought to life by an interface responsive to the artist. The main highlighting feature of CavePainting is that a CavePainter can walk *through* his work, grab and rotate it in his hands, shrink or enlarge it on a whim, and finally manipulate colour variations and stroke size, shape, and placement to create a visual representation for complex forms[22].

B. Diode LASER simulation

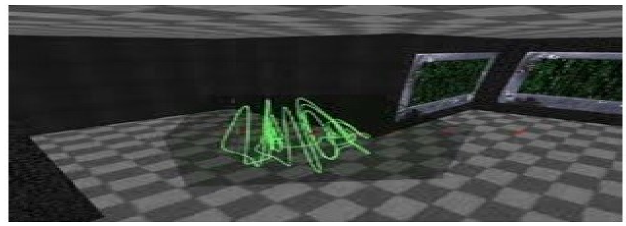

Fig. 2. A Diode LASER Simulation using CAVE

Diode laser simulation gives a visualization of diode laser behaviour. At first, the simulation computes some fixed points in the phase space for a given set of parameters[22]. The user can interactively set the values of selected parameters using sliders. The fixed points serve as starting point of the simulation. Once these points are visualized, the scientist can directly select one of these points to start the simulation[18]. The computed trajectory is sent incrementally to the CAVE. The trajectory is visualized and can be manipulated by the scientist. The interactive way in which physicists could test hypotheses and investigate the behaviour of the diode5 laser helped them to gain a better insight in this complex system.

C. Interactive RoboCup

Fig. 3. RoboCup soccer using CAVE

Interactive RoboCup is an application which lets a team of cooperating autonomous agents play a soccer match, using either real robots or simulated players[18]. A virtual reality environment is constructed in which humans in CAVEs at different geographic locations can play along with a running RoboCup simulation in a natural way. A central role is played by the so called Soccer Server, which keeps track of the state of the game and provides the players with information on the game. The players are individual processes that can request state information from the server and autonomously compute their behaviour. The server also enforces the rules of RoboCup and ignores invalid commands from the players.

The CAVE program allows the user to be immersed in the game and to interact with it. Software is used to track the behaviour of humans in the CAVE. One tracker is connected to the viewing glasses and monitors positional changes of the human player inside the CAVE. The second tracker is connected to the wand (a 3D mouse), which is used for global movements over the soccer field. A third tracker is attached to the foot of the human player and is used to recognize a kick. We convert tracker changes into soccer commands and transmit these to the server.

D. Interactive Molecular Dynamics

Fig. 4. Using CAVE to study the molecular structure in 3D

Interactive molecular dynamics is an application which concerns the coupling of a molecular dynamics (MD) simulation to a virtual reality(VR) system[18]. VR allows the scientist to gain a deeper understanding of the complex molecular structure in 3D. Moreover, modifying 3D structures or expressing forces is intrinsically a 3D process, for which the use of an immersive virtual environment is a perfect match.

VI. ENHANCEMENTS

For decades, immersive systems included bulky Head Mounted Displays, with limited resolution and field of view. In 1992, the original CAVE created a paradigm shift in Virtual Reality. CAVE [2] consisted of a cube measuring 10 feet at each side, with projector-based stereoscopic graphics on five of its sides, and it allowed users to experience stereo 3D wearing much lighter shutter stereo glasses. The system was large enough to fit multiple individuals who could simultaneously experience the visualization. Additionally, head tracking enabled scientists to explore complex datasets using embodied interaction such as walking around in the CAVE or using a tracked ‘wand’ to fly through the virtual world.

While the original CAVE provided limited resolution (4 Megapixels) and poor contrast ratio, recent evolutions of the system utilize advanced projectors, yielding resolutions of up to 200 Megapixels[3][4]. However, both original and modern CAVE systems require specially designed rooms and low environment light levels to operate, making them difficult to integrate in office environments[17]. Furthermore, high resolution projectors can be extremely expensive, and require regular maintenance (calibration and bulb replacement). This held up their adoption in everyday scientific workflows and limited them to opportunistic use.

More recently, tiled LCD display walls have emerged as a practical platform for large-scale data visualization. Constructed by tiling multiple LCD monitors to form a contiguous display surface, these environments often span entire walls. LCD walls provide superior image quality and resolution, often reaching 100 to 300 Megapixels, and require low maintenance.

TABLE I. COMPARISION OF CAVE VS CAVE2

CAVE vs CAVE2	**Versions**		
	CAVE	***CAVE 2***	***Improvements***
Year	1992	2012	
Virtual Reality Environment (Cubic feet)	1000 cu. ft. (10Lx10Wx10 H)	3167 cu. ft. (pi x radius 12 ft 2 x 7H)	3%
Projection vs LCD	4 Projectors	72 LCD	n/a
Stereo Resolution (Megapixels)	2.6 (1260x512x4)	36 (1.366x736x72/2)	13%
Visual Acuity	20/110	20/20	n/a
Brightness (lumens)	4000	266400	66.6X
Contrast Ratio	< 500:1	3000:1	6X
Bulb life(hrs)	2000/projector	50000/LCD	25X
Display cost per stereo Megapixel	$35000	$14000	2.5X
Processor	4x100 MHz MIPS R4000	36x2.9 GHz 10 core Xeon E5-2000	4176X
Graphics	SGI Crimson VGXT	Nvidia GTX 680 2Gb RAM	n/a
Memory	256MB	36 x 64 GB	9000X
Storage	3.2 GB	36 x 2 TB	22500X
3D Tracking	Cabled	Wireless	
Networking	10 Mb/s	2x10Gb/s	2000X
Total Cost	$2M (today)	$926K	50% reduction

The qualities of CAVEs and display walls make them effective at visualizing different classes of data. CAVEs are extremely effective for visualizing 3D spatial datasets but are far less suited for 2D information [17]. Current technology trends lead to the productions of larger, affordable thin-bezel LCD monitors with built-in support for stereoscopic 3D. Such recent advancements made it conceivable to merge the best-in-class capabilities of immersive Virtual Reality systems, such as CAVEs, with the best-in-class capabilities of Ultra-high-resolution Display Environments, thus creating conceptually new immersive environments which we refer to as Hybrid Reality Environments (HREs). However, the CAVE2 [12] system, to date, is the first full implementation of a true Hybrid Reality Environment.

VII. Conclusion

This paper describes the practical requirements and gives a system overview of the modern CAVE systems. We also discussed applications of CAVE systems in diverse fields. CAVE 2 has simplified the interaction transitions between 2D and 3D content, and deals efficiently with multiple 3D applications.

Virtual reality is still rapidly growing and generating great expectations. Future research will be to integrate the CAVE into an environment that allows researchers to accomplish a given task collaboratively, even when such users are geographically dispersed. This way, the user can share remotely what he/she is looking at, at that moment, via a Head-Mounted-Display or even a 2D display.

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