DATA VISUALIZATION AND EXPLORATION VIA VIRTUAL REALITY — AN OVERVIEW

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1. Introduction

"Virtual reality refers to immersive, interactive, multi–sensory, viewer–centered, three–dimensional computer generated environments and the combination of technologies required to build these environments." (Carolina Cruz–Neira) — this is one (of multiple) possible definitions of *Virtual Reality* (VR), summarized in Cruz-Neira (1993). The origin of VR dates back to 1965 when Ivan Sutherland proposed the *Ultimate Display* (Sutherland 1965). Later, Sutherland also built and refined the *Sword of Damocles*, the first *Head Mounted Display* (HMD). In 1985 Thomas Zimmerman designed the *DataGlove*, a device that is capable of measuring the degree to which each of the user's fingers is bent. Another VR device, the *Binocular Omni–Orientation Monitor* (BOOM) was commercialized in 1989. A brief chronology of further events that influenced the development of VR can be found in Cruz-Neira (1993). A more detailed overview can be found in Pimentel & Teixeira (1995).

In this paper, we provide an overview of current VR technology and we describe how this technology can be used for data visualization and exploration. We conclude this paper with a discussion on VR and visual data mining.

2. Current VR Technology

The virtual environments described in this section began with emergence of VR hardware in the late 1980s. The PlatoCAVE at George Mason University is an immersive display system installed in a room approximately 20 feet on a side. It consists of a Stereographics CRT projection system driven by a Silicon Graphics workstation. The Stereographics projection system is a reworked Electrohome CRT projector with capability for using Crystal Eyes shutter glasses for stereoscopic display. The Crystal Eyes shutter glasses are light weight and contain active electronics which alternately obscure left and right eyes at a rate of 60 frames per second for each eye. They are controlled by an infrared sending unit which synchronizes the shutters with the projected image. The images are projected on a wall of the PlatoCAVE and are approximately 15 feet in diagonal measurement and span the entire wall from floor to ceiling.

Cruz–Neira and her colleagues developed a much more ambitious visualization environment at the Electronic Visualization Lab (EVL) of the University of Illinois in Chicago, known simply as the "CAVE" (Cruz-Neira, Sandin, DeFanti, Kenyon & Hart 1992). The abbreviation "CAVE" stands for *CAVE Audio Visual Experience Automatic Virtual Environment*.

The CAVE is a projection–based VR system where the illusion of immersion is created by projecting stereoscopic computer graphics into a cube of projection screens that surround the viewer. Many of the salient features of the CAVE and PlatoCAVE are the same, e.g., the use of Crystal Eyes Stereographics' LCD shutter glasses. The first CAVE environment was essentially a cube approximately 10 feet on a side. Using mirrors for folding the light path and rear projection, the CAVE projects stereoscopic images on the front and two side walls. Using direct down projection, the fourth projector is used for a stereoscopic image on the floor.

In addition to the three walls and floor, the CAVE typically features head–tracking of one user so that the computed viewpoint is dynamically adjusted according to the location of the tracked head within the 10^3 cubic foot volume. The dynamic head tracking allows the user to see his or her entire environment from the correct perspective and thus creates a compelling illusion of reality.

A detailed technical comparison of the CAVE with other display devices for VR such as CRT, BOOM, and HMD can be found in Cruz-Neira et al. (1992). The CAVE is an easy–to–learn, high–resolution VR interface that is superior to these devices in particular because of its full field–of–view, its visual acuity, and the lack of intrusion. Overall, the CAVE is a very helpful tool for collaborative work.

Carolina Cruz–Neira moved to Iowa State University where she was involved in the development of a second, larger CAVE–like environment known as the "C2". During the last five years, the CAVE has been commercialized and many clone installations have been made worldwide. The CAVE and its successors belong to *Immersive Projection Technology* (IPT) systems where the user is visually immersed within the virtual environment. Latest developments on CAVEs and IPT technology often are presented at the International Immersive Projection Technology Workshop (Bullinger & Riedel 1999, Cruz-Neira, Riedel & Rössler 2000).

Certainly the CAVE and its successors and even the PlatoCAVE are costly affairs and beyond the reach of most academic and industrial groups. In addition, the CRT–based projection systems tend to be relatively dim and notoriously temperamental. The hardware typically is not portable so that the components must be permanently installed. With this in mind, researchers at George Mason University considered the possibility of converting the CRT–based projection system to a LCD–based projection system.

The decision to do so was cemented with the release of MATLAB 5.0 in 1996. This software was installed on a then state–of–the–art 200 megahertz Pentium Pro running Windows 95 and also on a Silicon Graphics Onyx with Reality Engine^2. We ran the benchmarks on both computers and much to our surprise, neither machine dominated. A $3,000 Pentium Pro personal computer held its own against a $120,000 SGI workstation. Coupled with the fact that the Crystal Eyes shutter glasses had Windows NT drivers available, we launched on a project to downsize the PlatoCAVE into what we had designated as the MiniCAVE. Whereas the hardware for the MiniCAVE installation cost initially about $175,000, a full CAVE environment including mechanical supports for the screens, projectors, and mirrors, the projectors and the computers price out closer to $1,000,000. In addition, a full CAVE environment demands considerably more space than the MiniCAVE.

The MiniCAVE is co–located with the PlatoCAVE in the same room at George Mason University, but it is PC–based. We currently use a dual 450 megahertz Pentium III, running Windows NT 4.0. The commodity chips such as those in the Intel series have in many aspects overtaken the specialty RISC–chips used in workstations and certainly the commodity graphics cards compete favorably with the specialty graphics processor once only available through such vendors as SGI. We were able to port the SGI–based application ExplorN and the Stereo SkyFly to the PC and using the Windows NT drivers, we were also able to integrate the Crystal Eyes shutter glasses into the PC environment.

The monitor/projector end proved to be somewhat more difficult. Most monitors designed for PCs are unable to cope with the high frame rates required for the Crystal Eyes shutter glasses. Initially we were forced to use a SGI monitor attached to the PC. However, we are currently using a Dell monitor quite successfully. We were able to connect the NT–based PC to the CRT projection system which made the PlatoCAVE essentially transparent to the driving computer. The attempt to use LCD projectors with the Crystal Eyes technology met with no success. We have since used polarized light LCD–based projectors. Rather than using a data glove or other artificial input devices, the MiniCAVE can be operated via speech. More details on the MiniCAVE can be found in Wegman, Symanzik, Vandersluis, Luo, Camelli, Dzubay, Fu, Khumbah, Moustafa, Wall & Zhu (1999).

3. Data Visualization and Exploration via VR

Dynamic statistical graphics enables data analysts in all fields to carry out visual investigations leading to insights into relationships in complex data. Dynamic statistical graphics involve methods for viewing data in the form of point clouds or modeled surfaces. Higher–dimensional data can be projected into one–, two– or three–dimensional planes in a set of multiple views or as a continuous sequence of views which constitutes motion through the higher–dimensional space containing the data.

There is a strong history of statistical graphics research on developing tools for visualizing relationships between many variables. Much of this work is documented in videos available from the American Statistical Association Statistical Graphics Section Video Lending Library at

`http://www.bell-labs.com/topic/societies/asagraphics/library/index.html`.

Additional material on statistical graphics can also be found in journals such as "Journal of Computational and Graphical Statistics" and in "Computing Science and Statistics", the proceedings from the Interface conferences. Readers unfamiliar with this topic might want to use these sources to check some of the keywords such as grand tour, linked brushing, scatterplot matrices, and parallel coordinate plots.

Before VR technology became accessible for statisticians, stereoscopic displays and anaglyphs have been used to display statistical data in three or more dimensions (Carr, Nicholson, Littlefield & Hall 1986, Wegman & DePriest 1986, Symanzik 1993). One of the first implementations of red–green anaglyphs in statistical software was the "real–time rotation of 3–dimensional scatterplots" in *Mason Hypergraphics*, described in Bolorforoush & Wegman (1988), page 125.

Researchers at George Mason University in the late 1980's were intrigued by the possibility of using time–multiplexed stereoscopic displays to visualize more complex structures. Four major applications within statistics which capitalize on stereoscopic displays have been developed at George Mason University. *ExplorN* includes stereoscopic rotating and scalable scatterplots animated with a grand tour. *Mason Ridge* includes stereoscopic density plots and density contours and features use of rendering and transparency to visualize complex abstract functional surfaces. *3–D MRI* uses stereoscopic displays, rendering and transparency to visualize solid voxel data such as MRI, PET, and ultrasound data. *Stereo SkyFly* is an adaptation of SGI software that allows a flythrough of an elevation database using texture mapping on the triangulated surfaces derived from the elevation data. The adaptation allows not only a stereoscopic view, but also real–time access to the elevation database. All these stereoscopic applications run on a monitor and in the PlatoCAVE.

Iowa State University and George Mason University probably are the two leading academic institutions with respect to the use of VR and IPT hardware for data visualization. In addition to the work on VR–based data visualization conducted at these two universities, independent work also has been conducted elsewhere, e.g., at Georgia Tech and the Delft Technical University, The Netherlands, resulting in the "Virtual Data Visualizer" (van Teylingen, Ribarsky & van der Mast 1997), and at the University of South Carolina, using the *Virtual Reality Modeling Language* (VRML) for VR applications on the World Wide Web (Rossini & West 1998).

The use of Iowa State University's C2 for statistical visualization is based on the framework of three–dimensional projections of p–dimensional data, using as a basis the methods developed and available in XGobi (Swayne, Cook & Buja 1998). VRGobi, i.e., a partial implementation of XGobi in a VR environment, and the statistical visualization in the C2 have been extensively explored and documented in the literature (Cook, Cruz-Neira, Kohlmeyer, Lechner, Lewin, Nelson, Olsen, Pierson & Symanzik 1998, Nelson, Cook & Cruz-Neira 1999, Cook 2001).

In and Nelson et al. (1999), experiments have been conducted on structure detection, i.e., visualization, and ease of interaction. With only 15 human test subjects, one cannot expect to obtain statistically significant results. However, at least these experiments showed that there was a clear trend that the test subjects performed considerably better on visualization tasks in the C2 than with XGobi on the workstation display. In contrast, interaction tasks such as brushing provided better results for the workstation. However, subjects with some VR experiences already performed considerably better on the interaction tasks in the C2 than subjects with no prior VR experience, suggesting that there is some learning needed to effectively use the VR hardware.

In Deisinger, Cruz-Neira, Riedel & Symanzik (1997) experiments have been conducted with subjects using HMDs, monitors, and IPT environments. Again, with only 18 participants in 2 experiments (6 and 12 participants), no statistically significant result has been obtained. However, the IPT environment gave inexperienced users the best feeling of immersion and was liked most by all test participants.

4. Discussion

Much of the motivation for the PlatoCAVE and the MiniCAVE environments at George Mason University has been to provide a collaborative environment which facilitates group dynamics. We have given more than one hundred demonstrations in our environment to groups ranging widely from medical doctors, technically–oriented statisticians, engineers, potential donors to the university, prospective high school students and their parents, and groups of handicapped individuals. The success of the environment as a collaborative tool has been thoroughly demonstrated. Software systems capable of supporting stereoscopic images such as *ExplorN*, *Mason Ridge* and *3–D MRI* have been used extensively and lead to an excellent technical interaction and often animated discussions.

Because of the low cost of a one–walled MiniCAVE, approximately \$6,000 for the computer and \$13,000 for the polarized light stereo projectors, this technology is feasible on a much broader scale than more elaborate immersive systems such as the CAVE.

Cook (2001) lists three fields, "environmental studies, especially data having a spatial component; shape statistics; and manufacturing quality control", that would most benefit from IPT environments. In addition to Cook's fields, we think that medical, genetic, and biological statistical data would also considerably benefit when being explored in an IPT environment.

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