Designing a Low Cost Immersive Environment System Twenty Years after the First CAVE

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Abstract – The earliest CAVE systems were a breakthrough technology made possible by the availability of graphics hardware capable of moderately high resolution and update speed. In the following twenty years the cost of computing and display equipment has decreased sufficiently that it is possible to configure a system with display capabilities equivalent to or better than early systems at orders of magnitude less cost, thus extending use to a much wider range of applications and users. In this paper we report our experience in design and implementation of an immersive environments laboratory used for research and education. The principle design considerations were that the system be relatively low cost, easy to configure and maintain, and fit in a small space, considerations common to the design of many similar systems. The paper also summarizes advances in cost/performance and ease of use since the first CAVE systems for each of the principle elements of an immersive environment system.

Keywords: virtual reality, virtual environment, visualization, virtual reality tools, case study, design, low cost

1 Introduction

Immersive displays for virtual environments have been a hallmark of advanced graphics displays for twenty years. The first CAVE system [6, 7] was a breakthrough technology made possible by the availability of graphics hardware capable of moderately high resolution and update speed. These early CAVE systems typically employed a three sided space with walls and floor illuminated by stereoscopic projectors displaying graphic representations of physical environments. Essentially the same display paradigm is employed today in many systems, yet the quality of graphics and rate of display have dramatically changed in state of the art systems. The cost of computing and display equipment has decreased sufficiently that it is possible to configure a system with display capabilities equivalent to or better than early systems at orders of magnitude less cost, thus extending the range of immersive virtual environment displays to a much wider range of applications and users.

In addition to the reductions in computing and display cost, there has been significant decrease in effort required to program immersive virtual environments. The earliest CAVE systems, as well as visualization systems generally, required significant programming efforts, typically unique to the system and application at hand. Much of the programming challenge was due to the need to use relatively low level graphics commands and individual computers for each display surface. In many current applications, programming approaches can rely on relatively high level tools for the programming needs of virtual environments. For display, a single computer can now readily control four or more graphics outputs, each with independent graphics processing unit. When individual computers are required, reliable software tools for configuration are available. Importantly for cost considerations, satisfactory tools for these programming tasks are publicly available.

In designing the system described in this paper our goals were to create an immersive display and virtual environment system with capabilities for both research and education. In its research capacity the system would support prototyping and development for work to be carried out in a CAVE located away from the university’s central campus area, as well as stand-alone efforts. For educational purposes the system would be used in courses in graphics and visualization. The space available was quite constrained, yet the system needed to be of sufficient size to achieve high field of view with some measure of viewer mobility. Both hardware and software cost and maintenance were important factors. The system was to be designed to be easily reconfigured and extended.

The next section describes Related Work relevant to our design considerations, especially that for which cost was a significant factor. The section examines display techniques, computing and graphics systems, and software. The following section describes the System we have developed with a focus on its application in its targeted domains of education and research. Component costs are provided. Conclusions and References follow.

2 Related work

Predictably, the price/performance ratio for costs associated with immersive virtual environment systems has decreased by orders of magnitudes since the development of the first CAVE systems twenty years ago. However, for the several system elements decreases in costs have varied
widely. The most dramatic decrease in costs has been for computing and graphics equipment. Indeed, development of graphics processing units in the past decade, driven by a development focus on consumer demand for gaming and other visual elements, has provided some of the largest advances in computing hardware. For display elements, such as projectors and screens, decrease in cost has also been substantial, but these partially analog elements do not follow the cost reductions achieved for computing hardware, nor do the software elements required to integrate the system’s components and create virtual environments.

The need to design and construct an immersive virtual environment under constraints of cost and space is not new, and many solutions have been offered. The remainder of this section considers this past work in the context of our system design and current product cost and availability, with sections focusing on displays, computing systems, and software.

2.1 Display

Room sized display systems with images displayed on walls, floor, and ceiling are the most widely used technique for highly immersive virtual environment systems. Such systems can be characterized by the number of surfaces illuminated, from six, in the case of a fully immersive system with four walls, floor and ceiling used for display, to one, for a single wall display. Surely there are variants, such as the STARCAVE [10] with five sides, each with three panels, and spherical displays [11].

The essential design consideration for visual immersion is the portion of the viewer’s complete field of view that is taken up at any time by displayed images [4]. As the user moves his or her view direction and/or position, the displayed image needs to be visible in the new area. Even a large single surface display will cover all of the field of view with static view direction and the user close to it. However, only with all six surfaces illuminated will full mobility with complete visual immersion be possible. Nonetheless, “successful” immersive displays have been constructed with less than all surfaces illuminated. “Success” depends on task at hand, nature of display content, and a host of other factors [23].

2.1.1 Single Surface Display

Single surface displays have long been proposed as alternatives to larger multi-surface displays, due to their lower cost, while still retaining elements of immersion suitable to the task at hand [36, 8]. Desktop size (~4’ x 6’) systems, such as the ImmersaDesk [8] and Responsive Workbench [17], providing stereoscopic viewing of rear projected images, were developed shortly after the first CAVE systems and have seen continuing application. Recent desktop systems have been developed that utilize commodity stereoscopic television panel displays to significantly decrease cost [34].

Larger scale single surface stereoscopic displays were also developed during the early 1990’s, such as the Infinity Wall [8] and PowerWall [36], again using rear projected images. Current approaches range from auditorium sized front projected stereoscopic displays to tiled displays made up of dozens of commodity monitors [19]. Research has shown that for appropriate applications single surface displays can provide a useful, low cost alternative to multiple surface displays [20, 23].

2.1.2 Two Surface Display

Two surface displays are capable of increased visual immersion for the viewer, but at increased cost and complexity. Typically, the image is as if projected in the corner of a room. With two surfaces the viewer has many of the advantages of display with three or more surfaces, but without complete mobility and scanning freedom. Nonetheless, with rear projection the user can stand and move about between illuminated surfaces, thus providing relatively high lateral field of view and mobility found to be useful in enhancing the viewer’s experience of immersion.

Early examples of low cost two surface projection are the WEDGE [12] and VR2Go [27] systems, both using stereoscopic rear projection. Contemporary with these efforts is Jacobson et al.’s development of a low cost front projection system [14]. The system uses a display with vertically oriented projectors illuminating two screens using front projection. Vertical orientation of projectors results in the longer side of the projector’s display being vertical, rather than horizontal. Arrangement of the two projectors allows the viewer to approach the corner to a point slightly within the screens on both sides without obstructing the illumination.

2.1.3 Three or More Surface Displays

A wide range of solutions has been offered to deal with the challenge of creating systems that provide three or four surface displays and achieve acceptable results with very limited cost. As noted, viewer mobility results in a more immersive experience for the user, and this is achieved most completely by rear projection. The increased sense of immersion is achieved with additional costs, including the translucent surface material for projection, together with its framing. Also, higher projector output is required, compared to front projection, due to loss through the translucent projection material. For space conservation, mirrors are used to fold the projected image.

A very low cost immersive system with images projected on three walls and the floor is described by Peternier and Cardin [22]. Rear projection onto canvas that allows some measure of light transmission is used for the walls. The wall
framework uses nylon line for corner tension, with image distortion due to line stretch corrected by software. Projection illumination is not folded by mirrors, saving cost, but resulting in an overall size some three to four times the length of a wall. To achieve active stereoscopic display, two projectors are used for each wall. Shutters for projector pairs control sequential left and right eye image display, and projector shutter timing is synchronized with viewer LCD glasses. Anaglyph display is also provided without shutters.

Recently, Juarez et al. [15] describe a similar approach to creating a room sized system using rear projection onto canvas, but without stereoscopic display. The use of short throw projector lenses allows overall size to be only about twice the size of the enclosed area. Pougnadoresse et al. [24] describe an extremely low cost room sized system using tracing paper for projection. Cliburn [5] presents a user study using a very low cost three wall passive stereo rear projection system with on site painting of commodity acrylic display surfaces. Commodity mirrors are used to create a single fold of projections to reduce system size. Stereoscopic rear projection systems have been developed with space for only a single person [31, 39] in efforts to minimize space, as well as cost.

Front projection systems significantly constrain viewer mobility compared to rear projection due to possible occlusion of projected image, but offer significant reduction in cost and complexity. Additionally, front projection has the important advantage that space requirements are significantly reduced. The LAIR [9] system demonstrates a clever solution to four wall display using front projection. Two projectors are used for each wall, so that the projected image for each covers half of the wall. The viewer can then stand between the two projectors so that the projection is not occluded. With viewer position half the distance between the walls in front and behind, this arrangement of two projectors per wall can be repeated for the other walls to create a four wall display with an area in the center of the room in which a viewer does not block any of the front projections.

2.2 Computing Systems

In the decade following CAVE introduction, the most dramatic advances in cost were in the computing equipment required to achieve the frame rates and scene complexity necessary for interactive display of virtual environments. Relatively low cost computers and graphics systems replaced the early special purpose equipment with several orders of magnitude decrease in cost. In the decade following that, relatively low cost graphics processing units (GPUs) with hundreds of processors have become available to support double buffered stereoscopic viewing of complex scenes at appropriately high refresh rates. Advances in computer architecture for moderately priced computers allow multiple GPUs in a single system, thus for many applications eliminating the need to network multiple systems and the associated cost of display synchronization.

The ability to achieve acceptable performance through the use of commodity computing and graphics hardware marked early efforts at low cost solutions [e.g., 1, 13]. A decade after the first immersive virtual environment systems were introduced in the CAVE, Pape et al. [20] and Lin et al. [18] provide 2002 graphics benchmark results comparing specialized graphics hardware, SGI Onyx, and low cost hardware of the day, detailing the order of magnitudes in improvement in price/performance ratio during that first decade. Today’s commodity computers and moderately priced graphics hardware provide far greater performance than even specialized equipment of that era with yet more orders of magnitude improvement in price/performance.

Additionally, to achieve acceptable graphics performance in low cost systems during the first decade of immersive virtual environment systems, it was necessary to utilize multiple computer systems with the associated complexities and cost of network communication and display synchronization. Early work focused on networking solutions as one component of low cost solutions [13, 18]. Much of the challenge of networked computer communication and configuration for low cost solutions was reduced by development of public domain software, e.g., ClusterJuggler [3].

Currently, it is possible to achieve acceptable computing and graphics performance far superior to early state-of-the-art systems at very reasonable cost. Indeed, for many applications satisfactory performance can be achieved using a single computer housing multiple graphics cards capable of stereoscopic display. A single computer system has the advantages of eliminating hardware costs associated with multiple computers and the complexity of networking the systems. Additionally, use of a single computer eliminates the need to synchronize display signals to projection devices, which often requires separate hardware components.

2.3 Software

In the first decade following CAVE introduction, software development changed from the major efforts of the first systems’ completely unique applications, specific to hardware and display, to the widespread use of tools for graphics display and system configuration. The use of these early software libraries reduced much of the development effort, but nonetheless required application development in relatively low level languages, still requiring advanced programming skills and significant time tied to the integration of computing system and display. In the following decade and to date, such libraries are still widely used and necessary for many applications. However, the game industry has provided a set of tools that has crossed over to the development of immersive environments and can support
rapid low cost development of rich virtual environments with public domain tools, though integration of multiple displays still presents challenges with these tools.

CAVElib [21] was developed for use with Cruz-Neira et al.’s original CAVE system. Originally designed to run on specific hardware, it evolved to provide general display facilities for multiple display and computer systems, as well as interaction devices. It was once among the most widely used systems by researchers and offered a reasonably robust and freely available solution for many immersive system software needs. Unfortunately for the wider research community, the system was commercialized, and now license costs present a barrier for low cost system development.

A number of other multiple display and computer integration software systems are freely available. VR Juggler [2] provides relatively high level multiple display management and device integration facilities. Its architecture allows the close coupling of additional native code in its use. It was extended to provide support for networked systems with Cluster Juggler [3]. Both are widely used and updated for new operating systems and languages [37]. OpenSG [26] provides another relatively low level software solution for multiple display immersive systems using scene graphs. The VRPN [38], Vrui [17] and FreeVR [33] libraries provide suites of interaction handling routines. Raffin and Soares [25] provide a review of multi computer and display systems for low cost immersive systems.

Within the past decade, the widespread availability of computer games and freely available programming tools to support them has led to their use in the development of immersive systems. These tools provide efficient graphics software and typically provide authoring tools for interaction handling, as well as display and modeling. An early example is Jacobson and Lewis’ [14] use of the Unreal Tournament game software to develop a system supporting multiple displays. Their approach utilizes a multiplayer version of the game with separate computers executing different instances of the game. All instances use a single viewpoint, but with view direction set to provide views appropriate for the each of the displays. Views and positions on all computers are updated based on the viewpoint of the single user. Game engines for Half-Life [30] and CryEngine2 [15, 32] have also been used for virtual environment creation and display.

### 3 The System

The principle design considerations for the system we have implemented were that the system be relatively low cost, easy to configure and maintain, and fit in a small space, considerations common to the design of many similar systems. The system’s design required that it serve both research and educational purposes. In its research role the system would serve as a satellite development system for a CAVE located some distance away and maintain as much software and hardware compatibility as possible. It would also be used to conduct experiments suited to its capabilities. The system’s educational role would be to support courses in visualization and computer graphics.

Low cost for both hardware and software was a primary consideration. Additionally, the available space was only 12’ wide. Nonetheless, the system needed to achieve a high field of view for users. We also determined that some measure of viewer mobility, however limited by space, was required. To accommodate multiple uses the system had to be easily reconfigured. In anticipation of future expansion the system design had to be readily extendable.

In considering the type of display system the principle decision was whether to use rear or front projection. Though tiled display walls can be used for large viewing surfaces, projects we are to undertake require clear legibility of text, which is difficult to achieve due to the bezels of tiled displays. Rear projection has clear viewer mobility advantages over front projection, with viewers able to move anywhere in the viewing space. This advantage comes at the cost of more complex and typically more expensive screen material and mounting fabrication. Importantly for our design considerations, there is a much larger space requirement for rear projection than front projection, even with folded projection using mirrors. Given the available space, we could construct a viewing space 12’ square with front projection, but only about half that size using rear projection.

We decided on front projection. This would allow a larger space for viewers than possible with a very small rear projection system, as well as more readily permit multiple configurations to support the multiple uses of the laboratory. Active stereo display was chosen, rather than passive stereo display, to minimize number of components. Figure 1 below shows two of the configurations routinely used with four stereoscopic projectors. Figure 2 shows an image projected using the three wall display.

The stereoscopic projectors used in the system are relatively low cost Lightspeed DepthQ projectors. For the three wall configuration shown in the left of Figure 1 the projectors are mounted vertically. Each projector’s image is 8’ tall and 6’ wide. For the two wall configuration shown in the right of Figure 1 projectors are mounted horizontally and each projector’s image covers an area 6’ wide and 4.5’ tall, providing a smaller, higher resolution display. This second arrangement of projectors leaves an area in the center of the projected area in which a single user can view the display area from within the projected area. Though mobility is restricted, the user is still able to turn left and right, and the viewing location within this projected image space provides much of the advantages of immersion provided by a rear projection system. The configuration is easily extended to four walls by adding an additional four projectors to supply images for the other two walls, as in the LAIR system [9]. Though not shown in the figure, projectors can be stacked to project a
Figure 1. Two configurations of the 12’ wide laboratory. On the left is a three wall, four projector display allowing multiple viewers to “look into” an 8’ tall area. On the right a two wall four projector configuration with higher resolution allows a single user to sit or stand within the projected volume without obstructing the front projected image. The projectors can be also be stacked to provide a single 12’x7’ 3.6 mp display.

Figure 2. Three sided display. Several viewers can stand across the front area to view the scene.

A single 12’x7’ image with a total display resolution of 2560x1440. Conventional ceiling mounting of a single projector illuminating a 12’x7’ wall accommodates 12 viewers.

A single computer system providing four stereoscopic outputs is used. The computer (HP Z800) and two graphics cards (nVidia 5000), each with two stereoscopic outputs, use nVidia’s SLI (Scalable Link Interface) architecture. The architecture provides transparent gpu scalability and eliminates much of the programming required for multiple displays. Using a single computer avoids display synchronization issues and their associated software and hardware costs. Results with the single computer system have been satisfactory, and suitably high frame rates are possible due to the gpus’ handling of the graphics processing. Other systems utilizing less expensive graphics cards and stereoscopic monitors are also available for development and educational use.

The principle software tools for virtual environment development are VTK (Visualization Toolkit) [28, 29] and UDK (Unreal Development Kit) [35]. Each is used for both educational and research efforts. Both are freely available. VTK serves a wide range of needs. It is the principle software package used in the visualization class supported by the laboratory. Students typically execute programs that are developed on other systems to explore stereoscopic and immersive display in the lab. In research efforts its wide range of libraries, together with its extensibility using native code, supports efficient iterative design. VTK also provides a simple means to create programs for multiple displays through its multiple viewport capabilities. VTK’s support for multiple languages, e.g., TCL, Python, allows prototyping and experimentation with modest programming effort. UDK is a game engine with its own scripting language, supporting a range of interaction and high level functionality. A significant element in the context of the laboratory is the ease with which moderately complex textured scenes can be created with UDK so that additional tools for scene creation are not needed. In addition to VTK and UDK, VR Juggler, VRPN, and OpenGL are extensively used.

System cost was a primary factor in design decisions and component selection. We chose components that would provide a reasonable compromise between the very lowest cost and satisfactory performance. During component identification a game development laboratory with less demanding computing and display requirements was also under development, which provides comparison of lower cost components.

Total cost for the system was about $20,000. The largest cost was for the four stereoscopic DepthQ projectors, $10,000. The single computer and two nVidia Quadro 5000 graphics cards were $5,000. Six pairs of nVidia shutter glasses and rf emitter cost $1,500. Tracking is performed by a relatively fast camera based system, NaturalPoint’s OptiTrack S250, at a cost of $3,500. It was selected to maintain compatibility with the CAVE system. For the relatively small space of the system, tracking could be done satisfactorily with game hardware based components, e.g., Kinect or Wii Remote [40]. Fabrication costs for projector stands, together with screen frame and materials, were less than $1,000.

A similar monoscopic system with less expensive computer and graphics cards that would be quite suitable for many applications could be configured for less than half the cost of the system. Projectors of similar resolution and lumen output would cost less than $4,000. Computer and graphics controllers would cost about $2,500 using, for example, nVidia GeForce cards. Six pairs of nVidia glasses and ir emitter would cost less than $1,000. Tracking could be
performed using a game hardware based system for a few hundred dollars. Mountings and screen material would cost the same, less than $1,000.

4 Conclusions

Current technology allows the construction of immersive display systems for virtual environments for orders of magnitude less cost than the earliest CAVE systems. This work describes one such system to be used for both research and education and details a relatively low cost solution to a set of design considerations common to many systems. The stereoscopic front projection display provides a means to create immersive environments that minimizes space utilization, while maintaining a relatively high degree of display immersion and configuration flexibility. The single computer, four graphics gpu system provides a computing solution that helps minimize both software configuration effort and cost. The use of publicly available software demonstrates viable low cost solutions to immersive display systems configuration and virtual environment development.

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6 References


