2013-12-12

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Introducing the VuePod: Development and Testing of a Low-Cost Large-Scale Stereoscopic Immersive System Using 3D LCD Televisions

Shane Makana Hayden

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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December 2013

ABSTRACT

Introducing the VuePod: Development and Testing of a Low-Cost Large-Scale Stereoscopic Immersive System Using 3D LCD Televisions

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Department of Civil and Environmental Engineering, BYU
Master of Science

3D immersive visualization systems, or CAVEs™, have found wide adoption for use in geosciences, planetary science, medical research, and computer science. However, much of the potential for such systems in practical civil and environmental engineering settings has been severely limited due to 1) extreme costs in both hardware and software; 2) immobility due to calibration and darkroom requirements; and 3) extensive and expensive manpower requirements for both operation and maintenance. This thesis presents the development and testing of a new mobile low-cost immersive stereo visualization system – the "VuePod" – that attempts to address these challenges through the use of commercial-off-the-shelf technologies, open source software, consumer grade passive 3-D television monitors, an active tracking system, and a modular construction approach. The VuePod capitalizes on recent functional advancements and cost decreases in both hardware and software and is demonstrated herein as a viable alternative to projector-based walk-in CAVEs and their limitations.

Additionally, I have selected twelve representative 3D immersive systems and performed a side-by-side analysis of each in terms of cost, viewing capabilities, computing and user experience. The purpose of performing this analysis is to classify the variety of systems available and simplify the system procurement and configuration processes. The availability of this comparative system information should facilitate the increased utilization of immersive 3D interface technologies in science and engineering.

Keywords: Virtual Reality, CAVE, VuePod, LiDAR

ACKNOWLEDGEMENTS

I would like to express a special thanks to Dr. Daniel P. Ames and the Department of Civil and Environmental Engineering for the opportunity to further my research and educational goals. I would also like to thank my family including my wife, Kalei, and children, Drew, Ty and Malia for their support in pursuing a master's degree. Lastly, I thank my parents for their constant encouragement and reminders of the importance and value of a quality education.

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1 INTRODUCTION

The overarching problem addressed in this thesis is the display of stereoscopic (3D) images in a large human-immersive system for the purposes of improved engineering design and analysis, prototyping of constructed environments, visualizing changes in the natural or man-made environment, viewing complex high resolution data sets and exploring high dimensional scientific data. While technology for this type of system has existed for several years, I believe that it has not become widely used largely to three key factors: 1) the overall expense; 2) physical deployment challenges and constraints; 3) operations and maintenance requirements. These and related issues are addressed in this thesis through the development of a new system and analysis of existing systems.

1.1 CAVE Technologies and Costs

The term Computer Automatic Virtual Environments or CAVEs™ is generally used to indicate an immersive stereoscopic data visualization system. There are multiple configurations and applications of CAVEs that have been developed and used. The objective of a CAVE system is to aid scientists, engineers, technicians, teachers and others in enhancing workflows by providing viewers with a viewer-centered perspective (Cruz-Neira, Sandin et al. 1992, Sherman, O'Leary et al. 2010). Over the years, with advances in technology and computer science, the quality of CAVE systems continues to improve (Peterka, Kooima et al. 2008, DeFanti, Acevedo et al. 2011). For example, newer CAVE technologies have about 15 times the resolution compared to the first CAVE that was created in the early 1990's (DeFanti, Acevedo et al. 2011).

CAVE immersive systems have been created using multiple combinations of projector displays, 3D TV's and LCD zero bezel panels. Each configuration provides its own set of advantages and disadvantages relating to cost and quality of user experience.

A common CAVE configuration consists of 4-6 projection screens forming walls – and in some cases floors – that surround the viewer with a rear projection projector associated with each wall (Cruz-Neira, Sandin et al. 1992, Browning, Cruz-Neira et al. 1994, Sherman, O'Leary et al. 2010, DeFanti, Acevedo et al. 2011). In this environment, a user wears stereo glasses which allows for interaction with the screens that surround them on multiple sides and in certain cases, on the floor below (DeFanti, Acevedo et al. 2011). User interaction is made possible with a tracking system that interacts with a six degrees of freedom sensor worn by a user which communicates to the software the location and orientation of the user's head or hands (DeFanti, Acevedo et al. 2011, Kreylos 2013). One of the primary benefits of the projector-based CAVE configuration is that multiple users can view data in the CAVE at the same time (Cruz-Neira, Sandin et al. 1992, DeFanti, Acevedo et al. 2011). A projector-based CAVE configuration has several additional benefits. Notably, there are no bezels (the plastic border around an LCD screen) to interfere with the user experience. Additionally, a walk-in CAVE provides the user with full field of view coverage including peripheral vision. Also, a large network of academic and commercial projector wall CAVE users and developers exists – enhancing access to guidance and support.

The largest disadvantage of projector based systems is often report is cost (Cruz-Neira, Sandin et al. 1993, Sherman, O'Leary et al. 2010). The capital cost such a system ranges from

$500,000 to more than $1,000,000 for the hardware alone. Also, such systems typically require significant facilities remodeling to effectively construct a room-within-a-room that meets the needs for space, room darkening, rear projection configuration, dust removal, computer hardware rack mounts, and technician or operator workstations (DeFanti, Acevedo et al. 2011, Margolis, DeFanti et al. 2011). Continual maintenance and manpower requirements require additional expenses that are necessary with large scale projector CAVEs due to the complexity of the hardware and software as well as the physical infrastructure required by CAVE systems (DeFanti, Acevedo et al. 2011). These factors make it extremely difficult for small research organizations and laboratories, businesses and other agencies to justify the investment of a virtual reality system despite the proven benefits of the technology (De Moraes, dos Santos Machado et al. 2003, Sherman, O'Leary et al. 2010).

A less expensive virtual environment option is the IQ-Station set-up. The IQ-Station was developed by a group from Indiana University and Idaho National Laboratory with the purpose of provided a CAVE like user experience for a fraction of the cost (Sherman, O'Leary et al. 2010). By providing a lower-cost virtual reality environment, businesses and government agencies can justify the cost. The typical cost for such a system can range from $15,000 to $25,000; with difference options for the visualization computer and mounting hardware (Sherman, O'Leary et al. 2010). The basic setup for the IQ-Station consists of a large 3D-TV, a tracking system, two computers (one for tracking and one for rendering) all set up and mounted on a mobile table (Sherman, O'Leary et al. 2010).

Another low-cost virtual environment that has been developed is called ImmersaDesk (Margolis, DeFanti et al. 2011). This system is a rear projected screen tilted at a 45 degree angle allowing the user to look both forward and down at the screen (Czernuszenko, Pape et al. 1997).

The reason for the 45 degree angle was due to the opinion that part of the virtual reality experience is lost in a CAVE without a floor (Czernuszenko, Pape et al. 1997). This system is much more affordable than a projector based CAVE due to the fact that only one projector is needed and the special space requirements are not required (Margolis, DeFanti et al. 2011). However, with a cost of more than $100,000 (Margolis, DeFanti et al. 2011), it is still more expensive than the IQ-Station.

Another recent development in low-cost virtual reality environments is the "heads-up virtual reality" or HUVR system which is about 1/10 the cost of the ImmersaDesk system. The purpose of this system is so provide a lower cost alternative which allows the user to experience an augmented reality immersion (Margolis, DeFanti et al. 2011). The hardware configuration of this system is unique, requiring the use of a 3D display, a semi-transparent mirror, and a camera tracking system (see Figure 1-1). The 3D display is mounted above the user facing downward onto the semi-transparent mirror which is tilted at an angle. The user can then interact with the virtual objects below the semi-transparent mirror with their hands (Margolis, DeFanti et al. 2011).

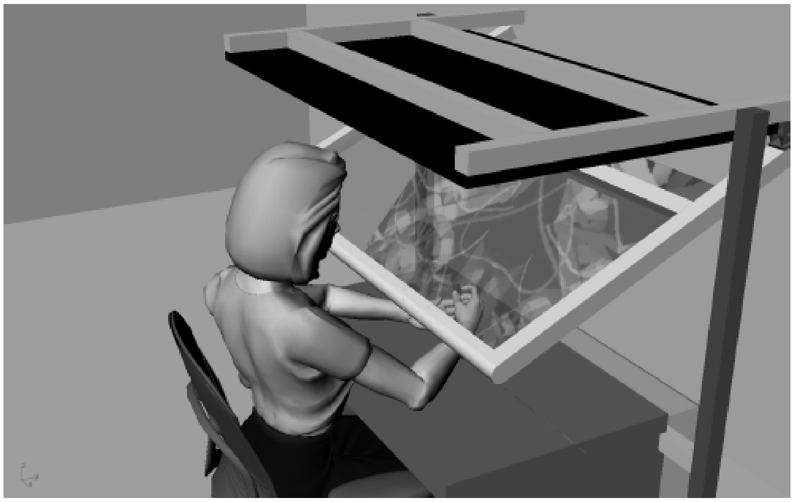

Figure 1-1: HUVR system hardware configuration.

Several other research and development efforts have approached the goal of lowering the cost virtual environments. De Moraes, dos Santos Machado et al. (2003) created projector-based system called a “VirtWall” which included a single computer and two projectors with polarized filters in front of the projector lenses to create stereoscopy. This system was designed to be mobile and reduce required manpower and room space. Cliburn (2004) discusses the development of a low cost LCD projector based system on a single wall by using a repurposed projector and computer. Similarly, Jensen, Pair et al. (2005) demonstrate the development of a low cost system, the Non-Expensive Automatic Virtual Environment or NAVE which was built for less than $60,000. The NAVE is a three-screen configuration where the screens are placed at a 120-degree angle of each other and are driven by off-the-shelf desktop computers.

1.2 **Head-Tracking**

Head-tracking is a critical aspect of most virtual reality visualization systems (Kreylos 2013). The head-tracking aspect of the system is essentially what separates a virtual reality visualization system from a 3D movie theater or 3D television. Head-tracking is powerful because this aspect of the technology is what makes the viewer’s brain see an object as being “real” or not. The reason that the brain perceives and object to be real is because when the user turns his or her head, the head tracker tells the software where the user’s eyes are in relationship to the screen and therefore the software alters the image to account for the movement of the user’s head (Kreylos 2013).

1.3 **Demonstrated Usefulness of Virtual Reality Technology**

Stereo 3D visualization is proving to be a valuable method of interacting with data for engineers, researchers, scientists and designers. For example, Bryson (1996) discusses the need to view datasets in three dimensions to study the behavior of parameters, such as streamlines in a vector field. Kwaw and Gorny (2000) introduce a CAD software (VCAD) used to produce design drawings for reinforced concrete and structural engineering applications to aid in presentations to project stake holders. Gruchalla (2004) illustrates the value of immersion in solving a “real-world industrial problem” of planning an oil well-path. Kreylos, Bawden et al. (2006) introduce software specifically designed for earth science researchers to be able to interact with data at multiple scales. Bowman and McMahan (2007) discuss how virtual reality is more than just impressive demonstration technology and how it has been successfully used in psychology, military training and in the entertainment industry. Barham, Preston et al. (2012) propose the idea of improving engineering learning techniques by implementing 3D immersive simulations in a virtual environment that would allow users to “explore engineering phenomena in new ways that are not safe or cost-effective in physical, real-world laboratories.”

1.4 **Challenges with the Current State of the Technology**

Upon reviewing the current state of virtual reality visualization technology in journal articles and other research publications, there are two recurring issues that consistently arise: cost and user interactivity. The issue with cost consists of expenses related to initial equipment purchases, space and building renovations as well as long-term operations and maintenance expenses. The user interactivity issue is associated with user interface problems with available virtual reality software. Also, most virtual reality systems around the world are large projector based systems. Consequently, they are not mobile and cannot be taken to trade shows, conferences or even construction sites for others to be able to benefit from the immersion experience.

1.5 **Research Hypothesis**

My primary research hypothesis is that with advances in video cards, head-tracking technology and 3D LCD televisions in recent years, a mobile 3D visualization environment can be developed for less than $40,000. My proposed technology, the VuePod, consists of multiple 3D LCD televisions with small bezels stacked on top of one another and side-by-side. The VuePod also consists of one computer that powers the whole system using three NVIDIA Quadro K5000 video cards. The head-tracking system is the SMARTTRACK from Advanced Realtime Tracking (ART). This creates a level of immersion similar to a multiple wall CAVE while at a much lower cost. Another important goal of the proposed technology is that it minimizes manpower requirements so that it can be operated and maintained by part-time undergraduate and graduate students. This thesis addresses both my primary hypothesis (Chapter 2) and a secondary research goal of developing a classification approach for large scale immersive visualization systems (Chapter 3).

2 A MOBILE LOW-COST LARGE-SCALE IMMERSIVE DATA VISUALIZATION ENVIRONMENT FOR CIVIL ENGINEERING APPLICATIONS

Co-authors: Daniel P. Ames, Derrick Turner, David Andrus, Thomas Keene
Submitted for Publication to ASCE Journal of Computing in Civil Engineering (11/2013)

2.1 Abstract

3D immersive visualization systems, or CAVEs™, have found wide adoption for use in geosciences, planetary science, medical research, and computer science. However, much of the potential for such systems in practical civil and environmental engineering settings has been severely limited due to 1) extreme costs in both hardware and software; 2) immobility due to calibration and darkroom requirements; and 3) extensive and expensive manpower requirements for both operation and maintenance. This paper presents the development and testing of a new mobile low-cost immersive stereo visualization system – the "VuePod" – that attempts to address these challenges through the use of commercial-off-the-shelf technologies, open source software, consumer grade passive 3-D television monitors, an active tracking system, and a modular construction approach. The VuePod capitalizes on recent functional advancements and cost decreases in both hardware and software and is demonstrated herein as a viable alternative to projector-based walk-in CAVEs and their limitations. A full description of the hardware and its assembly, software and its configuration, and the modular structural system is presented as well as results from several benchmark computation and visualization tests.

Key words: CAVE, stereo visualization, immersive computing

2.2 **Problem Statement**

Stereoscopic 3D visualization is proving to be a valuable method of interacting with data for engineers, researchers, scientists and designers. For example, Bryson (1996) discusses the need to view datasets in three dimensions to study the behavior of parameters, such as streamlines in a vector field. Kwaw and Gorny (2000) introduce a CAD software (VCAD) used to produce design drawings for reinforced concrete and structural engineering applications to aid in presentations to project stake holders. Gruchalla (2004) illustrates the value of immersion in solving a "real-world industrial problem" of planning an oil well-path. Kreylos, Bawden et al. (2006) introduce software specifically designed for earth science researchers to be able to interact with data at multiple scales. Bowman and McMahan (2007) discuss how virtual reality is more than just impressive demonstration technology and how it has been successfully used in psychology, military training and in the entertainment industry. Barham, Preston et al. (2012) propose the idea of improving engineering learning techniques by implementing 3D immersive simulations in a virtual environment that would allow users to "explore engineering phenomena in new ways that are not safe or cost-effective in physical, real-world laboratories."

In spite of a relatively long history of developments in the field of immersive stereo 3D technology and clear applications to engineering problems related to the human built environment, 3D immersion has not become fully adopted in civil and environmental engineering practice. We submit that the three key reasons for this include: 1) extreme capital cost of constructing an immersive virtual reality system; 2) general immobility of the technology and special physical room and/or building constraints; and 3) expensive operational manpower and maintenance costs.

This paper presents the design, development, and testing of a new immersive virtual reality system for civil and environmental engineering applications that attempts to address limitations of cost, mobility, and manpower. Our research goal was to create a system with a full field of view, participatory immersive stereoscopic display with head and hand tracking that maximizes pixel density, computational power, and mobility, while minimizing cost, operational expertise and maintenance requirements.

2.3 Stereoscopic Immersive Technologies

A wide variety of hardware and software configurations are used in immersive virtual reality systems including: projector based wrap-around video systems, LCD panel walls, single monitor systems, and large walk-in rooms. These systems can all be loosely grouped under the common term, “Computer Automatic Virtual Environment” or CAVE. Among these CAVE systems, the common purpose is typically to aid scientists, engineers, technicians, teachers, and others in enhancing workflows by providing users with a viewer-centered perspective (Cruz-Neira, Sandin et al. 1992, Sherman, O’Leary et al. 2010). With advances in technology and computer science, the quality of CAVE systems continues to improve (Peterka, Kooima et al. 2008, DeFanti, Acevedo et al. 2011). For example, the first CAVE that was created in the early 1990’s had a “resolution of less than a megapixel per wall per eye; newer ones have up to 15 times as many pixels” (DeFanti, Acevedo et al. 2011).

A common CAVE configuration consists of 4-6 projection screens forming walls – and in some cases floors – that surround the viewer with a rear projection projector associated with each wall (Cruz-Neira, Sandin et al. 1992, Browning, Cruz-Neira et al. 1994, Sherman, O’Leary et al. 2010, DeFanti, Acevedo et al. 2011). Within this CAVE environment, a user wears either active or passive stereo glasses that provide an immersive 3D view of the images shown on the surrounding screens. Interaction with the views is made possible by a tracking system that follows the movements of a six-degrees-of-freedom sensor worn by the user that communicates to the software the location and orientation of the users head or hands. One of the primary benefits of the projector-based CAVE configuration is that multiple users can view data in the CAVE at the same time (Cruz-Neira, Sandin et al. 1992, DeFanti, Acevedo et al. 2011).

A projector-based CAVE configuration has several additional benefits. Notably, there are no bezels (the plastic border around an LCD screen) to interfere with the user experience. Additionally, a walk-in CAVE provides the user with full field of view coverage including peripheral vision (see Figure 2-1). Also, a large network of academic and commercial projector wall CAVE users and developers exists – enhancing access to guidance and support.

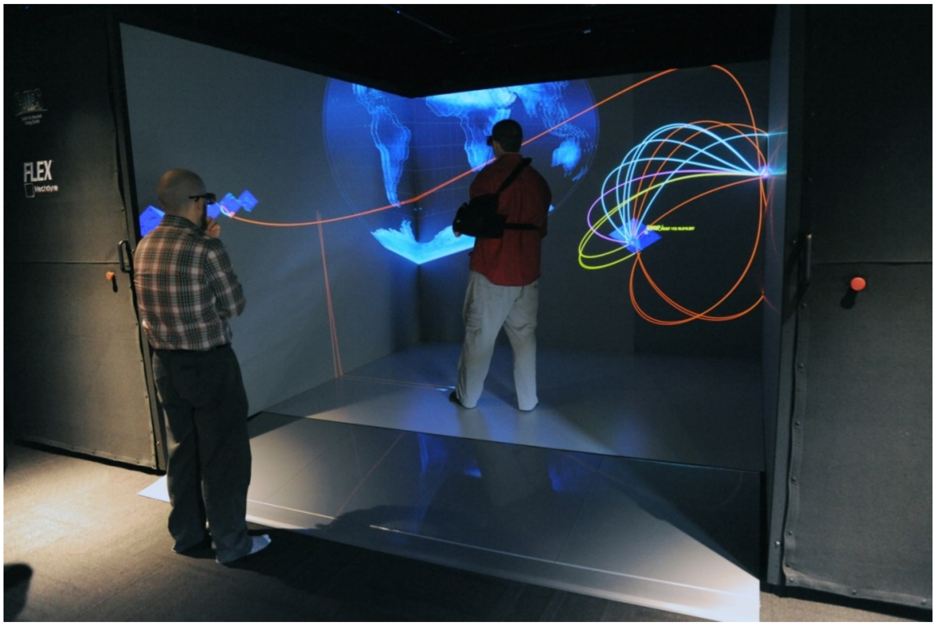

Figure 2-1: Projector based four-wall CAVE at Idaho National Laboratory in Idaho Falls, Idaho (Courtesy: Idaho National Laboratory).

The largest disadvantage of projector-based systems commonly discussed is cost (Cruz-Neira, Sandin et al. 1993, Czernuszenko, Pape et al. 1997, Sherman, O'Leary et al. 2010). The capital cost for such a system ranges from $500,000 to well over $1,000,000. Also, such systems typically require significant facilities remodeling to effectively construct a room-within-a-room that meets the needs for space, room darkening, rear projection configuration, dust removal, computer hardware rack mounts, and technician or operator workstations (DeFanti, Acevedo et al. 2011, Margolis, DeFanti et al. 2011). Ongoing maintenance and operator expenses can also be large due to the complexity of the hardware and software as well as the physical infrastructure required by a large-scale projector CAVE. These factors make it extremely difficult for small research organizations and laboratories, businesses and other agencies to justify the investment of a virtual reality system despite the benefits of the technology (De Moraes, dos Santos Machado et al. 2003, Sherman, O'Leary et al. 2010).

Several research and development efforts have approached the goal of lowering the cost virtual environments. For example, De Moraes, dos Santos Machado et al. (2003) created projector based system called a "VirtWall" which included a single computer and two projectors with polarized filters in front of the projector lenses to create stereoscopy. This system was designed to be mobile and reduce required manpower and room space. Cliburn (2004) discusses the development of a low-cost LCD projector based system on a single wall by using a repurposed projector and computer. Similarly, Jensen, Pair et al. (2005) demonstrate the development of a low-cost system, the Non-Expensive Automatic Virtual Environment or NAVE which was built for less than $60,000. The NAVE is a three-screen configuration where the screens are placed at a 120-degree angle of each other and are driven by off-the-shelf desktop computers.

Sherman, O'Leary et al. (2010) introduced the IQ-Station, which is a highly mobile system that uses a single active stereo television, a single computer and a complete head-tracking system for $15,000-$25,000. The IQ-Station was created specifically to address the high cost of immersive technologies and to increase use by reducing the training and maintenance requirements of such a system. The basic configuration for the IQ-Station consists of an 84-inch 3D DLP TV screen, a tracking system, two computers (one for tracking and one for rendering), mounted on a mobile table (Sherman, O'Leary et al. 2010) (see Figure 2-2).

The benefits for using the IQ-Station configuration include; low maintenance costs, a growing network of users around the United States (over 10 deployments thus far), good pixel density, no bezels to interfere with user experience and no special required room renovation. The primary disadvantage of the system is the reduced field of view provided by a single 84-inch screen.

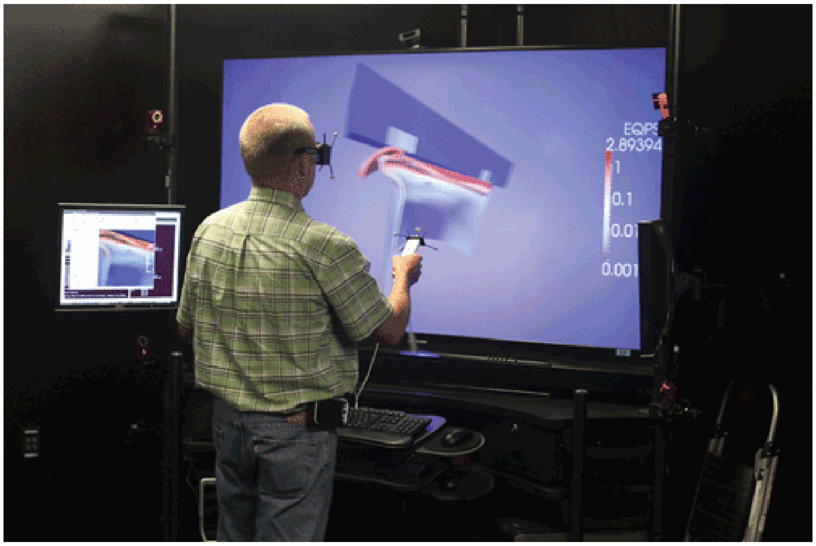

Figure 2-2: IQ-Station at Idaho National Laboratory

King Abdullah University of Science and Technology (KAUST), in collaboration with UCSD's CalIT2 Institute, developed a multiple-monitor configuration that combines some of the most advantageous features of both the IQ-Station and a walk-in CAVE. This “NexCave” is described as having 21 LCD displays curved at an angle as shown in Figure 2-3. The configuration uses multiple computers (one computer per two monitors) in a cluster configuration and optical tracking. No synchronization is needed as the panels use micro-polarized passive stereo.

Figure 2-3: NexCave at KAUST (Courtesy: KAUST Visualization Laboratory).

2.4 A Large Scale, Low-Cost Alternative

Our research is centered on the question of creating a large-scale, low-cost, low maintenance alternative to existing CAVE configurations. Combining the NexCave multiple-monitor configuration concept with the low cost and simplicity of an IQ-Station, we have created a new type of CAVE system that we call the “VuePod.” The VuePod was made possible due to rapid recent advances in video card technologies and consumer grade passive 3D LCD displays.

Simplification decisions, such as the use of a single high-end gaming computer to run the system also significantly reduced costs in comparison to the NexCave while the twelve-panel display rivals the IQ-Station for immersion potential. By using passive 3D technology long-term maintenance and operator costs are significantly reduced – glasses are inexpensive and do not require continual maintenance or battery replacement. The system is installed on mobile framework that allows for its relocation to job sites or training facilities. The total cost of all of the materials to construct the system was approximately $30,000.

In addition to constructing the VuePod system, we have conducted a number of tests and experiments with the equipment to help establish its veracity. These tests were introduced to ensure that the VuePod is capable of displaying the same types of datasets as more complicated, more expensive, and less mobile systems. Three categories of benchmarks were explored and results will be presented hereafter. These three categories are; computer hardware benchmarks, a stereoscopic performance benchmark, and video card performance benchmark. We will also present a brief qualitative assessment of the experiences of viewing specific datasets that are used in other CAVE facilities.

The remainder of the paper is organized as follows. In section 2.5 we introduce the design and development of our new immersive stereoscopic virtual reality system called the VuePod. In section 2.6 we present the results of several benchmark tests of the system. In section 2.7 we discuss these results in terms of the original goals of the research and make recommendations for future work.

2.5 **Development of the VuePod**

The four key components of the VuePod include: computer hardware, visualization software, rack and mounting components and operations and maintenance. Each of these components are described below.

2.5.1 Hardware

Televisions: The visualization module of the VuePod is comprised of twelve LG brand LCD televisions (LG 55" Class Cinema 3D 1080P 120HZ LED LCD TV, model number 55LM4600.) These specific television monitors were chosen because they use passive 3D technology rather than active 3D technology – significantly reducing cost of stereo glasses (disposable theater-style glasses versus battery-powered active-shutter glasses). The selected monitors were also very inexpensive at a cost of $800 each. Additionally, they have a relatively small bezel (1") on three of the four sides. Other models of passive 3D televisions are available with much smaller bezels (less than 0.5") however at the present time these units are significantly more expensive. For example, the Samsung 55" Class 1080p 240 Hz 3D Smart LED HDTV has a 0.2" bezel and a list price of $1,679.99.

Computer Components: The VuePod computer must provide simultaneous synchronized stereoscopic video output to all twelve televisions. To enable this capability with a minimal hardware investment, we chose to use three NVIDIA Quadro K5000 video cards installed in a single high-end computer comparable to a custom-built gaming PC. Each video card has four video outputs and occupies two PCI card slots on the computer mainboard. Space was also needed for an additional PCI-size card that synchronizes the refresh rates of the three video cards – the sync card does not need to plug into the motherboard via PCI as it interfaces with the video cards via ribbon cables. It needs space in the computer chassis; however motherboard support for the sync is not necessary. Standard desktop computer mainboards typically only have six PCI slots; therefore a server-grade motherboard, the Asus P6T7, was acquired for use in the VuePod computer. Additionally, the computer case is a full-size tower typically intended for gaming applications due to its extensive ventilation system with multiple cooling fans. The system also includes a mid-range Intel processor and 24 GB of RAM.

Motion Tracker: A key component of the system is a motion tracking SMARTTRACK unit developed by Advanced Realtime Tracking (ART). This unit tracks motions within a volume of approximately two cubic meters (Figure 2-4). It also has extremely high depth resolution for high precision tracking. This tracker is accurate enough to pinpoint the user's eyes to render the scenes based on head position. This device is comprised of two cameras, infrared lights and a controller contained in one unit. This was found to be very easy to calibrate and use. Our observation is that, in practice, the SMARTTRACK device actually tracks volume that is nearly twice the two cubic meters advertised.

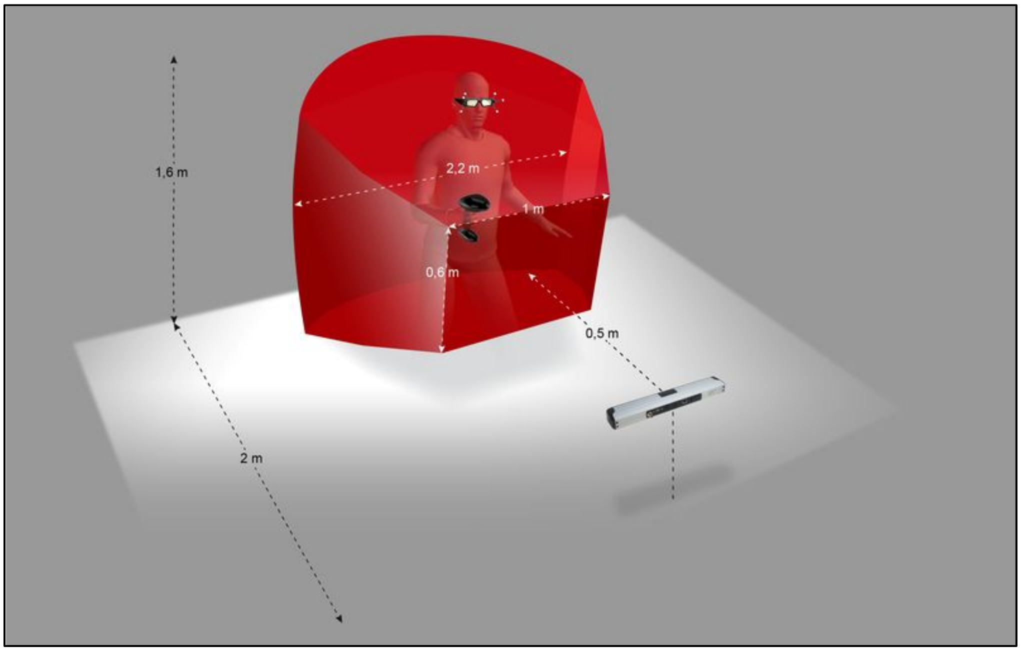

Figure 2-4: The volume of tracked area using the SMARTTRACK motion tracking unit is indicated in red (figure courtesy ART).

Interactive Controller: A Nintendo Wii remote controller was selected for use as an input device for the VuePod to capitalize on its Bluetooth radio, large number of input buttons (eleven), infrared sensor camera, accelerometer, and hardware expansion slot. The infrared sensor and accelerometer are intended to work together to produce simplified motion input in an environment where precision is not as important as general motion. The Wii remote controller interacts with VuePod software via Bluetooth connection (using a USB Bluetooth receiver attached to the VuePod computer) by binding specific software commands (e.g. zoom, pan) to each of its eleven buttons.

2.5.2 Supported Software

Operating System: The VuePod computer runs both Linux and Microsoft Windows 7. This allows for a number of different visualization applications and data analysis tools to be used in the environment. Separate hardware drivers have been installed for each operating system and GNU GRUB dual booting has been used to simplify accessing hardware drivers (instead of using virtual machine operating system images.) The two primary visualization tools installed on the VuePod include Vrui (running on Linux) and Navisworks (running on Windows) as described below.

Vrui VR Toolkit: The Vrui VR Toolkit (http://idav.ucdavis.edu/~okreylos/ResDev/Vrui) is a general purpose virtual reality software application development environment. It is open source and extensible and supports development of add-on applications (e.g. for LiDAR viewing, modeling, and teleconferencing). Vrui is capable of outputting stereoscopic images to multiple monitors simultaneously and can be networked for displays connected to multiple computers. A key feature of this software is that it supports both head-tracking and curved monitor configurations by treating each monitor as a separate virtual “window” that displays a section of the scene based on the viewer's position. Vrui extensions have been built for tracking the Wii remote infrared sensor for motion detection, though we are using the SMARTTRACK for this purpose due to its improved accuracy.

Navisworks: Navisworks® is an Autodesk® product that allows different file formats such as .dwg, .dgn, Revit and point cloud data to be viewed in 2D or 3D. The software itself has many engineering design and analysis capabilities. However for the purposes of the VuePod it is used strictly to view design drawings in 3D.

2.5.3 Mounting, Accessories and Room Space

The VuePod is currently located in a 26.5 feet by 18.5 feet room where it occupies approximately 6 feet by 18 feet of floor space. No special room renovations were required for the VuePod. The VuePod mounting frames described below are sized such that they may pass easily through a standard doorway. Adequate electrical outlets were already available in the room to power the television monitors, computer, and motion tracker (14 outlets total required).

The twelve VuePod monitors are mounted to steel frames welded out of one inch square steel tubing with a wall thickness of 1/16". Four frames were built with three monitors mounted on each frame. Construction of the frames required approximately 300 linear feet of square steel tubing material. Concrete blocks were also formed and poured to fit on the back of each frame as a safety precaution to avoid tipping. Monitors are attached to the steel frames using Rockfish™ 32"-70" wall mounts. Figure 2-5 shows a screenshot of a CAD drawing created while designing the monitor mounts. Figures 2-6 and 2-7 show what the completed steel mounts look like after construction.

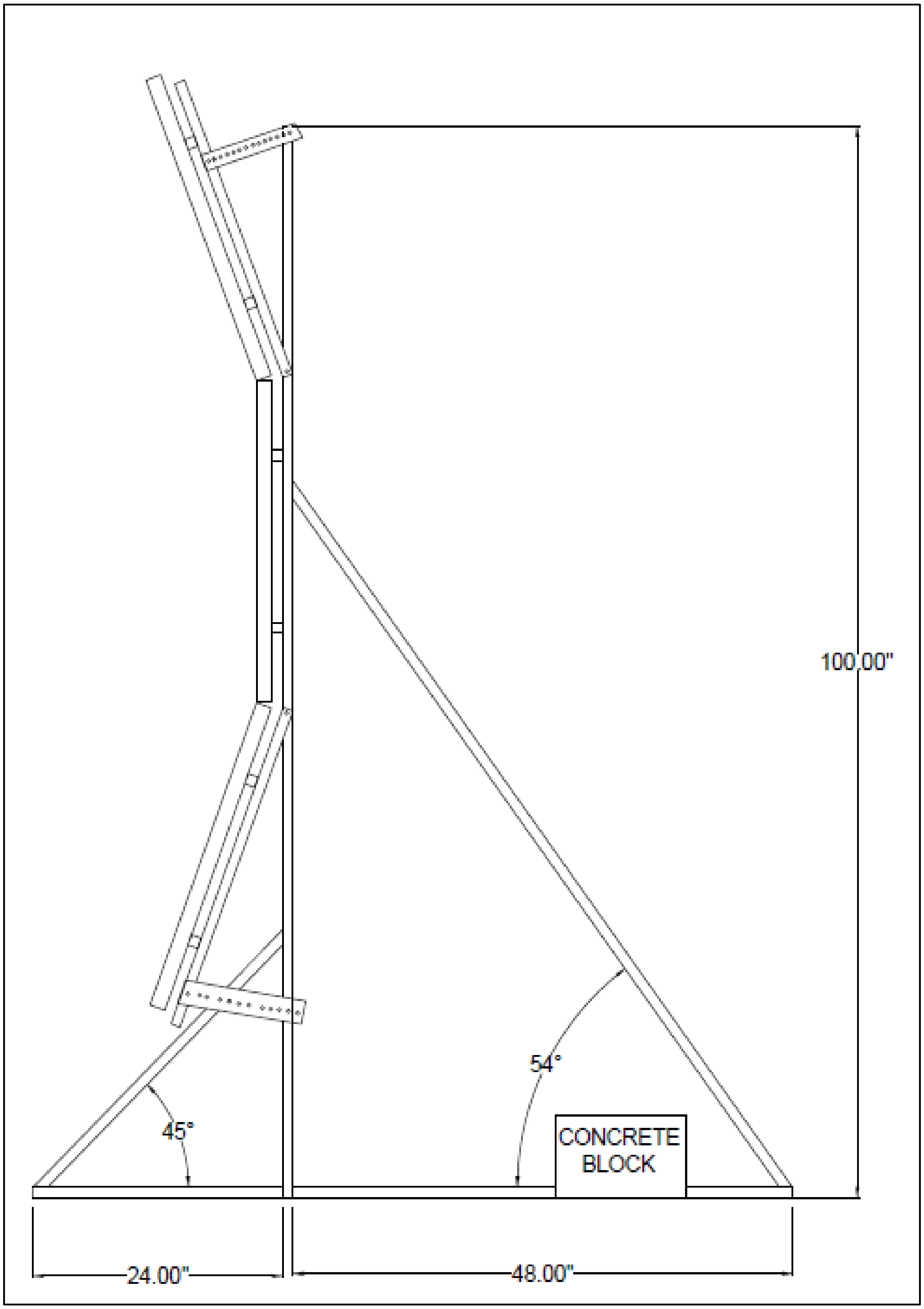

Figure 2-5: CAD sketch of the frame used to mount TV's (side view). Each frame is 30 inches wide.

Figure 2-6: Finished steel frame to support three monitors.

Figure 2-7: Three monitors attached to a steel frame with adjustable tilting arms and Rocketfish wall mounts.

2.5.4 Cost

Table 2-1 shows all costs associated with the VuePod hardware. Our original goal was to build the system for less than $40,000. The final cost of the system came out to be well below that figure at just over $30,000. The largest expenses included the computer, the SMARTTRACK motion tracker and the televisions.

Table 2-1: VuePod Cost Breakdown

Category	Item	Total Cost
Computer	Computer	$ 2,696.92
	Video Cards	$ 6,219.97
	Accessories	$ 197.06
Mounting	Nuts, bolts, Screws, etc.	$ 389.09
	Steel	$ 242.00
	TV wall mounts	$ 1,199.88
Other	Televisions (55" LCD-3D)	$ 9,599.88
	Cables, Adaptors, etc.	$ 336.51
	Wii Controllers	$ 183.55
	Student Labor (computer, mounting)	$ 720.00
	Head Tracker	$ 8,795.89
Total		**$ 30,580.75**

2.5.5 Personnel Requirements

Our experience has shown that the VuePod hardware and software system can be maintained and operated by a single part-time technician; at our institution, we have hired an undergraduate computer science student for this purpose. With training, other students who have little computer expertise are able to successfully operate the system to view datasets. The VuePod was designed and constructed with extensive input and feedback from individuals at other institutions – a benefit of working in a shared open-design paradigm. One of the goals of this project was to design and construct the system such that it does not require any full-time salaried computer technicians for maintenance and operation (as we have observed is the case with other CAVE-like systems).

2.5.6 Required Maintenance

The only hardware component of the VuePod configuration that needs to be monitored closely is the performance of the graphics cards. It is estimated that within three years of use that they may need to be replaced. Also, because of the sometimes difficult process involved in setting up certain software packages on a system that is as complex as this one, it may be a benefit to be extremely cautious in upgrading software packages after they are configured and running successfully.

2.6 **Results**

Figure 2-8 shows a picture of the final construction of the VuePod. After the system was successfully completed, a number of hardware and software benchmark and performance tests were performed. These tests indicate the veracity of the system and show its ability to produce a quality user experience.

Figure 2-8: The VuePod at Brigham Young University

2.6.1 Computer Hardware Benchmark Tests

The Windows Experience Index (WEI) is a benchmark test created by Microsoft to rate the performance of a processor, memory, graphics, gaming graphics and the primary hard disk on a scale from 1.0 to 7.9. WEI calculates a base score for the entire system using the lowest score of the five key components measured. Table 2-2 shows the results of the WEI for the VuePod computer. The lowest subscore of 7.4 is based on the performance of the disk data transfer rate. Overall, the five scores are very good, and based on the description provided by Microsoft Windows, the VuePod computer is capable of supporting "high-end, graphics-intensive experiences, such as multiplayer and 3-D gaming and recording and playback of HDTV content." This is significant because rendering to a 24 megapixel composite display at 60 frames per second is beyond the capabilities of most computers. Experiments have proven that a frame rate of 30 to 60 frames per second improves user performance in a virtual reality environment (Claypool, Claypool et al. 2006).

Table 2-2: Results of Windows Experience Index on a Scale of 1.0 to 7.9.

Component	What is Rated	Subscore
Processor	Calculations per second	7.8
Memory (RAM)	Memory operations per second	7.8
Graphics	Desktop Performance for Windows Aero	7.9
Gaming Graphics	3D business and gaming graphics performance	7.9
Primary hard disk	Disk data transfer rate	7.4
Base score (lowest subscore)		**7.4**

2.6.2 Stereoscopic and Video Card Performance Benchmark Tests

To test the limits of the three Quadro K5000 graphics cards, the Heaven Benchmark from Unigine was used. This benchmark test was designed with the purpose of "hammering graphics cards to the limits." It does this by creating exceptionally taxing conditions to test how stable the GPU is and to measure the cooling system performance. Using the VuePod computer, the benchmark was only able to achieve a frame rate of about five frames per second; however the high rendering quality was maintained throughout the test. We believe this is because of the 24 megapixel display, which is about twelve times larger than the 1080p resolution for which the majority of real-time engines are designed. A machine that could maintain 60 frames per second on a 1080p display would likely only be able to achieve five frames per second on a monitor with the same resolution as the VuePod displays.

Another environment that can test the video card and system performance is Vrui. The VuePod was able to render at least ten million LIDAR points in Vrui with a steady frame rate of 60 frames per second. This test used Vrui 2.6, which does not implement multi-core rendering optimization. Consequently, we believe that the VuePod's hardware met and exceeded our needs for rendering scientific data.

2.6.3 Testing Sample Data for Functionality

Three datasets that are used for demonstrating functionality at other virtual reality facilities were chosen to view in the VuePod. The first dataset is a LiDAR scan of the San Diego skyline. The second dataset is a LiDAR scan of a forest. The third dataset is a LiDAR scan of a river and canyon area. The following are a description of the experiences reported by multiple users in the VuePod.

In viewing the LiDAR scan of the San Diego skyline, the overall experience has been a good one for repeat and first time users. The stereo or 3D image is very apparent and users are able to identify certain buildings or parts of the city that are recognizable such as the San Diego Padres baseball stadium or the convention center. When looking at the same LiDAR scan in 2D, it is difficult to recognize certain aspects of the data. For example, at the time that the scan was taken, there was construction occurring near the baseball stadium where excavation had created a deep hole with piles of dirt around it. When viewing this in 2D, it is not apparent that there is a deep hole in that location, however when looking at the same image in 3D and with head-tracking, the user is able to easily see exactly what is going on in that location.

The second dataset that was analyzed was a forest LiDAR scan produced by Murgoitio, Shrestha et al. (2013) .This data is quite interesting because it is a combination of an aerial LiDAR scan and a scan performed by a Terrestrial Laser Scanner (TLS). The two scans were overlaid on top of one another and in the location where the two scans overlap; the point cloud density is extremely high. Because of this, the user is able to see a very high resolution of points and is able to analyze and view very fine details in the forest area such as bark on the trees, cracks in rocks and pine needles on trees. With head-tracking, the user is able to look over, around and underneath objects in the image by simply moving their head. When viewing this same image in 2D, the user is able to see a high resolution representation of the area and can identify objects; however they do not experience the immersion from the head-tracking and the 3D by being able to interact with the data.

The third dataset used to analyze the functionality of the VuePod was a LiDAR scan of canyons, cliffs and a river area in Idaho prepared by Glenn, Streutker et al. (2006). This dataset is a combination of LiDAR scans taken at different times with the purpose of being able to analyze changes in the area over a specific time period. When the dataset was processed, the scan from the earlier time period was colored green and the scan from the later time period was colored purple. In viewing the data using 3D and head-tracking in the VuePod, users are able to easily identify areas that have eroded over time, vegetation that has grown as well as a gravel pit area that has been altered during the time period. When viewing the data in 2D, it is easy to see that there are differences between the two datasets mainly because of the colors; however it is difficult to recognize depth of the image and landmarks in the distance.

We identified two specific challenges that users experienced while viewing all three of the above described datasets. First, the bezels between the monitors can interfere with and/or distract from the image presented on the screens. Interestingly, the use of the head-tracking system tended to reduce the negative effects of the bezels as the user tended to “look around” them in the same way one looks out a set of window panes, ignoring the window frames. Second, some users noted a small degree of motion sickness. A further discussion of these concerns is given in the conclusion of this paper.

2.7 **Conclusions**

This paper presents the design, development, and initial testing of a mobile, low-cost, low maintenance, large-scale, immersive stereoscopic data visualization system called the VuePod. Results of this effort indicate that it is clearly possible to develop such a system that meets all basic usability and functionality tests. We expect that this system can serve as a model or recipe for other institutions and companies that have a desire to view, present, and analyze scientific data in a 3D human immersive environment. We successfully constructed a system that can be disassembled and moved to new locations (we estimate approximately 2 hours for disassembly and 2 hours for assembly) – for example to a remote field site or field office. The system has been operational for six months as of this writing, and has proven to be maintainable using minimal technician time. The total cost of the system using current technologies is well below our target price point of $40,000 – a cost level that should be significantly more achievable than the alternative walk-in CAVE systems.

A few observations and opportunities for improving the VuePod system are as provided here. We suspect that the VuePod could be constructed with even greater mobility. Because of the manner in which the frames were designed and built, they would require a larger transport vehicle and space requirements to move. This is because they are not built to be able to collapse or disassemble individually. If one were to consider making a similar system, it may be important to consider building the frames to be easily assembled and disassembled. This would make it easier to take the system to trade shows, conference events, construction sites, mobile offices, or other locations.

We recognize that the television monitor bezels may become a distraction or may otherwise interfere with viewing data in the VuePod. This is a challenge that can only be addressed through the use of ultra-thin bezel monitors which are available for a greater expense. However, VuePod users have noted that once they begin studying data in the VuePod in earnest, they found it easy to ignore the bezels unless pointed out to them because their eyes are completely focused on the image on the screen. Additionally, if the user is wearing head motion tracking glasses, the effect of the bezels essentially is a non-issue. The effect is as if the user is looking through twelve “windows” or “picture frames” and is able to move their head to look around the bezels. Some people do experience motion sickness in the VuePod and this is a common issue in all virtual reality systems. However, the effect has been found to be significantly minimized if the person who is navigating the scene has been adequately trained and had opportunities to practice using the system. If multiple users are viewing the VuePod simultaneously, it is important for the user with the motion tracker to not make sudden movements that cause disorientation for the other users. Also it helps for other users to stand very close to the person who has the head tracker as this will reduce any disorientation.

Despite the challenges discussed above, this VuePod system had met the stated research goal of building a large-scale mobile 3D immersive environment that minimizes cost, while maximizing pixel density, viewable area, and mobility. This system has shown to be very maintainable by a part time technician and meets the goal of being able to provide user immersion at a level that is similar to other virtual reality systems.

Our expectation is that with this current technology in place, engineering firms and scientific researchers have the capability of exploring new analyses problem solving using information dense data sets like LiDAR data. Other users and developers of systems like the VuePod are encouraged to follow the recipe provided here and to help develop a larger network of users who can share their experiences, knowledge, software and data.

All hardware and software used in the construction and operation of the VuePod are described in detail at www.vuepod.org.

3 RESEARCH PAPER – A CLASSIFICATION APPROACH AND DATA ANALYSIS FOR LARGE-SCALE IMMERSIVE STEREOSCOPIC DATA VISUALIZATION SYSTEMS

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To be submitted for Publication to Computers and Geosciences (12/2013)

3.1 **Abstract**

The development and use of large-scale immersive stereoscopic data visualization systems has increased in recent years due to availability of massive scientific datasets, significant decreases in core technology costs, and remarkable advances in hardware and software computational power. This has resulted in the proliferation of virtual reality systems of various display/projector configurations, computational requirements, software capabilities, and performance potential/suitability for particular purposes. In this study we have identified twelve large-scale immersive stereoscopic data visualization systems that are representative of the variety of such systems currently under development and in use throughout the world, and we have performed a side-by-side analysis of each in terms of key parameters related to cost, viewing capabilities, computing and user experience. The purpose of this analysis is to assess the current state-of-the-art and practice with respect to these systems, and to develop a simple classification approach that adequately captures their key differences and similarities. This classification approach combined with all of the information collected in this study are intended to aid developers, funding agencies, managers, and users with the procurement and configuration of such systems by normalizing their descriptions in terms of three primary classes related to

viewable area, pixel density, and display technology. We expect this classification approach to be refined in time and ultimately to facilitate the increased use of large-scale immersive stereoscopic data visualization systems.

Keywords: CAVE, 3D visualization virtual reality, IQ Station, stereoscopic display

3.2 Introduction

Large-scale immersive stereoscopic data visualization systems are generally developed with the goal of improving scientific and engineering understanding of massive, complex, often multi-dimensional, datasets through advanced visualization and analysis capabilities (Billen, Kreylos et al. 2008). Recent advances in 3D visualization technology (both in tracking systems and stereo glasses) together with decreases in the computational technology costs, present researchers with unlimited opportunities to create customized configurations of large-scale immersive stereoscopic data visualization systems ranging from one screen LCD systems costing less than $25,000 (Sherman, O'Leary et al. 2010) to $10 million six screen high resolution walk-in CAVEs (DeFanti, Acevedo et al. 2011).

Within this environment of rapidly increasing technology and proliferation of visualization tools, it becomes challenging to clearly articulate the form and computational capabilities of a given system in comparison to other systems. Indeed, in spite of the wide variety of configuration options of stereoscopic immersive technologies, there is no established classification system to easily identify and define the technology. The purpose of the research presented herein is to address this need through a proposed classification approach for large scale stereoscopic visualization technologies to simplify the process for researchers, developers, funding agencies and others in defining and comparing virtual reality systems during the procurement and configuration processes.

3.2.1 Background of 3D Immersive Technologies and Classification

In the early 1990's, the first large-scale stereoscopic immersive technology was developed at the University of Illinois and was referred to as a computer automatic virtual environment or CAVE™. Though "CAVE" is a trademarked reference to a specific visualization system and configuration, the term continues to be used both formally and informally to refer to any large-scale stereoscopic immersive technologies. The original CAVE technology consisted of 4-6 screens with a rear projection projector associated on each wall (Sherman, O'Leary et al. 2010). Within this configuration, a user wears stereoscopic glasses which produce an immersive viewing effect on the screens that surround them on multiple sides and in some configurations, on the floor below (DeFanti, Acevedo et al. 2011).

In the early 2000's, the GeoWall was introduced to the industry as a low-cost alternative to a CAVE (Johnson, Leigh et al. 2006). From that point forward, with advancements in video card technology and increased production of 3D LCD displays, many other 3D immersive technologies have been created and adapted to meet specific needs.

While the traditional 4-6 screen projector based CAVE is still the most commonly used system configuration in the industry, there are now many other large-scale stereoscopic immersive systems that have been created. In 2010, a 21-screen LCD monitor configuration was introduced known as the NexCave (DeFanti, Acevedo et al. 2011). Also in 2010, a single LCD screen stereoscopic immersive technology known as an IQ-Station was introduced (Sherman, O'Leary et al. 2010). In 2012, a 72 screen panoramic display of stereoscopic LCD panels known as the CAVE2 was created (NSF 2012). In 2013, another technology similar to the NexCave was created and called the VuePod which runs on only one computer and uses twelve 55" 3D LCD televisions (Turner, Keene et al. 2013).

3.2.2 Research Objectives

At the current rate of growth in the availability of massive datasets and inexpensive visualization technologies, we expect that in a short period of time there will be hundreds of customized large-scale immersive data visualization system configurations in research institutions and industrial applications around the world. The lack of a well-defined classification approach for these systems is viewed as a hindrance to systematic growth in the area.

Also, for scientists, engineers, medical personnel and others who desire to view their data in an immersive data visualization environment, it may be helpful for them to understand the advantages and disadvantages between different systems. For example, if a scientist has a dataset that they want to view in a system that offers very fine resolution and small pixels, a classification system could offer clarification of whether or not a system meets the needs of that particular user. In contrast, another user may not be concerned with pixel size but they may need a very large viewing area. It may be beneficial for a classification system to reflect that information as well.

We propose that the solution to this problem is a simple and well defined classification approach for large-scale stereoscopic immersive technologies. The purpose of this classification approach would not be to portray any particular system as being “better” than others (i.e. we are not proposing a “rating system”) but rather hope to better characterize the systems that have been and will be developed. This classification approach is designed to normalize the primary components of each system in terms of three primary classes related to viewable area, pixel density and display technology.

3.3 **Methods**

To create a successful classification of stereoscopic immersive environments, data were collected from twelve large-scale 3D immersive systems around the world. The collected data are used to analyze and determine the most important components of each system. In collecting this data, it was imperative that the systems analyzed represented a sample of the variety of virtual reality system configurations. Also, we determined two requirements while choosing the systems to analyze; 1) motion tracking technology and 2) active or passive stereoscopy capability. The collected data were organized into three separate categories; Facility Components, Viewing Components and Primary Computer System Components.

The Facility Components category consists of general information about each system. This information includes, name of system, facility name or organization, year built, approximate capital cost, approximate operations and maintenance cost, number of part-time staff and number of full-time staff members.

The Viewing Components category consists of information that portrays the viewing capabilities of each system. This information includes; the number of display surfaces, display layout, total screen area, total number of pixels, pixel size, display technology, display model and vendor, type of stereoscopic capability, intensity, tracking technology and tracking vendor. This information is perhaps the most significant element of the analysis because it tells exactly what a user will experience and see when they use each system.

The Primary Computer System Components category is information that represents the computing power of each system analyzed. While many system configurations may have more than one computing option to power a system, this analysis only includes the components of the primary computing system used to run the system. These components include; number of computer sources, number of processors, RAM, operating systems used, number of video cards, video card model as well as primary and secondary software used. This information is a critical element of the analysis because it communicates whether extremely large datasets can be used as well as many of the software options and capabilities with each system. It also can give a computer technician a general idea of what is needed to power and operate a particular type of virtual reality configuration.

3.4 **Data Comparisons and Analysis**

After collecting all of the data of the large-scale 3D immersive systems, they are analyzed in tabular and graphical form. A cluster analysis of the graphed data was used to identify commonalities across multiple variables. Also, a pyramid graph was developed to visualize and classify collected data in terms of pixel-count. In high-performance computing, the Branscomb Pyramid is commonly used to help separate computational power of supercomputers (Berman 2008). The Branscomb pyramid approach essentially separates the normal “every-day” computer systems from the middle tier and more powerful computer systems. The top tier systems in the pyramid are the most powerful supercomputing systems. This analysis approach shows that the bottom tier of the pyramid is much larger that the top tier which signifies that there are more consumer-grade computing systems than powerful high performance supercomputers. The same type of analysis can be done with virtual reality systems where for example, we show a tier separation approach to visualize the difference in number of pixels. Seeing the data in this manner, allows for better data analysis while formulating a successful classification system.

Based on analyzing the data in a tabular, graphical and pyramid tier format, a proposed classification method or categorization of large-scale stereoscopic immersive systems was created. Some of the most notable components to consider while proposing a classification were identified as; physical size, type of display (projector, LCD), number of pixels and pixel size. One important part of our proposed classification approach is that it will be sustainable over time by allowing for further industry advancement and improvement.

After completing a survey of several of the leading large-scale stereoscopic immersive systems, Tables 3-1, 3-2 and 3-3 were created. The majority of this information was collected directly from the owners of each system, however some of the information was found on university websites, news releases or other online webpages. One of the requested pieces of data that was not provided by the majority of the people contacted is cost information. For those systems, a cost was estimated by evaluating the components that were provided. For the systems where costs were estimated, they are noted with an asterisk. However, for the cost information that was provided, it is helpful to see how certain aspects of each system correlate with a higher cost or how the date that it was built may have contributed to the higher or lower cost of the system.

3.5 **Results**

The Facility Components category shown in Table 3-1 provides general information regarding each system analyzed. Columns 6 and 7 contain information about the number of staff members who contribute to operating and maintaining each system. The C6 and the Cornea systems both require the most manpower. I-SPACE and VERITAS require only two part-time staff members to run those systems. One observation that can be drawn from this is that the more a CAVE facility costs, a high number of staff members are required to operate and manage the system.

Table 3-1: Facility Components

Facility						
Name	VR Facility	Year Built	Approximate Capital Cost	Approximate Operations & Maintenance Costs (Annual)	Part-time Staff	Full-time Staff (Count/Role)
VERITAS	Wright State University	1997	$750,000*	Not Provided	2	0
KeckCAVES	U.C. Davis	2005	$500,000	$10,000	0	0
DiVE	Duke University	2005	$1,000,000	Not Provided	1	2
C6	VRAC-Iowa State University	2007	$10,000,000	$ 630/hour	1	6
Cornea	KAUST	2009	$10,000,000*	Not Provided	2	5
NexCave	Calit2 - UC San Diego	2009	$100,000*	Not Provided		
CAES CAVE	Idaho National Laboratory	2009	$1,000,000	$200,000.00	0	3
IQ Station	Idaho National Laboratory	2009	$25,000	Not Provided	0	3
I-SPACE	Madrid, Spain	2010	$1,000,000*	Not Provided	2	0
CAVE2	EVL-University of Illinois at Chicago	2012	$750,000*	Not Provided		
VuePod	Brigham Young University	2013	$30,000	$25,000.00	3	0

The Viewing Components category information is shown in Table 3-2 (Page 42). This information is significant because it gives a good representation of what a user will see when they walk in the room to use each facility. The number of display surfaces column represents the number of screens that a user will view. The Display Plane Layout column provides a general description of the physical configuration of each system. Another piece of data collected in Table 2 is the total screen area. This represents a sum of the screen areas for all of the screens. The total number of pixels displayed and pixel size with each system analyzed is also displayed in separate columns. The other columns shown in the table include information about the display technology indicating whether or not projectors or LCD screens are used as well as the vendor and model information. The last two columns contain information about the tracking technology used with each system. The C6 and Cornea systems have significantly more pixels than any of the other systems. They also have the largest viewable screen area. They also have a pixel size that is very close to the same size as the systems with LCD screens. We see a correlation between the cost of these two systems and the values provided in this table.

Table 3-3 (Page 43) contains data about each of the primary computer systems used to run each of the 3D immersive configurations analyzed in this study. The first column in Table 3 shows the number of computer systems used to operate the 3D immersive technology. C6 uses 48 computers to power its system while the VuePod, CAES CAVE and the IQ-Station only use one computer. Column two presents the total number of processors used to run the system. C6 uses the greatest number of processors (96) while KeckCaves uses the least (6). On average the systems studied average 29 processors. Column five shows the number video cards that each system uses. The Cornea uses the most with 96 video cards whereas the VuePod uses three. The Cornea uses significantly more video cards to operate than any of the other systems studied.

Table 3-2: Viewing Components

	Viewing									
Name	# of Display Surfaces	Display Plane Layout	Screen Area (sq. ft)	Total # Pixels	Pixel Size (mm)	Display Technology (projector, LCD, etc.)	Display Vendor	Type of 3D	Tracking Type	Tracking Vendor/ Model
VERITAS	5	cube-four walls, floor	500	7,200,000	1.13	Projector	Barco	Active	Intertia Acoustic	Intersense 900
KeckCAVES	4	cube-front, left, right, floor	320	5,242,880	2.38	Projector-DLP	Christie Mirage	Active	Hybrid Intertial	Intersense 900
DiVE	6	cube-four walls, floor, ceiling	543	6,615,000	2.70	Projector	Christie	Active	Ultrasonic	Intersense 900
C6	6	cube-four walls, floor, ceiling	600	100,663,296	0.74	Projector	Sony	Beacon	Ultrasonic	Intersense 900
Cornea	6	cube-four walls, floor, ceiling	600	100,663,296	0.74	Projector	Sony	Active	Ultrasonic	Intersense 900
NexCave	9	Wall - 3 rows of 3	200	22,500,000	0.64	LCD	JVC	Passive	Optical	ART Smarttrack
CAES CAVE	4	cube--left, right, center, floor	300	5,880,000	2.18	Projector-DLP	Digital Projection	Active	Optical	Intersense 900
IQ Station	1	Single Screen	20	2,073,600	0.64		Mitsubishi	Active	Optical	ART Smarttrack
I-SPACE	5	cube-front, left, right, floor, ceiling	496	8,820,000	2.28	Projector-DLP	Barco	Active	Optical	ART
CAVE2	72	320 degree panoramic	480	37,000,000	0.73	LCD panels			Optical	
VuePod	12	Wall - 3 rows of 4	108	24,883,200	0.64	LCD	LG	Passive	Optical	ART Smarttrack

Table 3-3: Primary Computer System Components

Primary Computer System								
Name	# of Computer Sources	# of Processors	RAM (GB)	Operating System(s)	# of Video Cards	Video Card Model	Primary Software	Other Software
VERITAS	5	10	40	Windows XP or 7/Linux	5	Nvidia Quadro 5600	Presagis Vega Prime	Delta3D with VRUI, Trackd
KeckCAVES	6	6		Linux	5	Nvidia GeForce 470, Nvidia Quadro FX5800	Vrui	
DiVE	7	56	8	Windows XP/Windows 7	6	Nvidia Quadra FX 5600 With Gsync add-on	Virtools, Avizo, Syzygy, Unity	MATLAB, Maya
C6	48	96	32	Linux Redhat/Windows 7	8	NVIDIA Quadro 6000	VR Juggler, Open Scene Graph	
Cornea	25	50		RH SL6	96	Nvidia Quadra 5600	AVIZO, TECHVIZ, CALVR	
NexCave							CALVR	
CAES CAVE	1	8	24	Windows/Linux	4	Dual-Quadroplex G2	Vrui	
IQ Station	1	12		Windows/Linux			Vrui	
I-SPACE	6	12	48	Windows XP/Linux	6	Nvidia Quadro FX5800 Pcle w/ 4 GB of memory	3DVIA Virtools 4.0/5.0	Unity3D, MiddleVR, OpenSceneGraph
CAVE2	36							
VuePod	1	12	24	Windows/Linux	3	Quadro K5000	Vrui	Navisworks

3.5.1 Data Analysis

Multiple methods were used to analyze the information collected in the three above tables. It is important to analyze the data in different ways because it helps to group the different systems analyzed based on specific components.

Figure 3-1 (Page 46) is a pyramid created by separating the analyzed systems based on the total number of pixels. This pyramid can be used to compare with other plots, tables and pyramids to look for trends in the data shown.

The C6 and the Cornea systems shown in the top tier of Figure 3-1 are very similar to each other in that they are both six-sided projector based systems. The second tier in the pyramid contains the VuePod, CAVE2 and NexCave systems that are also very similar to one another being that they are all LCD television or panel based systems with a screen panorama type of configuration. The other systems shown in the third tier of the pyramid are made of mostly four or five wall projector systems. However, the IQ-Station is an LCD single screen system. The pyramid is also color coded to indicate the price range that each system cost to build. As expected, the C6 and Cornea cost the most to construct. The middle and bottom tiers show two price ranges. The least expensive systems shown in the pyramid are the VuePod, NexCave, IQ-Station and VERITAS. VERITAS is a low-cost projector system; however the other three are all made up of stereoscopic LCD television screens. The CAVE2 is also made up of LCD screens; however it is estimated to cost more than one million dollars because it uses 72 screens.

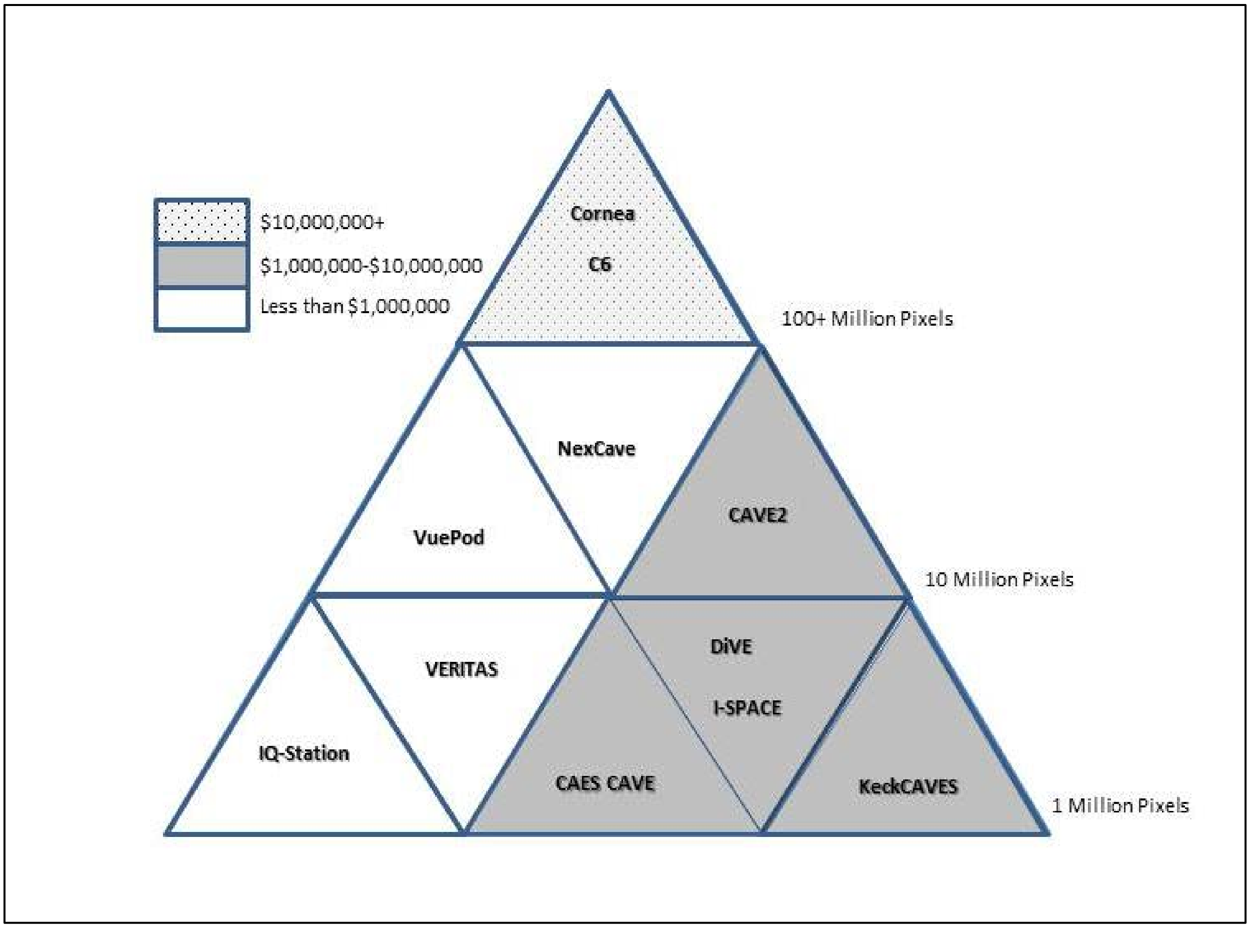

Figure 3-1: Pixel-count Branscomb pyramid analysis

Figure 3-2 displays a graph which was plotted with the idea of comparing the relationship between the number of pixels and the screen size. Each plotted system is labeled for ease of analysis. The circles shown around certain systems portray the natural clusters based on this comparison. The primary conclusion from this graph is that one cluster contains only LCD screens, another one contains projector systems that have a low resolution and the final cluster contains the most expensive high-end projector systems that were designed to also have a very high resolution.

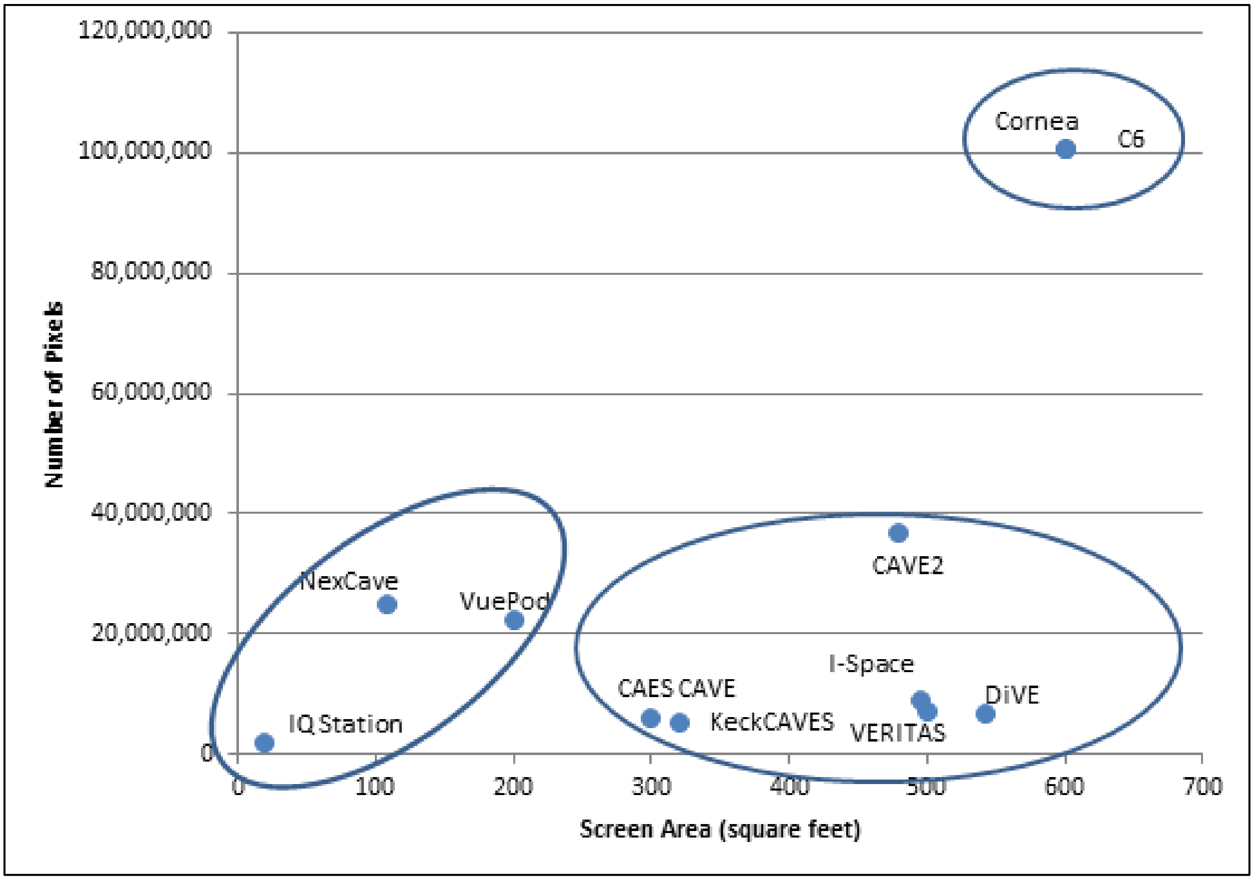

Figure 3-2: Comparison between number of pixels vs. screen size in square feet. The circles indicate clusters.

The three distinct clusters in Figure 3-3 are made up of almost the same identical clusters as in Figure 3-2. The only difference is that one projector based system, VERITAS, which has a smaller pixel size as the other lower resolution projector based systems is contained within the same cluster as all of the LCD monitor systems. Other than that one minor difference, the results between the two cluster analyses are very consistent with one another.

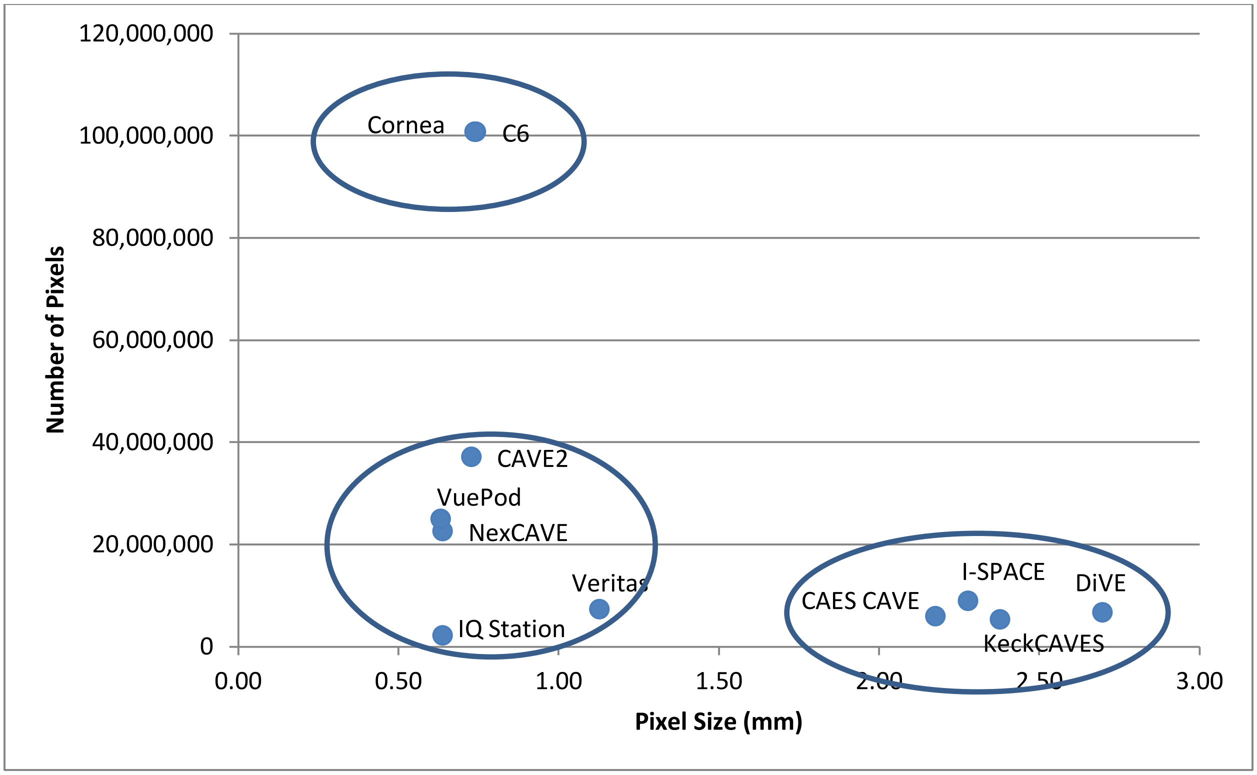

Figure 3-3: Comparison between pixel count and pixel size. Circles indicate clusters.

3.5.2 Summary of Data and Results

Based on the data shown in the tables, pyramid analysis and graphical analysis, there are elements of stereo visualization technologies that appear to be most important and need to be reflected in any classification system. The first aspect is pixel size. This is an important component to include because it communicates how the data will appear on the screen(s).

Another apparent differentiator in the data is screen size. It is important to include screen size in a classification system because understanding the amount of screen area combined with a pixel size gives an understanding of how their data will appear and how fine a resolution will be portrayed.

Lastly, the pyramid analysis and both graphical plots give an indication that there is an obvious distinction between LCD displays and projector displays. As a result, it we have determined that a reflection of whether or not a system is made up of an LCD display or projector display is meaningful information that should certainly be included in our classification approach.

3.6 **Conclusions**

The purpose of this study was to collect and analyze data of existing large-scale stereoscopic immersive visualization systems around the world and use that information to propose an approach for classifying the technology. Our resulting classification approach for immersive data visualization technologies should clearly communicate information about the pixel size, screen(s) size and display type. These three aspects of the technology give a potential user a distinct idea of what to expect before entering a room to use the technology. The following table shows all twelve of the systems analyzed properly classified.

Table 3-4: Final Classification Table for each 3D Visualization System

VR System	**Viewable Areas (Sq. Meters)**	**Projector (A) or LCD (B)**	**Pixel Size (1-3)**	**Final Classification**
VERITAS	46	A	1	**46A1**
KeckCAVES	30	A	1	**30A2**
DiVE	50	B	1	**50B1**
C6	56	A	2	**56A2**
Cornea	56	A	3	**56A3**
NexCave	19	A	3	**19A3**
CAES CAVE	28	A	3	**28A3**
IQ Station	2	B	1	**2B1**
I-SPACE	46	A	3	**46A3**
CAVE2	19	B	1	**19B1**
VuePod	10	B	1	**10B1**

Based on Table 3-4, the final classification approach follows this format; Screen Size (square meters) + Projector (A)/LCD (B) + Pixel Size Classification Number (1-3). The pixel size classification number signifies that a smaller classification number represents a smaller pixel size. Table 3-5 represents how the pixel size classification number was selected.

Table 3-5: Pixel Size Classification Number

Pixel Size (greater than)	Class Number
2 mm	3
0.75 mm – 2 mm	2
less than 0.75 mm	1

It is important to understand that this classification approach was not created to portray any type of 3D visualization system as being better or worse than any other system. This approach has been created and explored to help users and virtual reality facilities communicate what each system has to offer. Furthermore, all of the information portrayed in this analysis can be useful to educate those who have a desire to build or expand stereo visualization technologies. Ideally, others can take the approach discussed in this paper and add to it or suggest another approach that could help further the science.

The 3D immersive technology industry is no longer made up of a few research organizations that house a small number of virtual reality systems. The advances in stereoscopic technologies have allowed researchers to practically custom build each system to suit almost any data viewing necessity. Discussions such as those provided in this analysis are absolutely essential to help industry leaders and others to collaborate and communicate their ideas and advancements.

Additionally, we believe that our classification approach should remain time independent. For that reason, we chose to use pixel size, screen size and display type in our approach. As technology continues to evolve and improve, we believe that these three fundamental aspects will remain a crucial part of any 3D immersive system.

4 CHAPTER 4 – CONCLUSIONS AND FUTURE WORK

The primary problem addressed in this thesis was to build a large scale, low-cost, human immersive, mobile 3D immersive system for less than $40,000. Based on research of similar immersive technologies, including projector based and LCD systems, the construction and operation of the new technology, the VuePod, addresses two commonly discussed issues; cost and mobility. The primary purpose of building the VuePod is to use the technology to view, analyze and solve engineering and scientific problems.

A classification approach and data analysis for virtual reality systems were also created as a secondary research study of this thesis. This classification approach was created for two reasons. The first reason is because based on my research; no one has attempted to classify 3D immersive visualization systems. The second reason is to help others in making decisions during the procurement and configuration processes of building a large-scale stereoscopic system. Due to technological advancements in recent years, researchers are now able to essentially customize virtual reality technologies to meet their desired needs. Consequently, it is likely that there could be dozens of configurations in the near future. I believe that my proposed classification approach combined with the data provided in the study could contribute to the organization and order the industry as a whole and could provide others with one way of comparing the technology based on the components that each system offers.

The most important aspect of the development of the VuePod is its usability. Based on multiple benchmark and usability tests, this system performs at a level that meets or exceeds that of similar systems. The Vrui toolkit software is the primary software used on the VuePod where LiDAR data and MRI scans can be displayed in 3D.

All virtual reality immersive technologies have their own advantages and disadvantages. The biggest advantages of the VuePod include low construction cost at just over $30,000, low operations and maintenance costs, large screen area at 108 square feet, high pixel count (24 megapixels) and small pixel size at 0.64 mm. There are also two minor shortcomings that have been observed while using the VuePod. These include; minor motion sickness and in some cases interference due to the bezels. The motion sickness issue is an issue with all stereoscopic immersive visualization systems and is primarily due to frame rate speed. As video card technologies continue to improve, I believe this will become a non-issue. The issue of the bezels interfering with data visualization is more prevalent when viewing datasets that have solid surfaces. While viewing LiDAR data, the televisions appear like twelve windows that the user is looking through. Thus, the user can simply ignore the bezels and look “around” the bezels. However, it is a real issue while view CAD drawings.

In hindsight, there is one aspect of the VuePod construction that could have been done differently to improve the mobility of the VuePod. Instead of welding the television mounting stands, it would be better to build stands that can be collapsed and folded. This would make it much easier to disassemble the system to transport to trade shows, conferences or other events. As it is, I estimate that it would take about two hours to disassemble and two hours to reassemble the system.

4.1 **Future Work**

Now that the VuePod has been successfully constructed and has the capability of viewing any stereoscopic type of data, future researchers should focus their efforts on finding engineering applications that can be solved and analyzed using the VuePod's capabilities. Based on the current software that is used in the industry, I see a strong need for further development of software that is capable of being used to analyze engineering problems. For example, the measuring tool in the Vrui Toolkit is not accurate because it does not allow the user to "snap" to points on the screen.

Aside from being able to use the technology to solve and analyze engineering problems, I see an additional benefit of using the VuePod for presentation purposes. I see a definite value of simply being able to visualize data in a similar way that the natural eye sees it in the real world. I think that viewing certain types of data, such as LiDAR, in 3D helps the brain in processing and understanding the information better than 2D visualization. A few civil engineering applications where I think 3D data visualization could be beneficial include; groundwater modeling, surface water modeling, erosion analyses, contaminant transport modeling, structural analyses and highway studies.

Due to the fact that very little or no work has been done in stereoscopic visualization and civil engineering, this presents a tremendous opportunity for those who wish to contribute to immersive virtual reality research.

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