THE VDEN: AN AFFORDABLE IPT DESIGNED FOR CONFERENCES

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THE VDEN: AN AFFORDABLE IPT DESIGNED FOR CONFERENCES by Alexander Jaeger, December 2019

ABSTRACT

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

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CHAPTER 2

REQUIREMENTS

Introduction

To help guide our development, we created a few key requirements. These not only guide but also help differentiate our solution from the previous implementations.

Cost

The advent of head-mounted displays has brought forth an expectation of low-cost virtual reality. In 2019, PC Magazine wrote an article on the Best VR Headsets of 2019, the listed price range goes from $100 – $600. [1] In 2010, Carolina Cruz-Neira notes that a typical CAVE system of 3 vertical screens and a floor can easily cost over $750,000. [2].

In a world where you can get a VR headset for $200 and build immersive content, it is easy to see why CAVEs have fallen out of favor. We want to help reinstate the CAVE and provide a solution for less than $40,000.

Footprint and Room Location

Not only should a CAVE be used in conference and laboratories, but also in the standard office space. We want to showcase immersive content everywhere, so we will target a maximum footprint of 8' x 8' and a height of 10' for the entire system. Lastly, the room should not be required to be on the first floor with large doors to carry parts through. Each part should be lightweight enough to carry and small enough to fit through a standard door. If the room is on a higher floor, then the the loading on the elevator should not be hampered by the size of the parts.

Resolution

The current demand for display technologies is 4k resolution, making 1920x1080 ubiquitous.

Floor Projection

While the front projection is the most important as it draws the most visual area, the floor projection is a debatable runner-up. Not does it help to fill your vision vertically, but also the corner formed provides a large amount of immersion.

Development

Designing new media in a intuitive way is the highlight of research and development for a wide range of fields. Game Engines, such as Unity3D and Unreal, have largely taken over the face of the computer graphics industry. These tools make it easier than ever before to build immersive media. We want an SDK that is compatible with a game engine to render into a CAVE.

Setup and Shipping

The Emerging Analytics Center goes to several conferences per year all across the world. Bringing the VDEN to these events would be great for PR. Therefore, the final design of the system must be able to be setup within one day and has to fit within the back of a van or shipping container.

Computing

Although distributed computing is still required for high performance CAVE graphics, the capabilities of a graphics card has risen dramatically. Modern cards can handle a system with 4 displays, hinting at the possibility of running a CAVE.

CHAPTER 3

PREVIOUS LOW COST CAVES

3.1 *The MiniCAVE: A Voice Controlled IPT Environment* By Edward Wegman Et Al 1999

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	6’x6’x6’	✓
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	intentionally left out	✗
Stereoscopy	active stereo	✓

Table 3.1. Wegman Et Al compared to VDEN Rubric

This paper marks the earliest attempt found to create a more affordable CAVE system. The researchers found that the 200Mhz Pentium Pro Processor ($3000) was competitive to the SGI Onyx RE2 ($120,000) when running matrix-oriented mathematics software. With the advancements in computing and projection, they hypothesized that using a PC system could run a CAVE for less than $100,000. [3]

3.2 *Immersive Virtual Reality on Commodity Hardware* By Robert Belleman Et Al 2001

Topic	System	
Cost	not specified	✗
Ease of Development	CAVELib	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.2. Robert Belleman Et Al compared to VDEN Rubric

Robert Belleman Et Al describes the work by researchers at SARA and UvA to build a CAVE system based on commercially hard- and software. By utilizing CAVELib and OpenGL—Performer, they were to minimize porting efforts for preexisting applications. This minimization naturally makes life easier for programmers used to these platforms. Finally, they tested the performance by rendering 204,480 triangles in 39,134 triangle strips without texture mapping in active stereo. The SGI CAVE system rendered at 5.5Hz whereas the PC solution rendered at 6.3Hz.

3.3 *Implementation of a Low-Cost CAVE System Based on a Networked PC*
By Po-wei Lin Et Al **2002**

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.3. Po-wei Lin Et Al compared to VDEN Rubric

In 1999, the researchers installed the first CAVE system in China based on an SGI machine, almost immediately after they began implementing an alternative using a cluster of PCs. Po-wei Lin Et Al wrote a custom architecture to render on their CAVE using MPI and OpenGL. In the end, their system rendered 60,000 triangles at 18Hz. They further tested the performance of an SGI Onyx2 versus a single PC with a 3DLabs Wildcat 5110-G Graphics card. A test of rendering 1.2 million triangles, the SGI rendered at 2-3Hz whereas the PC at 8-9Hz.

3.4 *Low-Cost, Portable, Multi-Wall Virtual Reality* By Samuel Miller Et Al 2005

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.4. Samuel Miller Et Al compared to VDEN Rubric

This CAVE system developed by researchers in NASA's Applied Sciences DEVELOP Program is focused on affordability and portability. They presented a solution for <$30,000 as opposed to the goal for a CAVE system at <$100,000 in 1999 with the MiniCAVE. Stereoscopy is derived through the use of two LCD projectors and a mechanical shutter. The researchers found a number of issues with 3D glasses and the shutter. The 3D glasses used polarizing lens and were destructive to the polarized light from LCD projectors. The shutter failed to adapt to DLP technologies due to the internal color wheel. DLP projectors spin a color wheel and use a chip of mirrors to compose an image. Active shutter glasses cycle at a specific speed, this should be such that a fully composed image is displayed for the appropriate speed causing issues with calibration. Lastly, the system still relied on mirrors even though a floor projection is intentionally missing.

3.5 *Practical Design and Implementation of a CAVE System* By Achille Peternier Et Al 2007

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.5. Robert Belleman Et Al compared to VDEN Rubric

Peternier et Al's CAVE is composed of 3 walls with a floor, a cluster of PCs, and 8 LCD projectors (1 per eye). They adapted a preexisting internal graphics engine. Like Miller's CAVE, they use single screen for the entire system and wire to attach [4]. They use an optical tracking approach, but they also tested a custom tracking solution using ARToolkit and fiducials. The final system managed a framerate of 25 while rendering 15,000 triangles in stereo and with one light source casting soft shadows.

3.6 *A Virtual Reality Installation*
By Francois Sorbier Et Al **2008**

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.6. Robert Belleman Et Al compared to VDEN Rubric

Although monoscopic, this CAVE system tested new strategies for screen materials and tracking while maintaining the goal of affordability and transportability. They handmade the projection screens using tracing paper and remark their lastingness. This paper allowed the projectors to be rear projecting. To cut costs, the researchers created their own tracking system. A tracking system has to determine two things: orientation and position.

3.7 *The LAIR: Lightweight Affordable Immersion Room*
By Barry Denby Et Al **2009**

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.7. Robert Belleman Et Al compared to VDEN Rubric

3.8 *Implementing a low-cost CAVE system using CryEngine2*
By Alex Juarez Et Al **2010**

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.8. Robert Belleman Et Al compared to VDEN Rubric

3.9 *An Affordable Surround-Screen Virtual Reality Display*
By Carolina Cruz-Neira Et Al **2010**

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.9. Robert Belleman Et Al compared to VDEN Rubric

3.10 *Designing a Low Cost Immersive Environment System Twenty Years After the First CAVE* By Richard Fowler Et Al 2012

Topic	System	
Cost	<$100,000	✗
Ease of Development	not specified	✗
Transportability	not specified	✗
Minimum Room Size	not specified	✗
Ease of Setup	not specified	✗
Computing Power	Cluster of PCs	✗
Tracking	electromagnetic	✗
Stereoscopy	active stereo	✓

Table 3.10. Robert Belleman Et Al compared to VDEN Rubric

3.11 Discussion

	Wegman	Belleman	Lin	Peternier	Miller	Sorbier	Campbell	Cruz-Neira	Juarez	Fowler
Cost	✓	✗								
Footprint	✓	✗								
Resolution	✓	✗								
Floor Projection	✓	✗								
Development	✓	✗								
Setup and Shipping	✓	✗								
Computing	✓	✗								

Table 3.11. All Implementations compared to VDEN Rubric

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CHAPTER 4

PREVIOUS CAVE FRAMEWORKS

4.1 *Designing a Low Cost Immersive Environment System Twenty Years After the First CAVE* By Richard Fowler Et Al 2012

CHAPTER 5
HARDWARE

5.1 Introduction

A typical CAVE installation has four major sources of hardware: projectors, screens, a tracking system, and a structure to mount everything. High resolution CAVEs can contain multiple displays per screen and become difficult to setup.

— FIX ME —

5.2 Projectors

The display of computer generated content is dominated by projectors and monitors. Projectors use a lamp and lens to project light onto a surface. Monitors utilize a two dimensional array of light cells to present an image to the user.

You can think of these technologies on a loose spectrum, similar to figure 1. On the left end, a large or far image is required, this is ideal for projectors because the resultant image size is a factor of throw distance. As you move closer to the monitors, a close or small image is preferred. This spectrum is loose because you can apply monitor technology that is ideal for a projector (and vice versa), there is an increase in cost and innovation to make it happen.

The ideal CAVE system would be powered by monitors. They are superior in terms of pixel density and resolution, fast response times, physical size, and ease of calibration. A disadvantage is their bezel will cause some issues with rendering and make content like text hard to read. When we increase the pixel density and resolution, there is a increase in power and computing requirements. A cluster of PCs will be required to render and this will drive costs up. Due to this, affordable CAVE systems prefer projector setups.

Although projection based CAVEs suffer from pixel resolution and brightness, we see a savings in computing and cost. It is not necessary for a CAVE to have multiple projectors per wall, although high-end CAVEs may include it to help bridge the gap in performance between the two techniques.

In this project, we decided with using a single projector per wall in order to minimize the complexity and cost of the system. We created a few requirements to filter when we performed a search.

1	1920x1080 Resolution
2	Capable of 3D stereoscopy
3	Ultra Short Throw
4	Less than $2000 MSRP

An EBU Technical Report from 2012 states that 1080p is technically mature and almost all new flat panel displays use FullHD. By 2012, some 4K displays have entered the high-end sector of the market. [5] In 2019, 4K flat panels are becoming commonplace and FullHD displays are ubiquitous. Therefore, we make FullHD a requirement for the resolution of the projector.

Reading the history of affordable IPTs, multiple projectors per wall is a common theme to enable stereoscopic imagery. Each projector would represent an eye and some technique of shuttering is used to block light. Stereoscopic alignment and portability are special concerns for this technique. Multiple projectors are necessary because

CHAPTER 6
SOFTWARE

6.1 Introduction

Providing just a hardware solution is unacceptable for adoption, a software package that is easy to use and extensible is a necessary feature. Long are the days of the average VR graphics programmer using OpenGL to create simple prototypes. Game engines dominate the interactive media industry and VR SDKs were quick to target them.

The Choice of the Unity3D Game Engine

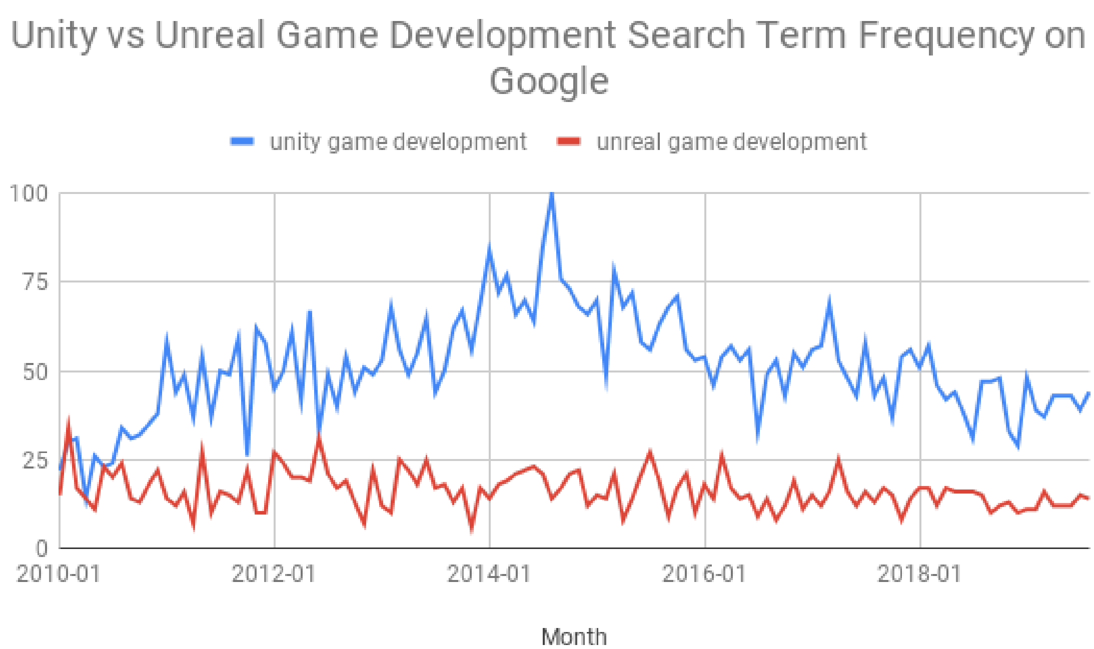

Figure 6.1. A graph from Google Trends showing the search term frequency of "unity game development" versus "unreal game engine development" from 2010 (Marking the release of version 3 of Unity). The vertical axis represents the percentage of popularity.

Unity3D is a game engine for creating interactive media. Launched in 2005, the goal was to create an affordable system for amateur game developers. [6] By focusing on a simple asset pipeline and workflow, Unity3D thrived and by 2010 had over 200,000 registered users. Quickly, Unity became the #1 platform for game development. [7]

The major competition to Unity3D is the Unreal Engine. Initially developed by Tim Sweeney, this engine was designed to push the limits of graphics and realism. Not only has it received a 2014 Guinness World Record for "Most Successful Game Engine", but also a long list from game developers and film productions alike. [8] However as shown in Figure 6.1, Unity3D is more searched on Google for game development topics supporting the notion that it is the preferred tool for most games.

A Bachelor's thesis written by Simo Ahola describes the steps necessary to build a Virtual Reality application in the Unity3D game engine supporting two different headsets: the HTC Vive and Oculus GO. By just downloading the individual SDKs then dragging and dropping the associated prefabricated component, Simo had easily developed a VR application. [9]

It is of my personal desire to make CAVE development as simple and accessible as a headset. Unity's history of simplicity has positioned it in the forefront of VR development, making it the preferred platform for the vDen.

6.2 Unity SDK

The simple act of downloading an SDK and dragging the necessary components into your scene sounds so fundamental, however it was not until WYSIWYG game engines became popular for this to happen. The architecture of the vDen SDK revolves around this concept.

To guide development, we defined three goals for our system: rendering immediately upon importing, allowing full extension and of peripherals, and lastly simulating the vDen rendering in Unity itself.

The core rendering system govern the functionality of the eye and display cameras.

Eye Cameras

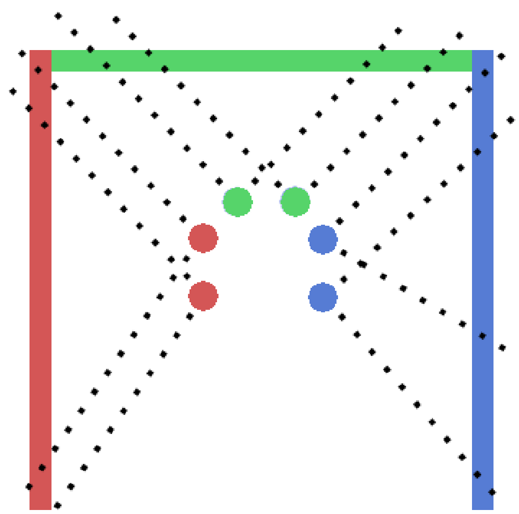

Figure 6.2. The Eye Cameras are paired together and are related to a specific screen. Each camera pair has space in-between related to the inter-pupillary distance of the user's head. The floor cameras are missing in the graphic, but are in the SDK, bringing the total to 8 eye cameras.

Eye cameras capture an image that represents the view from a user's physical eye. As shown in Figure 6.2, there are two cameras per screen, totaling 8 in the SDK. A pair of cameras are spaced apart along the shared axis with the distance equivalent to the user's interpupillary distance. Futhermore, each pair needs to remain orthogonal to the others. Lastly, because the screens represent a window to the world, we need to calculate a custom frustum for each camera.

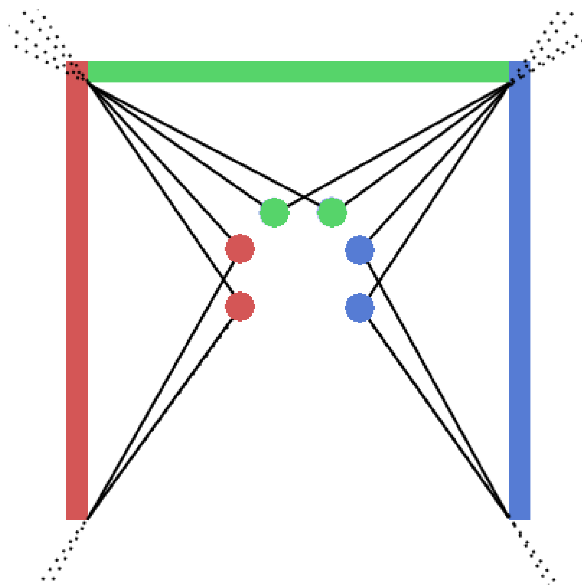

Figure 6.3. Shows the new frustum of each camera after calculation. This provides the correct view as our physical screens represent windows into the world

Looking at the differences between Figure 6.2 and Figure 6.3, we can immediately see the frustum is bounded to the the screen. This bounding guarantees that nothing is rendered outside of the screens.

— FIXME — The calcuation of a new frustum is easy. We need to determine the

Display Cameras

Display Cameras will output the final image for the projectors. With one camera per projector, the vDen has four total. The camera is associated with a pair of eye cameras and is responsible for merging their output together, left-right or top-bottom, for sterescopy, then rendering on the calibration mesh.

Head Tracking

A core feature of Virtual Reality is the generation of perspective correct imagery. This is done by understanding the head position and how the eyes view the scene. In order to track the head, the user dons a trackable baseball cap the tracking system syncs its position with the collection of eye cameras.

6.3 Calibration

There are several sources of error when using the vden that have to be corrected. This section outlines the most common ones that we have found.

Projector Misalignment and Overfill

Projector Misalignment and Overfill occurs during setup when the images between two projectors does not exactly align or the image is larger than the screen.

If the projector structure could lock in the position of the screens, then we could make guarantees about alignment and overfill. This can be seen in High-End CAVEs that implement multiple displays per wall via tiling. However, locking the screen to the frame would increase the setup time and we cannot guarantee perfect results without substantial infrastructure. The vDen is designed to be modular, since we can use software to correct, we should require overfill and calibrate for the error. This strategy at least minimizes physical setup time and guarantees the screen will be filled.

In order to accommodate this source of error, the user needs to calibrate each screen's shape to fill the screen. A grid of movable dots is rendered, allowing a more precise positioning. In the background, is a fine checkerboard, this lets the user align two screens together and verify uniformity by physically measuring the size of each square across the screens.

Perspective Distortion

Perspective Distortion occurs when the projector is off axis from the screen causing warping.

This is solved by a technique called Homography which states there is an affine transformation between two planes. Simply put, there is a system of equations to transform each point in one coordinate system A to another B by distorting A to match B. In this case, we have a real mesh R and we want to become a uniform grid G. We can apply homography onto R to get G and thus the screen's coordinate system because ideal for rendering. This technique only needs to happen on startup and requires the calibration data.

6.4 Dashboard

CHAPTER 7

DISCUSSION

CHAPTER 8

CONCLUSION

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