The "CABANA": A Re-configurable Spatially Immersive Display

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Abstract

This paper describes a reconfigurable spatially immersive display. Limitless configurations are possible by physical transformations of the display units along with the appropriate software settings. We describe several configurations within.

The system is composed of four main components: three self-contained rear-projected display units and a fixed front projection floor. Each of the three display units is constructed from a cube that is approximately 8 feet on a side and has an 8x8 feet fresnel lenticular screen, a high resolution projector, a double first surface mirror framework, and a supporting superstructure. Each display unit is set on retractable casters and can be positioned anywhere with little or no re-calibration of the display hardware since the unit components are rigidly mounted together. The projectors themselves generally do not need to be re-aligned every time a display unit is moved; they move with the unit. This makes repositioning the units a bearable chore.

A standard room sized CAVE ™[1] configuration of our system supports a left display unit, right display unit, front display unit, and floor. The display units of this system can be mechanically unfolded to provide a high-resolution flat video wall for large audiences. Additionally, the left and right display units can be moved to form arbitrary angles with the front display unit. The floor can also be used in these configurations to allow users to look down for partial projection onto the floor. Near full immersion can also be experienced by folding the left and right units into an equilateral triangle shape. In this way, a stereo image completely surrounds the user on the vertical displays.

This paper describes hardware and software issues related to providing the least amount of user interaction when switching between configurations. Problems encountered will also be discussed in detail such as tracking, projection geometry, and edge matching.

Keywords:

Spatially immersive display, virtual reality, immersive environments, collaboration, user tracking.

1 Introduction

At the onset of this project, we had the need for two different types of display systems. The first system would be a video wall capable of displaying an unbroken high-resolution image across an area approximately 6 feet high and three times as wide. The second system would be a 5-foot immersive “CAVE” display with edge-matched images projected on three sides that were to be placed at 90° and a fourth edge-matched image projected onto the floor. Our room size was approximately 40 feet x 26 feet x 9 feet with a drop ceiling and approximately 8 feet of space above the ceiling. The area above the ceiling was cluttered with electrical conduit and fixtures, water lines and HVAC ducting among other things. After investigating the costs involved, we determined that the cost for building two separate display systems as well as the space required to set them both up was prohibitive. We decided to take a fresh approach: we set out to design a video display system that would meet both requirements, and could also be easily reconfigured with little or no re-calibration. We found that the best way to accomplish this task was to design separate, quasi-portable vertical display units. We needed to design them so that the display screens’ edges would be able to butt against each other and allow seamless image edge-matching. Having three separate units would allow us many more configurations than we had originally intended.

We needed to set up at least these display configurations:

1. A video wall with the three units side by side (Figure 1).
2. A CAVE-like configuration with two side units oriented 90° with respect to a front unit and a floor display (Figure 2).
3. A "theater" configuration with two side units oriented 45° with respect to a front unit (Figure 3).
4. A near full immersion triangle created by placing three units in an equilateral triangle above the floor (Figure 4).
5. An "L shape" which allows an immersion type of experience yet at the same time allows a more open view to an audience.

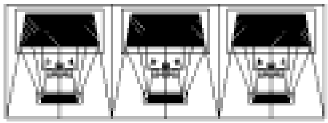

Figure 1. Video Wall Configuration

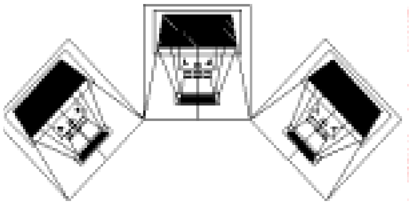

Figure 3. Theater Configuration

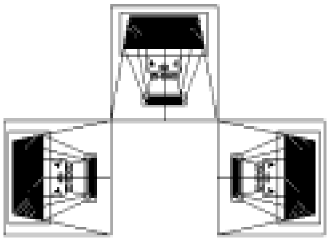

Figure 2. CAVE Configuration

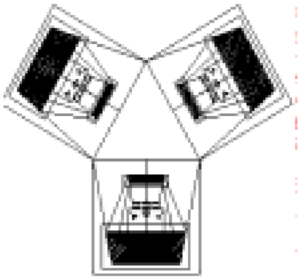

Figure 4. Immersive Triangle Configuration

We call our system the CABANA. In keeping with recent practice, CABANA is an acronym that conveys some sense of the local culture: CAVE At the Beach And Nearby Attractions. In the following sections, we discuss the physical and optical properties of the system, software used to provide imagery and help calibrate the displays, CABANA issues, and software, including several applications we are currently using with different system configurations. We close with a section describing future CABANA work.

2 Hardware Configurations

This section describes the CABANA design process, its hardware realization, and how it can be reconfigured into different display environments.

2.1 CABANA Module Design

In our first design step we determined how large we wanted our images to be. We had originally planned to create a 5-foot cube for our CAVE (which would allow a subject to sit in front of the images in a chair) and a video wall 6 to 7 feet high. After evaluating all of the space we had, we decided to design a system that would give us an 8-foot square image on each of the three screens as well as the floor, which would allow a subject to both sit and stand inside the CAVE. We needed the structures to be rigid and the projectors and mirrors to be mounted solidly inside so that movement would not affect their calibration and alignment. The display units would also have to be on retractable, lockable casters so the units could be rolled into position and then leveled.

We investigated several ways of projecting images and determined that only rear projection met our needs. Our biggest concern with this approach was that historically, rear-projected images had a "hot spot" – an area of the screen that is noticeably brighter than the rest of the display. A second major concern was that typically as one moves closer to a rear-projected image or off of the projector's principal display axis, the image becomes blurry and unrecognizable. Since we wanted an immersive environment, we had to make sure our images would appear sharp at close range and off-axis. We looked at several different screen materials and found that the material of choice would be a Fresnel-Lenticular screen. The screen we chose is constructed of heavy gauge Lexan™. With this type of screen, the image is projected onto diamond-shaped vertical striations, which act as tiny prisms and thereby allow a more even distribution of light, which avoids the “hot spot” problem.

Our second step was to decide which type of projector technology to use. We determined that a CRT-type projector would suit our needs perfectly. The projector we chose was the Ampro 4600 (9-inch) with the “fast phosphor” green CRT option which enables us to use interlaced stereo video formats at high refresh rates for flicker-free stereo imaging with electronically polarized glasses.

Our third step was to determine what materials would be used and how to build the display units. Because we had limited hallway access and several narrow doorways leading to the laboratory where the units would be installed, and with projector units that were nominally 8-foot cubes, each unit had to be fabricated in pieces outside of the facility and assembled at our site. We also wanted removable doors on each unit so that we could effect repairs on the projector and clean the mirrors when necessary. All of the pieces would have to be as lightweight as possible for easy reconfiguration. Aluminum seemed the best choice for the structure because of its light weight. Even using aluminum, the projector units (with projector installed) weigh close to 800 pounds each.

The final design step was to determine the required throw distance of the projector and determine if a single-fold (Figure 5) or a double-fold (Figure 6) image would be needed. We decided on the double-folded image so that we could reduce the depth of the display boxes. We used first-surface mirrors to reduce the loss of image quality.

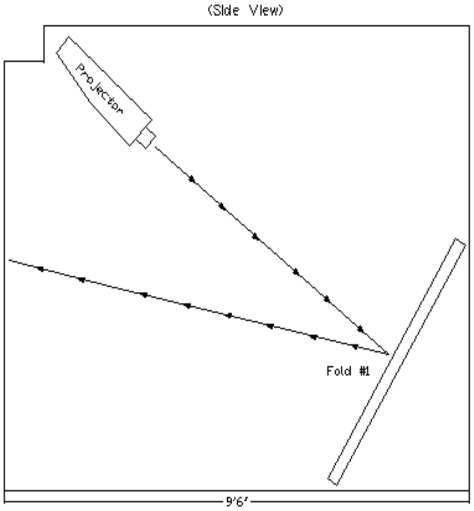

Figure 5. Single-Fold Projection

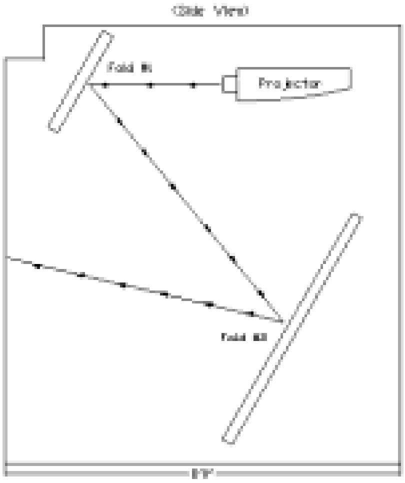

Figure 6. Double-Fold Projection

The last phase of our project required the removal of the drop ceiling and relocation of three electrical conduits, two fluorescent light fixtures, one emergency fire sprinkler and about 20 feet of HVAC ducting. We relocated these items to make room for the floor image projector. We were able to mount this projector above the ceiling and use a single fold with a first-surface mirror to project to the floor below. Figure 7 and Figure 8 show the CABANA environment before installation and afterwards, in the CAVE configuration.

Figure 7. CABANA Space Before Installation

Figure 8. CABANA in CAVE configuration.

2.2 Reconfiguration.

The CABANA is designed for relatively rapid configuration. In general, reconfiguration follows this procedure:

1. Remove specialized equipment and cabling from the current CABANA area and from the proposed CABANA area.
2. Disconnect all power cabling to the units and place the cable ends inside their respective units.
3. Raise the front of each unit to be moved by turning the leveling screws on the unit casters.
4. Remove the CABANA floor if necessary for free movement of surrounding units.
5. Move the CABANA units to their approximate new positions.
6. Align each unit with adjoining units.
7. Reattach cabling and specialized equipment for the new configuration.
8. Recalibrate projectors as necessary.

We present Steps 5 and 6 in more detail in the reconfiguration from video wall to CAVE.

5.1. Position the front CABANA unit by rolling on its internal casters.
5.2. Position the side units by rotating them 90° with respect to the front unit. Precise alignment is not necessary at this point.
5.3. Position the floor so that its forward edge matches the bottom edge of the front unit and its side edges match the bottom edges of the side units.
6.1. Precisely align the bottom edge of the front unit with the front edge of the floor, but do not lower the unit's front end. The edges and corners should match exactly in the plane of the front unit's screen.
6.2. Precisely align the bottom edges of the side units with the side edges of the floor. Again, the edges and corners should match exactly in the planes of the side units' screens.
6.3. Using the casters, lower the front unit's screen until its bottom edge touches the top of the floor's front edge.
6.4. Lower the side units' screens until their bottom edges touch the top of the floor.
6.5. Make minor adjustments until the side edges of the vertical units touch as well.

In practice, Steps 1, 2, and 6 dominate the reconfiguration process. Actual gross movement of each unit is simple but requires up to four people due to the weight of each unit and the desire to protect protruding edges from damage. Target configurations that do not include the floor are predictably simpler to achieve, especially if there are no three-display unit corners to align. Video wall configurations are the simplest, but cabling and unit paths must be considered in advance to avoid carefully placing a unit only to find that there is no longer any room to run necessary cabling. Step 8 is usually necessary only on units that have experienced gross position changes that can cause movement of the projectors within their frames.

Our first reconfiguration attempt changed the CABANA from a four-display unit CAVE configuration into a three-display unit video wall configuration. The process took approximately 3 ½ hours to complete, of which one hour was required for actual unit movement. Our second reconfiguration (back to CAVE) took only 2 hours. In each case, four people were required to position the units.

3 Programming Toolkits

We have used three software packages with the CABANA: the CAVE Library, WorldToolKit™ with the Immersive Display Option (WTK IDO), and GM's VisualEyes™[2]. We use each of these in different ways depending on our application requirements and development time.

3.1 The CAVE Library

The CAVE Library (created by the Electronic Visualization Laboratory - University of Illinois at Chicago, and sold through VRCO Inc.[3]) is used when low level control is required for developing CABANA applications. It provides a great deal of utility functionality such as calculating the perspective of each display surface and synchronizing the display devices, while giving the application easy access to all needed elements at runtime. For example, the library directly supports the Ascension Flock of Birds™[4] magnetic tracker, yet also support any other type of motion tracker when provided with an appropriate tracker "daemon" program. The application developer supplies rendering functionality such as OpenGL™ or Performer™.

3.2 WorldToolKit

WTK IDO is an add-on to the WorldToolKit 3D programming suite from EAI/Sense8[5]. The IDO is analogous to the CAVE library, and allows a developer to use any application written with WorldToolKit in an immersive environment. WorldToolKit offers a higher-level graphics toolkit that gives considerable functionality through an extensive API. Unlike the CAVE Library, the WTK IDO does provide rendering support. Both the CAVE library and the IDO make excellent use of configuration files, giving impressive control over display configurations and other aspects of a spatially immersive environment. With multiple configuration files, we can easily move between different arrangements of the CABANA displays.

3.3 VisualEyes

General Motors Research & Development (GMR&D) created VisualEyes as an interaction tool for visualizing data through the use of mathematics and light. GM uses this tool for testing car designs and collaborating on projects in virtual environments. Imagine being able to sit in the driver's seat of a car before anything is built and change the placing of a dashboard control because it's too difficult to reach from the driver's seat. VisualEyes allows this kind of interactive design via an easy-to-use scripting language that allows control of the environment. Virtual environments can be built much more quickly than with other toolkits by merely bringing in models and applying simple rules.

4 Applications

Several existing HRL projects have integrated surprisingly easily into the CABANA. This section briefly describes three applications:

1. Distributed Design Review In Virtual Environments (DDRIVE)
2. Advanced Battlespace Visualization (ABV)
3. Air Traffic Management (ATM)

DDRIVE, ABV, and ATM have all been used successfully as demonstrations.

4.1 DDRIVE

DDRIVE enables distributed design reviews in immersive 3D environments. DDRIVE features include collaborative tools such as avatars, speech recognition, digital audio, and shared artifact manipulation using VisualEyes and HRL proprietary software. In this way multiple users located at arbitrary sites can review and dynamically change data. The remote user is seen and heard as if located in the same room. Whatever changes the local user perceives the remote user also perceives. Figure 9 shows a local user sitting in the passenger seat of a vehicle while the avatar, which represents a user who is physically located at a remote location sits in the driver's seat. Figure 10 shows the same session where both users are inspecting and modifying the exterior of the vehicle. Successful demonstrations have been shown between HRL Laboratories in Malibu, California and GMR&D in Warren, Michigan

Figure 9. A user interacting with an avatar in the interior of a vehicle.

Figure 10. Two users trying different color schemes of an automobile.

4.2 ABV

ABV is a demonstration of complex 3D battlespace visualization, with the goal of reducing defense staffing requirements even as more battlespace information is available. It features real-time track updates, track history and future display, realistic track models, drop lines, and pseudo-shadows. 3D terrain is constructed on the fly from the standard U.S. National Imaging and Mapping Agency data sources, and is fully textured (also from NIMA sources). ABV enables collaboration between multiple ABV users and users of other Raytheon-developed displays by networking them and providing mechanisms for transferring terrain and viewpoint information between them. ABV runs on a variety of Unix and Windows platforms, and was originally designed as a single-display system.

Transforming ABV to run in the CABANA in a CAVE configuration was straightforward. ABV is written in a combination of Tcl/Tk [6] (GUI), WorldToolKit, proprietary software, and SWIG[7] (a software "glue" between scripting languages and other software). Code changes were limited to adding IDO initialization calls and replacing references to specific viewpoints with references to a single global viewpoint under IDO control.

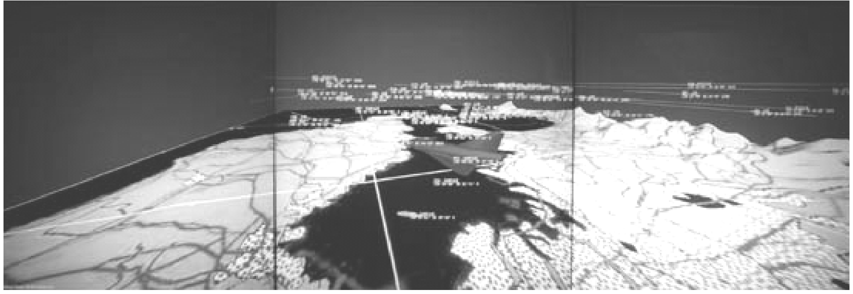

Figure 11 ABV executed in wall configuration

4.3 ATM

HRL's Air Traffic Management (ATM) visualization system is one of the most successful applications demonstrated in the CABANA's video wall configuration. ATM is a testbed for the construction and evaluation of conflict detection, resolution, and visualization tools for the Free Flight environment. Free Flight is the next major step in air traffic management, and will allow aircraft pilots more freedom to change flight paths for optimal performance. ATM currently uses two 2D GUIs and both a 2D plan view and a 3D perspective view.

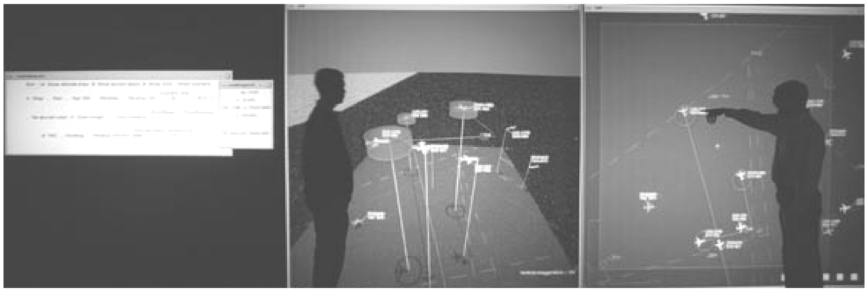

Figure 12 ATM executed in wall configuration

4.4 Utility Software

We have developed several utility applications to aid in configuring and using the CABANA. All of the following tools have been developed by HRL.

We often interact with CABANA software using a *wand*: a baseless joystick with a 6-DOF sensor and several buttons. We developed software to use a Virtual Technologies CyberGlove to convert finger movements to wand button controls. The index, middle, and ring fingers act as buttons when the fingers are bent beyond a specified angle at the proximal interphalangeal joints. The thumb approximates a pressure-sensitive joystick. The thumb abduction maps to left and right while the Thumb Interphalangeal Joint maps to forward and backward. There is a non-reading area in the center of the virtual joystick that allows the thumb to rest with no translations.

Several C++ classes make displaying text in the CABANA simple. **CABANAtxt** is the parent class of **CABANAtxt2d** and **CABANAtxt3D**. **CABANAtxt** works by overloading the += operator. This technique allows quick and easy addition of simple 2d text to the CABANA. For example

```
txtobject += “some new text\n”;
```

CABANAtxt3d class performs a similar operation for 3D text.

WandProjection allows the wand to be used as a cursor that is projected onto a CABANA surface. This is done by a simple intersection test between a ray oriented with respect to the wand and square polygons at the screen locations. If an intersection is detected then the x and y coordinates in pixels of that display unit are computed. These coordinates can then be passed onto any GUI to be interacted with.

Test and calibration software is constantly being developed to get a better understanding of the magnetic field used for tracking within the CABANA. This software allows sample physical points to be taken and viewed to see the differences in physical space and tracker perceived virtual space.

5 Tracking and Calibration

Tracking and calibration have been of great concern with the CABANA. There are a number of issues dealing with tracker error and projection alignment that must be solved. The following section talks about the problems as well as proposed solutions.

5.1 Tracking in an extremely noisy environment

With the CABANA in its CAVE configuration, we use an Ascension Flock of Birds™ (FOB) magnetic tracking system to determine position and orientation of a user’s head and one hand. The degree of tracking error in our CABANA is much worse than is normally evident in other systems that use this type of sensor. For example, EVL’s CAVE calibration file shows a maximum consistent error of one foot along a single axis. We have found errors of several feet that seem to be a function of many elements, including distance of the receiver from the transmitter, proximity of the receiver to the display units, nearness of corners, and height above the floor. In some cases when multiple sample points are taken physically along a line from the rear of the CABANA to the front unit screen, the receiver signal reverses its direction of increase. We have seen the receiver readings within the CABANA go far beyond the confines of the physical units in certain areas; then, when the receiver is moved a few inches, the readings jump back inside.

The FOB’s transmitter consists of three orthogonal loop antennas to which a 2-millisecond pulse of DC current is applied to one antenna at a time. The amount of current applied to the antenna, and hence the strength of its magnetic field, is controlled by the requirement to maintain field strength of approximately one Earth's magnetic field at the receiver. One Earth's field is equal to approximately 0.6 gauss. Since the current input to the transmitter cannot be increased without bounds, there is a transmitter to receiver separation distance at which the current can no longer be increased. This separation distance is approximately 32 inches diameter for the Extended Range Transmitter. For receiver to transmitter separations outside of this cutoff distance, the field strength is calculated as one over the cube of the ratio of the receiver's 'actual' distance over the separation distance (32" diameter described above). Hence, at a distance of 64 inches for an Extended Range Transmitter, the field strength at the receiver will be one eighth of 0.6 gauss $\{1/(64/32)^3\}$.

Thus, the accuracy of the tracking is greatly affected by the distance of the transmitter to the receiver. Close to the transmitter, a change in position has a large effect on the induced field at the receiver. As can be seen in Figure 13, farther from the transmitter a similar change in position causes a lesser field change. The closer the receiver is to the transmitter (outside of the 32" diameter range) the more accurate the tracking. The same principle also implies that the accuracy is affected by outside material more at greater distances from the transmitter.

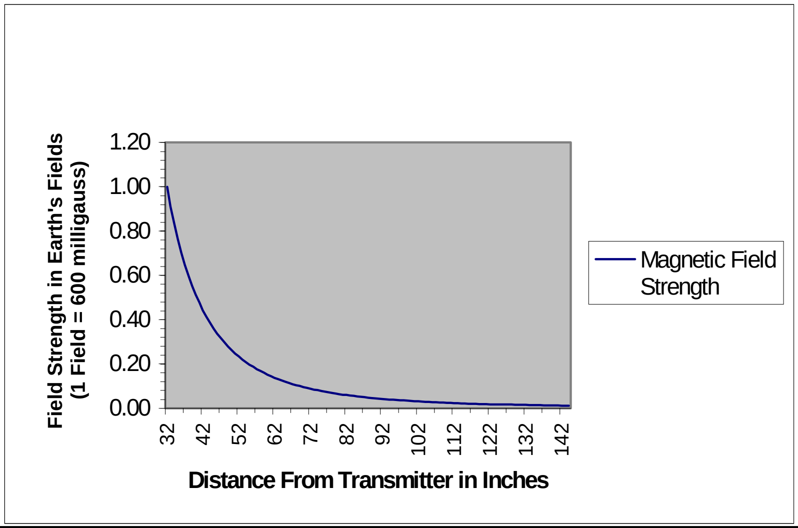

Figure 13 Field Strength of the FOB Transmitter

Since the CABANA is formed of self-contained units (except for the floor projection system), each unit must contain its own projector and mirrors. Stability and safety demand a strong, rigid housing; maneuverability demands low weight. As noted in Section 2.1, the CABANA uses aluminum for its structural components. The mass of electrically conductive aluminum interacts with the FOB even though aluminum is not a ferrous material (magnets are not attracted to it). A magnetic field as large as the one produced by the FOB transmitter induces a current in the aluminum that degrades the receiver's magnetic field readings. In effect, we have three giant induction coils surrounding the area. Because of this, our readings can vary wildly over a small distance.

The CABANA's useful tracker volume in CAVE configuration approximates a sphere with a radius of two feet in the center of the floor, when the tracker is used at normal CAVE settings. Measurements outside this volume are extremely noisy, as described, with the noise increasing away from the tracker transmitter towards the CABANA display unit edges. If the user stays within this sphere, tracker performance is tolerable, although not entirely satisfactory. Calibrating a tracker with problems such as these using the most common methods of linearly interpolated lookup tables becomes an exercise in futility. Such methods do not work because there is not a one to one mapping from physical space to virtual space. However, calibration techniques should work fairly well within this spherical space.

The WTK IDO provides an unusually simple auto-configure program. The program creates a triangle by taking sample readings on the center of each vertical display. However, due to the tracking error at these locations the triangle formed by the center of the three displays is an obtuse triangle rather than an expected acute triangle. Thus, this useful program does not work correctly in our situation. Fortunately, this program does not need to be used as the configuration files can be created manually.

One solution is to lower the rate at which the FOB operates, and therefore lower the rate at which the transmitter pulses its DC signal. The effects of large amounts of conductive metal (i.e. aluminum supporting frames) on the magnetic field are minimized because the fields in the aluminum structural elements have more time to dissipate before a receiver measurement is taken. The only way to do this is via direct communication to the FOB through low-level calls. Since none of the software packages we use provides the ability to change the rate and source code is not provided, an entire new driver must be written for this modification. With it in place however, the useful CABANA volume can be increased to approximately a 6-foot radius hemisphere.

Another variable is the actual position of the FOB transmitter. The three loop antennas where the magnetic field originates are enclosed in a heavy one-foot cube. When using the CAVE configuration, the transmitter normally sits on a wooden pedestal at the rear of the CABANA, four feet above the floor. This is a fairly good position for the transmitter, but as the receivers move toward the front of the CABANA, the quality of the readings degrades rapidly. In fact, with the transmitter in this location, the receivers will not report a position closer then two feet from the front display surface, no matter how close to that display unit the receiver moves. This problem is a combination of the aluminum and distance from the transmitter.

One solution suggested by Ascension is to make the distances from the center of each display to the transmitter approximately the same distance to minimize the irregular errors we were seeing. The problem with this solution was that if we were to put the transmitter in the center of the CABANA we would surely obscure the floor projection, and most likely interfere with any users. We found an acceptable position near the top middle of the CABANA, between the floor mirror and the floor projector, under and in front of the projector's RGB lenses. The magnetic field causes interference in the projector CRTs, similar to when a magnet is placed close to a computer monitor or TV. Synchronizing the transmitter pulses with the projector's horizontal refresh minimizes the effect. Unfortunately, in this CRT synchronization mode, the FOB's read rate is determined by the CRT's horizontal refresh. Using this mode with the partial solution of lowering the FOB rate mentioned above is impossible. The receiver readings with the transmitter in this position still show many of the same types of errors we saw in the other position, but in general the readings improved.

5.2 Projection Alignment

The alignment of the CABANA displays relative to each other must be accurate for the images to be continuous. Discontinuities in the images destroy the illusion of an unbroken display surface. The pixels may be lined up by adjusting the projectors as well as through software. A combination of both has been used for best results.

If the display units are properly placed physically there is approximately a 3/16-inch gap between adjoining units. This distance is comparable to a standard CAVE with a 1/8-inch cable running down each corner.

CABANA optics are somewhat restricted by the display unit's shape and size. With our current projectors, we are unable to squeeze an image with a standard computer aspect ratio completely onto the display surface. This limitation implies that, in general, only a 1:1 aspect ratio can be used; this in turn limits the horizontal resolution to the vertical resolution even when the image generator can generate much higher horizontal resolutions. For example, when a video resolution of 1024x768 pixels is selected, the projectors are not able to fit the whole width of pixels onto the display surface because of the restricted throw of the projectors within each unit. Thus, we display a resolution of only 768x768 in this mode. The remaining 256 pixels are still there: they are simply not being projected onto the display units. To date, we have used image sizes of 768x768, 1024x1024, and 1200x1200 pixels. In the video wall configuration, our highest overall resolution is 3600x1200 pixels.

These resolution settings can be set within the CAVE library and WTK IDO. However, with VisualEyes one can only define window width and placement within the virtual world but not window locations within a graphics channel. To compensate for this, the virtual displays are made to overlap and protrude beyond adjacent displays so the images will match on the edges. More pixels are being rendered than are actually needed. This is a correct solution, but it is not an optimal solution.

6 Conclusions and Future Work

We have described the CABANA, a modular, easily reconfigurable spatially immersive display. This section describes several ongoing CABANA issues, our approaches to their resolution, and our future plans.

The CABANA design is optimized for reconfiguration flexibility, display hardware stability, and high brightness. These attributes necessary imply some compromises. Section 5.1 noted the difficulty in obtaining good position and orientation information from electromagnetic sensors.

Interaction of a human user with applications in immersive environments remains a difficult challenge. For applications developed expressly for display in such an environment, a suitable interface can be custom-built. A problem we have not noted elsewhere, however, is that of converting or embedding the interface for an existing non-immersive application into an immersive version of the same application. One approach we are pursuing will allow the mapping of standard 2d windows to a texture map that is then mapped to a polygonal surface in the displayed image. This approach enables standard 2D interfaces for use in 3D environments; indeed, any 2D graphical entity can be mapped to a polygon and manipulated within the environment. Potential problems may include blurry images, unreadable text for smaller polygons, and stretching the polygon and thus the textures in a non-uniform way.

Another approach simply retains the 2D graphical user interface of the non-immersive application and enables its use within the immersive environment. We took this approach in our modification of the ABV to the CAVE configuration of the CABANA. Using this method, a six-DOF “wand” drives the mouse pointer on the screen, allowing the existing GUI to function as in the non-immersive environment.

We continue to look for better materials and methods of minimizing the effect of materials on a user’s experience. For example, while each CABANA unit’s brightness is high when looking directly at a surface, the brightness falls off as the view moves off-axis in any direction. This viewing angle sensitivity is most noticeable in two- or three-surface corners. Where we would like to see a seamless image transition (so that the corner “disappears” when using stereoscopic displays), the surfaces instead show an abrupt change in brightness, especially if one surface has a high viewing angle and another has a low angle of incidence. For most applications and users, we have not found this brightness discontinuity to be a problem. When viewed from the center of the CABANA in its CAVE configuration, the brightness of all surfaces in a corner is about equal. Although the corner appears dimmer than the wall directly in front of a user, the smooth change masks the difference to the point it is usually not noticed.

7 References

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