TIVS: Temporary Immersive Virtual Environment at Simon Fraser University: A Non-Permanent CAVE

Wolfgang Stuerzlinger*
Simon Fraser Univ., Vancouver

Andriy Pavlovych
York Univ., Toronto, Canada

Dayson Nywton
Federal Univ. of Maranhao, Brazil

ABSTRACT

CAVE systems are an immersive environment that surrounds one or more viewers with multiple large screens, which portray a virtual 3D environment. CAVEs use generally between three and six sides and are thus effectively permanent installations, due to the required floor and room space.

We describe TIVS, the Temporary Immersive Virtual environment at Simon Fraser University, a system whose defining feature is that it does not consume any permanent floor space. Yet, TIVS can be in operation in less than a minute. Viewers sit on swivel chairs in the center of an 8' × 6' space, where TIVS's frame is mounted onto the ceiling. The bottom of said frame is 7' above the ground, making it easy for people to walk below it. The screens mounted on the frame are rolled down whenever the system is being used and are otherwise stowed away. That frees the floor space for other uses when the system is not in use. The projection geometry ensures that people sitting in the center area of the space do not cast shadows onto the screens. A tracking system attached to the frame provides for head tracking. Overall, the non-permanent nature of the system makes it surprisingly easy to integrate Virtual Reality into everyday environments.

Keywords: VR system and toolkit, large-format displays, immersion.

Index Terms: H.5.1 [Information Interfaces and Presentation (e.g., HCI)]: Multimedia Information Systems—Artificial, augmented, and virtual realities.

1 INTRODUCTION

CAVE, cave automatic virtual environment [4], systems provide an immersive surround environment to one or more viewers. The viewer is surrounded by multiple, wall-sized screens, which portray a virtual 3D environment via computer graphics imagery. Screen sizes of 2.5 × 2.5 m or 3 × 3 m (8' × 8' or 10' × 10') are common for 6-sided installations, but some larger installations exist. Four wall screens provide full 360° surround imagery, but also necessitate some mechanism to permit the viewer to enter and exit the facility. A fifth and sixth screen provide a ceiling and floor (supported by glass or acrylic) to permit the viewer to look up and down. Some systems combine a few walls with a floor and/or ceiling. Together with stereo graphics rendering, a CAVE provides a very compelling visual illusion as the viewer can see the virtual world in any direction. More than one viewer can also use a CAVE the same time, but the perspective is typically only correct for a single person. An exception is the functionality provided by the C1x6 system [13]. A (likely incomplete) list of current CAVE installations can be found on Wikipedia [4].

---

* http://ws.iat.sfu.ca

Current CAVEs are more or less permanent installations, as the size of the screens necessitates sufficiently stable mounting. Systems with five or six sides often need a room that is two or even three stories high with sufficiently stable floor construction to support the heavy glass or acrylic screen that viewers stand on. The exception are reconfigurable CAVE systems where some or all of the walls can be moved, e.g., [3].

Most CAVE systems use back-projection screens, where the projectors are behind the screens. This avoids that the viewer casts a shadow onto the projection, which might break the illusion. Back-projection also deals with the technical necessity of providing enough distance between the projector and the screen to generate such a large image. A few recent CAVE systems use short-throw projectors to reduce space usage. Some CAVEs also use front-projection with short-throw projectors. This solution is typically used for the floor in 5-wall CAVEs, when only a single-story room is available.

Here we present a new CAVE system that does not consume permanent floor space and which is targeted at seated participants. This supports extended interactive sessions in the system.

2 PREVIOUS WORK

Designing a low-cost version of a CAVE has been a goal of several researchers since the original CAVE was presented in 1992 [6]. The original CAVEs relied on large rooms with back-mounted projectors forming images on diffuse screens rigidly mounted in a custom frame. In the beginning systems used multi-rack computers and then later clusters of high-end computers to drive the system, as the processing and rendering requirements were difficult to meet with low-end systems graphics at that time. The utility of CAVE systems for prototyping, design, graphics and visualization in both research and educational settings was often restricted by the high cost of such systems, consisting of both the cost of the systems themselves and the associated need for dedicated space. Another factor was the specialized computing setup, both in terms of hardware and software. Finally, specialists were needed to operate and to program the system. While the price of components has decreased substantially since then, especially for computers and high-resolution projectors, the space requirement constraint is still relevant. Thus the total costs associated with this type of immersive systems are still prohibitive for many applications.

Other immersive virtual environment systems aim to encase the users as completely as possible, by using tiled or spherical displays, e.g., [1][8]. The cost and space requirements of such systems are often comparable to that the original CAVE. Thus, one of the approaches to reduce costs is to use fewer screens. One such low cost immersive system with images projected on three walls and the floor is described by Peternier and Cardin [20]. It uses two projectors per wall, with shutters to enable stereo output, and a dedicated machine per screen for graphics output. The screens are made of flexible fabric, and the system relies on back projection, which still needs a correspondingly large space to house it. Short-throw (wide-angle) projectors and/or removing stereo capabilities can reduce some of the space requirements.

Nevertheless, the space requirements remain substantial and the cost of such a system was still high, about US$ 25,000 [12].

One simple way to reduce the space requirements is to use the front projection. However, front projection systems significantly restrict viewer mobility compared to rear projection due to potential occlusion of the projected images. One such system, LAIR [9], surrounds a user from four sides and uses two projectors per wall with them being positioned off-center, which reduces the occlusion issues. The space usage of this (permanently installed) system was about 3.5 × 3.5 × 2.5 m (11' × 11' × 8'). The cost was listed as US$ 60,000.

Potentially the least expensive immersive system reported in the literature is by Fowler et al. [11], with costs ranging from US$ 10,000 to 20,000 depending on the included features. It uses several reconfigurable screens and still requires about 4 × 4 m (12' × 12') of dedicated space.

Finally, while early system had to rely on using clusters of computers to achieve reasonable performance [7][12], one can now potentially use only a single computer with (typically) multiple high-end, stereo-capable graphics controllers with typically multiple outputs per graphics card to generate the imagery [9][11]. This greatly simplifies the architecture of the system and permits a larger variety of toolkits or game engines to be used to develop the interactive software and to run the system.

3 A Non-Permanent Immersive Virtual Environment

TIVS, the Temporary Immersive Virtual environment at Simon Fraser University, is a successor to a previous CAVE system at York University, IVY [22][23]. The first instantiations of TIVS were designed at York University under the name TIVY, for temporary IVY. The current instantiation is called TIVS. Its defining feature is that it does not consume any permanent floor space. Yet, TIVS can be in operation in less than a minute. In the current instantiation of TIVS the viewers sit inside a 2.5 × 1.8 m (8' × 6') space, where TIVS's frame is mounted onto the ceiling. The bottom of the frame is mounted high enough above the ground to make it easy for people to walk below it. The screens are rolled down whenever the system is in use and can otherwise be rolled away. Projectors with a very short throw are mounted in the frame and positioned so that the viewer does not impede the projection whenever they sit on swivel chairs roughly in the center of the floor space of the system. Rolling up the screens after use frees the floor space for other uses.

In summary, the contributions of this paper are:
- The design of a CAVE system that does not consume permanent floor space.
- A CAVE system designed for seated participants to enable longer-term interaction.

In the following, we list and discuss the main design considerations and trade-offs that we made during the creation of TIVS. We consider space, image parameters, and cost.

3.1 Size and Position

Several considerations influenced our design. The primary one was the requirement that the setup should be temporary. Thus the space occupied by it must be easily convertible for other uses. Consequently, we decided to mount nothing on the floor and fixed (almost) nothing to the walls. In essence, all system components are suspended from the ceiling. The screens are rolled down when the system is in use. We effectively rely on a weighted rod at the bottom of each screen as well as the weight of the screen itself to stabilize the shape of the screen.

Another consideration was that the system should be usable by multiple people. This has implications on the size of the system.

We still wanted the system to be as small as possible. To support work (or play) for extended periods and to limit potential fatigue effects, the system was designed around seated users. After several experiments we determined that in order to limit geometric distortions and to provide a reasonable degree of freedom for movement, we needed at least 2.5 × 1.8 m (8' × 6') of horizontal space for three people sitting comfortably side-by-side on roller/swivel chairs. This permits each user to rotate their chair to fully appreciate the immersive qualities of the system. The roller chairs also permit users to move around, to a degree. Once we settled on seated users, this determined the height of the screen. The eyes of an adult person sitting on a typical office swivel chair are at approximately 1.1 m (3.5') height. Assuming the eyes are vertically centered relative to the screens, the screens should thus be about 2.2 m (~7') high, starting from the floor.

Once we had the minimum desired dimensions, we measured the amount of floor space available in typical office and residential rooms. In our experience, it was often possible to find an unoccupied 2.5 × 1.8 m floor-to-ceiling area, but sometimes chairs and/or other minor furniture items had to be moved. In residential settings the ceilings are typically the biggest limitation, often at about 2.4-2.5 m (8') height. Given that almost all people are less than 2 m (6'6") tall and with adequate tolerances, this implies that if we mount the equipment from the ceiling and above the screens, the hardware should not extend more than about 30 cm (1') from the ceiling. This guarantees that the equipment does not (1) interfere with the projected images and (2) does not impede people walking in the area when the screens are rolled up and the system is not in use.

3.2 Image Parameters

To ensure good image quality, we aimed for an image brightness of at least 40 cd/m^2 (approx. 11fL), the minimum value considered by cinema engineers to be "sufficiently bright" [24]. Similarly, we aimed for a contrast of at least 100:1 (or at least as high as possible) and the maximum possible resolution.

As collaboration usually requires face-to-face communication, we deliberately did not include stereo capability in our core design requirements, even though we haste to add that our system is capable of displaying imagery in stereo due to the choice of projectors. We consider stereo display and particularly the stereo optional as they hinder eye contact, a critical aspect of human-human communication [2][15]. Thus, even video conferencing systems are now being adapted to account for this [14].

3.3 Cost Consideration

Cost is a natural limiting factor. Many parameters of the system, such as resolution, brightness, and contrast, directly depend on the choice of projectors, screen materials, and overall construction complexity. For example, using more than one projector per screen could provide better resolution or using special screen coatings could potentially provide for higher contrast. In general, we decided to optimize for lower cost, whenever this did not impact a critical design criterion.

4 Implementation

We built our system with readily available components, the most expensive being the four projectors, each slightly under US$ 1,000. Screens were the next highest cost, followed by the frame hardware (aluminum tubing, fasteners, steel cables and pulleys), and the video cables and electrical extension cords. In total, the system cost was less than US$ 4,900. This number excludes the PC with a 4-output video card, which was already available in our lab. If the cost of the image generation system is included, the system totals about US$ 6,000. With an optional

low-cost 3D tracking system, say six NaturalPoint OptiTrack V120:Slim cameras and rigid body tracking software [18], the cost increases to about US$9,500. Table 1 details the costs of various components of the basic version of TIVS.

Table 1.   Summary of TIVS cost.

Item	Cost, US$
Projectors	4,000
Screens	400
Aluminium tubing	150
Fasteners	50
Steel cables, pulleys, winch	150
HDMI cables, extension cords	150
Total	4,900

In the following we describe how we met the design challenges described above.

4.1   Frame and Support

The projectors and the screens are mounted in a custom-built aluminum frame. Square aluminum tubing was chosen for its lightness, good strength and rigidity, and easy workability. All tubing was 25 mm (1") in outside width, and the wall thickness varied from 1.5 to 3 mm, depending on locations and local loads. For convenience during construction and because our lab is about 3.6 m (12') high, we chose to suspend the frame from the ceiling on steel cables (see Figure 2). Together with a roller-system, this made it possible to lower the complete system with a hand winch for easy hardware changes and adjustments. For standard installations in normal rooms we would simply mount the whole frame directly on the ceiling or suspend it from fixed wires. With projectors and screens installed, the total mass of the system is less than 50 kg (110 lb). Figure 1 demonstrates the overall layout of the system. Figure 2 shows the cable system as well as the winch.

4.2   Projectors

The geometry of the system necessitated projectors that (1) have a small and negative image offset – as they are located above, just outside of the projected volume; (2) are able to project an image 2.2 m (7') high at a distance of not more than the shortest side of the system (1.8 m), less the projector depth; and (3) are able to form an image with brightness of at least $40\,cd/m^2$ at the projection distance. We chose BenQ MW821ST lens-based, short-throw projectors with a light output of 2900 lm and a resolution of 1280×800. This projector is DLP-based and supports stereo with 120 Hz. The throw distance to form a 2.2 m (7') high image is about 1.5 m (5'), which permits the projectors to be located completely inside the perimeter of the system. Assuming white screens with a gain of 1.0, i.e., fully diffuse white material, the projectors are capable of forming an image with $133\,cd/m^2$ brightness at such a distance.

4.3   Screens

As all of our screens are front-projected and thus are used in reflective mode, stray or parasitic light reflection becomes a concern. Such reflections create a veiling glare in the image, substantially reducing the contrast, especially in darker areas of the images. Systems relying on back projection or emissive can reduce this problem by selecting screen materials that are highly transmissive and diffuse, but have low albedo from the side facing the viewer.

In our system we use an approach known to home theatre builders: grey screens increase apparent contrast. When home theatres are built in regular living rooms, the materials of the walls and furniture cannot always be selected to account for optimal image quality, as the room is used most of the time for other purposes. Due to the highly reflective properties of the typical room environment the amount of light reaching the screen through secondary and higher-order reflections, such as projector-screen-surroundings-screen, can be substantial. These reflections create a veiling glare in the image, substantially reducing the contrast, especially in darker areas in the image.

For one of the first prototypes of TIVS we used white screens and observed significant cross-illumination, at a level where image quality suffered substantially and noticeably. Yet we realized that the projectors are capable of providing substantially higher brightness than required. As we were aiming for at $40\,cd/m^2$, but were able to achieve $133\,cd/m^2$ with white screens, we targeted a reflectance of $40/133 = 0.3$. Such a screen gain is hard to find in regular cinema screen materials. Consequently, we looked elsewhere. To avoid color tinges we chose screen materials as close as possible to monochrome matte grey. We found a major roller blinds manufacturer who makes medium-dark grey blinds that have a reflectance close to our target value (measured 0.24). When we used them in our setup, we measured the white level of our images to be $32\,cd/m^2$. This luminance level is about 20 % below our target value of $40\,cd/m^2$. We measured the contrast to be at least 80:1. Note that white screen materials would decease this contrast by a factor of 4.

A secondary problem was that the screens were not made in sufficiently wide versions to span the whole walls of TIVS. To address this issue, we decided to go with two partially overlapping screens per wall. See Figure 3 for a close-up of the mounting system for the roller blinds. For each wall, we chose two roller blinds in total about 20 cm (8") wider than necessary and mounted them one above the other so that one rolls down directly in front of the other. The two screens then overlap somewhere off center for each wall. Due to the fact that the screen material is fairly flat and thin, the seam in the middle of the walls is barely noticeable from normal viewing positions in the central area of the system. Due to the vertical offset of the two roller blinds in each corner, see the back corner visible in Figure 3, we were also able to mount them so that the screens align reasonably well in the corners, with gaps of well below 5 millimeters (1/5").

Figure 1: System overview without users. Note the barely visible overlap of the two screens on the far wall. On the left wall this is practically invisible. Here, a single rolling swivel chair is positioned in the middle of the floor space.

Note that the projection aspect ratio does not align with the size of the walls of TIVS. We solved this problem by masking the rendered images with black bars in software. Due to the dark

screen material and the high inherent contrast of the projectors the light from the "dark" areas of the adjacent projectors does not have a visible effect on the image projected onto the other walls.

Figure 2: Cable system to support the frame, on which all system components are mounted. We created this for development convenience.

Figure 3: Roller screens used in our system. Note the overlap.

4.4   Tracking System and Interaction

In order to display perspectively correct images, head tracking is required. The choice of a specific tracking system is largely independent of other design decisions in our setup. We initially experimented with a (first generation) Microsoft Kinect as tracking system to accommodate a single user. The Kinect is attractive due to its wide availability and good community support. Yet, we experienced quite a few problems, due to the high latency and jitter. While the spatial jitter could have been remedied with smoothing algorithms, that would increase latency even further. We suspect that the problem was primarily due to the fact that Kinect software was not designed to track *seated* people. It is possible that this problem could be resolved with better software and/or device drivers. Using two Kinects could also decrease the jitter. Still, the high latency makes this solution unattractive.

To address this issue, we replaced the Kinect with a re-purposed NaturalPoint OptiTrack system with six Flex:C120 120Hz IR cameras. This worked quite well for a single user. As we currently do not use the stereo display, we attached the markers to a set of protective eyewear, used in construction. This provides the user with a practically limitless field of view, while still providing good tracking accuracy and low latency.

For all other interaction we use a wireless keyboard and mouse. These are either held in a users lap or are placed on a keyboard and mouse tray from Mobo [17] mounted onto the armrests of some of the chairs (not shown here).

4.5   Computer Setup

To drive TIVS we use a Windows 7-based PC system with a single six-output graphics adapter. The DisplayPort outputs of the graphics adapter are converted to HDMI and conveyed to the projectors via long HDMI cable extensions. The graphics driver presents the four outputs of the graphics card to the developer as a single, very wide display at 5120×800. The single-display mode enables the use of many different software packages.

Figure 4: (Non-stereo) glasses with head-tracking markers.

4.6   Software

To generate the images, we adapted several applications based on the Unity game engine, by Unity Technologies [25]. In each application we render four camera views in the appropriate areas of the virtual 4-screen wide display, which covers all four walls of our system. As our projectors have an aspect ratio substantially different from the aspect ratio of the walls, the unused areas of the projector images are simply masked by displaying black bars.

For stereo projection, we rely on the MiddleVR plugin [16] for Unity. In this case rendering has to be handled on a wall-by-wall basis. MiddleVR also provides convenient ways of interfacing hardware devices such as trackers. As discussed and motivated above, we do not enable stereo by default in our system. We also did not use stereo during our evaluations.
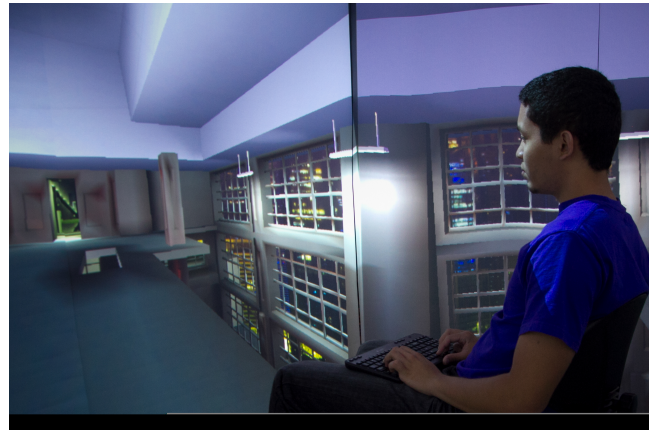

Figure 5: TIVS in use. Note the slight projection misalignment in the corner as well as the (barely visible) seam on the left wall and the slight seam on the right (back) wall.

5   EVALUATION AND DISCUSSION

We informally evaluated our system with several users, some of who had first-hand experience with six-sided CAVEs. The low cost of the system was one of the first comments from the people familiar with research on VR systems. The rest of the users' feedback centered on the high level of immersion the system provided. Figure 5 shows one of the example applications we created.

The seams in the corners of the screens are only a few millimeters wide. We chose to optimize the seam appearance at eye level by adjusting the projectors accordingly. As the images are not 100 % rectangular and not every projector is aligned optimally, this leads to slight gaps and/or misalignments, mostly towards the top of some walls. One such corner gap is visible in Figure 5 above. However, none of the users that have seen TIVS found the artifacts in the corners objectionable, as they are relatively small, similar to seams in other CAVE or tiled wall systems. It may help that these gaps are towards the periphery of the "obvious" view directions, which center on each wall. Interestingly, the overlap of the two screens in the flat part of each

wall was not remarked upon, as it is barely visible. The effective resolution of TIVS is about 9 arcminutes per pixel, (~1 pixel per 2.5 millimeters, ~10 pixels per inch). We expected this to receive negative comments. However it appeared that during interactive use the low resolution was not objectionable.

None of the users complained about the lack of brightness or contrast of the system. In fact, some were surprised at how dark the screens were when they saw them lit by room lights after the demo. We take it as a confirmation that our brightness and contrast-related design considerations are sound. Also, we seem to have addressed the problem of inter-reflections sufficiently well, as even critical viewers did not notice any artifacts. The seams in the corners of the screens are a few millimeters wide. However, none of the users that have seen TIVS found the seams objectionable, as they are relatively small, similar to seams in tiled wall systems.

Due to various space constraints, TIVS is installed in the front part of a long room in a lab, close to the door. That means that some lab members have to go "through" the system to work on their (unrelated) research projects. One of the walls even abuts onto two desks with systems that are used for other experiments. Yet, there have not been complaints about the installation, as the system is effectively "out of the way" when not in use. During demos, it is easy enough to navigate around, as there is a gap of about 0.6 m (2') to the wall.

None of the users found the absence of stereo a limitation. Most users commented that the system "felt" quite immersive due to the 360° field of view and the relatively high image contrast. In fact, many people commented positively about not having to put on stereo glasses. Still, it would be interesting to formally compare opinions about the system with stereo on and off.

The rendering performance of the system did not appear to be limited by graphics hardware, as the frame rate was always above 60 Hz for the virtual environments we experimented with. Moreover, the responsiveness of the system was always subjectively high.

Another noteworthy outcome of our evaluations is that people enjoyed *sitting* in TIVS. In fact, some of our discussions in the system continued well beyond one hour, with people even pulling out tablets and/or smartphones to look up information on the web, communicating points to other viewers, or even to look up 3D content. We observed that people moved the chairs around as necessary to either view whatever content was being discussed or to be able to face other people and to see their eyes to judge their reactions better. Thus we believe that being able to see the eyes of other people in the system is an asset of TIVS.

The OptiTrack system requires markers. For a single user the wide-field of view "glasses" worked very well, also because of the low latency of the OptiTrack system, Yet, for multi-user operation we found that generating images from the viewpoint of one tracked user be distracting for the other users, especially if the main viewer moved (too) fast. Thus, for multi-user operation we use the system with a static viewpoint in the center of the space.

Interestingly, some people commented that it was necessary to turn the light off in the room. In large rooms, such as research labs, this might affect the usability of the room for other needs during the time the system is being used. However, this limitation is easy to address by installing an opaque cover on the top of the system, which we plan to add in the future. The bottom of the screens is touching the floor and the screens themselves transmit almost no light. Thus, the system can easily become completely self-contained.

During our evaluations we also found that the non-rigid screens afford an additional convenient feature: one can enter and exit the system at corners with only minimal disruption. Additionally, since each wall consists of two screens each, one can keep a portion of a single wall open whenever necessary, which then effectively creates a 3-and-a-half screen environment with easy access.

While the original version of TIVS was designed to hang from the ceiling, we also created four "legs" out of the same 25mm aluminum profiles, which attach with appropriate braces at the corners of the frame and which are slightly angled outwards for stability. This enabled us to demonstrate TIVS at a different location, where we could not install wires from the ceiling [19]. The trade-off associated with these four legs is that they introduce four (small) obstacles into the environment. Thus this configuration cannot claim to have no permanent footprint. On the other hand this configuration requires no external mounts, i.e., requires no modification to the ceiling or walls of a room.

5.1 Application Scenarios

TIVS is an interesting alternative to provide fully immersive Virtual Reality in many physical environments where CAVEs are not an option, typically because CAVEs use either too much space or there is not enough room for permanent installations.

One such scenario is floorshows, where a high-end version of TIVS version can provide a quick way to immerse small numbers of viewers into a virtual environment, e.g., to show off a new building, industrial plant equipment, cars, or any other type of product. Another related application scenario involves installation in sales environments, where TIVS can be used to show a planned kitchen or other interior and exterior design projects in (close to) life size. Yet another fairly similar scenario is installations in the offices of companies that use computer-aided design to create their products. There small conference rooms can be used for TIVS, where the system would be mounted to the ceiling to facilitate multi-purpose use of the rooms.

Finally, TIVS can also be installed in high-end home theatres and/or gaming setups. Here it makes again sense to have the TIVS frame installed on the ceiling, potentially also flush with some of the walls of a room.

6 CONCLUSIONS & FUTURE EXTENSIONS

We presented a new, self-contained, immersive CAVE system with several novel design features. Most importantly, the floor space of the system is available for other purposes if the system is not in use. The system is also small and cheap relative to most other CAVE installations. It also supports multiple, seated users who can collaborate even for extended periods of time.

Many options can be added to this system. Using adaptive LED lighting on the ceiling could be used to hide the lack of a top display to some degree. With this, a dark tunnel scene could have a dark ceiling, whereas a sunny outdoor scene could have more light coming from the top. Another option is to add a projector that points directly downwards to generate imagery on the floor, potentially using a mirror. Naturally, the size of the whole system can reasonably easily be adapted to other dimensions. For our implementation, the size was dictated by the amount of floor space available in our research lab.

Finally, the projectors could be replaced with higher resolution and/or brightness/contrast models, as they become more affordable. Assuming the projection geometries are similar, such a replacement is expected to be straightforward, as our system is highly modular and adjustable. We may also experiment with the Kinect One as a tracking system in future work.

REFERENCES

[1] X. Amatriain, J. Kuchera-Morin, T. Höllerer, S. Pope, The AlloSphere: An Immersive Multimedia Instrument for Scientific

Data Discovery and Artistic Exploration, *2009 IEEE Multimedia* 16:2, pages 64-75.

[2] M. Argyle, and M. Cook. *Gaze and mutual gaze*. Cambridge University Press, 1976.

[3] Barco, http://www.barco.com/en/products-solutions/visual-display-systems/reconfigurable-cave-displays/multi-purpose-virtual-environments.aspx, last accessed February 2015.

[4] Cave automatic virtual environment, http://en.wikipedia.org/wiki/Cave_automatic_virtual_environment, last accessed February 2015.

[5] M. Chen, Leveraging the asymmetric sensitivity of eye contact for videoconference. In *CHI 2002*, pages 49–56.

[6] C. Cruz-Neira, D.J. Sandin, T.A. DeFanti, R.V. Kenyon and J. C. Hart. The CAVE: Audio Visual Experience Automatic Virtual Environment, *Communications of the ACM*, vol. 35(6), 1992, pages 64–72.

[7] C. Cruz-Neira, D.J. Sandin and T.A. DeFanti. Surround-Screen Projection-based Virtual Reality: The Design and Implementation of the CAVE, *SIGGRAPH'93*, pages 135–142.

[8] T. A. DeFanti, G. Dawea, D. J. Sandin, J. P. Schulze, P. Otto, J. Girado, F. Kuester, L. Smarra and R. Raoa, The StarCAVE, a third-generation CAVE and virtual reality OptIPortal, *Future Generation Computer Systems*, vol. 25, pages 169–178, 2009.

[9] B. Denby, A. G. Campbell, H. Carr, H. and G. M. P. O'Hare, The LAIR: Lightweight affordable immersion room, *Presence: Teleoperators and Virtual Environments*, vol. 18, no. 5, pages 409-411, 2009.

[10] K. J. Fernandes, V. Raja and J. Eyre, Cybersphere: The fully immersive spherical projection system, *Communications of the ACM*, vol. 46, no. 9, 2003.

[11] R. H. Fowler, M. D. Carrillo, R. A. Huerta, & W. A. L. Fowler. Designing a low cost immersive environment system twenty years after the first CAVE. *Proceedings of the International Conference on Computer Graphics and Virtual Reality (CGVR '12)*, pages 65–71.

[12] A. Juarez, W. Schonenberg and C. Bartneck, Implementing a low-cost CAVE system using the CryEngine2, *Entertainment Computing*, vol. 1, pages 157–164, 2010.

[13] Alexander Kulik, André Kunert, Stephan Beck, Roman Reichel, Roland Blach, Armin Zink, and Bernd Froehlich. C1x6: a stereoscopic six-user display for co-located collaboration in shared virtual environments. ACM Trans. Graph. 30, 6, Article 188 (December 2011), 12 pages.

[14] C. Kuster, T. Popa, J. C. Bazin, C. Gotsman, M. Gross, Gaze Correction for Home Video Conferencing. *Proceedings of ACM SIGGRAPH Asia (Singapore, November 28 - December 1, 2012), ACM Transactions on Graphics*, 31(6), 174:1-174:6.

[15] C. N. MacRae, B. Hood, A. B. Milne, A. C. Rowe, and M. F. Mason, Are you looking at me? Eye gaze and person perception. In *Psychological Science*, pages 460–464, 2002.

[16] MiddleVR, http://www.imin-vr.com/middlevr , last accessed February 2015.

[17] Mobo, http://www.getyourmobo.com, last accessed February 2015.

[18] OptiTrak, http://www.naturalpoint.com/optitrack, last accessed February 2015.

[19] A. Pavlovych, D. Nywton, W. Stuerzlinger, TIVY: Temporary Immersive Virtual Environment at York: A Non-Permanent CAVE, GRAND Experience demonstration at GRAND 2014 conference, May 2014.

[20] A. Peternier, S. Cardin, F. Vexo, and D. Thalmann, "Practical design and implementation of a CAVE environment," *Proc. Int. Conf. Computer Graphics, Theory and Applications GRAPP*, pages 129–136, 2007.

[21] K. Petkov, C. Papadopoulos, M. Zhang, A. E. Kaufman, and X. Gu, Conformal visualization for partially-immersive platforms, in *IEEE Virtual Reality*, 2011, pages 143–150.

[22] M. Robinson, J. Laurence, J. Zacher, A. Hogue, R. Allison, L. Harris, M. Jenkin, W. Stuerzlinger, Growing IVY: Building the Immersive Visual Environment at York, ICAT 2001, 85-89, Dec. 2001.

[23] M. Robinson, J. Laurence, J. Zacher, A. Hogue, R. Allison, L. Harris, M. Jenkin, W. Stuerzlinger, IVY: The Immersive Visual Environment at York, IPT Symposium 2002, March 2002.

[24] Standard: SMPTE 196M-2003 Motion-Picture Film - Indoor Theater and Review Room Projection - Screen Luminance and Viewing Conditions. Society of Motion Picture and Television Engineers.

[25] Unity Technologies, http://unity3d.com, last accessed February 2015.