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Utilizing Consumer 3D TV Hardware for Flexible and Reconfigurable Visualization Systems

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Abstract
The availability of 3D consumer hardware offers new means for use in semi-immersive visualization systems. The smaller size of such displays compared to the volume required for back-projection systems allows using smaller spaces for the installation. The smaller scale of the displays also generates a higher flexibility for reconfiguring the display setup.
The conceptual benefits of such displays come in combination with issues to be met when putting such commodity hardware into operation. With this article, we provide a broad overview about issues and solutions when integrating such hardware into scientific visualization environments. Information usually not available due to less technical support for consumer products compared to high-end systems is given and solutions for integration are presented. Together with discussion about display size, a reconfigurable visualization system is presented that can dynamically be configured to CAVE-, Power-wall-like and other setups.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities I.3.4 [Computer Graphics]: Graphics Utilities—Virtual device interfaces

1. Introduction

Visualization environments gain an increasing importance, not only for virtual reality applications but also for visualization of simulation data. While fully immersive visualization systems are important or almost mandatory for presence in virtual environments, simulation systems do not necessarily require high immersivity levels. Simulation researchers rather might need a wide field of view, but eventually want to inspect specific effects at certain locations of the simulated space. Visualizing this portion of the simulated space such researchers might want to sit down to further examine and discuss. Situations like *„See that effect over there? What happens when I change this parameter?“* are frequent occurrences when exploring simulated spaces. This generates a demand for a flexible system whose display components can be set up according to user preference.

Other demands when building new visualization systems are the capabilities to meet the often occurring issues concerning available space and building infrastructure. Using existing facilities, the available space might be too small to host, for instance, a CAVE with back-projection whereas front-projection systems come with the inherent issue generating artifacts on the clothes of the users and thus concealing some portion of the projection area. The room of the setup might also be equipped with an undesirable floor, with carpets for instance. Such a floor produces dust that gets into projections. If the floor then is leveled, too, such a non-tremor-free ground floor lets screens swing so that the image distorts. Another issue might be problems to darken the room sufficiently. At Technische Universiät München we have a room with all these drawbacks. This room nevertheless was the only location to put the visualization system.

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With the demands for a flexible system and with the environmental constraints, panel displays become the remaining alternative for system setup. They do have bezels reducing immersion, but are easier to handle than large scale projection walls.

As 3D display technology now has reached the consumer market, such commodity displays seem to provide an option for use with semi-immersive visualization systems. Such commodity hardware also raises new issues requiring to be dealt with, among others, synchronization over multiple displays to achieve the 3D impression over all displays.

With this paper we introduce our approach for a flexible visualization setup built with consumer 3D TVs. The system is based on the vision of an environment where users set up their visualization displays according to the views into the virtual world they need to accomplish their specific task. The system provides a semi-immersive visualization environment by combining three-side user-enclosing 3D environments such as CAVEs with flexibly placeable displays that allow for repositioning. Display elements can be arranged freely, facilitating examinations from different directions without having to reposition within the virtual world.

Our system, the *FRAVE*, a *Flexibly Reconfigurable CAVE* builds on commodity panel displays. We employ consumer display hardware and investigate all issues when integrating such off-the-shelf hardware. We present various experiences and findings regarding the use of such 3D consumer products naturally not coming along with the same level of technical support as specialized high-end presentation systems.

The following sections first give a brief overview of related approaches and system concepts that influenced our work. We then illustrate our concept, the combination of a large field of view with movable displays. This is followed by a deeper discussion of problems arising with consumer 3D TVs and the findings and solutions we discovered to get the system in operation. Among others, these issues deal with synchronization over multiple 3D displays and tracking systems, mainly resulting from multiple use of infrared lighting. The paper concludes with a brief overview about the FRAVE system.

2. Related Work

When speaking of CAVEs, we target on the high-end version of CAVEs coming mostly from an all-in-one supplier with high-resolution projectors, appropriate frames for the projection walls and all other matters. Of course there are other solutions to build CAVEs. The Lancelle et al. [LSF08] introduced a so called „definitely affordable virtual environment“, a DAVE. Lancelle et al. built a four side CAVE by using standard hardware components to reduce costs compared to commercial systems. However their setup requires a large room and raised efforts for the operator in installation and maintenance. For stereoscopic immersion they use LCD shutter glasses that are synchronized with the projectors. For tracking they use a self developed optical tracking system on the basis of infrared lights and cameras that can see retro-reflective marker balls. Modified video projectors were used for time interlaced stereo. The projector based system is comparably cheap and builds on a rigid setup of all components.

Another projector based system is the FLEX system by Fakespace Inc., i.e. set up at the visualization laboratory of Jackson State University. The corresponding publication [Hin01] introduces a „Reconfigurable Advanced Visualization Environment“, allowing the two side walls of the CAVE to be turned around their common joints at the center wall. Thus either a CAVE-like setup, an angled theater or a fully planar power-wall can be configured by a single person.

The most related work w.r.t. alternative approaches for CAVE-like systems has recently been published while we already had our panel-display-based approach planned. The work by DeFanti et al. [DAA*10] nonetheless covers lots of the aspects that also lead our decision. They provide a detailed survey about demands on CAVE systems and current issues. Furthermore they postulate that panel-based displays might be the future of the CAVE because such technology has a much more compact footprint than projector-based solutions. The collection of desirable features is followed by a survey about visualization systems that already employ panel displays, introducing the NexCAVE developed by the university of San Diego and built in full extend at KAUST university in Saudi Arabia. The NexCave at KAUST incorporates 21 passive stereo 46 inch HDTV displays set up in three rows to seven displays. Alternately polarized lines generate two 540 line images for each eye of the user. All displays are mounted on the surface of an imaginary sphere, each having another orientation with the normal vector of the display facing to the center point of the sphere. Their setup is still rigid, but shows that panel displays can be facilitated for immersive and large field of view virtual environments.

Another influencing element for our work has perhaps first been published by Rekimoto [Rek96] and has been widely used since in many other published systems w.r.t. Augmented Reality (AR). The work of Rekimoto introduces the use of hand-held displays as devices to open windows into an enriched world using Augmented Reality technology. Rekimoto motivates his work by a collaborative process, the design of a new automobile, where different people can share the experience of the same virtual object at the same time wit different displays. Position and orientation of the hand-held displays are tracked so that the computer-generated model appears to be at a fixed position in the real space which is a video feed of a camera placed in the background of the scenery. The argumentation aims towards AR because other users and their gestures do not have to be mapped to virtual objects. A user, for instance, can point at a specific sub-object and the other users directly perceive this pointing action in their hand-held displays.

Another innovation in terms of display technology was introduced by Fraunhofer FIRST and their project VR Object Display [Fra]. The FIRST team has developed a digital pillar which allows still images, video rendering and realistic 3D projection of panoramas and objects. The prototype of the VR display is in the form of a cylinder, where the users can walk around and explore the virtual 3D object inside the cylinder. It is equipped with eight projectors that project the image on to the special screen. The light coming from the projectors is filtered using the Infinitec method. A magnetic tracking system is used to determine the exact position and perspective of the viewer. The VR Object Display is not suitable for all application areas, it is more suitable for the exploration of smaller VR objects that fit in the cylinder.

3. Combining Immersive and Portable Displays

This section illustrates our approach facilitating movable panel displays and presents our specific concept for the hardware setup of a user centered visualization and simulation laboratory.

3.1. User-centered Concept

Our vision postulates a flexible environment that supports researchers in simulation and visualization systems. Researchers shall be able to dig into their work without having to make confessions to a system with a rigid display setup that would enforce them to adapt to hardware specific layout constraints. Besides the experience of the computer generated visual data, such researchers run their simulation, change parameters or even pieces of the generating code and then inspect the result again. If the result shows an interesting effect, they might sit down and discuss the perceived effects. In some cases researchers need to inspect the effects from different, maybe opposing directions. With a rigid, CAVE- or power-wall-like setup they would have to rotate and move the virtual world to yield views from different directions.

An alternative approach allows inspecting the scenery from different directions. While the NexCAVE [DAA*10] already showed that panel displays can be used to build CAVEs, we go one step further, making the display setup reconfigurable while keeping the opportunity of a CAVE-like setup available. Rather than rotating and translating the virtual world on the screens, users locate the display screens so that they are facing in the required directions. To reach this freedom, we treat each display as a separate window into another world, similar to Rekimoto [Rek96]. This allows users to perform the inspection without having to translate the virtual world iteratively. Fig. 1 illustrates such a setup in a sketch. The virtual world remains rigidly registered to the real world. Users do not have to memorize positions of different viewpoints to iterate between. Neither do the users have to deal with spatial relations. Users rather can yield different views by looking at the virtual scenery through the differently aligned displays. Bowman [BKLP04] states that each 60 degree rotation requires 1 second to mentally execute, not to speak of the mental demand to maintain different perspectives with spatial control devices. Mounting the virtual, simulated world to the real world bears the potential to let users neglect such issues.

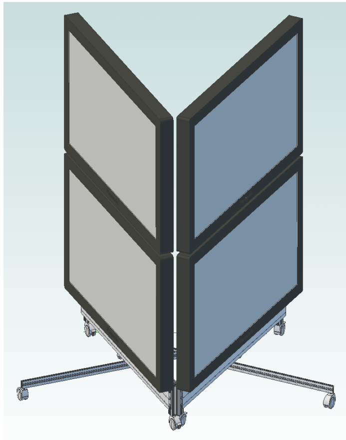


Figure 1: *Two display walls with displays facing inwards*

In our concept, the users would just locate their own screen (or set of screens) at the position and with the orientation w.r.t. the real world they require for their work. Teams could work on their own visualization in parallel without having to use control devices for viewpoint changes. Instead, the users walk through the real world to change their viewpoint. The screens themselves become the input and steering devices for viewpoint control.

3.2. Specific Panel-based Approach

Visualization systems require tracking capabilities to track the user's head position for relative alignment of the field of view onto each display. We employ the tracking system to keep track of the actual position and orientation of all displays, too. By tracking each display independently, the spatial setup of the visualization panels no longer needs to stay in a rigid setup, displays rather can be moved to any location. Display screens are physically decoupled from one another, or are coupled to groups. The frustum for each display is computed according to the viewer's eye positions and the relative location of the display. The displays become portable windows into the virtual world. Fig. 2 shows the general principle on an earlier system we built. Users can turn and tilt the display in any direction and always get exposed to what they would see as if they were looking through a glass window but see the virtual world instead.

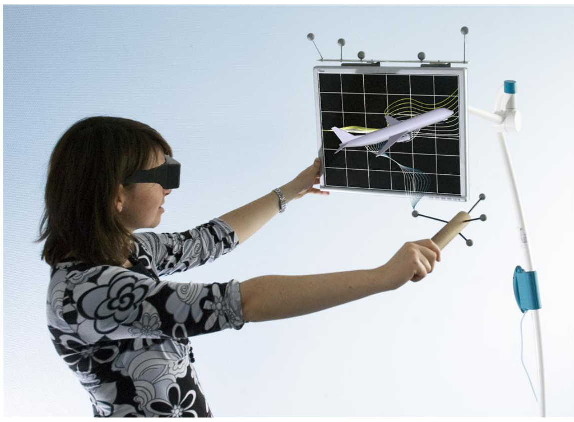


Figure 2: *The principle idea of a window into a virtual world: The user can position the display freely and always sees what lies in the viewing frustum defined by the four screen corners and the eye position*

As mentioned, the demand for a visualization system used for simulation data slightly differs from those for fully immersive virtual worlds. While a large field of view still is required, the demand on the level of immersion might be lower, having small bezels might not the major demand. Having only small bezels of course enhances immersion, but the existence of bezels in fact compensates for possible misalignments in rendering. As each display is tracked and the location of the corner points of the displays have previously been measured, small tracking errors at both stages might lead to alignment errors of the pictures on different screens. Without any bezels neighboring pictures could be offsetted, bezels reduce perception of such effects. By tracking the displays bending effects of a leveled floor can be neglected, too.

4. Issues, Findings and Proposed Solutions

A general issue when dealing with end-consumer hardware is getting valuable information about technical details to select a suitable display model for the visualization system. Unfortunately, we were unable to get any significant answers from all major manufacturers of 3D TVs to general specification related questions. Questions ask were w.r.t. issues such as the possibility of displaying 3D contents in full HD resolution or the risk of shutter sync interference over multiple 3D TVs and their stability versus additional IR lighting (i.e. from optical tracking systems).

This section therefore provides answers to all questions necessary to bring consumer 3D TVs into operation in a well equipped setup including infrared tracking facilities. As it is almost impossible to bring testing hardware to 3D TVs to vendors and stores, we can not provide information for other displays than the one we tested (Panasonic VT20 series, see next section). The following sections therefore provide alternative approaches where applicable if one of the issues arises with other displays.

4.1. Display Choice

General properties of displays had been checked beforehand. Properties were image quality, size and, if equipped with IR 3D shutter, radiation angle of the infrared shutter. At the time of investigation in summer and early autumn of 2010, all end-consumer TVs used infrared LEDs for driving shutter glasses.

Image Quality Generally three types can be distinguished, edge-blending, full LED and plasma illumination. Edge-blending TVs in general showed artifacts when displaying computer generated graphics. When working with simulation data, specifically with particle systems, such effects are rather disturbing. This effect comes from the different size of the LEDs in and the light modulating LCD panels. Full LED displays did not have this effect but the picture, especially the coloring often generated an artificial impression, also brightness had not been too high. This will surely change when the new generation of green LEDs in the range of 530*nm* [Ste10] gets into mass production. Plasma TVs in the end showed best results in picture brightness, contrast and color appearance. The picture quality is subjectively better to the cost of a still higher power consumption which on new current models has significantly decreased compared to older plasma TV generations.

Display Size For the main components of the visualization system a choice in the display size was required. Smaller displays often have smaller bezels. However, the absolute number of bezels increases by a factor of 4 when reducing the diagonal by 2. Taking into account that average height users (180*cm*) should be able to see some portion of a picture above their straight forward horizontal line of sight and that the lowest line of a display should have the smallest possible gap to the ground floor displays, the following calculation resulted. If the displays are larger than 60 inch, two displays, one above the other, are sufficient. Between 40 and 60 inches, three display are required and below 40 inches, four displays are necessary to reach the required height in display space.

Usually smaller and mid size displays are cheaper than the largest and resolution of a system built with smaller displays would be higher. However, the calculation of the number of displays has to factor in the cost of computers and graphics cards. As most of the displays use active shutter technology, the graphics cards must provide functionality for hardware-based synchronization (i.e. G-Sync). Our choice therefore went to displays of at least 60 inches in the diagonal. A pixel thus has a diameter in a maximum of 0.78*mm* as no display did exceed 65 inches at the time of evaluation.

3D Generation To keep the level of immersion as high as possible, a 3D presentation was aimed on. Panel displays are available with either passive or active presentation. Passive 3D for instance is available with the 46 inch micropolarized displays of JVC. Here, image resolution per eye is reduced by a factor of two as each line has an alternate polarization for each eye. With active shutter technology, the full resolution is available for each eye when the bandwidth of the whole pipeline has a sufficient throughput. The HDMI 1.4a standard [Wik] achieves this demand for Full-HD in stereo.

Shutter LED Radiation A test that almost led to rejection from some stores checked the radiation angle of the infrared shutter LEDs. Technical specification data sheets often list such information, but give reduced values to ensure optimal operation. We used a standard digital pocket camera to get an impression of the angular distribution of the LED light. Most TVs had larger values than specified, but the VT20 series by Panasonic showed the best results in this pragmatic test. Later, after we finally decided on the model PX-T65VT20E from Panasonic (including two sets of shutter glasses in the shipment), we conducted a more accurate test, finding that one TVs can synchronize the glasses to a horizontal transmission angle of $\pm 50 degrees$ and a vertical angle of $\pm 30 degrees$. For comparison, the specification lists $\pm 35 degrees$ horizontal and $\pm 20 degrees$ vertical. We also tested the reception angle of the photo diode in the shutter glasses by tilting the glasses relative to the display. Here, the glasses loose the signal at a horizontal angle of $\pm 60 degrees$ and at a vertical angle of $\pm 40 degrees$. Concerning the distance the glasses can receive a signal, the specification lists $3.2m$, but our tests showed distances up to $5m$. Worth mentioning is that the glasses do have their own clock and can maintain the shutter functionality for about $6sec$ when the direct line of sight between IR LED and the glasses is concealed.

4.2. Synchronization of Shutter-glasses over Multiple Displays

With the initial choice made, two displays were ordered to conduct further tests in house. An initial test showed that there is no issue in displaying computer generated 3D graphics. The main question to answer was, if multiple displays are able to display content synchronized, so that a pair of active shutter glasses can be used to perceive the 3D picture over all displays without any flicker? Also this test succeeded, confirming our expectations. The processing time of the pictures inside the TVs is equal, the only requirement is that the graphics cards provide the images at the same point in time. As we employ the NVidia QuadroPlex series, this synchronized output is guaranteed by the built-in G-Sync functionality.

While the first tests had been conducted under Windows 7 we later were able to achieve G-Sync synchronization on Linux (Ubuntu 10.4 and 10.10), too. So far, one issue remains under Linux. The graphics card drivers do apparently not store the synchronization settings, thus forgetting about the synchronized nodes after a reboot of a node.

With multiple displays and each flashing with its own sync flash, a much larger volume for the synchronization of the shutter glasses is reached. Also the maximum distance in which the glasses do receive a signal increases.

If one display (in more detail, its graphics card) is not synchronized with the others, this one display shows the double image. The flash only disturbs the the glasses if more or less directly looked into the corresponding display. In that case, all other displays to no longer show 3D and only this one display provides 3D. Looking onto another display again quickly lets the glasses sync back.

4.3. Synchronization between IR-Tracking and Shutter Glasses

The major issue when integrating 3D TVs with infrared LED driven active shutter glasses into an environment that requires tracking may be conflicts when the tracking facilities also operate in the infrared spectrum. We expected interferences between the infrared flashes of the optical tracking cameras, in our case A.R.T. smarTrack 2, the IR emitters in the displays and the shutter glasses, see figure 3

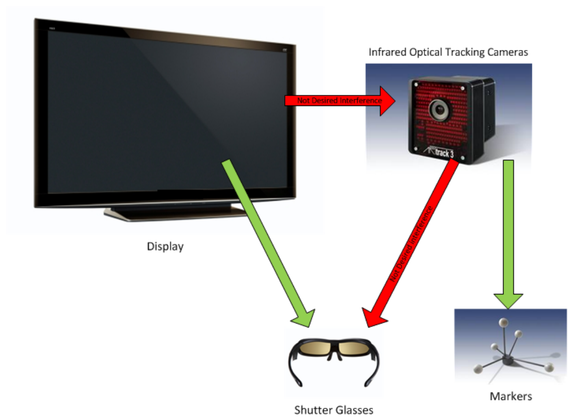


Figure 3: *Interferences between shutter glasses and infrared optical tracking*

The shutter glasses might, in addition to the desired IR light from the display, receive the undesired infrared flash from the infrared flashes of the tracking system. Also the infrared optical tracking cameras might detect the undesired IR light from the display.

We ran some experiments with the TVs running on $50Hz$ with a side-by-side rendered picture (alternate-frame sequencing), giving a repeat frequency of $100Hz$ for the IR sync to the glasses, and the infrared tracking system running on $60Hz$. The tracking system detected the light of the shutter sync LEDs but only as small spots in the camera pictures, not causing any further problems for tracking quality. The shutter glasses also did not suffer, even under frontal and near illumination of the IR flashes of the cameras.

4.3.1. Wave Patterns

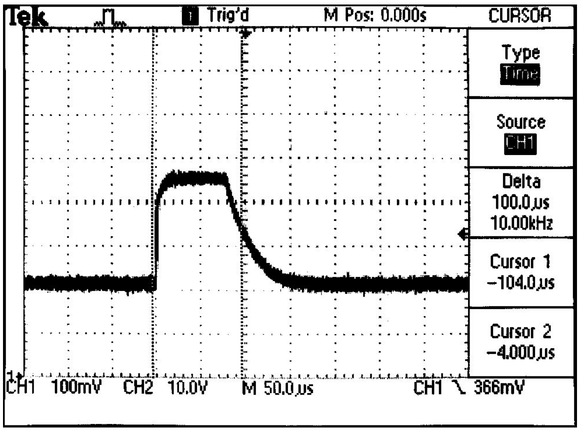
To determine why there was no interference, we analyzed the different signals. We used an oscilloscope and a photo diode as signal receiver, to draw the infrared signal waveforms emitted by the camera flashes and the IR TV emitters respectively.

A.R.T. The specification of the smarTrack 2 cameras states that the IR flashes operates at a wavelength of $880nm$ in the near infrared spectrum. Fig. 4 shows the wave patterns of the flashes with low flash intensity and high flash intensity. The pattern at low flash intensity is a single burst with a duration of $100\mu s$. The pattern at high flash intensity is a single burst with a duration of $400\mu s$ and a higher amplitude. Fig. 5 shows the wave patterns of the modulated flash. The modulated pattern is used to trigger active marker targets. The first part of the burst then has a modulated sinus pattern in a frequency of $500kHz$.

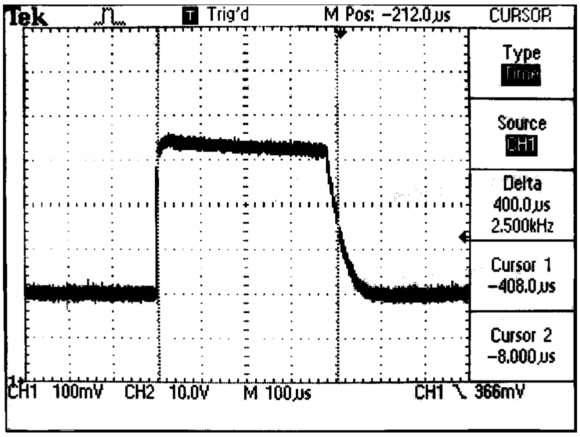
Panasonic VT20 Series TV IR emitter emits two different modulated wave patterns for the synchronization with the shutter glasses, see figure 6 Both signals are alternated with a delay of $10ms$, thus synchronizing the glasses at $100Hz$. The synchronization patterns have a duration of $700\mu s$. Multiple checks on the average patterns over 128 samples showed that there are only those two signals.

No information concerning the wavelength of the IR signal can be provided as no spectrometer was at hand to measure the wavelength. However, we are pretty convinced that broad-band near-IR LEDs are used and that no spectral filter is used for shielding.

Discussion Due to the differently modulated codes used by the 3D TVs there is no risk that the shutter glasses will misinterpret an IR signal emitted from the A.R.T. cameras. However, what could happen, is that the shutter glasses will miss a signal emitted from IR TV emitter, as it can be blinded by the strong ART IR flash. This will occur if both IR signals are reaching the shutter glasses at the same time. The shutter glasses however have a built in timer that preserves a sync signal for $6sec$, most likely for the case that some other person passes through the illumination signal of the TV. If both signals from the TV and the tracking flash would be perfectly synchronous, the sync would be lost after those $6sec$. This effect is very unlikely to occur because two independent systems never have an exactly equal repeat frequency even if both, for instance, state to run on $50Hz$, actual values differ at least in the decimal place. Also either the TVs or the



(a) Wave Pattern with lowest Flash Intensity



(b) Wave Pattern with highest Flash Intensity

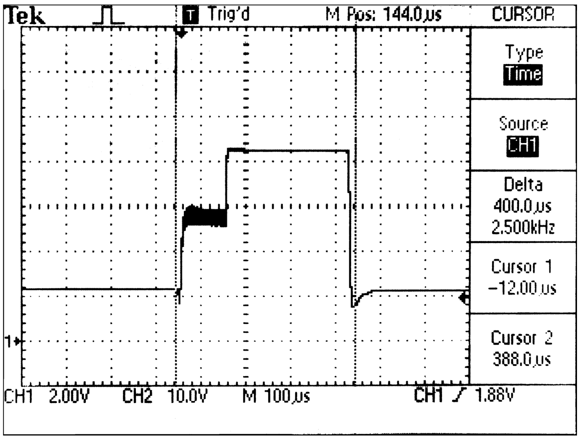
Figure 4: *The Wave Patterns used by A.R.T. for Tracking Illumination*

tracking system can be adjusted to either operate on $50Hz$ or $60Hz$. We can conclude that the IR signals from the shutter glasses and the ART tracking do not interfere and that the setup integrates smoothly.

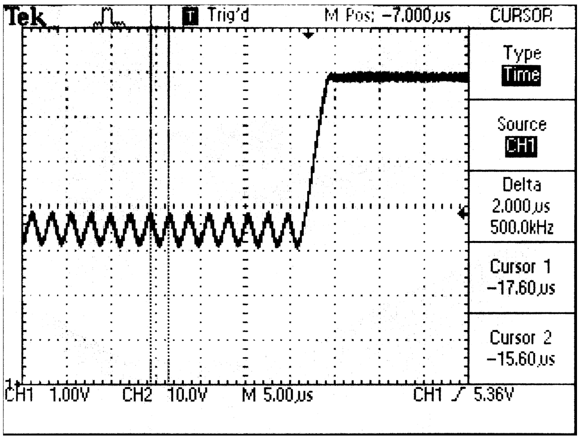
4.3.2. Alternative Approaches

Using other TV models by other manufacturers or other optical tracking systems, the synchronization issue could become a problem. The following paragraphs therefore provide alternative approaches to circumvent the problem.

Hardware Sync As systems operating with active shutter technology already require hardware synchronized graphics cards, their sync signal can be fed into the external sync input for the tracking system if existent. The A.R.T. system provides such an input. The tracking software software D-Track then can be used to add a specific phase delay to customize for the TV internal processing time of the video signal to let

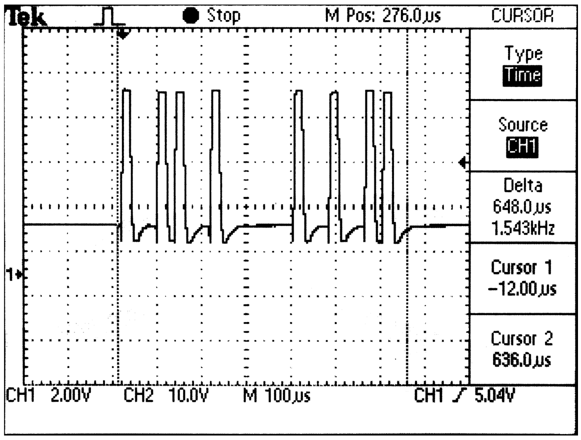


(a) Wave Pattern with highest Flash Intensity and modulated Flash

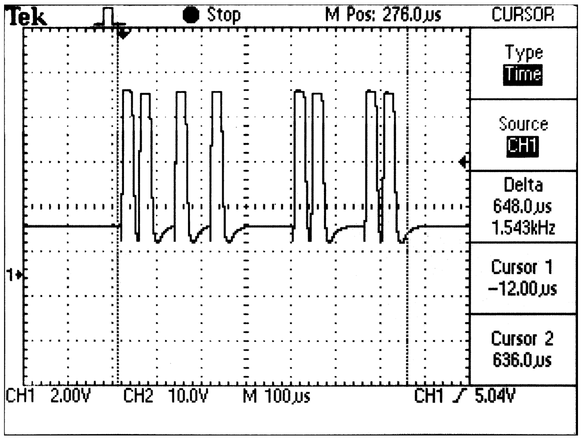


(b) Frequency of modulated Flash

Figure 5: *The Wave Patterns used by A.R.T. for Tracking Illumination*



(a)



(b)

Figure 6: *The two Wave Patterns used by Panasonic for Shutter Glasses Synchronization*

the shutter flash LEDs for each eye illuminate alternating to the tracking flash. For other systems a custom made circuit board can be built to add this phase delay to the sync signal.

Radio Signal Conversion An alternate approach uses radio signal transmitters instead of IR signals. Some manufacturers of TVs provide such radio signal transmitters and suiting shutter glasses. By using those, the illumination issue can be dissolved but usually requires to by new sets of glasses being able to receive the radio signal.

4.4. Temperature

The TVs have a surprisingly low maximum operational temperature of 35 *degrees Celsius*. We were wondering how such a TV could be used on a warm summer day. In the case that a ground floor is built, the used TVs will be covered with glass plates to enable users to walk on top. We tested on the necessity for extra cooling.

In our setup, we have an elevated leveled ground floor. This elevated floor, among other things, is used for air conditioning. We set the air condition to 18 *degrees Celsius* and replaced all tiles underneath the frame by those with openings for the air flow to generate a constant current. Already this setup is sufficient to keep the temperature near to the displays at a low level. Only the space between display and glass heatens as the cooling current from below can not reach there. We therefore installed some extra tangential fans to generate an air current through this space. This is sufficient to stay some degrees Celsius below the maximum operational temperature. To the end, no additional cooling mechanism is required, the already existing air conditioning is sufficient. Anyhow should be mentioned that working in a closed setup with the side walls put together to a CAVE-like structure creates a warm working environment for the user.

4.5. Bezel Size

The 65 inch Panasonic VT20 series has rather large bezels. The casing could be taken off if another stabilizing frame is installed. The remaining distances from the out-most pixel row or column to the out-most element of the internal frame have the following distances: 40*mm* at the bottom, 28*mm* at the top, and 30*mm* at both sides. The distance between two displays could be reduced by a factor in the magnitude of 2. For fully immersive displays such bezels are way too large.

4.6. Dynamic Off-Axis Frustum

To compute the frustum w.r.t. the viewpoint of the user and to the tracked display, the pose of the marker-target attached to the display is saved. With a pointing device the corner points of the display panel relative to the marker target are measured.

The positions of the marker-target and of a marker-target at the user's head are provided by the tracking system at run-time. To compute the screen position, orientation and dimension of the screens are required. This can be calculated from three of the four screen corners. Here the lower left (P_{ll}), lower right (P_{lr}) and upper left (P_{ul}) edges are used. The screen width is given by $width = |P_{lr} - P_{ll}|$ and height is defined by $height = |P_{ul} - P_{ll}|$.

With this at hand, three vectors can be computed that form a coordinate system local to the screen.

$$
\begin{aligned}
X_s &= P_{lr} - P_{ll}/|P_{lr} - P_{ll}| \\
Y_s &= P_{ul} - P_{ll}/|P_{ul} - P_{ll}| \\
Z_s &= X_S \times Y_S
\end{aligned}
$$

These vectors are a rotational transformation from the world to the local screen coordinate system M_s.

$$
M_s = \begin{pmatrix} \begin{pmatrix} X_s \end{pmatrix} & \begin{pmatrix} Y_s \end{pmatrix} & \begin{pmatrix} Z_s \end{pmatrix} & \begin{matrix} 0 \\ 0 \\ 0 \end{matrix} \\ 0 & 0 & 0 & 1 \end{pmatrix}
$$

The relative position of the viewpoint E to the lower left corner of the screen is $E_s = E - P_{ll}$. The distance from a ray perpendicular to the screen plane going through the viewpoint, the view vector, to the near clipping plane needs to be calculated. This can be explained with the theorem of intersecting lines. The distance of the edge of the viewport to the view vector is scaled to match the near clipping plane. The distance of the viewpoint to the screen is $d = E_s \bullet Z_s$.

$$
\begin{aligned}
L &= E_s \bullet X_s \\
R &= width - L \\
B &= E_s \bullet Y_s \\
T &= height - B \\
left &= -L * near/d \\
right &= R * near/d \\
bottom &= B * near/d \\
top &= T * near/d
\end{aligned}
$$

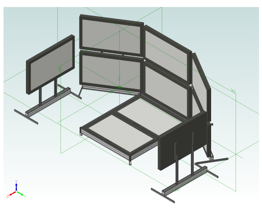
The last four values and the near and far clipping planes describe the frustum and can be used to fill the corresponding projection matrix.

Finally, the viewpoint needs to be expressed so that it looks orthogonal to the screen plane. The rotation of the screen M_s and the translation of the eyepoint E express the view-dependent viewpoint.

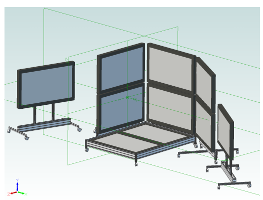
5. The FRAVE System

Our demand for a flexible visualization environment is driven by a project with the focus on visualization of simulation data in combination with terrain data. The project requires a wide field of view for the exploration of a terrain and flexibility for the investigation of simulation data.

We developed a configuration that can serve all requirements in an equal manner. Fig. 7 shows the configuration capabilities for the flexible reconfigurable environment. The setup consists of a ground floor build with two displays and is covered with glass to be capable to carry two users. The glass plates of the ground floor are 39*mm* thick and weigh approx. 150*kg* each. Three wall segments are also built of two displays, one above the other. Especially the side walls can be moved in an open position to have a setup similar to a power-wall (Fig. 7(a)) or inwards to have a CAVE-like setup (Fig. 7(b)). The side walls can be combined with the center wall by joints to allow for easier alignment, but also can be moved around freely.



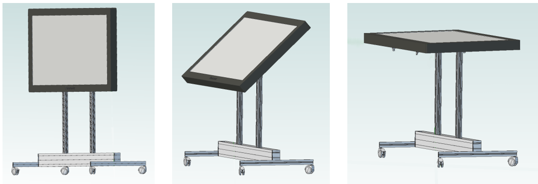
(a) A Power-Wall like setup



(b) One side moved inwards, a CAVE-like setup

Figure 7: *The Concept shown in Sketches*

Two additional displays are mounted on their own frame and are adjustable in height and tilt. In addition to freely move every element of the setup, these elements also can be adjusted to personal preferences of the users. Fig. 8 illustrates the range of possible adjustments of these displays. An upright position let's people stand while inspecting a situation in a horizontal viewing direction. A tilted setup enables users to look downwards and a lowered position let's users sit down for longer discussions.



(a) A Power-Wall like setup (b) One side moved inwards, a CAVE-like setup (c) One side moved inwards, a CAVE-like setup

Figure 8: *Concept for the adjustable Displays*

Fig. 9 shows the current setup of the FRAVE running the terrain rendering engine by Dick et al. [DSW09].

Figure 9: *The FRAVE running a terrain rendering engine*

The system already had to stem several presentations and is used by developers of various largely differing applications ranging from terrain rendering to particle simulations.

6. Summary

Rigid visualization systems are not necessarily the most suitable visualization systems for work with simulation systems. More flexible systems not only integrate power-walls and CAVEs into one setup, they also serve a wider range of purposes. Reconfigurability in terms of relocating displays to places where they are required have the potential to let researchers focus on their analyzing task rather than enforcing them to adapt to viewpoint specific issues. This becomes an imminent feature when more than one perspective onto the same simulation is required or when multiple teams need to work in parallel but with different viewing directions on the same simulated sample.

By experiences through employing off-the-shelf consumer products, we provide a wide-ranging overview about issues when putting such hardware into research environments, and gave solutions and alternatives.

We are now working towards an extension for the Equalizer toolkit, a framework that allows for the easy configuration of dynamic multi-view visualization systems. Equalizer currently only supports frustum adaptation for changing viewpoints but does not allow for dynamically changing the pose of the displays.

Concerning the usage of the new possibilities, the wide variety of different configurations with different spatial setups is an indicator for the potential of the vision and instantiation of the FRAVE system. For us, who set up the visualization environment, it is fascinating to see that the position of the side walls is different whenever we come back to the room.

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