Multi-projector VR Systems

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***Abstract*—Immersive multi-projection environments are becoming affordable for many research centers, but these solutions needs several integration steps to be fully operational, and some of these steps are difficult and not in a common domain. This paper presents the most recent techniques involved in multi-projection solutions, from projection to computer cluster software. The hardware in these VR (Virtual Reality) installations is a connection of projectors, screen, speaker, computers and tracking devices. This survey paper will introduce hardware options, explaining their advantages and disadvantages. We will cover software design and open source tools available, and how to administrate the whole solution.**

***Keywords*-Virtual reality; Computer displays; Interactive computing;**

I. Introduction

In order to have a virtual reality facility several points should be taken in consideration. In this first section a brief introduction will be presented about all the topics related to a complete multi-display solution and what are the core ideas behind these systems. We intend to answer why someone would want this kind of solution that can be very expensive depending the way people plan the solution, leading the reader to understand why and which kind of solution s/he needs. The section will also review part of the history behind these immersive solutions.

A. Background

Interest in multi-projector VR systems stems from the fact that users want to see 3D content in an immersive environment. Most of the time stereoscopy and tracking are used to improve the feeling of immersion and several possibilities are available to accomplish this demand of visualizing 3D and interacting with it. We can observe in the last years that this solution is getting more commonly available and feasible [1], [2]. The devices needed to assemble a VR facility are each time more affordable and better.

We intend to teach people about hardware and software issues, and even if you are not familiar with some points, we are going to cover as much as possible in a basic level, allowing anybody with a small knowledge in projection and computer graphics to understand the topics.

There are several reasons to use multi-projectors, but the most noticeable are field of view and resolution. Even using curved screens and special lens, just one display is not convenient to a high field of view. Due the limited resolution of the displays, the angular resolution may decrease as we spread the projection image in a larger area. But there are several issues in combining projections that leads us to a list of procedures in order to have a high quality immersive environment. This list has hardware specific questions like physical calibrations and edge blending, as well software issues like calculating the correct view frustum for each tile in your solution.

Driving these solutions is also a challenge, the computing system has to feed several displays very often with high resolution and high refresh rate. Until few years ago it was not possible to use just one computer for this. The Silicon Graphics released the Onyx computer capable of several video outputs, but the PC world was always limited by the internal bus. Currently, with solutions like Quadro Plex [3] or Crossfire [4], a single PC can drive a multi-projection facility. Nowadays some softwares are available for multi-projection environments. There are several isues related, like the multi-frustum, data redundance, video buffer synchronization. Software solutions are increasingly moving from the academic world to commercial solutions.

There are several uses for multi-projector VR systems in different domain areas. The industry is using to prototype objects or analyze the real environment, the military is using for training in simulated environments, artists can create new electronic art. Basically what these people want is an immersive environment having a feeling of a real scale world. Using real scale it is possible to check if a prototype, such as an automobile or an aircraft cabin, is ergonomically correct. This kind of simulation has many advantages over a model made of clay for instance.

B. History

Researches around the world are using multi-projector systems for several years, but the CAVE [5] introduced at Siggraph 92 was the project that presented fully immersive environment for the academic community. Since them sev-

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eral other projects appeared with different geometries, resolutions and usages. Today there are systems in a star shape [6] and other systems with an incredible resolution [7]. Immersive multi-projection systems are an active research area within the field of VR, with dedicated publications and conferences.

One tendency in this area is the miniaturization, today instead of using big pieces of wood to hold screens, lightweight Aluminum profiles are used and we can have powerful projectors that fits in the palm of your hand [8]. Of course the high-end solution are bigger than the commodity ones, but the speed new solutions and technologies are coming is so fast, that it is important to keep updated with the new products. Here we are more focused in the core technologies that take more time to be replaced.

C. *Outcomes*

After you have finished this text, we believe that you should have the following knowledge:

- An understanding of the several multi-projection solutions and which one best fits your needs;
- A good overview of the hardware and software solutions available to set up an immersive environment;
- Better knowledge even if you intend to acquire a complete solution.

This paper is organized as follows. Section II will present the display systems available. Section III discusses image generation with PC clusters. Section IV presents software for immersive environments, while Section V concludes the paper.

II. Display Technologies

Several technologies are available to implement a multi-display facility. We are going to present some of these technologies and devices, and try to link them. We also present an evaluation of the most common used projection techniques and their future, what kinds of screens are available and the best use for each one.

This section is going to explore the display technologies available for multi-projector VR systems. First we are going to cover the main display system possibilities based on taxonomies used by the virtual reality community, then we are going to view the most common projector features and technologies, and the kind of stereoscopy technologies that can be used with them. We are also going to verify the main elements for a projection solution like screen, lens and mirrors.

First we are going to do a brief introduction about display systems. There is a large range of options for display systems, for instance the ePaper [9] is an advanced display technology. In the last years we see that the color and resolution are increasing and possibly in the future we are going to see some VR systems using this kind of display.

Several projection technologies are available, they are evolving constantly, and every year we can see better features. Usually they have the same parameters that you can evaluate in order to decide which one is better for our needs.

A. *Brightness*

One of the important features of a projector is the brightness. Brightness refers to your perception of light, and it is actually a subjective term informing the amount of light reaching your eyes. It is not possible to measure brightness, although you can feel the difference. Several terms and units are defined to measure light, as well as better procedures to measure helping you to choose the best values for your needs. Depending on the situation, a projector can be too dim for your needs, but not always the brighter projector is the better one. Usually the brighter a projector is, the more expensive it is, and a brighter projector may cause undesired reflections in other screens, as in a CAVE, for instance. Unfortunately manufacturers rate projector lumen values differently, what makes it more difficult to evaluate if one projector is brighter than other.

There are several ways to measure the brightness. The measurement of quantities associated with light is the photometry. The following terms are commonly used:

- First, the light that is important for us is enclosed in the wavelengths between 380 to 770nm, which is the light that excite our retina. This excludes ultraviolet (UV) and infrared (IR) wavelengths.
- Luminous flux is the visible light energy per unit of time. It is measured in lumens and it is widely used for specifying projectors.
- Luminous intensity is the luminous flux per solid angle emitted from a point. It is measured in candela (cd) or lumen per steradian.
- Luminance is the luminous intensity emitting per unit area in a given direction. The unit is candela per square meter (nit is an old term but still used in some places). Luminance is probably the best way to evaluate this aspect of a display. The luminance of the sun is approximately 10^9 cd/m^2
- Illuminance is the luminous flux incident on a surface per unit area. The International System of Units (SI) unit is the lux.
- Radiant Flux is the light energy per unit time radiated from any source in the wavelengths range is from .01 to 1000 μm , including ultraviolet (UV) and infrared (IR). The Radiante flux is measured in watts (W) or Joules per second (J/s).
- Radiance is the amount of light from area in a solid angle and is measured in watts per steradian times unit area (w/sr*m^2)
- Brightness is a subjective feeling of light, it has a non-linear and complex response.

The SI defines Lumens, as the luminous flux, a way of measuring of the perceived power of light. It is based on the candela that is the luminous intensity multiplied by the steradian the source is emitting. A steradian is the SI unit of solid angle. As a comparison, a wax candle generates about 13 lumens.

Luminance is the luminous intensity emitting per unit area in a given direction. It describes the amount of light that is emitted from a particular area, usually a screen. The SI unit for luminance is candela per square meter (cd/m2).

Foot-lambert is very used in the motion picture industry. They evaluate the luminance of images on projection screens. The Society of Motion Picture and Television Engineers recommends a minimum of 16 foot-lamberts (fL) for movie theaters without a film inside the projector. But for digital projection, the luminance standard is reduced to 14 fL. Although, 5.4 fL is used for stereoscopic movies.

Some conversions can be used to get the values in the desired format:

- Candela / m^2 = (lm / area) * gain / π
- Foot-lambert = (1 / π) candela / foot2
- Foot-lambert = 3.426 candela / m^2
- Lux = lumen / m^2
- Lumen = (radiant flux in watts) * (683 lumens/watts) * (luminous efficiency)
- If luminance drops 50%, the perceived brightness drops around 25%

Manufacturers rate projector lumen values differently and can show that a projector is brighter than another one, but actually it is not. Peak lumens is a standard that was used in CRT projectors. Just a central area of the projection surface is displayed with white and then it is measured. As you can imagine this lead to many possible different values.

Projector brightness is not homogeneous, for instance CRTs can have only 30% of brightness in the corners compared to the center of the image. Modern projectors usually have more than 90% the same brightness of the image center.

What very often is not told, however, is the fact that the maximum contrast and the maximum brightness are not achieved while adhering to the D65 color temperature (6504 K).

Then it was necessary produce a standard, a kind of procedure to measure the overall brightness. A standardized procedure for testing projectors has been established by the American National Standards Institute in 1993 (http://www.ansi.org/), the ANSI lumens. It is as a sequence of steps and patterns in order to avoid big differences in the lumens values presented by different manufacturers. The main idea behind the ANSI lumens procedure is the fact that the centre of projection is brighter than the corners. ANSI lumens are calculated by dividing a square meter image into 9 equal rectangles, measuring the centre of each rectangle, and averaging these nine points.

The procedure of ANSI Lumens is: let the room at the 25 degree Celsius, wait 15 minutes in order to stabilize everything, divide a square meter image into 9 equal rectangles, as in Figure 1, read each rectangle brightness, average the values divided by the screen size (m2). For lumen rating, calculate the average brightness (Foot Lamberts), multiply by screen area (square feet), then divide by screen gain. ANSI Lumens is something well-known but it is actually measuring the flux of light. ANSI Lumens is not a value, but just a standard procedure of light measurement.

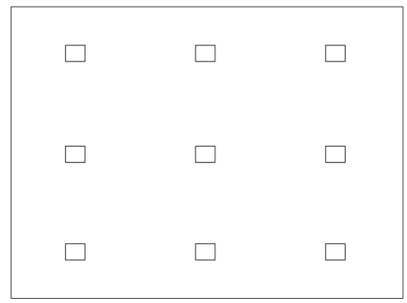

Figure 1. ANSI Lumens measurement image.

Photometers can be very expensive to measure your screen luminance. An alternative is to use a regular photo camera and the following equation:

$$L = \frac{K * N^2}{t * S} \quad (1)$$

where:

L = luminance of the display
K = the camera constant that changes for each camera
N = the relative aperture (f-stop number)
t = exposure time in seconds (shutter speed)
S = ISO speed

If you try to shoot a photo of your display, get the values of your camera and put in the formula you should get a good approximation of your screen luminance.

For measuring flat displays the FPDM (Flat Panel Display Measurements Standard) offered by the Video Electronics Standards Association (http://www.vesa.org/) can be used.

A typical CRT monitor has a brightness between 50 and 150 cd/m^2, an LCD display have between 250 and 450 cd/m^2 a plasma display goes from 1000 to 1500 cd/m^2, new LED TVs have between 450 and 550 cd/m^2 and finally DLP TVs have between 450 and 700 cd/m^2.

One important care about specifying the brightness of the display is that the human eye have problems constantly adapting to the illumination set. Usually the human eye needs about 1 second to adapt to brighter environments, but to adapt to a darker environment it can take more than 30 minutes depending on the situation. The problem for the eye occurs when your eye have to adapt all the time when you move your head from a dark and bright point. That way, it is important to have the same level of luminance of the projection screen and the walls.

How to choose the right brightness for your needs depends on several factors. First we need to evaluate how is the ambient light. If the projected image is too bright it can give to the audience a headache, but if it is too weak people will not be able to see what is going on and then you need a brighter projector. The screen size and type is also important, as the screen gets bigger, the light is spread across the screen, reducing the overall brightness. If you are using a back-projection screen and your projector is too bright hot-spots will appear. The stereoscopy can also define you brightness, since some filtering technologies can reduce more than 75% of the brightness and it should be taken in consideration when choosing the projector brightness.

We split the projector brightness in 4 ranges: less than 1.000 lumens is indicated for dark room, usually when the room is blacked out, they are the least expensive, and can be used at home for home theater for instance. Between 1.000 to 2.000 works for dimly lit room, like an office room with no natural light. Between 2.000 to 3.000, the amount of brightness is high enough for a normal room, these projectors are more expensive and present several features to adjust the projection quality. Over 3.000 ANSI lumens is indicated for really high-end projection systems, it can be used for large venue, but they are usually heavier than the other ones and are very expensive.

Unfortunately certain projectors are produced in order to have better values in a lumens measurement. Among the possibilities, the manufacturers can define the regions where the values are acquired to be brighter than the average. Another possibility is to tune the color temperature of the lamp in order to have better absolute values, but not useful for a real visualization.

B. *Contrast*

Contrast can be defined by the difference in brightness between the maximum white and deepest black in an image. Since any projector leakes some light even when presenting a pure black image, it is important to know the ratio the white is brighter than the black. A good contrast ratio is important because it creates an image with natural depth. A contrast rating of X:1 implies that the black level is X times darker than the pure white. Higher contrast ratios means less light leakage, of course, supposing the same overall brightness. Contrast perception is also influenced by the environment brightness. Besides the contrast it is important to make sure the projector is able to produce shades of any color. It is often referred to as Dynamic Range. Some projectors can go up to 500,000:1 or even more. Do not expect having the contrast specified be reproduced at your room, since any amount of light that comes from the environment will make the contrast ratio drops.

There are some procedures to calculate the contrast of a projector. It can be measured with the image completely black and after completely white; this procedure is known as full on/off. But a real test for a projector is to measure at the same time the minimum black and maximum white; the contrast value in a intra-image is limited by internal reflection of the light engine. This problem is even worse in a fixed-pixel display system like DLPs or LCDs, becoming a weakness of these solutions. ANSI is a contrast ratio test, that specifies that the reading should be done while the projector is showing black and white at the same time, as opposed to full on/off. Some photometer system allows us to calculate the contrast ratio of a device measuring the light output at a specific screen location. An average contrast ratio is about 400:1 for LCD projectors, whilst some DLP projectors have contrast ratio of 4000:1.

A dynamic iris is a device built into some projectors that sits between the lamp and the lens. Many times per second, the projector evaluates the overall brightness of the image being projected at the moment, and then opens or closes the iris to allow more or less light through. The presence of a dynamic iris in a projector substantially increases full on/off contrast values, but does not improve the ANSI contrast of a projector.

C. *Color*

Metamerism occurs because each type of cone inside our eyes responds to light energy from a range of wavelengths, then two colors could appear to be the same even when the spectral power distribution is completely different. Different combinations of wavelenghts can give the same color result for you. The digital color image reproduction processes use this resource to produce metameric color matches.

The CIE (Commission Internationale de l'Eclairage) was founded in 1913 and defines several standards for illumination (http://www.cie.co.at/). It is known that about 95% of the population have statistically the same color vision, what makes it easier to define standards for our visual system. The CIE did three main revisions (1931,1960 and 1976), and the advantage of the 1960 and 1976 revisions is that the distance between points on the diagram is proportional to the perceived color difference. Then it makes simpler to detect variations in a color perceived by our eyes.

The CIE defines Color matching functions that are numerical description of chromatic perception of the observer. The three CIE colour matching functions (CMFs) are called Xbar, Ybar and Zbar. They always produce positive tristimulus values.

Here are some equations to convert between the different CIE transfer functions versions:

From CIE-1976 u', v' to CIE-1931 x, y

$$x = \frac{(\frac{27u'}{4})}{[(9u'/2) - 12v' + 9]} \tag{2}$$

$$y = \frac{(3v')}{[(9u'/2) - 12v' + 9]} \quad (3)$$

From CIE-1976 u', v' toCIE-1960 u, v

$$u = u' \quad (4)$$

$$v = \frac{2v'}{3} \quad (5)$$

The white color can be defined by the temperature of an ideal black-body radiator (Planckian-radiator), this temperature is stated in Kelvin (K); Higher color temperatures (5,000K or more) are cool colors (bluish) and lower color temperatures (3,000K or less) are warm colors (reddish). There are some standards to define colors based on their temperature as the table I.

Table I
COLOR TEMPERATURE STANDARDS

Standard	Temperature
D50	5003
D55	5503
D65	6504
D75	7504

The number of bits per color channel is also important o define how many shades of color a system can reproduce, the following list presents what happens when changing the amount of bits per color channel:

- 24 bits colors (8 bits per channel)
  256 gray scale, 256 for each color
  total of 16.7 million colors
- 30 bits colors (10 bits per channel)
  1 billion colors
  1024 gray scale and each pure color
- 36 bits colors (12 bits per channel)
  69 billion colors
- 48 bits colors (16 bits per channel)
  2800 trillion colors

D. Resolution

Standards for display resolution were created during the last years. For instance the Super VGA was defined by the Video Electronics Standards Association (VESA), an open consortium set up to promote interoperability and define standards. The resolutions are increasing a lot these last years and the aspect ratios are changing to widescreen due to cinema decisions. One aspect ration that is being used for computer graphics is the 16:10 aspect ratio.

The resolution should be carefully chosen and it depends on the size of your display surface and the distance you are looking at. Angular resolution is a good way to choose what to do; a normal person can detect details of 1 arc minute 20 feet away. Spherical screens might have a different behavior from a planar screen; some fisheye lens have a larger concentration of pixels in the center than in the borders, but this behavior can be avoided using multiple projectors.

Visual Acuity is a value used to measure the ability to visually identify symbols. It is used by ophthalmologists to determine if a person has a normal visual capacity. It uses some standardized patterns and distances. The standard distance to check the visual acuity is 6 meters (20 feets in US) away from a chart, for instance the Snellen chart. A normal person should see the details of one arc second, in this case we say this person is 6/6 (20/20 US). If the person is not able to see the details bigger symbols are used and the person will have a small value for the visual acuity, for instance 6/8, in this case a person will be able to see something that a normal person will see in 8 meters away. The opposite is possible too, but rare, some birds like hawks could have a visual acuity in the order of 6/1.

E. Projection Technologies

Currently there are several projection technologies, five of them will be presented here.

1) CRT - Cathode Ray Tubes: Based on 3 independent tubes (Red, Green, Blue), this kind of projector has the advantages of: calibration flexibility, high refresh rate ($>$ 120MHz), high resolution, and better anti-aliasing. On the other hand, it has the following disadvantages: low brightness, noise signals, and complex color convergence.

2) LCD - Liquid Crystal Displays: Based on liquid crystal technologies, they have the advantages of being inexpensive and the existence of several options in the market. Their disadvantages are low refresh rates and screen door effect.

3) DLP - Digital Lighting Processing: Based on Digital Micromirror Devices - DMD, this kind of projector has the following advantages: supports high lumens lamps, and some models supports active stereo. But it has the disadvantages of some screen door effects. DLP projectors can be three-chip or single chip. In order to a single chip projector display several color it uses a "color wheel" that is a spinning wheel split in color filters segments where the light pass through and gets a particular color each time.

4) LCoS - Liquid Crystal On Silicon: Based on reflexive liquid crystal, this kind of projector has the following advantages: high resolution, small screen door effect, and high contrast. The disadvantage is the existence of only a few models.

5) Laser - Diffraction and Raster: There are two main types of laser projectors, the first is the GLV that is based on diffraction in 1D light scanning and laser as light source. It has the following advantages: ultra high resolution, support to active stereo, no screen door effect, and is always on focus. On the other hand, its disadvantages are: speckle, not very bright, expensive, and presence of a line pattern. The second type of laser projector is based on a 2D light scanning of a laser light source. It has the advantages of providing vivid colours and can be very small. The disadvantages are: speckle and not very bright.

F. Fill Rate

Screen door effect (Figure 2) is a problem that appears in digital projectors where viewers closer to the screen can observe a grid-like structure around the pixels. The LCD pixels have wires around it to control the pixels, in DLP the pixels need to tilt and then they need some space around it, also the old DMD chips has a black spot in the middle due to the hinge that rotates the mirror. Some people solve this problem by setting the projected image a little out of focus, but in this case the image get blurred, what is undesired.

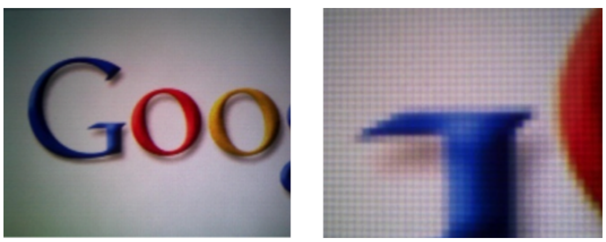

Figure 2. Sample of Screen Door Effect.

The ratio between the visible area and this black area of the pixel is known as fill-rate, fill-factor or even aperture ratio. Figure 3 presents some comparison between the technologies.

Figure 3. Fill Rate comparison.

G. Lamps

The lamps used in the modern projector have several important characteristics that must be reviewed. One important issue related to the lamps is the life cycle. Some very powerful lamps have a short life expectancy, what can be a problem since often lamps replacements can happen. On the other hand these lamps usually have a better spectrum, producing a more homogeneous color output that will be filtered anyway by the color filters. The lumens maintenance is another feature of each lamp, some of them keep the same brightness during all their life, others shift the brightness and sometimes differently for each primary color.

Regarding the fact that these lamps usually get very hot, a cooling solution is necessary, some of these solutions can be very noisy an become a problem for the environment. Some companies use two lamps instead of only one; this can produce a better final brightness and allow you to use just one lamp in the case of failure in the other lamp.

There are several kind of lamps, the most common are:

1) Incandescent: Incandescent lamps are not very common in projectors, althougt they were very common in the past, in slide projectors for instance.

2) Arc-lamps / Gasdischarge: The two main types of arc-lamps are the UHP (Ultra-High Performance) and the Xenon arc lamps. The Hg pressure inside the UHP lamp has to be higher than 200 bar for good color quality and high efficiency. This requires bulb temperatures above 1190K at the coldest spot inside the lamp. At the same time the hottest parts of the quartz envelope have to stay below 1400 K Xenon short-arc lamp is based on the noble gas (atomic number 54). It is usually more expensive and have a short lifetime, but at the same time it is possible to achieve higher brightness and a more homogeneous light spectrum. Figure 4 presents an open UHP lamp.

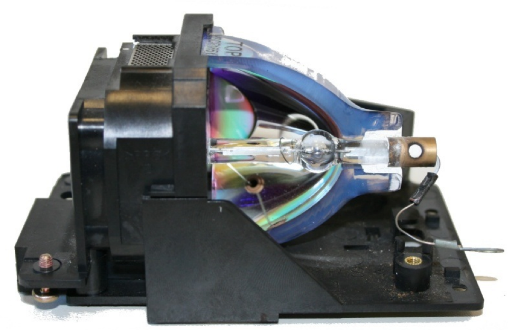

Figure 4. UHP lamp.

3) LED - light-emitting diode: A LED light projector has several advantages, one of them is the fact that it has a longer life and little maintenance, since you do not need to replace the lamp. Also it does not loose brightness as they age and in most point of views it has some improvements in color reproduction. Unfortunately, it is not yet very efficient, with a small luminous flux. But it can avoid color wheels in single-chip solutions.

4) Laser: Lasers are very powerful light sources, unfortunately not all light wavelengths are available for laser, what makes it more difficult to use. Another problem is the fact that when spread, the light of the laser it can become very dim.

H. Other Points to Evaluate in Projectors

Beside the points presented, the following other points are important for specifying a visualization system:

- Aspect Ratio: Determines the size of the screen, some projector have a square resolution, like 4:3, and this will demand a narrower screen. FullHD projector on the other hand has a aspect ratio of 16:9 that is very wide.
- Color and Geometric Alignment: Color temperature is easily found in projectors, but sometimes it is necessary to have a better control to match multiple projectors [10]. Geometric alignment is also important, but it can compromise the quality of the image, for instance many keystone resources create an aliasing effect in the image [11].
- Weight: Some projectors can be as small as a wallet, but others can have more than 300 Kg.
- Audio (speakers): Speakers integrated in projectors are usually very simple and used in specific application, depending on your needs, it must be replaced by a professional sound system.

I. Screens

Although there are several kinds of screens in the market, the material and substrate can be divided into the following categories:

Material Type:

- Flexible
- Semi-rigid
- Rigid
- Painted

Substrate Used:

- Glass
- Acrylic

The gain is defined by the ratio of the light intensity in the perpendicular direction of the screen compared to the reflection of a standard diffuse screen (MgC03), this standard screen has a gain of 1.0. A screen with gain higher than 1 is a high-gain screen, and presents brighter images, but at the same time hot-spots can occur. On the other hand, low-gain screens will dim the image, but will present a more homogeneous image. The name of this measurement is Peak Gain at Zero Degrees Viewing Axis. Figure 5 presents a diagram of possible screen situations.

Other important points in screens are the Half-gain Angle and Viewing Angle. The viewing angle where the luminance decreases by half, compared when you look straight in front of the screen, is known as half-gain angle. This angle can be measured at horizontal and vertical positions, but this is not common, usually the horizontal is the most important and the difference between the vertical and horizontal half-gain is quite small.

The viewing angle of a screen is defined when the contrast gets smaller than 10:1 in a dark room. If the contrast is below this value it is not possible to easily recognize what is being presented, then from this angle we can assume that the image is not readable.

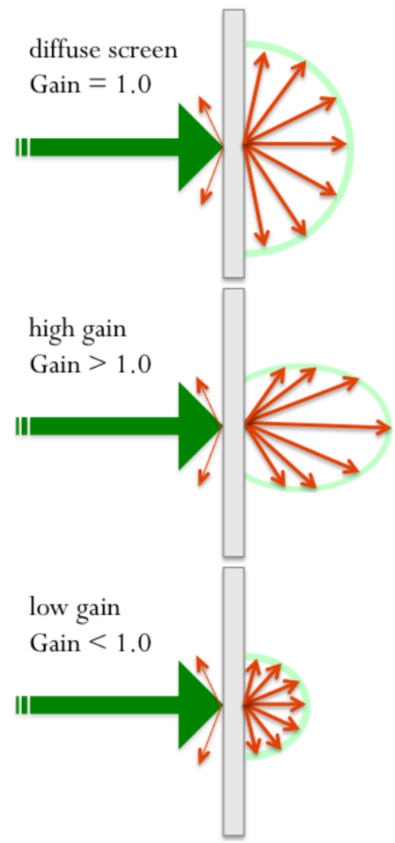

Figure 5. Screen gains.

Some front projection screens can also be perforated for several reasons, like air circulation and sound dispersion. The size of the holes can range from 0.5 milimeters to some millimeters.

J. Mirrors

Mirrors are used to fold projection image paths and then reducing space necessary for projection. One problem with mirrors is the fact that they increase complexity in the system. It is also important that they have a good reflection ratio and be stable, or in other words, that they do not deform with the time.

As the screens, the mirrors can be assembled over many subtracts. Although acrylic and plastic are possible, the most common are glass and polyester films. Glass is easy to fabricate and very common, although it is necessary that the reflection happens in the frontal face of the mirror. It has a good rigidity and good scratch-resistance. Usually the reflective material used is silver or aluminum. It can be very heavy depending on the size and may loose polarization in stereoscopic systems. On the other hand, polyester film, known as Mylar, although the correct name is Polyethylene Terephthalate (PET), can have a thickness from $12\mu m$. Then it is not heavy, but it is very fragile.

K. Display Hardware Infrastructure

Multi-projection systems are widely used in research centers to visualize complex simulation or even to just analyze in 3D some product. The main idea of these systems is to put projectors, one beside the other, with or without some overlap. In order to build these systems a structure must be provided. This structure will hold screens, projectors, mirrors among other devices. There are many materials that can be used for it, but usually these structures are made of wood, aluminium or even plastic, like the CaveUT proposal (http://planetjeff.net/ut/CUTCave.html). Of course one must take care about some aspects like the weight of the structure, if it supports vibrations, and if it interferes somehow with your tracking systems, like metal or infra-red response.

It is important to avoid using very cheap solutions to hold the system, because one may have more problems to calibrate and keep the system stable, besides it might be dangerous and you can loose your hardware or even hurt someone. Aluminium T Slotted Profiles / Extrusions are very good solutions, unfortunately these profiles are a little bit expensive, but they are very stable and allows you to test many configurations.

In order to hold and control the position and orientation of a projector, one can put it over a movable platform. Usually it is interesting to have the 6 DOF with some control, then any possibility can be set for a high precision physical geometric calibration. It is recommended to use bolts in the bottom of the projector to make sure the projector will not move. Just make sure the output air flow of one projector is not going to the other, making one projector heating other projector.

If the images of the projectors overlap, it is necessary to use some sort of edge blending technique [12]. This edge blending will reduce the brightness of the portion of the images that are overlapping. This is a good technique because maintain a homogeneous image, but reduces the overall resolution. Optical blinders are very often used in front of the projector to make the edge blending, it solves problems of light leak, but only software solutions are also very used.

III. Image Generation

In this section we start with the evolution from the expensive mainframes to cheaper PC clusters, showing some configurations with the standard commodity hardware [13], [14]. Issues related to clusters, such as parallelism, frame-locking, gen-lock and data-lock are also discussed. Finally, we present some available software for image generation in multi-projection environments driven by PC clusters.

A. History

Not all the computers are ready for displaying images in high resolution and refresh rate. The computers were simpler and slower than they are today. But these systems were for sure an important starting point for the current graphic workstations. Some well-known computers like the main-frames were not designed to present high quality graphics, although they are quite robust to be used accessed by text terminals. The mini-computer or superminis faced the same issue as the main-frames, but they were smaller and represented a step in the evolution, since sometimes it was possible to connect them to a graphical terminal. Even the powerful supercomputers that are capable of doing millions of float point operations per second were not designed to have a high resolution video output, but they are capable of processing all the mathematical formulas need to render graphics.

In the late 90's, the emergence of high-performance 3D commodity graphics cards paved the way to the use of PC clusters for high-performance VR applications. It was first motivated by the need to have multiple video outputs to drive multi-projector immersive environments. One PC was not able to support multiple video outputs, via one or even several graphics cards, for high-performance 3D graphics.

A PC cluster is a set of interconnected PCs dedicated to process high-performance parallel applications, usually gathered in a single room. This architecture can range from low-end single CPU PCs connected through a common Ethernet or Gigabit-Ethernet network to high-end multi-CPU PCs connected through some high-performance network like Myrinet or Infiniband. In recent years, the PCI-Express bus has been probably the most important hardware evolution for PC clusters. It enables a significant increase in data transfer bandwidth for both the high-performance network and from memory to the graphics card.

64-bit processor architectures allow addressing beyond 4 GBytes of memory, the limit imposed by 32-bit architectures. This is useful for memory-intensive applications.

Memory architecture may also affect how programs can run. In a shared memory environment every processor in a multi-CPU environment can access any memory location with the same address, depending only on the architecture. Some memory locations will be accessed faster by some CPUs. On the other hand, in a distributed environment memory is usually allocated for a set of processors, if one CPU needs to access a memory in another node it has to request to the other CPU to send the memory content to copy in the local memory.

Graphics cards have become more versatile, and it is possible to program part of the graphics pipeline through programmable shaders to achieve high-quality and high-performance final rendering results. As PCs usually provide several PCI-Express slots, it is now possible to install several graphics cards, while only one AGP slot was previously available. Also notice that most commodity graphics cards now provide two digital video outputs.

The difference between a PC cluster and a dedicated supercomputer is getting thinner (at least for small-to mediumsized configurations). They currently use the same CPUs and GPUs, and high-performance networks that provide about the same performance. They run the same operating system (Linux). The main difference lies in the vendors ability to deliver turn-key solutions with strong hardware/software integration, validated configurations and quality user support.

B. Parallelism in VR

The goal when using a cluster is to take advantage of the additional resources available to alleviate performance bottlenecks. To achieve this goal it is necessary to split processing amongst the different cluster nodes. There are basically two different approaches:

- Data parallelism, where several instances of the same task are executed concurrently but on different datasets.
- Task parallelism, where different tasks are executed concurrently.

Parallelism implies data communication and synchronization to ensure proper task coordination. In particular, data redistribution (or sorting) steps are required to make data computed at source tasks available to the target tasks. Depending on the nature and amount of data to be redistributed, the cost can vary significantly. For instance, input events retrieved by a position tracker are limited to a few bytes, while graphics primitives can be significantly larger.

Task parallelism can be used to execute several simulations concurrently. Large simulations, like collision detection or fluid dynamics, may be internally parallelized. For instance, data parallelism is a classical approach for parallelizing fluid simulations. The space where the fluid can evolve is split into regular cells that are then cyclically distributed by blocks [15].

Data parallelism is the main approach for rendering. The standard taxonomy for parallel rendering distinguishes three broad classes, depending on where parallelism occurs in the graphics pipeline [16]:

- Sort-first: Each task is assigned a sub-section (tile) of the entire image to render (Figure 6). Then each task processes independently the graphics primitives that project into its tile until the final image is obtained. This approach is very classical on clusters. Data distribution can occur at the input layer only, all subsequent tasks working locally for their own tiles. Because this scheme only requires carrying lightweight data (input events) over the network, it is widely used for VR applications. However, an important part of the data and computation (mainly simulations and animations) are repeated on each task, thus limiting the benefits of using a cluster for multi-projector rendering and input-event capture parallelization. Henceforth we will call this approach the replication approach. The other classical scheme consists in having the application executed on a single node up to the generation of graphics primitives. Then primitives are distributed to different nodes, each one in charge of computing a tile. Though this helps avoiding most of the replications of the previous approach, performance is impaired by the cost of distributing the graphics primitives, whose amount is proportional to the complexity of the scene. For better scalability, load balance policies [17] are also important; otherwise the overall speed will be defined by the slowest rendering node.
- Sort-middle: Each task is assigned a set of graphics primitives that it processes up to rasterization. Then, data are sorted according to the tile they belong to before rasterization is performed. Because commodity graphics cards integrate both geometry processing and rasterization without giving users the ability to retrieve data before rasterization, this approach is seldom used on clusters.
- Sort-last: The geometry dataset is split and sent to different tasks. In a final step, the images computed by each task are redistributed for compositing (Figure 7). Image compositing can be performed by dedicated hardware reading the images from the video output [18], or through software solutions reading back the images in the frame buffer of graphics cards and using the cluster network to move the data [19]. The complexity is then proportional to the image resolution rather than to the scene. It is also easier to achieve load-balancing, as there is no locality constraints on graphics primitives when they are initially distributed to the different tasks. This solution has been used mainly for scientific visualization, where datasets tend to be very large.

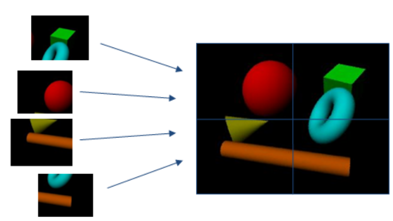

Figure 6. Sort-first distribution and compositing.

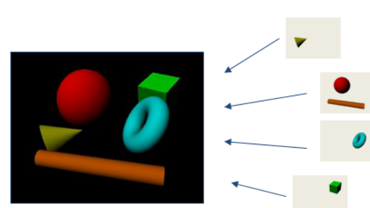

Figure 7. Sort-last distribution and compositing.

C. Consistency and Locking

PC clusters were first used in VR to drive multi-projector environments. The first issue is to ensure that the image streams displayed by the different projectors are coherent, even though they have been computed on different nodes: the images displayed with the different projectors should appear as a single high-resolution image. This image-lock constraint can be decomposed into three synchronization levels: gen-lock, frame-lock and data-lock, presented as follows.

Gen-lock ensures that all video signals generated by the cluster are compatible regarding the color and black level as well as synchronization, which is the most important factor in PC clusters. Synchronization can occur at a pixel, line or frame level. A frame-level gen-lock is mandatory for active stereo. If gen-lock is not properly ensured, the user may see with the same eye a right-and a left-eye image displayed by two different projectors, which would affect the stereo quality. Systems that do not use active stereo usually do not require gen-lock to obtain a good-quality image.

Frame-lock, also called swap-lock, ensures that the images computed on each PC node are released at the same time, i.e., the buffer swaps are synchronized. Failing to ensure a proper frame-lock results in discrepancies, where images that are displayed at the same time correspond to different rendering steps.

The goal of data-lock is to guarantee that the data used to compute the images for the different projectors are coherent. For instance, all images related to the same time frame must be computed from 3D objects that are at the same position or have the same color. Data-lock is a complex issue that can be tackled at different levels of the application.

There are several possibilities to achieve image-lock. Some require specialized hardware, but usually it is possible to synchronize using only software techniques [13].

IV. Software

In this section we list different software tools for VR that support PC clusters. Most of them are open source. This list is not exhaustive, but its covers the most common and advanced uses of parallelism for VR applications. Each tool is positioned according to the parallelism it enables. Surveys on this topic are presented in [20] and [21].

CAVELib [22] was developed at the Electronic Visualization Lab to drive the first Cave [5]. Initial versions ran on a cluster of SGI machines, using a replication approach. Some fixed data, such as a navigation matrix and input device values, were shared throughout the cluster. Further data sharing could be implemented by transferring blocks of memory between nodes. Nowadays it supports PC clusters following a similar replication approach.

VR Juggler [23], [14] is a software framework for developing portable VR applications. VR Juggler relies on a client/server paradigm where inputs are executed on servers while clients take care of parallel rendering. Both approaches use a replication approach.

Syzygy is a software library dedicated to VR applications running on PC clusters [24]. Syzygy supports networked input devices and sound rendering. It includes two application frameworks, both based on a master/slave paradigm. The first one relies on a classical duplication paradigm, while the second proposes to distribute the data from the master at the scene-graph level (or animation level according to our classification). Syzygy provides a special protocol to transport the scene-graph primitives. The replication approach is normally used when a scene-graph approach is not appropriate, such as for volume rendering.

DIVERSE [25] is a modular collection of complementary software packages designed to facilitate the creation of device-independent virtual environments. DgiPf is the DIVERSE graphics interface for OpenGL Performer. A program using DgiPf can run on platforms ranging from fully immersive systems such as CAVEs to generic desktop workstations without modification. On clusters, DIVERSE relies on a replication paradigm.

Chromium [26] proposes a stream processing framework for OpenGL graphics primitives. A network of Stream Processing Units (SPUs) enables the application of different transformations to the primitive stream. Chromium is mainly used for sort-first and sort-last parallel rendering. SPUs implement various optimizations to reduce the amount of data to be sent over the network. Chromium enables the execution of an unmodified OpenGL application by intercepting the graphics primitives and broadcasting them to rendering SPUs, each one in charge of its own image tile. Commercial solutions based on a similar approach are available today, such as TechViz Fusion [27] for instance.

OpenSG [28], [29] is a portable scene-graph system. It allows multiple asynchronous threads to independently manipulate the scene graph without interfering with one another. As scene-graph data can get very large, a distinction between structural and content data has been introduced, with a method to replicate the latter only if necessary. OpenSG also runs on PC clusters and is implemented as an extension of the multi-threaded model. Changes in the environment are propagated when they are applied to another node. OpenSG has a Multi Display Window mode, used to render one virtual window on a number of cluster servers, allowing the use of OpenSG in a CAVE configuration. OpenSG can also be used with a replication approach when combined with other tools such as VR Juggler.

Among other challenges, software tools have to be adapted and developed for cluster architectures. The main difficulty lies in developing software solutions that enable taking advantage of the performance offered by clusters while keeping the complexity of application development, deployment and execution as low as possible. Today such solutions are available for distributed rendering while others are emerging to provide extra computing capabilities for processing input data from sensor networks, or handling multi-modal applications involving 3D graphics, spatialized sound, haptics systems, multiple simulations, etc.

V. Conclusions

Several possibilities for projection solutions are available, the main issues related to these technologies were presented and based on the information presented here, one may get a better idea of the resources more adequate for her/his needs. It is important to note that technology is evolving quite fast and new products are released every day, and further analyses of what is available is important to define new visualization projects.

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