Proceedings of the IMProVe 2011
International conference on Innovative Methods in Product Design
June 15th – 17th, 2011, Venice, Italy

Fast Correction of Tiled Display Systems on Planar Surfaces

Carlos Zoido [(a)], Joaquin Maroto [(a)], Gregorio Romero [(a)], Jesus Felez [(a)]

[(a)]CITEF – Universidad Politécnica de Madrid. c/ José Gutierrez Abascal, 2. 28660 Madrid - Spain

Article Information

Keywords:
Tiled displays,
Projection,
Simulation,
Blending,
Geometric alignment.

Corresponding author:
Jesus Felez
Tel.: +34 91 336 31 16
Fax.: +34 915 618 618
e-mail: jesus.felez@upm.es
Address: CITEF – Universidad Politécnica de Madrid. c/ José Gutierrez Abascal, 2. 28660 Madrid - Spain

Abstract

A method for fast colour and geometric correction of a tiled display system is presented in this paper. Such kind of displays are a common choice for virtual reality applications and simulators, where a high resolution image is required. They are the cheapest and more flexible alternative for large image generation but they require a precise geometric and colour correction. The purpose of the proposed method is to correct the projection system as fast as possible so in case the system needs to be recalibrated it doesn't interfere with the normal operation of the simulator or virtual reality application. This technique makes use of a single conventional webcam for both geometric and photometric correction. Some previous assumptions are made, like planar projection surface and negligibleintra-projector colour variation and black-offset levels. If these assumptions hold true, geometric and photometric seamlessness can be achievedfor this kind of display systems. The method described in this paper is scalable for an undefined number of projectors and completely automatic.

1 Introduction

Building a large area high resolution display system hastraditionally been and expensive task involving the use of specialized hardware for manual adjustment and maintenance by qualified personnel. This is the reason why lately a lot of research has been done in order to reduce costs for adjusting such systems [17]. Thanks to advances in PC graphics hardware, projector technologies and digital capture devices,there are a lot of new tools available that can be used for calibrating a tiled projection display at a low cost.

The goal in the development of a tiled projection display is suppressing all perceptible discontinuities, caused by geometric misalignment and colour variations across the projectors,while trying not to reduce the image quality. The final image must beseamless both geometrically [18] and photometrically[3].

The first challenge in building a tiled display system is the alignment of the projectors. This implies eliminating the effects of a casual projector placement.Each projector output image is transformed so it perfectly aligns with adjacent projectors. This is achieved by projecting structured light of a known geometrical pattern, like a checkerboard or temporal coded light patterns[19]. Through this pattern,camera-projector correspondences are established in order to relate all the projectors to a common reference frame. This reference frame is usually set along the display surface using a "fiducial border" [16] or taking anarbitrary reference frame.

Once the geometric correction is applied the colour discontinuity problem needs to be solved. There are noticeable photometric continuity breaks in the projector overlapping regions and colour shifts between projectors can also appear.

Years ago all these problems were treated with Hardware-based solutions[20]. Geometric discontinuity was solved with special projector mounts to get a precise projector alignment. Photometric correction was achieved putting metal plates physically interfering with the beam of light in order to tone down the brilliant areas in the overlap zones. This approach is extremely expensive and slow. Thanks to the advances in graphics hardware it is possible to implement software image correction in real time using geometric transformations, correction masks and colour look up tables.

Although several methods have been developed to correct tiled projection systems, most of them are not fast enough recalibrate the display in a short time.Some of them also use expensive equipment such as spectrorradiometers or expensive digital cameras. The proposed implementation can achieve automatic geometric and photometric correction in a few seconds using a conventional webcam and graphics hardware.

The most popular methods of correction for tiled display systems are listed and explained next.Then,the proposed implementation is presented.

2 Geometric correction of tiled displays

Although several methods have been developed for geometrical correction of multi-projector systems on flat surfaces the same idea lies behind them. Using a camera to find out the relationship between the camera, surface and projector coordinate systems. These coordinate systems are shown In fig. 1. The notation adopted by [1] is followed.

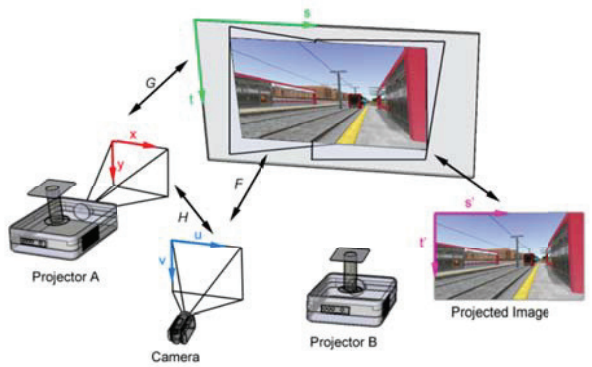

Fig. 1Planar projection surface with all the coordinate systems involved.

The surface projection is denoted as S, with horizontal and vertical coordinates (s,t). The total projected image I is parameterizedby (s',t'). The relation between (s',t') and (s,t) in planar projection surfaces is a scale plus a translation so they can be considered equivalents. Each projector in the system P_i has its own coordinates (x_i, y_i). The transformation that relates each projector to the projection surface $G_{(x_i,y_i)\to(s,t)}$ (eq. 1) has to be found. This transformation can be calculated as the composition of the function that relates the camera coordinates $C(u,v)$ to the display coordinates $F_{(u,v)\to(s,t)}$ and the one that relates the camera coordinates to the projector coordinates $H_{(x_i,y_i)\to(u,v)}$.

$$G_{(x_i,y_i)\to(s,t)} = F_{(u,v)\to(s,t)} \cdot H_{(x_i,y_i)\to(u,v)} \qquad (1)$$

The most usedmethods to establish these mappings between coordinate systems are described below.

2.1 Linear methods

This method assumes geometric linearity in both the camera and the projector. If this assumption is true, or if the camera and the projector have non-linearities, but they can be corrected (to make them behave as linear devices), then a linear transformation called homography can be used to make the mapping between all the coordinate systems [2].

2.2 Piecewise linear methods

Geometric correction can also be achieved via *piecewise linear* methods[3].Instead of having a model for the transformation functions, a dense correspondence between camera and projector features is established. This method is valid when the projector lens distortion is not negligible. Once the pattern has been registered, the coordinates systems are parameterized interpolating. This interpolation can be done with three points using barycentric coordinates or with four points defining a homography matrix.

The disadvantage of this method is that it needs a high resolution camera to capture the correspondences with enough precision.

2.3 Non-linear models

When non-linearities are present, cubic polynomials can be used to relate the camera and projector coordinate systems [4]. This model can deal with projector's lens distortion but it requires iterative algorithms to estimate all the parameters and a dense correspondence of features to establish the model.

Recently another method has been developed where a rational Bezier patch is used for relating the projector to the other elements of the system. Bezier patches can model different kinds of distortion with great accuracy [5].

3 Photometric correction of tiled displays

One of the challenges when designing multi-projector projection systems is to solve the color variations that may appear on the projection surface. These variations break the projected image continuity. In this section, the causes of color variations in tiled display systems and the different methods for avoiding them are discussed.

3.1 Colour discontinuities in tiled projection displays

Colour variations can be produced in greater or lesser degree depending on factorssuch as the optics of the projectors, their spatial distribution, their technology or the type of projection surface which displays the image. The causes of colour variationsare analyzedbelow.

3.1.1 Intra-Projector variations

Such variations are those that can be seen within the area of influence of a single projector. Several studies have determined that projectors show color variations mostly due to changes in luminance. Chrominance variation inside the area of the projector is minimal [6].Also, the normalized transfer function of the projector remains constant throughout the projection surface[7].

3.1.2 Inter-Projector variations

If the projection system is composed from projectors of different makes and models colour discontinuities will occur due to the different colour outputs.

Sometimes, even if the projection systemis composed of projectors from the same make and model these variations can happen if they have different lamp age or are configured with different settings.

3.1.3 Overlapping areas

The areas where two or more projectors overlap show a significant increase in brightness. These areas have to be corrected through an attenuation factor that mitigates this effect.

3.2 Colour correction methods

In recent years various color correction methods have been developed in order to achieve photometric uniformity across the display, or at least smooth colour variations.Some of these methods are presented in the following sections.

3.2.1 Luminance attenuation maps

This method corrects the inter-projector, intra-projector and overlapping regions luminance variations[9]. It uses per channel maps that scale the the luminance response in order to produce smooth transitions between projectors. Since it cannot adress chrominance variations it doesnt perform very well for flat colours when projectors have large colour shifts.

3.2.2 Gamut matching

Gamut matching based methods [10]only adress the inter-projector colour variations. They usually use a sensing device such as a spectrorradiometer to measure the 3D gamut of each projector. This gamut is a parallelepiped for three primary projectors. Then a common gamut is defined resulting from the intersection of all the parallelepipeds.Finally, the colour output of all the projectors is mapped to this common gamut.This method is only valid for three primary projectors where linear transformations can be applied.

This method was expanded to handle four primary devices such as DLP projectors[11].Making a dense sampling of the colour output to measure the gamut with nonlinear primaries dependencies. This procedure is expensive and slow as it requires an spectrorradiometer and dense colour sampling.

3.2.3 Gamut morphing

This method addresses spatial colour variations in both chrominance and luminance [12]. It morphs the gamut across the display in order to make smooth chrominance and luminance variations. This morphing is constrained by perceptual parameters producing a seamless display.

4 Proposed implementation

The correction method explained below is used to correct tiled projection displays for driving simulators. Maintenance of these displays must be fast and completely automatic as a break in the normal operation of a simulator can cause economic losses.

The described methodis completely automatic and can achieve both geometric and photometric correction in seconds. As far as we know previous methods require some user intervention or are segmented in different applications that have to be executed manually, usually with Matlab coded parts that slows the correction procedure. This method is implemented in C++ and offloads some of the most intensive calculations to the graphics card GPU. This allows us to make fast corrections that don't alter normal operation when the system needs to be recalibrated.Thetechnique makes some assumptions like the black level of the projectors is negligible and that there are not intra-projector colour variations. The inter-projector variations are considered negligible. This assumption holds almost true for displays with projectors from the same make and model with the same settings where only small variations in the white point and maximum luminance could appear due to different lamp ages. The method can still be used in the case that the assumptions are not true, where projectors show large colour shifts, but the final result could show undesirable perceptible colour differences.

4.1 Geometric correction

The proposedimplementation uses structured light techniques to establish the correspondences between camera, projector and projection surface. Temporal coded patterns with gray codes (fig. 2) are projected.Gray codes reduce the probability of detection errors between consecutive patterns [13]. These patterns are captured by a conventional webcam with all of its settings fixed.

Fig. 2 Complete sequence of vertical and horizontal gray codes emited by each projector.

The webcam is synchronized with the pattern output and can capture at a rate of 10 patterns per second. Usually no more than 5 patterns are needed for precise geometric alignment. This means that it takes about two seconds to retrieve the pattern information for each projector.

Fig. 3 Vertical and horizontal gray codes combined to produce a checkerboard pattern.

Once all the images have been captured they are processed in order to get correspondent points between reference frames. The intensity levels of the horizontal $I_h(u,v)$ and vertical $I_v(u,v)$ images are processed in eq. 2 to produce a checkerboard pattern image(fig. 3).

$$I_{checkerboard}(u,v) = \left| I_h(u,v) - I_v(u,v) \right| \qquad (2)$$

The checkerboard corners are extracted using computer vision techniques(fig. 4). Only the inner points of the checkerboard are kept. All the points lying on the outside contour are discarded. Gray codes are used to label all the points. The point labelling procedure is shown in fig. 5.

Fig. 4 Inner points are detected and labeled..

The found location of the checkerboard corners are refined usingsub-pixelaccuracy algorithms like the ones explained in [14],resulting in the points that will establish the correspondences between reference frames.

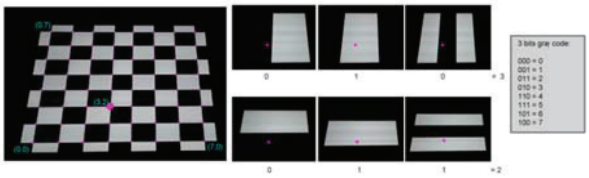

Fig. 5 Labeling the point at column 3, row 2 using gray codes.

Once all the points are detected and labeled in camera space (u, v) they are related to the projector (x, y) and the surface (s, t) to find the transformations between systems(fig. 6). As the projection display is planar and the webcam's lens distortion has been corrected using the method in [15], this relation is a homography transformation.

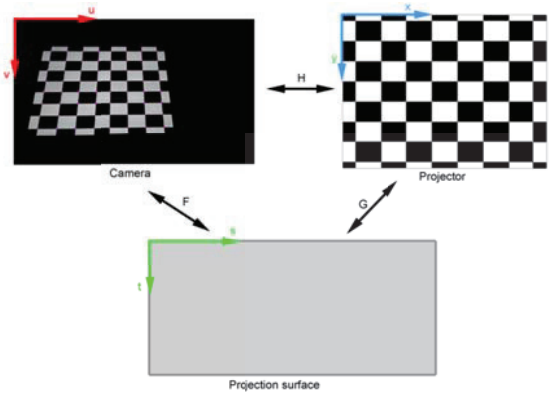

Fig. 6 Relations between reference frames of one projector and the projection surface.

The final projection surface reference is chosen via an automatic algorithm to use all the available space for projection. The only measure that has to be provided is the aspect ratio of the final projected image.The method is explained for a two projector display, but can be scaled for any number of projectors.

The area where the final image is going to be projected is a trapezoid. To calculate this trapezoid the outer contour of each projector in camera space Q_i is determined. These contoursare then joined (eq. 3), obtaining the total area of influence of all the projectors E .

$$E = \bigcup_{i=0}^{n} Q_i \tag{3}$$

The polygon E is taken to an arbitrary coordinate frame where the projected image of one reference projector is perfectly aligned. In this reference frame the algorithm finds the maximum inscribed polygon thatwill form the final projection trapezoid E'. For each projector the intersection of Q_i and E' is calculated(eq. 4). This intersection Q_i' gives the transformation that must be applied for each projector.

$$Q_i' = E' \cap Q_i \tag{4}$$

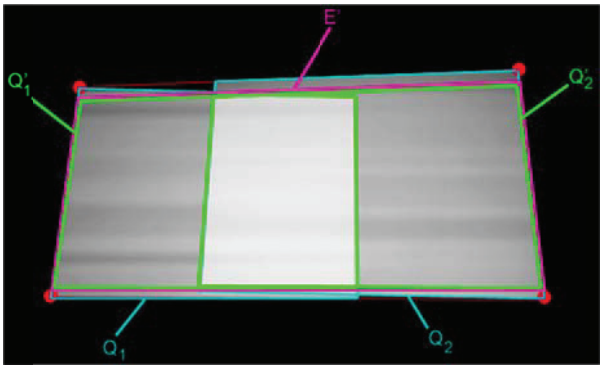

Fig. 7 Determining the final projection area.

This geometric correction algorithm (running in a mid-range PC) takes only about 10 seconds to make all the calculations for a four projector tiled display.

4.2 Photometric correction

The most noticeable photometric discontiniuities appear in the overlap regions. This method generates correction masks for these areasin a few seconds. Our experience indicates that in tiled projection systems with the same model of projector, inter-projector color variations are neligible, in case the projectors have similar lamp ages. If ages of lamps differ between projectors producing inter-projector colour variations, luminance and white point correction could be aditionally applied. The majority of the tiled displays use the same model of projector,so this method will perform well in most cases.

Overlapping region discontinuities are corrected via attenuation masks. These masks are calculated using the data obtained in the geometric registration. The masks multiply the output image in order to make brightness steps disappear.

The correction function $G(\vec{p}_i)$ presented in [16] for mask calculation is used in this step. The function is shown in eq. 5.

$$G(\vec{p}_i) = \frac{\xi_i}{\sum_{j=0}^{N} \xi_j}; \xi_i = \prod_{k=1}^{4} d_{i,k} \tag{5}$$

Where $d_{i,k}$ is the distance from one point of projector i to the edges of the k projectors that overlap it.

To avoid overcompensation effect (fig. 8) this function is corrected with a gamma transformation. This step is faster than estimating the projector tranfer functions like in previous studies ([9],[16]) with similar results.

Fig. 8 Four projector display with overcompensation (left) and with the gamma correction applied (right).

The final compensation mask $A(\vec{p}_i)$ is shown in equation 6.

$$A(\vec{p}_i) = G(\vec{p}_i)^{\gamma} \tag{6}$$

Typical calculation procedures for these masks involve a number of operations that increase with the projector resolution. In a SXGA projector 1.310.720 operations are needed to calculate the mask for each projector with standard procedures.

This implementation takes advantage of graphics hardware in order to speed up the calculation of these masks and reduce the number of operations.

First, a triangle mesh is generated in the projector reference frame.

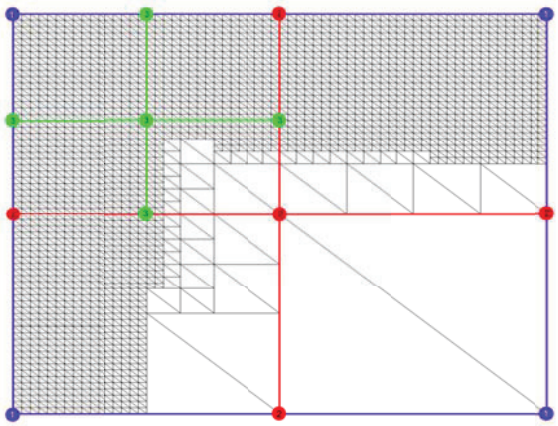

Fig. 9 Triangle mesh for mask calculation.

Each triangle vertex of this mesh has an associated color that contains the information of the mask correction factor, calculated with the function $A(\vec{p}_i)$. As can be seen in fig.9, this mesh is not regular. Some of the vertex will contain the same information that others and fine triangulesubdivision is not generated in those areas.

The parameter η is defined. This parameter represents what we call the "maximum partition level". This level defines the number of divisions of the mesh. A bigger η will produce more precise masks but will require more calculation time.

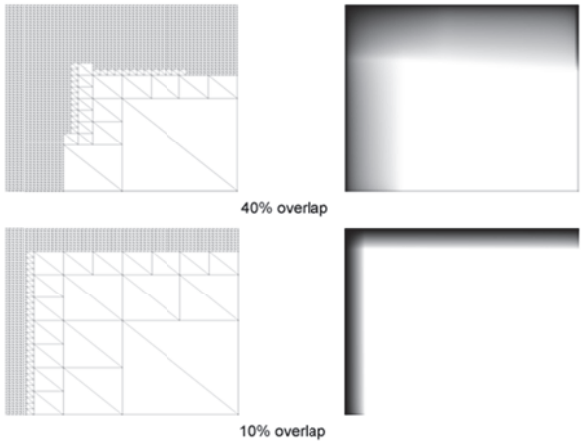

Fig. 10 Rendered triangle meshes for 40% and 10% overlap.

Once all the vertex colors are assigned, the mesh is rendered to a texture. The GPU makes all the interpolation between triangle vertex producing the correction factors for every pixel in the projector space. In fig 10 the rendered texture is shown for 10% and a 40% overlap regions.

The influence of η in the rendered texture quality is shown in fig. 11. Differences beyond $\eta = 32$ are imperceptibleso 32 is chosen as the default value.

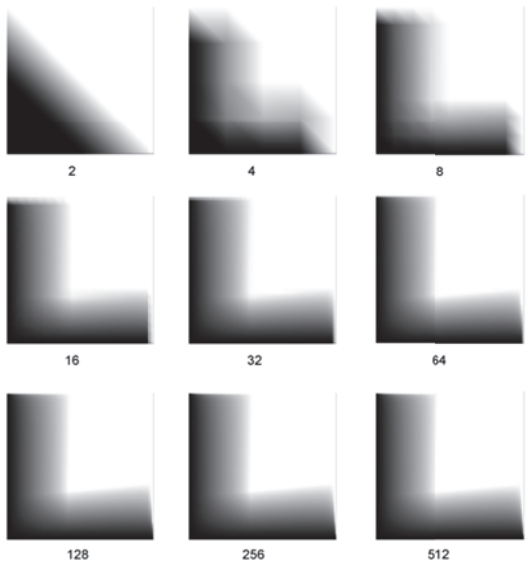

Fig. 11The same mask generated with maximum partition factor η from $\eta = 2$ to $\eta = 512$.

The results of the optimization are presented in tab. 1 (time in seconds). The following notation is used:

- *η: Maximum partition level. Number of subdivisions of the mesh.*
- *t_{TR}: Total timeto generate a correction masks through a regular triangle mesh for each η.*
- *t_{TI50} and t_{TI10}: Total time to generate the correction masks with the proposed irregular mesh for two different four projector system with 50% and 10% overlaps.*

- t_{CPU}: *Total time in generating the correction masks without any optimization.*
- I: *Measuresthe improvement in time usingthe proposed method for a 10% overlap. It is calculated as* $\frac{t_{CPU}}{t_{TI10}}$.

η	t_{TR}	t_{TI50}	t_{TI10}	t_{CPU}	I
2	0,977	0,977	0,978	204,300	208,93
4	0,992	0,993	0,993	204,300	205,64
8	1,086	1,058	1,029	204,300	198,62
16	1,307	1,279	1,115	204,300	183,16
32	2,896	2,581	1,705	204,300	119,79
64	10,876	7,704	3,939	204,300	51,86
128	36,562	27,796	13,734	204,300	14,87
256	126,919	97,656	43,315	204,300	4,71
512	508,548	483,713	187,399	204,300	1,09

Tab. 1Results for different η **values.**

These results are for one projector in the display. As can be seen, the masks for all projectors are generated in about 7 seconds for the default partition while it would take up to 13 minutes using a standard procedure without theoptimizations. Our method performs 120 times faster ($\eta = 32$) than standard CPU calculation. The algorithm runs on an Intel Xeon 3,06GHz and 2 GB of RAM with a NVIDIA GForce 6800 GT.

The final results of our implementation are showed in figures 12 to 14. As can be seen on the images, there are no photometric or geometric discontinuities.

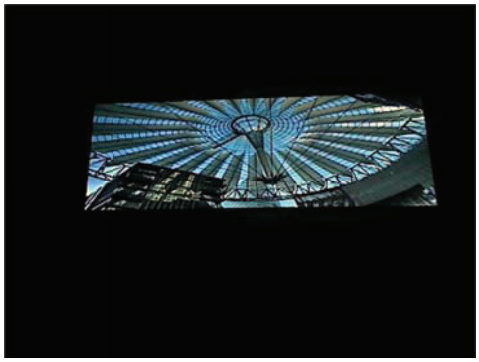

Fig. 12 Two projector display.

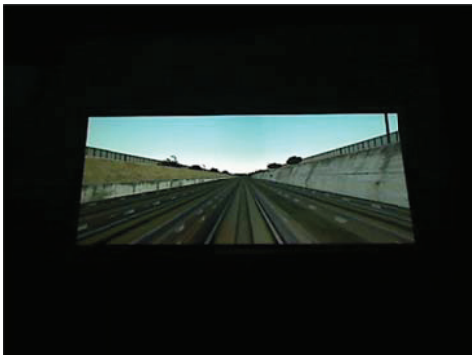

Fig. 13 Two projector display. Even in flat color areas photometric uniformity can be achieved.

Fig. 14 Four projector display system.

5 Conclusion

The proposed method has proved to have numerous advantages in projection systems where frequent recalibrations are needed. It's fast, fully automatic and can achieve photometric and geometric uniformity for the majority of tiled displays.

Thanks to the use of the GPU, correction of the projection system can be made in a few seconds. Also, the hardware required to perform the entire correction is extremely economical.

However, our method is limited to planar surfaces and to projectors that dont have large colour shifts. At the present time we are extending our implementation to handle a wider range of display types such as curved surface displays and the ones composed of different types of projectors.

References

[1] Aditi Majumder and Michael S. Brown. 2007. *Practical Multi-Projector Display Design*. A. K. Peters, Ltd., Natick, MA, USA.

[2] H. Chen, R. Sukthankar, and G. Wallace. Scalable Alignment of Large-Format Multi-Projector Displays Using Camera Homography Trees. In Proceeding of IEEE Visualization 2002, pages 339–346, 2002.
[3] Michael Brown, Aditi Majumder, and Ruigang Yang. 2005. Camera-Based Calibration Techniques for Seamless Multiprojector Displays. IEEE Transactions on Visualization and Computer Graphics 11, 2 (March 2005), 193-206.
[4] M. Hereld, I. R. Judson, and R. Stevens, Dottytoto: A measurement engine for aligning multi-projector display systems. Argonne National Laboratory preprint ANL/MCS-P958-0502, 2002.
[5] Ezekiel S. Bhasker, Aditi Majumder, "Geometric Modeling and Calibration of Planar Multi-Projector Displays Using Rational Bezier Patches," Computer Vision and Pattern Recognition, IEEE Computer Society Conference on, pp. 1-8, 2007 IEEE Conference on Computer Vision and Pattern Recognition, 2007
[6] Majumder, A.: Properties of color variation across multi-projector displays. SID Eurodisplay, Nice, France (2002).
[7] Brown, M., Majumder, A., and Yang, R. 2005. Camera-Based Calibration Techniques for Seamless Multiprojector Displays. IEEE Transactions on Visualization and Computer Graphics 11, 2 (Mar. 2005), 193-206.
[8] Aditi Majumder and Rick Stevens. 2005. Perceptual photometric seamlessness in projection-based tiled displays. ACM Trans. Graph. 24, 1 (January 2005), 118-139.
[9] Aditi Majumder and Rick Stevens. 2002. LAM: luminance attenuation map for photometric uniformity in projection based displays. In Proceedings of the ACM symposium on Virtual reality software and technology (VRST '02). ACM, New York, NY, USA, 147-154.
[10] Grant Wallace, Han Chen, and Kai Li. 2003. Color gamut matching for tiled display walls. In Proceedings of the workshop on Virtual environments 2003 (EGVE '03). ACM, New York, NY, USA, 293-302.
[11] Stone, M. C. 2001b. Color balancing experimental projection displays. 9th IS&T/SID Color Imaging Conference, 342-347.
[12] Behzad Sajadi, Maxim Lazarov, M. Gopi, and Aditi Majumder. 2009. Color Seamlessness in Multi-Projector Displays Using Constrained Gamut Morphing. IEEE Transactions on Visualization and Computer Graphics 15, 6 (November 2009), 1317-1326.
[13] E. Horn and N. Kiryati, Toward Optimal Structured Light Patterns," Image and Vision Computing 17(2), 87{89 (1999).
[14] Gary Bradski and Adrian Kaehler. September 2008. Learning OpenCV. Computer Vision with the OpenCV Library. O'Reilly Media.
[15] Zhang, Z. 2000. A Flexible New Technique for Camera Calibration. IEEE Trans. Pattern Anal. Mach. Intell. 22, 11 (Nov. 2000), 1330-1334.
[16] Michael Harville, Bruce Culbertson, Irwin Sobel, Dan Gelb, Andrew Fitzhugh, and Donald Tanguay. 2006. Practical Methods for Geometric and Photometric Correction of Tiled Projector. In Proceedings of the 2006 Conference on Computer Vision and Pattern Recognition Workshop (CVPRW '06). IEEE Computer Society, Washington, DC, USA, 5-.
[17] A.Majumder, A Practical Framework to Achieve Perceptually Seamless Multi-Projector Displays, PhD thesis, technical report, Univ. of North Carolina at Chapel Hill, 2003.
[18] A. Raij, G. Gill, A. Majumder, H. Towles, H. Fuchs, “PixelFlex2: a comprehensive, automatic, causally-aligned multiprojector display”. PROCAMS’03.
[19] N. Chang. “Efficient dense correspondences using temporally-encoded light patterns.” In PROCAMS’03.
[20] Daniel R. Schikore, Richard A. Fischer, Randall Frank, Ross Gaunt, John Hobson, and Brad Whitlock. 2000. High-Resolution Multiprojector Display Walls. IEEE Comput. Graph. Appl. 20, 4 (July 2000), 38-44.