Photometric and Chromatic Calibration for Multi-Projector Tiled Displays

Alain Pagani and Didier Stricker, Fraunhofer Institute for Computer Graphics Research IGD, Darmstadt, Germany

Abstract

We address the problem of calibrating the colors of a multiple projector tiled display. Differences in the characteristics of the projectors lead to varying color and intensity among the tiles of the display. These differences do generally not only arise between two different projectors, but also between different spatial locations on the projected surface of one single projector. In this paper, we present two algorithms for calibrating the colors of a tiled display. The first method is an automatic procedure to make the luminance uniform over the projected surface of one single beamer, using a common digital camera as a luminance measuring device. The second method aims at uniformizing the colors of multiple projectors by computing the set of color commonly displayable by all the beamers (the common gamut). We show how to find an optimal color gamut displayable by all the projectors in linear time, and derive the color conversion from one color gamut to the common gamut. We successfully tested the method on a tiled display made of 48 projectors with large chrominance shifts.

Introduction

Large multi-projectors displays have gained considerable importance in the last decades as scalable, inexpensive and high-precision visualization systems. Their extremely high resolution makes them particulary attractive for collaborative work, industrial design or edutainement.

Figure 1. *High resolution stereoscopic tiled display with 48 beamers (courtesy of Fraunhofer IGD).*

However, achieving the illusion of one large seamless display relies on a precise calibration of the system, which aims to solve three specific problems[7]: the variation of the geometric properties of the individual display units, the *intraprojector color variation* (color variation within a single projector) and the *inter-projector color variation* (color variation across different projectors).

Even if satisfying solutions have been proposed for the geometric calibration problem [2, 10, 11, 9], the *color calibration* of a tiled display remains an open issue.

In the past decade, the color calibration problem has been partially addressed using different approaches. The *Gamut matching* approach [12, 13, 5] assumes that the intra-projector variations can be neglected, and the color gamut of each projector (*i. e.* the set of colors the projector can display) is measured. A common gamut is then computed and a conversion from a specific gamut to the common gamut is done using linear transformations. The main limitations of this approach is the case of strong intra-projector variations, and the high time consumption. The *Intensity manipulation* approach [6, 9, 7, 8] assumes that the chromatic properties of the projectors are uniform across the display. In this special case, the color variations are only due to varying intensities of the different color channels. The display's intensity response function is first modelled and measured, and the input image is corrected using the inverse model to compensate the photometric variations. However, this approach excludes using different models of projectors in the same setup.

In this paper we present a new method to calibrate a tiled display. This method mixes the advantages of the gamut matching and intensity manipulating approaches in a two-step process. With the tenable assumption that the chromatic properties of each channel of a single projector is spatially invariant, we developed an iterative algorithm for intensity compensation of one single projector. We then derive fast algorithm for finding a common gamut between n projectors in time $O(n)$. The main contribution of this paper is the generality of the calibration method. Our fast gamut matching algorithm allows for tiled displays with large chrominance shifts (with *e. g.* projectors from different vendors), and our iterative shading correction does not make the assumption of a spatially invariant intensity transfer function for each projector.

The remainder of the paper is organized as follows. We first discuss the intra-projector calibration problem and present our iterative algorithm to address the photometric variation inside one projector. The inter-projector calibration is then addressed, along with our novel gamut matching algorithm. We then present our results and conclusions.

Intra-projector calibration

Single projectors generally present intensity or chrominance variations, leading to the characteristic color blotches of an uncalibrated projector(see Figure 4, top).

Actually, the chromatic properties of a single projector are generally spatially invariant. Majumder and Stevens showed that
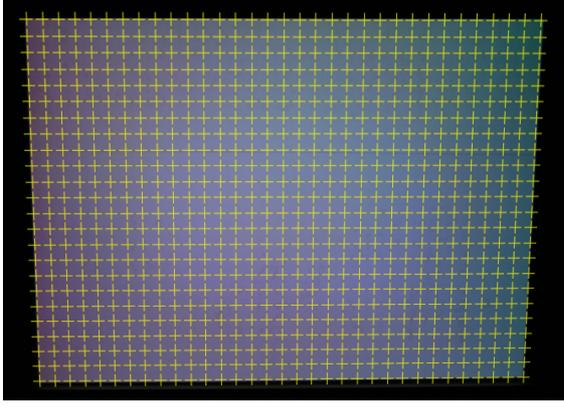
Figure 2. *Location of the 825 shading points over the projected surface (one beamer)*

Figure 3. *Shading correction for a single shading point*

the spatial variations in intensity within a single projector is much more significant than the spatial variation in chrominance [7]. We can therefore balance only the intensity variations for each channel.

The main idea of the method is to modify the intensity of the input pixels to compensate the original intensity differences. Known methods for intensity manipulation [7, 9, 6] define a parameterized model of the intensity variation, measure sample points of this model and apply the inverse of the model for correction. The disadvantage of model-based solutions is that they rely on simplifying assumptions to reduce the complexity of the model. For example, they often stipulate that the normalized intensity transfer function of a projector does not vary spatially.

To reduce the number of assumptions, we opted for an iterative loopback call method with progressive input manipulation.

Shading table

In order to manipulate input values, we use input correction tables or *shading tables*. A shading table is a set of *shading points*, each having a specific position on the displayed image (generally disposed as a grid, see Figure 2). At these specific positions, the input intensity can be modified. Between the points, the modification is interpolated from the neighbor points.

Figure 2 shows the location of 825 shading points over the projected surface of one beamer, and figure 3 shows a possible correction for a single shading point, with a 10-bits input range (0 to 1023). The original behavior for this point is the plain line of equation $x_{new} = x$. Each shading point has a number of *levels* that can be modified. The levels define which input value can be corrected and their values (positive or negative) the absolute correction. Between the levels, the correction is linearly interpolated. The final behavior of the point is represented by the dashed line.

We compute the intensity correction on a per-channel basis. For a single projector, one shading table per color channel is needed. The advantage of using shading tables is that the number of points and the number of level is modifiable. In our setup we used a grid of 33 by 24 points and 3 levels. Moreover, this model can be used for correction without any knowledge of the intensity transfer function of the projector. In some models of programmable projectors, such shading table already exist as functional-
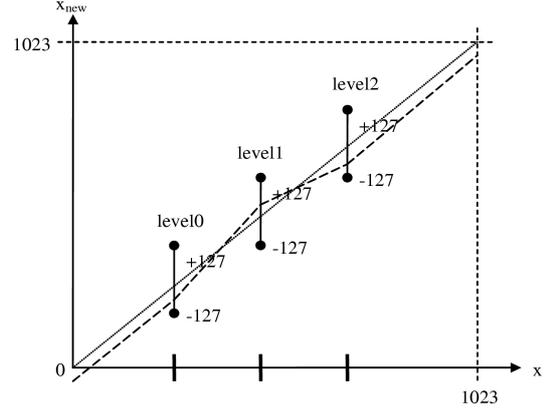
ity and can be easily read/written through a specific interface. If not, the shading tables must be applied earlier in the graphical pipe-line by modifying directly the input values.

Automatic shading correction

We now want to find the best correction value for each level of each point to achieve color uniformity for a projector. To this aim, we use the digital camera as a luminance measuring device. Because we use a camera with adjustable exposure time, we augment the dynamic range of the camera by taking the measurements in High Dynamic Range (HDR) images [3]. This allow us to recover the non-linearity of the camera for each color channel and to automatically adapt the camera's exposure time to the measured intensity. A preliminary geometric registration is performed using a homographic transformation of the camera image.

We experienced that the luminance of a projector continuously displaying the same picture is not constant in time as expected from an ideal projector. Instead, the luminance wavers from a maximum value to a minimum value with an unpredictable but relatively constant frequency. To work around this problem, we developed a method based on instant comparison between points at different spatial locations. To this aim, we define a set of points with similar measured luminance as *target points*, and measured the luminance of the other shading points relatively to the target points.

Considering just one shading level, each shading point P_i has a signed correction value v_i (the correction applied to the input for this point) and a signed step size s_i (positive when increasing the input value, negative when decreasing the input value).

For each color channel of the projector and each level defined above, we apply following algorithm:

1. Initialization: For all shading points, set the correction value $v_i = 0$. Measure the luminance for each point. Take a set of 5% from the points with median luminance and mark them as target points. Choose an initial positive step size s_{init} for input correction. For all points that are darker than the target points, set $s_i = s_{init}$ as individual step size. For all points brighter than the target points, set $s_i = -s_{init}$ as individual step size.

Figure 4. *A projector before (top) and after (bottom) intra-projector correction.*

2. For all points, apply $v_i = v_i + s_i$
3. Measure the luminance for each point
4. For each point, if $s_i > 0$ and the point is brighter than all the target points, divide s_i by 2 and inverse its sign. If $s_i < 0$ and the point is darker than all the target points, divide s_i by 2 and inverse its sign. If the luminance of the point is between the darkest and the brightest target point, set $s_i = 0$
5. Repeat steps 2. through 4. until all the points have $s_i = 0$.

This iterative algorithm can be run in parallel for all simultaneously visible projectors. In our setup, the number of pictures needed for the calibration of one projector was about 100. Figure 4 shows the result of the intra-projector calibration of one projector. The color blotches have noticeably disappeared.

Inter-projector calibration

We now dispose of calibrated individual projectors, each of them displaying uniform colors. Because the projectors can be from different type and models, the chromaticity of their individual primary colors are generally not the same. A chromatic compensation is therefore needed to match the colors of different projectors.

Existing solutions [12, 5] mention the fact that a common gamut for all the projectors has to be found, but a lot of them do not solve the crucial question of how tho find the optimal gamut. Known explicit methods [1, 13] have the disadvantage of having a high complexity, preventing their use for large system with over 40 projectors.

We therefore developed a method to find the common gamut between n projectors in time $O(n)$. In this section, we derive the corresponding algorithm.

Color gamut of individual projectors

In additive displays such as LCD projectors, the color of a pixel is the combination of a 3 independent channels. Thus, the color produced by an input value (r, g, b) is given by following matrix equation

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{pmatrix} r \\ g \\ b \end{pmatrix} \tag{1}$$

where (X_R, Y_R, Z_R), (X_G, Y_G, Z_G) and (X_B, Y_B, Z_B) are the normalized coordinates of the display's primaries red, green and blue (CIE XYZ normalization).

However, the color equation 1 is valid only if the display's black has a zero brightness. This is usually not the case, especially for LCD projectors where black is obtained by blocking the light by a non opaque LCD panel. Therefore, the coordinates (X_K, Y_K, Z_K) of the black level of the display have to be integrated into the color equation 1, leading to the more general following equation:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \mathbf{M} \begin{pmatrix} r \\ g \\ b \end{pmatrix} + \begin{pmatrix} X_K \\ Y_K \\ Z_K \end{pmatrix} \tag{2}$$

where $\mathbf{M}$ is the color matrix of equation 1.

Equation 2 is actually correct for a linear (*i. e.* gamma-corrected) display. However, the gamma correction leaves the color gamut globally invariant. Gamma correction is therefore not relevant for finding a common gamut.

With a hand-held color measuring device, we can measure the individual gamut of every projector, that is, find the coordinates (X_R, Y_R, Z_R), (X_G, Y_G, Z_G), (X_B, Y_B, Z_B) , and (X_K, Y_K, Z_K) for each projector. To this aim, the three primaries as well as a black image are measured in the middle of the tile with a colorimeter.

Displayability test

In this section, we use the notation of the CIE's Yxy color space, which has the advantage of clearly separating the luminance Y from the chrominance values (x, y). Having a color with chromatic coordinates x, y, we derive a method to find out if this color is displayable by a given display with known (measured) gamut, and if so, for which values of the luminance. Let call λ the luminance of the color. λ is a real positive value, and we want to find the range of possible values for λ such that the Yxy-color (λ, x, y) is displayable. The one-to-one conversion between the CIE's Yxy and XYZ color spaces give for the same color the XYZ-coordinates $(\lambda \frac{x}{y}, \lambda, \lambda \frac{1-x-y}{y})$. Using the inverse of the color equation 2, we find for this color the following (r, g, b) values:

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \lambda \mathbf{M}^{-1} \begin{pmatrix} \frac{x}{y} \\ 1 \\ \frac{1-x-y}{y} \end{pmatrix} - \mathbf{M}^{-1} \begin{pmatrix} X_K \\ Y_K \\ Z_K \end{pmatrix} \tag{3}$$

Now if the color is displayable, r, g and b must lie between 0 and 1. These 6 constraint generates 6 half-spaces for the possible values of λ. If the common intersection of these half-spaces is not null, then the chromaticity (x, y) is displayable and the possible range for the luminance is this intersection.
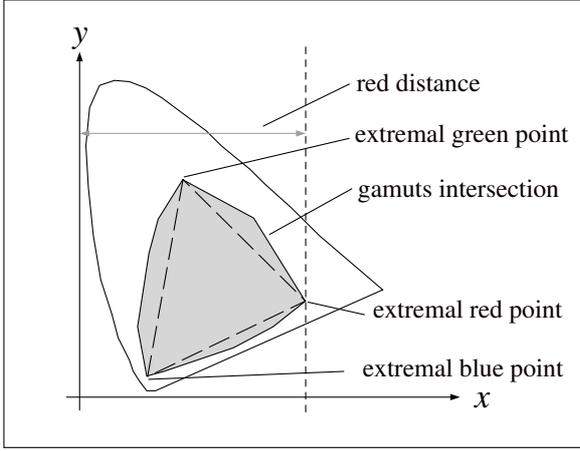
Figure 5. *Extreme chromaticity points in the gamut intersection. The red distance to maximize is given as an example.*

Having n displays, a similar test can be run to establish if a given chromaticity pair (x, y) is displayable by *all* the n displays. The number of constraints for λ is $6n$, the whole test is computed in time $O(n)$.

Finding the optimal common gamut

The color gamut of an additive display forms a parallelepiped in the CIEXYZ color space. Thus, the intersection of a number n of color spaces can be seen geometrically as a parallelepiped intersection problem. The classical geometric solutions are time-consuming (the common gamut is found in time $O(n^3)$), and does not take the difference between contrast and chromaticity into account. We developed a method for finding an optimal gamut by searching for the highest contrast and the biggest chromatic range separately.

To this aim, our method explicitly seeks colors that are *displayable by all* the projectors, and with extreme properties. In the luminance range, we will simply seek the darkest and brightest commonly displayable color, and call them $\mathbf{K}_e$ (extreme black) and $\mathbf{W}_e$ (extreme white). For the chrominance, the idea is to find the farthest colors in the red, green and blue directions. To this aim, we define reference lines in the CIE-xy diagram and measure distances relative to these lines. In practice, we measured the distance to the lines with following equations: $(x = 0)$ when seeking for the maximal red $(\mathbf{R}_e)$, $(y = 0)$ for the maximal green $(\mathbf{G}_e)$ and $(y = 1)$ for the maximal blue $(\mathbf{B}_e)$. Other line equations could be chosen, but these already give acceptable results. Figure 5 shows the considered extrema and distances.

To find these extreme colors, we apply following steps:

1. Initialization: using the displayability test, find one commonly displayable color $\mathbf{C}$ and set $\mathbf{K}_e = \mathbf{W}_e = \mathbf{R}_e = \mathbf{G}_e = \mathbf{B}_e = \mathbf{C}$.
2. Plot a grid of regularly spaced points over the half CIExy plane (a spacing of 0.1 units is a good start).
3. For each point, perform a displayability test for the n gamuts. If the color is commonly displayable, compare the minimal luminance value with the luminance of $\mathbf{K}_e$ and up-

date $\mathbf{K}_e$ (chrominance *and* luminance) if the new luminance is smaller. Similarly, update $\mathbf{W}_e$ if the new maximal luminance is greater, $\mathbf{R}_e$, $\mathbf{G}_e$ and $\mathbf{B}_e$ if the new red-, green-, or blue-distance is greater.
4. Divide the spacing by two and plot a 5×5 grid around the chrominance values of $\mathbf{K}_e$, $\mathbf{W}_e$, $\mathbf{R}_e$, $\mathbf{G}_e$ and $\mathbf{B}_e$.
5. Repeat steps 3. and 4. until a satisfying precision is attained (10^{-4} is a good precision for chromaticity values).

The number of global displayability tests needed to terminate depends only on the desired precision and the starting step. We used a starting step of 0.1 in the xy plane and a precision of 10^{-4}, which gives about 1300 global displayability test. One global displayability test has a computation time linear to n.

Constructing the common gamut

Now that we have found the colors $\mathbf{K}_e$, $\mathbf{W}_e$, $\mathbf{R}_e$, $\mathbf{G}_e$ and $\mathbf{B}_e$, we construct a common gamut based on their coordinates. We first construct a common color matrix $\widetilde{\mathbf{M}}_c$ as follows:

$$\widetilde{\mathbf{M}}_c = \tag{4}$$

$$\begin{bmatrix} X_{R_e} - X_{K_e} & X_{G_e} - X_{K_e} & X_{B_e} - X_{K_e} & X_{K_e} \\ Y_{R_e} - Y_{K_e} & Y_{G_e} - Y_{K_e} & Y_{B_e} - Y_{K_e} & Y_{K_e} \\ Z_{R_e} - Z_{K_e} & Z_{G_e} - Z_{K_e} & Z_{B_e} - Z_{K_e} & Z_{K_e} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This matrix correctly transforms the RGB colors $(0, 0, 0)$, $(1, 0, 0)$, $(0, 1, 0)$ and $(0, 0, 1)$ to $\mathbf{K}_e$, $\mathbf{R}_e$, $\mathbf{G}_e$ and $\mathbf{B}_e$. But as no constraint on the color white has been used, it is not guaranteed that the RGB white transforms to $\mathbf{W}_e$. We therefore run a white test, by computing the RGB color (r_w, g_w, b_w) corresponding to $\mathbf{W}_e$:

$$(r_w, g_w, b_w)^\top = \widetilde{\mathbf{M}}_c^{-1} \mathbf{W}_e. \tag{5}$$

If an element of the vector (r_w, g_w, b_w) is greater than 1, shrink it to 1. The matrix $\widetilde{\mathbf{M}}$ has then to be scaled with these values to obtain the final color matrix of the common gamut:

$$\mathbf{M}_c = \begin{bmatrix} r_W & & & \\ & g_W & & \\ & & b_W & \\ & & & 1 \end{bmatrix} \widetilde{\mathbf{M}}_c \tag{6}$$

This last scaling step reduces the luminance of the gamut's primaries (without changing their chrominance), but ensures that the white color will be displayable. We thus constructed a common gamut with optimized contrast and best color range.

Input correction

Now that have found the common gamut defined by a matrix $\mathbf{M}_c$, we are able to apply the correction to the input data.

The main idea is that having a picture, we consider it as taken by a virtual camera with transformation matrix $\mathbf{M}_c$. Thus, the picture is made of colors that are displayable by all the projectors.

For a specific projector P_p, with an individual gamut defined by a matrix $\mathbf{M}_p$, and for a color $\mathbf{C}$ in the RGB space from the input image, we find the modified input color $\mathbf{C}_p$ with following equation:

$$\mathbf{C}_p = h_p^{-1}(\mathbf{C}_{p,l}) = h_p^{-1}(\mathbf{M}_p\mathbf{M}_c^{-1}g(\mathbf{C})) \qquad (7)$$

where g is the intensity transfer function of the image (or by default an arbitrary one), and h_p is the intensity transfer function of the projector P_p. h_p is easily measured once for all by using the calibrated camera as a luminance measuring device for an increasing range of input values and storing the result in a lookup table.

We correct the entire picture by applying the transformation of equation (7) to all the pixels of the image.

Results
Wall calibration

The proposed method has been tested on the *HEyeWall* of the Fraunhofer IGD of Darmstadt, Germany (see Figure 1). This multi-projector tiled display is a system with 48 LCD projectors from the same model (Christie LX-41). The projection system is stereo-capable, with a stereo separation based on Infitec filters [4]. The Infitec technology uses spectral interference filters to select three narrow wavelength bands out of the visible spectrum. The three bands are different for each eye. It has the advantage of a very good image separation but induces visible color differences between left and right eye.

Figure 6 shows the different calibration steps. The leftmost image is a mid-grey uniform image without calibration. The intra-projector correction (middle image) uniformizes the individual tiles, but large chromatic shifts are still visible. The inter-projection calibration reduces these shifts.

Figure 7 shows the example of a street scene before and after correction.

Measured performance

We measured the gamuts of two projectors with different Infitec filters with a Minolta Chromameter CS-100. With our method, we found the common gamut and applied the correction to the projectors. Figure 8 shows photographs of the projectors before and after correction for the red color. Figure 9 plots the measured primaries and gamuts of the two projectors - before and after correction - on a CIE *xy* diagram.

The collected results show that our approach can achieve a good color balance with a mean error of less than 1% variance between the projectors.

Conclusion and future work

We presented a 2-step method for calibrating a tiled display. After having calibrated the camera to serve as a luminance measuring device, we used the advantages of input manipulation for a fast intra-projector calibration and derived an interative algorithm that use the camera in a loopback call to verify the uniformity of the displayed colors. The inter-projector calibration uses a novel approach to gamut matching whith the advantage of fast computation of the common gamut.

The individual parts of this calibration methods can be further adapted and enhanced. For example, the presented method does not allow for the correction of chrominance shifts inside one single projector due to real differences of the chromatic properties between two spatial locations. For projectors having this particularity, only a intra-projector gamut matching could uniformize
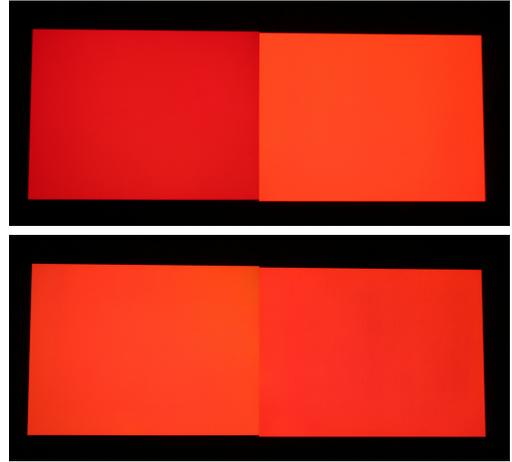

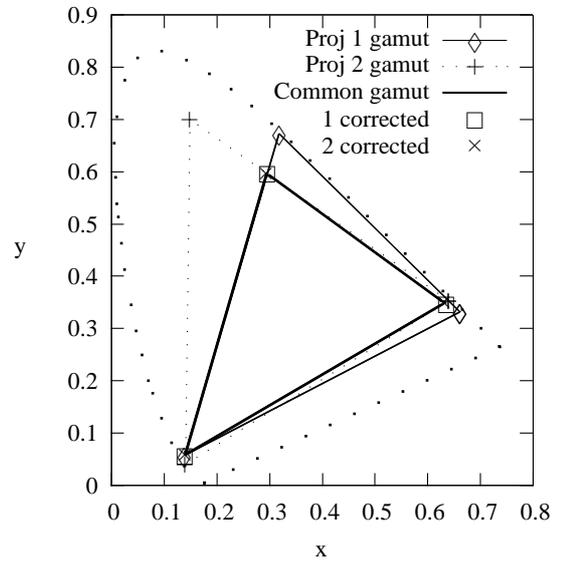**Figure 8.** *Two projectors before (top) and after (bottom) correction.*

Figure 9. *Common gamut and verification for two test projectors*

the colors. We could therefore adapt the gamut matching algorithm to a new kind of shading table, thus enabling chrominance modifications inside one projector.

Moreover, our current calibration method is not fully automatic, because the measurements of the chromatic differences are made with a colorimeter that must be pointed to the measured object. We are working on a solution using a digital camera to measure not only luminance but also chrominance of the color. In this case, the complete calibration will be done automatically.

Acknowledgment

Figure 6. *A subpart of the wall with nine projectors before any calibration (left), after intra-projector calibration (middle), and after inter-projector calibration (right).*

Figure 7. *Example of corrected image: before correction (left), after intra-projector and inter-projector calibration (right).*

References

[1] M. Bern and D. Eppstein. Optimized color gamuts for tiled displays. In *SCG '03: Proceedings of the nineteenth annual symposium on Computational geometry*, pages 274–281, New York, NY, USA, 2003. ACM Press.

[2] H. Chen, R. Sukthankar, G. Wallace, and K. Li. Scalable alignment of large-format multi-projector displays using camera homography trees, 2002.

[3] P. E. Debevec and J. Malik. Recovering high dynamic range radiance maps from photographs. *Computer Graphics*, 31(Annual Conference Series):369–378, 1997.

[4] H. Jorke and M. Fritz. Infitec - a new stereoscopic visualisation tool by wavelength multiplex imaging. In NETWORK-OSE, editor, *Electronic Displays*, September 2003.

[5] W. Kresse, D. Reiners, and C. Knoepfle. Color consistency for digital multi-projector stereo display systems: the heyewall and the digital cave. In *EGVE '03: Proceedings of the workshop on Virtual environments 2003*, pages 271–279, New York, NY, USA, 2003. ACM Press.

[6] A. Majumder, D. Jones, M. McCrory, M. E. Papka, and R. Stevens. Using a camera to capture and correct spatial photometric variation in multi-projector displays. In *IEEE Workshop on Projector-Camera Systems (PROCAMS)*, 2003.

[7] A. Majumder and R. Stevens. Color nonuniformity in projection-based displays: Analysis and solutions. *IEEE Transactions on Visualization and Computer Graphics*, 10(2):177–188, 2004.

[8] A. Majumder and R. Stevens. Perceptual photometric seamlessness in projection-based tiled displays. *ACM Trans. Graph.*, 24(1):118–139, 2005.

[9] A. Raji, G. Gill, A. Majumder, H. Towles, and H. Fuchs. Pixelflex2: A comprehensive, automatic, casually-aligned multi-projector display. In *IEEE Workshop on Projector-Camera Systems (PROCAMS)*, 2003.

[10] R. Raskar, M. S. Brown, R. Yang, W.-C. Chen, G. Welch, H. Towles, W. B. Seales, and H. Fuchs. Multi-projector displays using camera-based registration. In *IEEE Visualization*, pages 161–168, 1999.

[11] R. Raskar, J. van Baar, P. Beardsley, T. Willwacher, S. Rao, and C. Forlines. ilamps: Geometrically aware and selfconfiguring projectors, 2003.

[12] M. C. Stone. Color and brightness appearance issues in tiled displays. *IEEE Comput. Graph. Appl.*, 21(5):58–66, 2001.

[13] G. Wallace, H. Chen, and K. Li. Color gamut matching for tiled display walls. In *EGVE '03: Proceedings of the workshop on Virtual environments 2003*, pages 293–302, New York, NY, USA, 2003. ACM Press.

Author Biography

Alain Pagani received his M.Eng. from the Ecole Centrale de Lyon, France (2001) and his M.S. in computer science from the Technische Universitaet Darmstadt, Germany (2003). He is currently pursuing the Ph.D. degree at the Fraunhofer Institut for Computer Graphics IGD in Darmstadt, Germany. His work focuses on computer vision and machine learning.

Dr. Didier Stricker is the head of the department "Virtual and Augmented Reality" at the Fraunhofer Institute for Computer Graphics (IGD) in Darmstadt, Germany. Before joining the Fraunhofer IGD, he worked as a researcher and software developer at the Institute for Pattern Recognition in Karlsruhe, Germany. His research interests are virtual and augmented reality, computer vision, edutainment, and multimedia information services.