Spatially uniform colors for projectors and tiled displays

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Abstract — A major issue when setting up multi-projector tiled displays is the spatial non-uniformity of the color throughout the display's area. Indeed, the chromatic properties do not only vary between two different projectors, but also between different spatial locations inside the displaying area of one single projector. A new method for calibrating the colors of a tiled display is presented. An iterative algorithm to construct a correction table which makes the luminance uniform over the projected area of one single projector is presented first. This so-called *intra-projector calibration* uses a standard camera as a luminance measuring device and can be processed in parallel for all projectors. Once the color inside each projector is spatially uniform, the set of displayable colors – *the color gamut* – of each projector is measured. On the basis of these measurements, the goal of the *inter-projector calibration* is to find an optimal gamut shared by *all* the projectors. Finding the optimal color gamut displayable by n projectors in time $O(n)$ is shown, and the color conversion from one specific color gamut to the common global gamut is derived. The method of testing it on a tiled display consisting of 48 projectors with large chrominance shifts was experimentally validated.

Keywords — *Tiled display, color calibration, projector calibration.*

1 Introduction

Large-area multi-projector displays offer an inexpensive and scalable solution to the growing demand for increased image size and resolution. They have become commonplace in the areas of collaborative workspaces, industrial design, and scientific visualization and are extensively used for virtual-reality applications in edutainement and defense. In such displays, a varying number of projectors are tiled to produce one-single high-resolution image.

However, tiled displays can only be convincing if the resulting image appears seamless to the user. To this aim, the system must be precisely calibrated. A first *geometric calibration* aims at adjusting the geometric properties of the individual display units to correctly align the image sections between the projectors and remove radial distortion. Satisfying solutions have been proposed for the geometric calibration problem.[2,3,14–16]

A still-challenging issue is the *color calibration* of a tiled display. The first problem is the variation in the intensity among the projectors, mainly due to optical constraints and varying lamp states. We refer to the spatial variation of the intensity as *photometric variation* across the display. A second problem is that different projectors will generally have primaries with different chromacities (even if they are of the same model). We refer to the chromacity shift of the primaries as *chromatic variation*. Both photometric and chromatic variations can arise inside the display area of one projector (*intra-projector variation*) or across different projectors (*inter-projector variation*). The spatial non-uniformity is in particular considerable for LCD projectors.[6]

Several partial solutions have been proposed for the color-calibration problem.[2] In the *gamut-matching* approach,[8,17–19] it is assumed that the intra-projector variations are negligible, 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 linear transformations convert the colors from a specific gamut to the common gamut. Besides the limitation of neglecting the intra-projector variations, the proposed solutions have the drawback of high time consumption. Indeed, finding a common gamut for n projectors was seen thus far as a computational geometry problem of complexity $O(n^3)$,[1] which makes this approach unusable for large systems. The *intensity manipulation* approach[10–14] assumes that the chromatic properties of the projectors are uniform across the display. In this special case, the chromatic variations are only due to spatially 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

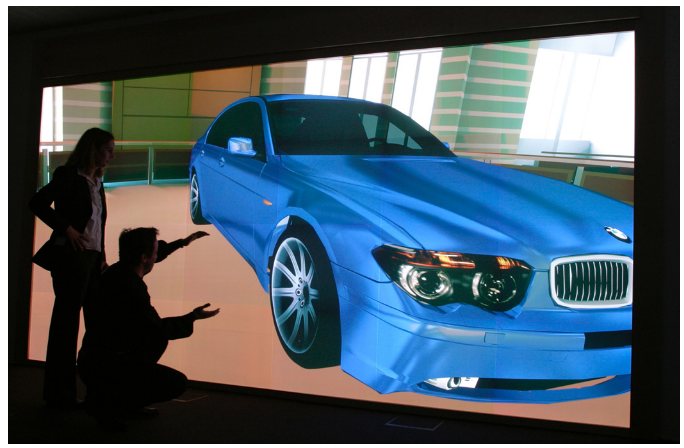

FIGURE 1 — High-resolution stereoscopic tiled display with 48 projectors (courtesy of Fraunhofer IGD).

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compensate the photometric variations. However, having uniform chromatic properties is a strong limitation. First, this excludes the use of different models of projectors in the same setup. Moreover, even projectors produced by the same manufacturer can still present slight but noticeable chromatic differences. These two approaches originally used a point light-sensing device (spectroradiometer or colorimeter) to measure the light variation of a number of sample points. Recent research in intensity manipulation[2,11,14] used a digital camera as the luminance measuring device, with an algorithm based on high-dynamic-range images (HDR).

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 are spatially invariant, we developed an iterative algorithm for spatial-intensity compensation of one projector. We then derive a fast algorithm for finding a common gamut between n additive 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. Formally, we achieve a *strict photometric uniformity* for each projector separately, followed by a strict *color uniformity* across the different projectors. As a measuring device, we use a commonly available digital camera for luminance measurements and a colorimeter for chrominance measurements.

The remainder of the paper is organized as follows. We first describe the preliminary calibration of the digital camera. We then 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 finally present our results and conclusions.

2 Camera calibration

In order to calibrate the colors of a display, we have to precisely measure color. Devices such as a spectroradiometer or a colorimeter are designed to provide very precise measurements of colors, but are also very expensive. Moreover, they can make only one measurement at a time and can therefore be considered as relatively slow. To speed up the entire process and make it less expensive, we used a standard digital camera as a color-measuring device. However, a digital camera does not provide normalized values but device-dependant values for color. In this section, we show how we calibrated a digital camera to use it as a reliable color-measuring device.

2.1 Vignetting

In almost all real images, especially for pictures taken at higher aperture settings, corners appear darker than the middle of the picture. This optical effect, called *vignetting*, induces undesirable spatial variations in pictures taken by a camera. We developed an algorithm to efficiently remove this effect and be able to compare the intensity values of different pixels.

The shape of the intensity transfer function (ITF) of the camera is assumed to be spatially invariant. This does not imply that the ITF is linear, but only that its normalized shape is identical for every pixel. This is especially the case for digital cameras, which use arrays of very similar charge coupled devices (CCDs). In this case, the intensity of every pixel of a flat field image (an image where all the pixels capture the same color) is a linear function of the maximum intensity of the image. The main idea of the algorithm is to recover for each pixel this linear behavior from a series of sample measurements. In our test setup, we used about 50 flat field images with different intensity levels. Flat field images are at best obtained from diffuse light sources. To generate these images, we took photographs of a hazy sky (our diffuse light source) under different exposure times, ranging from 1/4000 to 30 sec. For each pixel p_i of an image I_j, we note $x_{i,j}$ as the actual pixel intensity as captured by the camera. We note $m_j = max_i(x_{i,j})$ as the maximal intensity of the picture I_j. For each pixel, we thus obtain a set of pairs $(x_{i,j}, m_j)$ which must lie on a line. Through classical linear regression, we compute the optimal factors a_i and b_i that minimize the error $e_i = \sum_j m_j - (a_i x_{i,j} + b_i)$, thus obtaining a multiplicative texture $A = \{a_i\}$ and an additive texture $B = \{b_i\}$ that have to be applied to a given picture for a subsequent devignetting.

Figure 2 shows the results of devignetting on a sample picture. For better visibility, the intensity of one line of the picture has only been plotted (red line on the top picture). On the bottom plot, the blue line shows the normalized intensity value along that line for the original picture. The pink line shows the same intensity after devignetting. As expected, the effect of devignetting grows with the distance to the center of the image.

2.2 High-dynamic-range measurements

Because we use a camera with adjustable exposure time, we can augment the dynamic range of the camera by taking the measurements in high-dynamic-range (HDR) images. We used an algorithm adapted from Debevec and Malik's method.[4] The original method uses differently exposed photographs to recover the response function of the camera under different exposure times, up to a factor of scale. By using the known response function, the algorithm can fuse the multiple photographs into a single, HDR radiance map whose pixel values are proportional to the true radiance val-

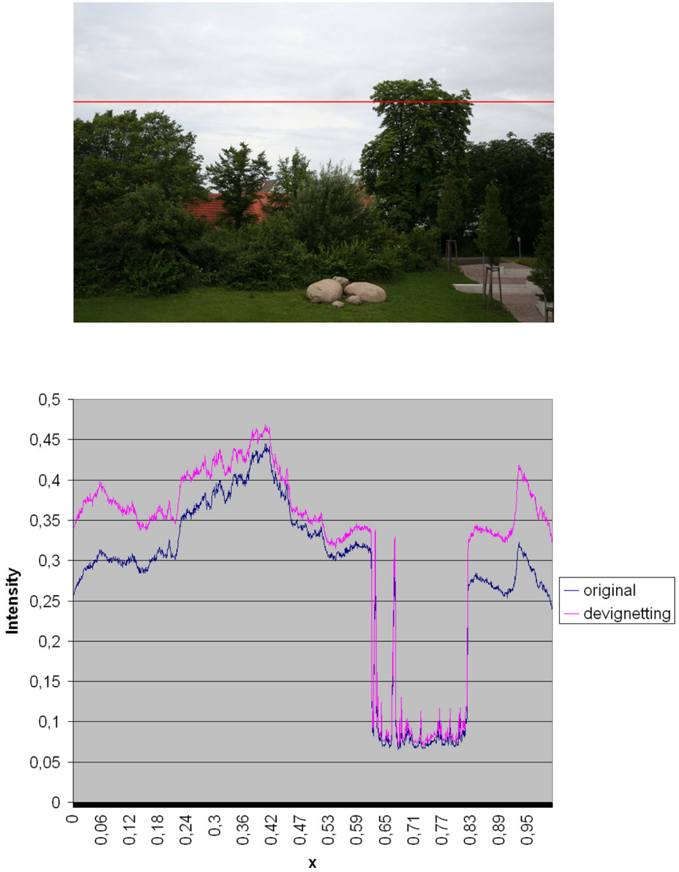

FIGURE 2 — Effect of devignetting (see text for details).

ues in the scene. In our case, we do not need to fuse multiple photographs into one single radiance map, but only to compute a pixel-based intensity value that is proportional to the true radiance value of the object, and which does not depend on the current exposure time. This can be seen as a special case of the HDR analysis as described in Ref. 4. The interested reader is referred to the original article for further information.

This approach has two benefits: we can recover the non-linearity of the camera for each color channel and we can automatically adapt the camera's exposure time to the measured intensity. After this calibration, the camera is ready to be used as an intensity-measuring device. Note that we recover the value of the luminance only up to a scale factor, but this is sufficient to compare the intensity of spatially distributed points.

3 Intra-projector calibration

Single projectors generally present variations in the intensity or chrominance. Majumder and Gopi[9] discussed the possible causes of these variations, showing, in particular, that chromatic variations can arise even for projectors with identical chromatic properties, if their photometric properties differ, leading to the characteristic color blotches of an uncalibrated projector (see Fig. 5, top).

Actually, the chromatic properties of a single projector are generally spatially invariant. Majumder and Stevens[12] showed that the spatial variations in intensity within a single projector are much more significant than the spatial variations in chrominance. We can therefore only balance the intensity variations for each channel and still reduce chromatic differences.

The main idea of the method is to modify the intensity of the input pixels to compensate for the original intensity differences. Known methods for intensity manipulation[11,12,14] define a parameterized model of the intensity variation, measure sample points of this model, and apply the inversed 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 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.

3.1 Shading table

In order to manipulate the 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 Fig. 3). At these specific positions, the input intensity can be modified, on a per-channel basis. Between the points, the modification is interpolated from the neighboring points. Figure 3 shows the location of 825 shading points over the projected surface of one projector.

For each shading point and each color channel, we define an intensity manipulation function (IMF) f. This function maps the true input intensity to the modified intensity.

Figure 4 shows a possible IMF for a single shading point and one color channel. The original behavior for this

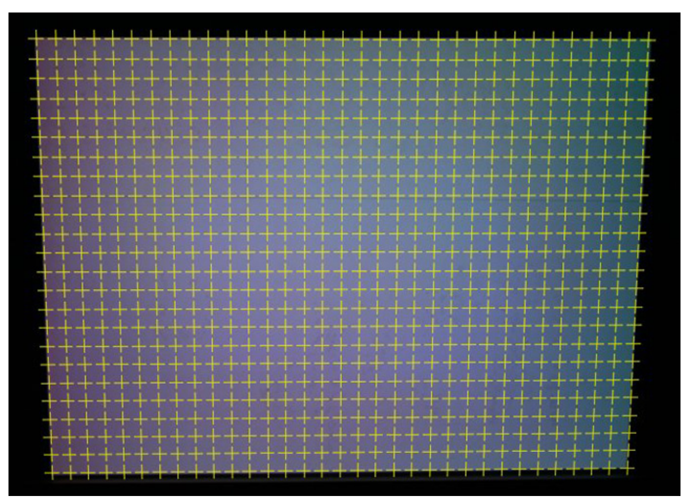

FIGURE 3 — Location of the 825 shading points over the projected surface (one projector).

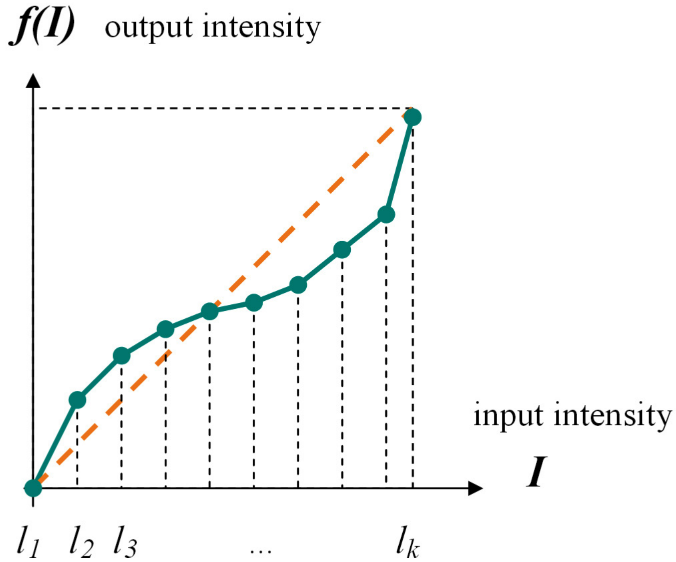

FIGURE 4 — Sample intensity manipulation function for a single shading point.

point is the dashed line of equation $f(I) = I$. Each shading point has k levels, l_k, that can be modified. The levels define which input value can be corrected and their associated values (positive or negative), the absolute corrected value. Between the levels, the correction is linearly interpolated. The final behavior of the shading point's intensity is represented by the plain line. We compute the intensity correction on a per-channel basis. For a single projector, one shading table per color channel is required. The advantage of using shading tables is that the number of points and the number of levels is modifiable. In our setup, we used a grid of 33 × 24 points and three levels. The exact value of the levels differs for every projector, but they correspond to approximately 25, 50, and 75% of the output intensity. Although the number of levels is small, it is sufficient to capture the IMF, which is usually near to linear (recall that the IMF does not capture the intensity transfer between input and output, but the variations of the intensity fall off between a reference point and a given point on the screen). Moreover, a series of measurements has to be taken for every level of every color channel. The time needed for measurements therefore increases with the number of levels, which has to be kept small. The IMF model can be used for correction without any knowledge of the intensity transfer function of the projector. In some models of programmable projectors, such a shading table already exists and can be easily read/written through a specific interface. If not, the shading tables must be applied earlier in the graphical pipeline by modifying directly the input values.

3.2 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. A preliminary geometric registration is performed using a homographic transformation of the camera image. Finding the correct homography is a well-known problem of single-view geometry[5] and is solved here using specific patterns displayed by the projector. When measuring the luminance of a shading point, we measure the mean value of the pixels luminance in a given neighborhood of this point.

Due to the sensitiveness of the projector's electronics, 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. In any case, this lack of stability prevented us from taking absolute luminance measurements and comparing measurements taken at two different moments. To work around this problem, we developed a method based on an 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.

We now detail the algorithm for automatic intra-projector color calibration. Let us consider the correction of one level l_i of one color channel. We define $\{P_i\}$ as the set of shading points. Each shading point P_i has a specific *corrected output value* v_i 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 l_i defined above, we apply following algorithm:

1. Initialization: For all shading points, set the corrected output value $v_i = l_i$. 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 an individual step size. For all points brighter than the target points, set $s_i = -s_{init}$ as an individual step size.
2. Correction: For all points, apply $v_i = v_i + s_i$.
3. Measurement: Measure the luminance for each point.
4. Refinement: 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.
5. Individual stop condition: For each point, if the luminance of the point is between the darkest and the brightest target point, set $s_i = 0$.
6. Global stop condition: Repeat steps 2 through 5 until all the points have $s_i = 0$.

This iterative algorithm can be run in parallel for all simultaneously visible projectors. In this case, one single camera is used to capture the entire spatial mosaic created

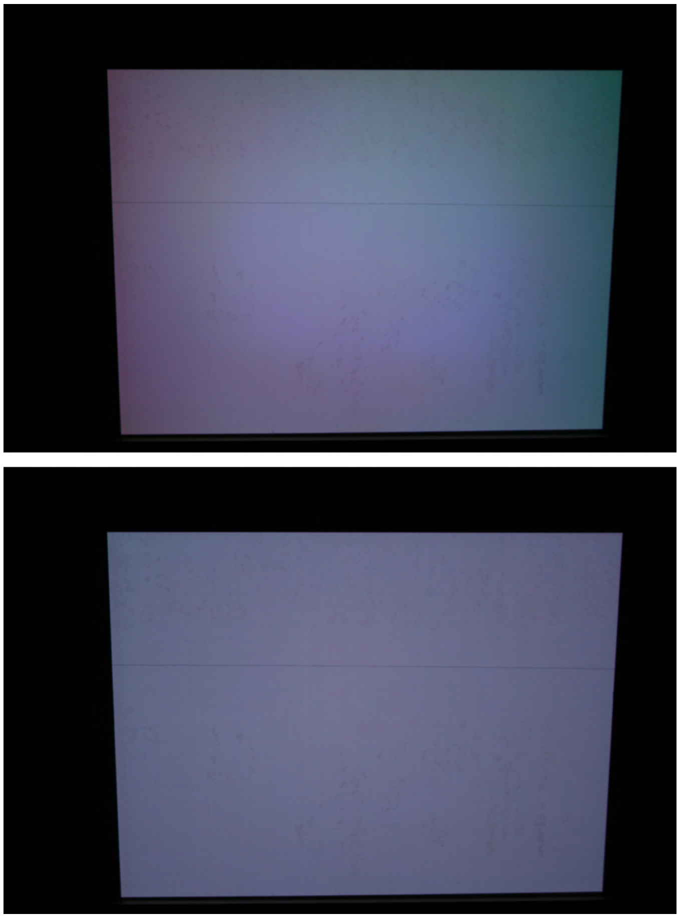

FIGURE 5 — A projector before (top) and after (bottom) intra-projector correction.

together by all the projectors. The advantage is that only one picture is analyzed in the measurement step (step 3) for all the projectors, thus reducing the time needed for data transfer between the camera and the computer running the main algorithm. In our setup, the number of pictures needed for the calibration of one projector was about 10 for each level and each color channel. Under- or over-exposition was avoided by using exposition tests. Figure 5 shows the result of the intra-projector calibration of one projector. The color blotches have noticeably disappeared.

Care has to be taken to not overrun the projector's capacity when applying the correction. As an example, for the highest correction level, only negative corrections can be made (having more than the maximal input intensity is just impossible). This can be solved by choosing different target points depending on the level considered. For the brightest level, the darkest points have to be chosen as target points. Inversely, for the darker level, the brightest points are taken as target points. Similar choices can be made for middle levels. With this method, we can achieve color uniformity for every level. A side effect of the intra-projector calibration is a slight reduction in the perceived contrast, due to the cut-off of the darkest and brightest pixels. However, we achieve the best possible contrast with the constraint of spatial uniformity of the colors.

4 Inter-projector calibration

We now dispose of calibrated individual projectors, each of them displaying spatially uniform colors. A widespread belief is that projectors from the same manufacturer and the same production chain will have exactly the same color gamut. Actually, the color properties of two identical projectors can be very different for two reasons: first, because projectors are mostly used in single-projector configurations, where direct comparisons between projectors are not possible. Therefore, the projector manufacturers do generally not guarantee a high precision for the color primaries. Second, the colors of a projector depend on the lamp. In particular, the colors of a projector can vary when the lamp ages (mainly in intensity, but also in chrominance). Two projectors with different lamps will therefore produce different colors. Moreover, we also consider the case of tiled displays with projectors from different types and models. In all these cases, the chromaticities of the individual primary colors of the projectors are generally not the same. This is especially the case after an intra-projector calibration. Indeed, the intra-projector calibration can modify the maximal intensity ratio between the primaries and thus produce different white colors. A true chromatic compensation is therefore needed to match the colors of different projectors.

Existing solutions[8,17,18] 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 to find the optimal gamut. Known explicit methods[1,19] have the disadvantage of having a high complexity, preventing their use for large systems having 40–50 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.

4.1 Color gamut of individual projectors

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

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

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, Eq. (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 Eq. (1), leading to the more-general following equation:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M \begin{pmatrix} r \\ g \\ b \end{pmatrix} + \begin{pmatrix} X_K \\ T_K \\ Z_K \end{pmatrix}, \quad (2)$$

where M is the color matrix of Eq. (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, *i.e.*, 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. For an increased precision, an average of multiple measurements for each primary can be taken instead.

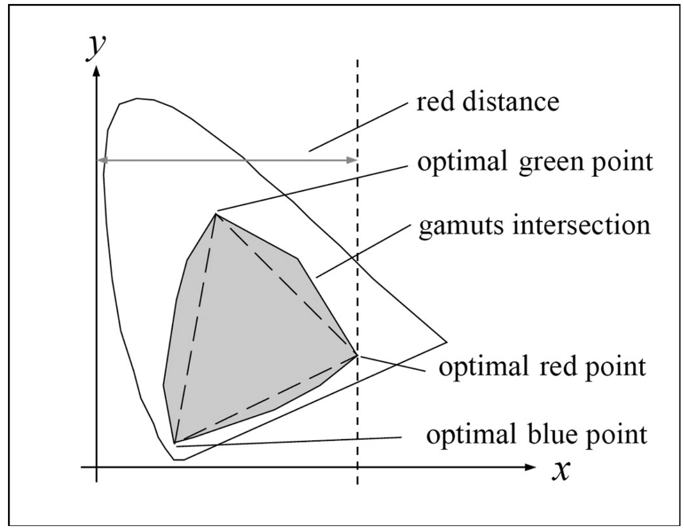

FIGURE 6 — Optimal chromaticity points in the gamut intersection. The red distance to maximize is given as an example.

4.2 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 determine if this color is displayable by a given display with a known (measured) gamut, and if so, for which values of the luminance. Let L be the luminance of the color. L is a real positive value, and we want to determine the range of possible values for L so that the Yxy-color (L, x, y) is displayable by a given projector. The one-to-one conversion between the CIE's *Yxy* and *XYZ* color spaces gives for the same color the *XYZ*-coordinates

$$\left(L\frac{x}{y}, L, L\frac{1-x-y}{y} \right).$$

Using the inverse of Eq. (2), we find the following (r,g,b) values for this color:

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = LM^{-1} \begin{pmatrix} \frac{x}{y} \\ 1 \\ \frac{1-x-y}{y} \end{pmatrix} - M^{-1} \begin{pmatrix} X_K \\ Y_K \\ Z_K \end{pmatrix}. \quad (3)$$

Now, if the color is displayable, r, g, and b must lie between 0 and 1. These six constraints generate six half-spaces for the possible values of L. 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.

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 L is $6n$, the entire test is computed in time $O(n)$. Note that this algorithm can easily be parallelized on a distributed network of computers. Tiled displays generally already have such clusters of computers in their architecture to control the different projectors. This cluster can be used for the displayability test. In this case, the computation time is even constant.

4.3 Finding the optimal common gamut

The color gamut of an additive display forms a parallelepiped in the CIE-*XYZ* 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 and do 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 widest chromatic range separately.

Note that the classical representation of color gamuts is triangles in the CIE-*xy* space. Finding the largest triangle that fits in the intersection of n triangles is a trivial problem (see, for example, Ref. 8), but this representation does not hold for gamuts with different black levels. In this case, the size of the triangle depends on the luminance, and the intersection problem has to be solved in three dimensions (CIE *XYZ* space).

Our method explicitly seeks colors that are *displayable by all* the projectors, and with optimal properties. Optimal here is defined as follows: In the luminance range, we will simply seek the darkest and brightest commonly displayable color and call them K_o (optimal black) and W_o (optimal 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 the following equations: (x = 0) when seeking for the optimal red (R_o), (y = 0) for the optimal green (G_o), and (y = 1) for the optimal blue (B_o). Other line equations can be chosen, but these already give acceptable results. Figure 6 shows the considered optima and distances.

To find these optimal colors, we apply the following steps:

1. Initialization: using the displayability test, find one commonly displayable color C and set $K_o = W_o = R_o = G_o = B_o = C$.
2. Plot a grid of regularly spaced points over the half CIE-xy 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 K_o and update K_o (chrominance *and* luminance) if the new luminance is smaller. Similarly, update W_o if the new maximal luminance is greater; R_o, G_o, and B_o 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 K_o, W_o, R_o, G_o, and B_o.
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 tests. One global displayability test has a computation time linear to n.

4.4 Constructing the common gamut

Now that we have found the colors K_o, W_o, R_o, G_o, and B_o, we construct a common gamut based on their coordinates. We first construct a common color matrix as follows:

$$\tilde{M}_C = \begin{bmatrix} X_{R_O} - X_{K_O} & X_{G_O} - X_{K_O} & X_{B_O} - X_{K_O} & X_{K_O} \\ Y_{R_O} - Y_{K_O} & Y_{G_O} - Y_{K_O} & Y_{B_O} - Y_{K_O} & Y_{K_O} \\ Z_{R_O} - Z_{K_O} & Z_{G_O} - Z_{K_O} & Z_{B_O} - Z_{K_O} & Z_{K_O} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (4)$$

This matrix correctly transforms the RGB colors (0,0,0), (1,0,0), (0,1,0), and (0,0,1) to K_o, R_o, G_o, and B_o. But because no constraint on the white color has been used, it is not guaranteed that the RGB white transforms to W_o. We therefore run a white test, by computing the RGB color (r_w, g_w, b_w) corresponding to W_o:

$$\begin{pmatrix} r_w \\ g_w \\ b_w \end{pmatrix} = \tilde{M}_C^{-1} W_O. \quad (5)$$

If an element of the vector (r_w, g_w, b_w) is greater than 1, we replace it by 1. Then the matrix $\tilde{M}_C$ has to be scaled with these values to obtain the final color matrix of the common gamut:

$$M_C = \begin{bmatrix} r_w & & & \\ & g_w & & \\ & & b_w & \\ & & & 1 \end{bmatrix} \tilde{M}_C. \quad (6)$$

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.

4.5 Input correction

Now that we have found the common gamut defined by matrix M_C, we are able to apply the correction to the input data.

The main idea here is that having a picture, we consider it as taken by a virtual camera with transformation matrix M_C^{-1}. Thus, the picture is made of CIE-XYZ colors that are displayable by all the projectors.

For a specific projector P_P with an individual gamut defined by a matrix M_p, and for a color C in the RGB space from the input image, we find the modified input color C_P with following equation:

$$C_P = h_P^{-1}(C_{P,l}) = h_P^{-1}\left[M_P^{-1} M_C g(C)\right], \quad (7)$$

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 measured value in a lookup table. We correct the entire picture by applying the transformation equation [Eq. (7)] to all the pixels of the image.

5 Discussion

The method we presented for inter-projector calibration is based on a conversion from the projectors' individual gamuts to a common displayable gamut. This actually reduces the gamut of every projector to a smaller one. In this sense, it effectively produces a loss of color appearance for each projector considered separately. But because our goal is to have spatially uniform colors across the tiled display, we can only display colors that fit in the gamut of every projector. A solution to augment the size of the common gamut would be to adapt the common gamut to the content of a specific image, in the cases where the colors of the image do not cover the entire gamut.

6 Results

The proposed method has been tested by the *HEyeWall* from Fraunhofer IGD, Darmstadt, Germany (see Fig. 1).

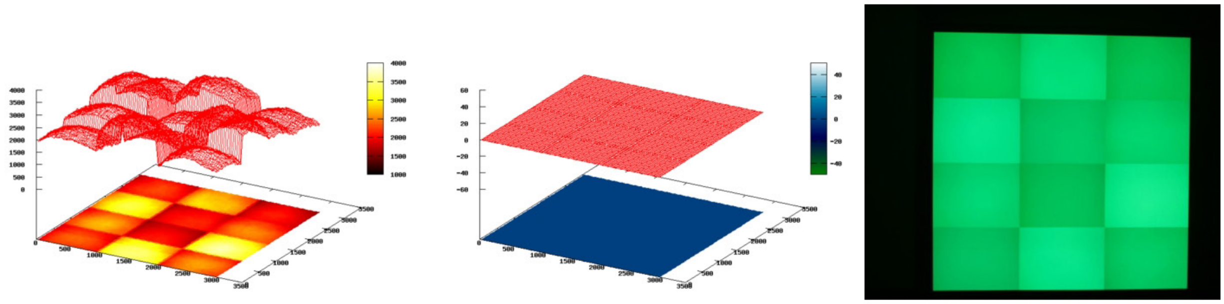

FIGURE 7 — Intensity profile, absolute correction, and corresponding picture of 12 projectors showing a level of green color before the iterative shading correction.

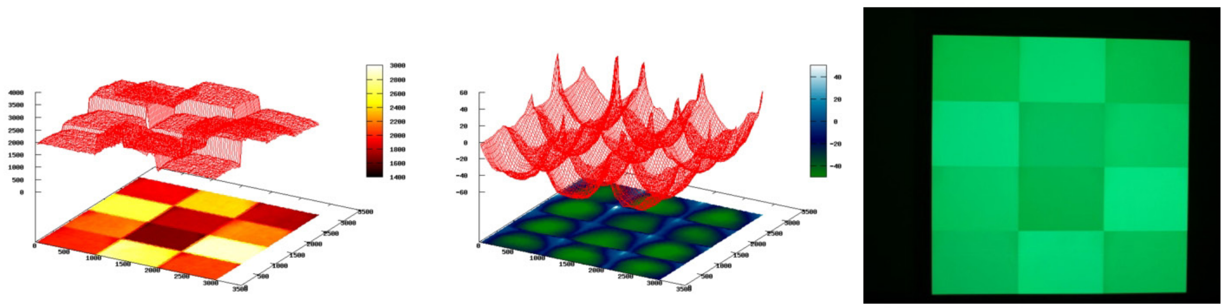

FIGURE 8 — Intensity profile, absolute correction, and corresponding picture of 12 projectors showing a level of green color after the iterative shading correction.

This multi-projector tiled display is a system with 48 LCD projectors from the same model (Christie LX-41). The images are displayed using rear-screen projection, on a screen made of diffuse material. The wall is stereoscopic, with a stereo separation based on Infitec filters.[7] 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 having a very good image separation but induces visible color differences between the left and right eyes.

6.1 Intra-projector calibration

We tested the parallel calibration of 12 projectors with an internal shading table. The ouput values of the IMFs are coded with 10 bits in this case, which enables us to make very fine corrections.

Figures 7 and 8 show the result of shading correction on a array of 3×4 projectors. As an example, the brightest level for the color green is shown. For both figures, the leftmost plot shows the spatial distribution of the intensity of the wall as measured by the camera. The central plot shows the spatial distribution of the correction values (with the above notation, the absolute difference $v_i - l_i$ is plotted). The rightmost picture is a photograph of the array of projectors as seen by the camera. The hotspot effect is especially visible on the intensity distribution graph before the correction. After the correction, the correction values have the inverse shape, and the intensity distribution is flat for each projector separately. Note that the intra-projector calibra-

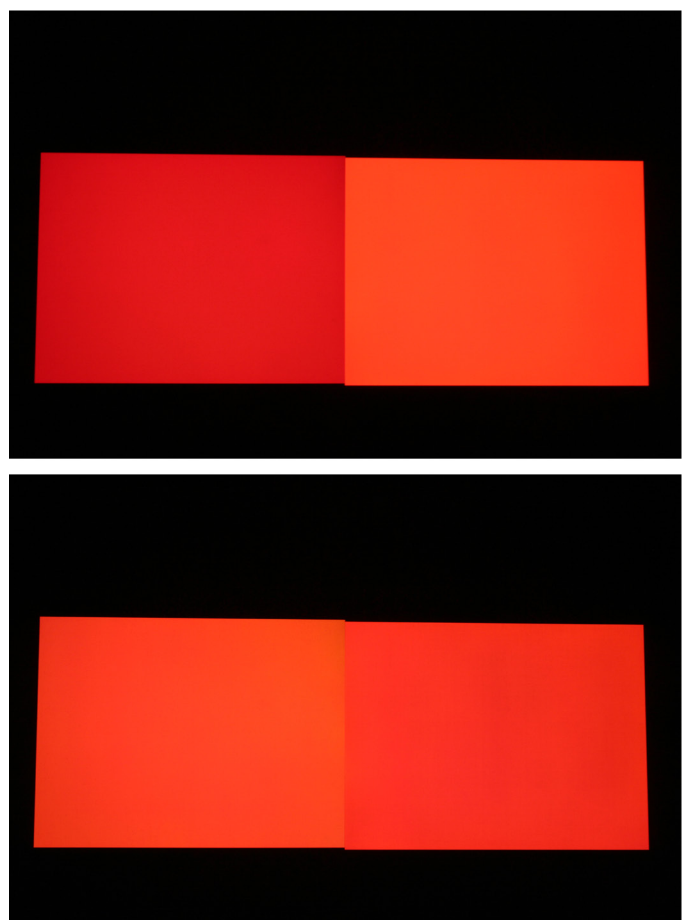

FIGURE 9 — Two projectors before (top) and after (bottom) correction.

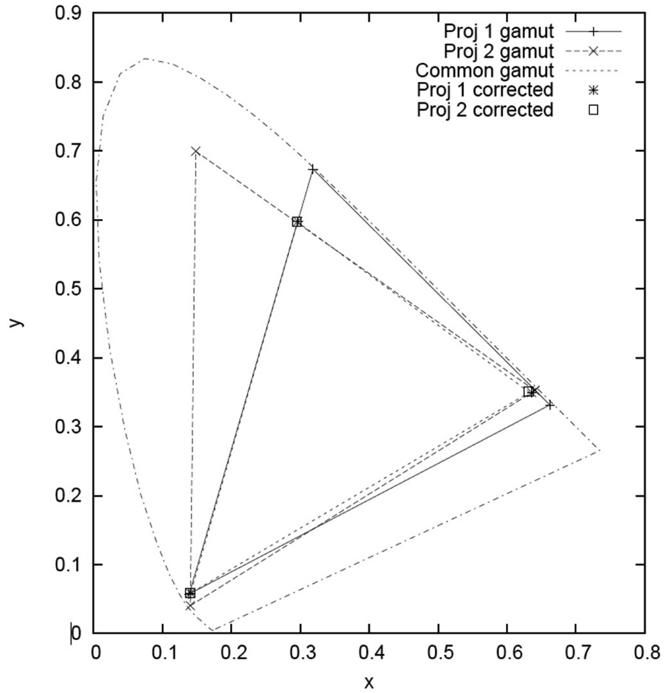

FIGURE 10 — Common gamut and verification for two test projectors.

tion does not attempt to compensate for inter-projector differences. The visible inter-projector differences are due to different values for different levels and for different lamp ages. These differences are eliminated after inter-projector calibration.

6.2 Inter-projector calibration

We measured the gamuts of two projectors having different Infitec filters with a colorimeter (Minolta Chromameter CS-100). With our method, we found the common gamut and applied the correction to the projectors. Figure 9 shows photographs of the projectors before and after correction for the red color. Figure 10 plots the measured primaries and gamuts of the two projectors – before and after correction – on a CIE *xy* diagram. The effect of the Infitec filters is clearly visible. The computed common gamut is shown as a dashed line. After finding the common gamut, the conversion matrices between the projectors and the common gamut were computed, and the primaries of the two projectors were corrected. The plotted coordinates of the corrected primaries match the modelled common gamut, thus validating the method. Table 11 shows the absolute color difference measured in ΔE_{ab}* between the primaries of the projectors and the primaries of the computed common gamut before and after the correction. The values of ΔE_{ab}* are below 1 after the correction, showing that the colors are very similar.

ΔE^*_{ab} common gamut	Red	Green	Blue	White	Black
Projector 1 Uncalibrated	7,04	56,29	3,48	18,41	4,73
Projector 2 Uncalibrated	43,45	62,12	29,39	22,13	8,8
Projector 1 Calibrated	1,22	0,68	0,26	0,74	1,21
Projector 2 Calibrated	0,8	0,57	0,26	0,1	2,09

FIGURE 11 — Color differences between the primaries of the individual gamuts and a common gamut before and after correction.

6.3 Wall calibration

The method serves as a general color-calibration method for the HEyeWall method from the Fraunhofer Institute. Due to the aging effects of the lamps, a complete calibration has to be performed about once a month. Our method is semi-automatic and takes about 4 hours to calibrate the 48 projectors (on average 5 minutes per projector). Most of the time is used to measure the gamuts of the individual projectors with a colorimeter.

Figure 12 shows the different calibration steps. The leftmost image is a mid-gray uniform image without calibration. The intra-projector correction (middle image) makes the individual tiles uniform, but large chromatic shifts are still visible. The inter-projection calibration (rightmost image) reduces these shifts. Figure 13 shows an example of a street scene before and after correction.

7 Conclusion and future work

We presented a two-step method for calibrating the colors of a tiled display. After having calibrated the camera to serve as a luminance measuring device, we used the advantages of

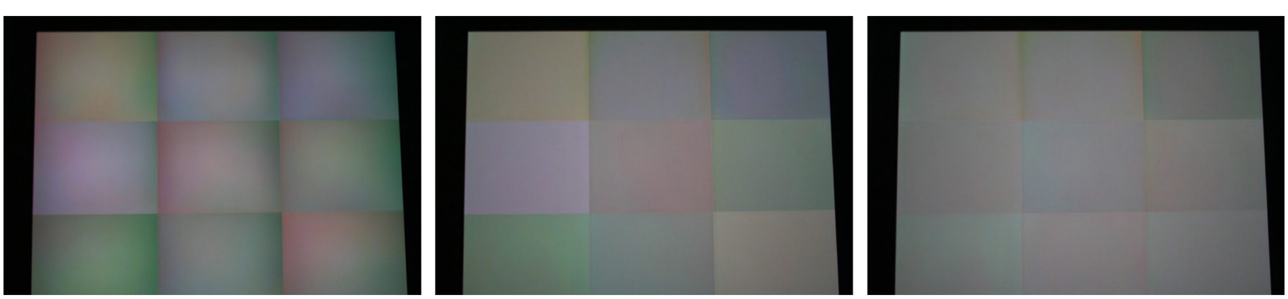

FIGURE 12 — A subpart of the wall with nine projectors before any calibration (left), after intra-projector calibration (middle), and after inter-projector calibration (right).

FIGURE 13 — Example of corrected image: before correction (left), after intra-projector and inter-projector calibration (right).

input manipulation for a fast intra-projector calibration and derived an interative algorithm that uses 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 with the advantage of fast computation of the common gamut. The individual parts of this calibration method 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 an intra-projector gamut matching could reduce the spatial non-uniformity of the colors. We could therefore adapt the gamut matching algorithm to a new type 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.

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