47.2: Luminance Management for Seamless Multi-Projector Displays

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Abstract

Multi-projector displays exhibit severe luminance variation. Matching luminance at every pixel to the pixel with most limited luminance range leads to severe degradation in the dynamic range of the display, rendering it practically useless. We present a new optimization technique to manage the luminance in a smooth constraint manner to maintain a perceptual seamlessness while improving the dynamic range of the display dramatically.

1. Introduction

Multi-projector displays, built by tiling multiple commodity projectors partially overlapping each other, offer an inexpensive way to create scalable, high-resolution life size displays that are popular for applications like scientific visualization and virtual environments for training, simulation and entertainment. Images from multi-projector displays should look seamless, i.e. they must appear to be projected from a single display device. The main challenges in achieving this seamlessness are the geometric misalignment and the color variation across the display (Figure 1).

Figure 1: Digital photographs of tiled multi-projector displays showing the geometric misalignment and color variation problem. Top left: Geometric misalignment at the boundary of two overlapping projector; Top right: The geometry is aligned by applying camera based automated geometric registration technique; Bottom left: Example of severe color variation across a display made of abutting projectors when every pixel is projecting the identical input of maximum intensity for green. Bottom right: A tiled display made of a 3 x 5 array of fifteen projectors (10' x 8' in size) with perfect geometric registration, but with color variation.

2. Previous Work

Initially, geometric calibration was achieved using precise manual alignment of projectors via expensive custom made mounts with six degrees of freedom and color seamlessness was achieved using expensive projectors with high precision optical elements like filters and Fresnel lenses. This, in turn, demanded an expensive maintenance crew to keep the display up and running at all times. Thus, such displays were rigid and expensive, making them the 'luxury' of high-tech institutes like universities and national laboratories. With the recent advancement in projection technology, commodity projectors have opened up the potential of using such displays in more common application like classrooms of educational institutes for teaching purposes; museums to explore historic sites in immersive interactive VR environments; airports, malls and trade-shows for advertising; and hospitals and medical centers for effective information transfer amongst the doctors, technicians and patients.

Several automated camera based geometric alignment techniques have been designed in the recent past to aid easy deployment and maintenance of multi-projector displays (Figure 1)[1,2,8]. But the color variation continues to be a significant obstacle. The spatial color variation in a multi-projector display can be severe (Figure 1) with many factors contributing to it. The most salient are commodity optics of projectors causing a center-to-fringe fall-off in luminance (commonly called the hot-spot effect) pronounced by distance attenuation of light and non-Lambertian screens, variation in age of projector lamps and properties of filters across different projectors causing difference in color across the projectors, and partial overlaps across adjacent projectors causing higher brightness overlap regions [3].

The color variation problem can thus be broken down into two parts: the variation in luminance and the variation in chrominance (hue and saturation). For most current displays, made of same brand projectors, the chrominance variation is negligible when compared to the luminance variation. In addition, humans are more sensitive to luminance variation than to chrominance variation [11]. Thus, luminance variation is the most significant contributor to the color variation problem.

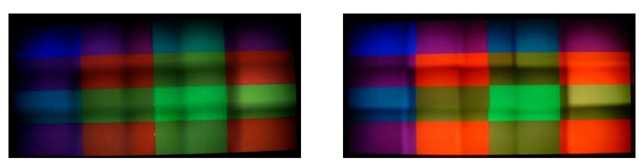

Figure 2: Digital photograph of a display made of 3x5 array of fifteen projectors using feathering techniques in the overlap regions across adjacent projectors. Left: Software blending. Right: Hardware blending realized using a metal bar on the optical path of each projector. Note that the number of projectors in the display can be easily deciphered

Initial color compensation techniques used feathering to blend the high brightness overlap region with the adjacent non-overlap region using software, or hardware/optical masks on the light path

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Figure 3: Digital photographs of a 3x5 array of fifteen projectors (a) Before luminance correction. (b) After matching the luminance of all pixels to the pixel with most limited luminance range. (c) After smoothing the luminance across the display by minimizing the perceptible variations while maximizing the dynamic range.

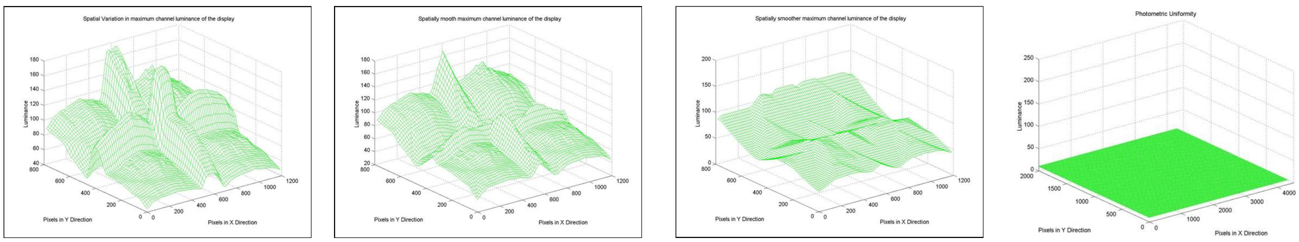

Figure 4: This figure shows the modification of L for different values of k in a 2x2 array of four projectors. L(x,y) (a), L'(x,y) for k = 0.0025 (b), for k = 0.00125 (c) and for k=0 (d). k=0 is the special case of luminance uniformity.

of the projectors [1,9,10]. To remove the variation due to projector lamps, engineering solutions were designed to replace the lamps of different projectors with a single high-power lamp from which the light was distributed to the projectors via optical fibers [7]. However, these methods did not estimate the spatial color variation accurately and hence resulted in softening the seams rather than eliminating them entirely (Figure 2). Next generation methods assumed that variation within a single projector does not exist (ignored the hot-spot effect) and used low resolution sensors like spectroradiometer to measure the color gamut at one spatial location for each projector and then applied gamut/luminance matching across the projectors [4,5,6]. Recently, a commodity digital camera was used to capture the spatial luminance variation at high-resolution both across and within projectors which was then removed to achieve a strict luminance uniformity by matching the response of every pixel in the display to the pixel with the most limited luminance range [3]. But, this resulted in severe compression in the dynamic range of the display, making it practically useless (Figure 3).

3. Main Contribution

In this paper, we present a luminance management algorithm that instead of aiming for a strict luminance uniformity, allows the luminance to vary smoothly across the display in a constrained fashion so that the variation is imperceptible to the human eye. This smoothing provides the leverage to increase the dynamic range of the display. We pose this as an optimization problem where the luminance variation is minimized using quantitative perceptual factors while the dynamic range of the display is maximized. The optimization is solved using a dynamic programming method resulting in dramatic improvement in the display quality (Figure 3). The correction is applied in real-time at interactive rates using commodity graphics hardware resulting in a seamless, high-quality, and usable multi-projector display.

4. Method

Our luminance management algorithm works in three steps.

1. First, the spatial luminance variation, *L(x,y)* of the multi-projector display is estimated using a commodity digital camera. *(x,y)* denotes the spatial display coordinates. For this, techniques described in [3] are used which depend on geometric calibration techniques presented in [2].
2. Next, the dynamic programming method is applied to *L(x,y)* to achieve a seamless, high-dynamic-range luminance response *L'(x,y)* that follows the optimization constraints and the objective function described in Section 3.1.
3. Finally, from *L(x,y)* and *L'(x,y)*, an attenuation map for each projector is generated that is used for per-pixel luminance attenuation of the projected image to achieve the seamless display

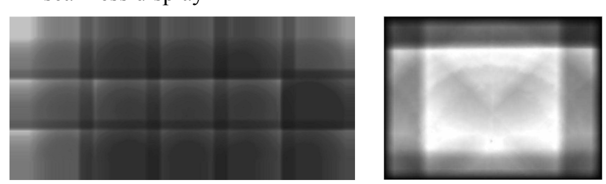

Figure 5: Left: A(x,y), the attenuation map for a 5x3 array of fifteen projectors. Right: The attenuation map for a single projector cut out from the attenuation map of the display.

3.1 Smoothing Luminance Response

We pose the smoothing of *L(x,y)* to *L'(x,y)* as an optimization problem defined by the following constraints.

1. $L'(x,y) \leq L(x,y)$ assures that the modified luminance response does not exceed the maximum luminance that each pixel is capable of projecting.
2. $\partial L'/\partial x \leq kL'$ assures that the spatial variation in *L'(x,y)* is smooth enough to be imperceptible to the human eye. This equation is derived directly from the contrast sensitivity function of humans [11] and is controlled by the parameter *k*, that we call the *dynamic range parameter*.

As k decreases, the dynamic range of the display decreases, but the smoothness of the luminance response increases. For $k=0$, the luminance response is flat and hence a strict luminance uniformity is achieved leading to compressed dynamic range [3]. The $L(x,y)$ *and* $L'(x,y)$ for different values of k is illustrated in Figure 4.

3. Of all the feasible $L'(x,y)$ generated by the above two constraints, the one that maximizes the total dynamic range of the display, given by $\sum L'(x,y)$ over all pixels (x,y), is the optimal solution.

We have designed a fast and efficient dynamic programming method that solves this optimization in linear time with respect to the number of pixels in the display. The time taken to compute this solution on Intel Pentium III 2.4GHz processor for displays with 9 million pixels is less than one second. The pseudocode for the algorithm, for a display of XxY pixels, is given in the appendix.

3.2 Attenuation of the Projected Image

The *attenuation map of the display*, defined by $A(x,y) = L'(x,y)/L(x,y)$ defines the pixel wise attenuation factor by which the luminance should be attenuated to achieve the smooth luminance response $L'(x,y)$ instead of the original response $L(x,y)$. Next, using the geometric calibration information generated while capturing $L(x,y)$, the *attenuation map for each projector* is generated from the attenuation map of the display (Figure 5). To achieve the luminance response $L'(x,y)$, every image projected from the projector is multiplied by this attenuation map in real-time. This correction is achieved at interactive rates using the pixel shaders of commodity graphics hardware. The seamless display achieved by this method for different values of k is illustrated in Figure 6 and 7.

4. Conclusion

In this paper we present a new method that quantifies the effects of human contrast sensitivity functions and applies it effectively in generating a display which is not strictly uniform but generates a perception of seamlessness successfully. To the best of our knowledge, this is the first work in automated color calibration of multi-projector displays that addresses the different types of spatial luminance variation across the display (within a single projector, across different projectors and in the overlap region) in a unified manner to achieve a seamless high-dynamic-range display at interactive rates.

5. Acknowledgements

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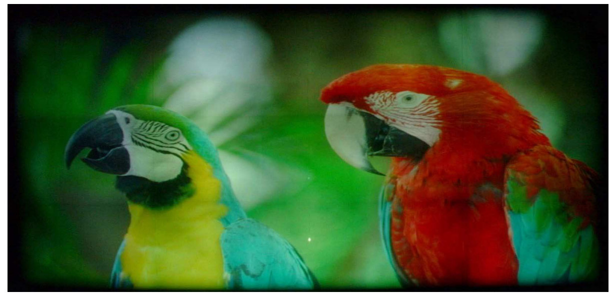
(a)

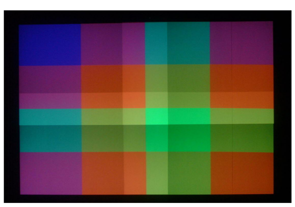


(b)

(c)

(d)

Figure 6: Digital photographs of a fifteen projector tiled display. Before any correction (a), after luminance smoothing for k = 0.0025 (b), for k= 0.00125 (c) and after luminance uniformity i.e. k = 0 (d). Note that the dynamic range of the display reduces as k decrease and for special case of luminance uniformity the dynamic range of the display is very low.



(a)

(b)

(c)

(d)

Figure 7: Digital photographs of displays made of 2 x 2 of four projectors (a, b) and 2 x 3 array of six projectors (c, d) of size 1.5′ x 2.5′ and 3′ x 4′ respectively.(a, c): Before correction. (b, d): After luminance smoothing. Note that we are able to achieve seamlessness even for flat colors, the most critical test for our algorithm.

Appendix

Algorithm *Smooth-Luminance(k, L)*

Input: Smoothing parameter k

Maximum Luminance Response of the Display L

Output: Smooth Maximum Luminance Response of the Display L'

forall (x, y), $L'(x, y) = L(x, y)$

for $x = 0$ **to** $X - 1$, **for** $y = 0$ **to** $Y - 1$

$L'(x, y) = \min(L'(x, y), (1 + \sqrt{2}k)L'(x - 1, y - 1), (1 + k)L'(x - 1, y), (1 + k)L'(x, y - 1));$

for $x = X - 1$ **down to** 0, **for** $y = 0$ **to** $Y - 1$

$L'(x, y) = \min(L'(x, y), (1 + \sqrt{2}k)L'(x + 1, y - 1), (1 + k)L'(x + 1, y), (1 + k) L'(x, y - 1));$

for $x = 0$ **to** $X - 1$, **for** $y = Y - 1$ **down to** 0

$L'(x, y) = \min(L'(x, y), (1 + \sqrt{2}k) L'(x - 1, y + 1), (1 + k) L'(x - 1, y), (1 + k)L'(x, y + 1));$

for $x = X - 1$ **down to** 0, **for** $y = Y - 1$ **to** 0

$L'(x, y) = \min(L'(x, y), (1 + \sqrt{2}k) L'(x + 1, y + 1), (1 + k) L'(x + 1, y), (1 + k)L'(x, y + 1));$