Properties of Color Variation Across a Multi-Projector Display

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Abstract

Large area multi-projector displays are becoming increasingly popular for scientific visualization and virtual reality applications. Though most of the geometric calibration issues for such displays have been addressed in the past, the color variation across the display is still not addressed in a comprehensive fashion. The two major components of this color variation are the color non-uniformity within a single projector's field of view termed as intra-projector variation and the variation across different projectors termed as inter-projector variations.

Understanding the properties of the color variation across a multi-projector display can help us make simplifying assumptions which in turn can render the problem of achieving color uniformity in such displays tractable. In this paper we study the properties of intra-projector variations in different kinds of projectors. We investigate the validity of the assumptions of channel constancy, spatial homogeneity, spatial uniformity and response non-linearity in case of projectors. It has been shown before that such assumptions for display devices like CRT monitors and LCD panels are valid or can be modeled by simple mathematical functions. We will show that the projectors are quite different in this respect and some assumptions that can be safely made about some of the other display devices cannot be made for projector.

1. Introduction

Large area high resolution multi-projector displays have the potential to change the way we interact with our computing environments. These high resolution life-size displays have several advantages over small screen monitors. The high resolution and large field-of-view make them extremely useful for visualizing large scientific models. Further, the compelling sense of presence created by such displays make them suitable for creating immersive virtual environments for 3D teleconferencing and entertainment purposes. Several such displays currently exist at Princeton, University of North Carolina at Chapel Hill, University of Minnesota, University of Illinois at Chicago, Stanford, MIT, Fraunhofer Institute (Germany) and United States National Laboratories like Argonne, Sandia and Lawrence Livermore National Laboratories. Recent efforts are directed towards building large displays comprising of 40-50 projectors (Sandia National Labs and National Center for Supercomputing Applications at University of Illinois at Urbana Champaign).

There has been considerable work on geometric registration [7,8], rendering architecture, algorithms and human interface [5.6] for multi-projector displays. But color variation across these display systems still continues to be a difficult problem. Further, there has been work in overlapping projector displays [11] where matching the colors of the overlapping projectors is required. In all such applications understanding the nature of color variation across a multi-projector display can help us make simplifying assumptions that can make the problems of color calibrating multi-projector or overlapping projector displays tractable.

In this paper, we define a simple parametric space to define the intra-projector color variation of a multi-projector displays. The parameters are space, time and input. Given a fixed input and time, the nature of the change of color over space characterizes *spatial color variation characteristics*. Similarly, given the same pixel location and input, the change in color with time defines *temporal color variation characteristics*. Finally, for the same pixel location and time, the color response with changing input defines *input response characteristics.* We analyze all three types of color variations for multi-projector displays. We show that multi-projector displays are different from traditional displays in many ways and hence assumptions that can be safely made about other display devices cannot be made for these displays.

2. Analysis

Projectors are inherently different from the traditional display devices because the physical device space is decoupled from the display space. Hence, projectors can be tiled in a seamless fashion when other devices cannot be used for such seamless tiling. As a result, the color characteristics of such tiled displays are unique and needs a separate study. It is important to point out here that we investigate off-the-shelf inexpensive commercial projectors which are more likely to be used for creating large area multi-projector displays.

2.1 Input Response Characteristics

The way the color of a projector changes with changing input at a particular pixel location at a particular point of time defines the input response characteristics of a projector.

Channel Constancy: The property of channel constancy assumes that the color projected at a pixel is a linear combination of the color projected by the maximum values of the red, green and blue channels alone when the values of the other two channels are set to zero. This property is indeed true for CRT monitors [1]. This can be represented mathematically as,

$$C(r,g,b) = C(r,0,0) + C(0,g,0) + C(0,0,b), \quad 0.0 \le r,g,b \le 1.0$$

where $C(r,g,b)$ denotes the color projected by input (r,g,b).

This property indirectly indicates that for increasing inputs values along each channel the chrominance of the projected colors remains constant while only their luminance changes in a monotonic fashion.

Unlike CRT monitors, the amount of light projected by projectors for black (the input $(0,0,0)$) is not exactly zero. We call this the black offset. This makes the color constancy assumption for projectors invalid. As a result, Figure 1 shows that the chromaticity coordinates for increasing input values for the red,

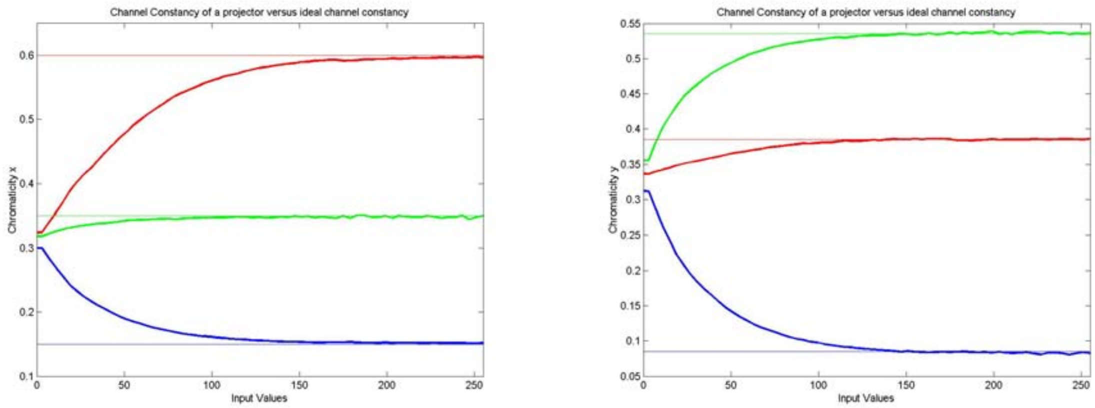

Figure 1. Plot of chromaticity coordinates against input values for the three channels

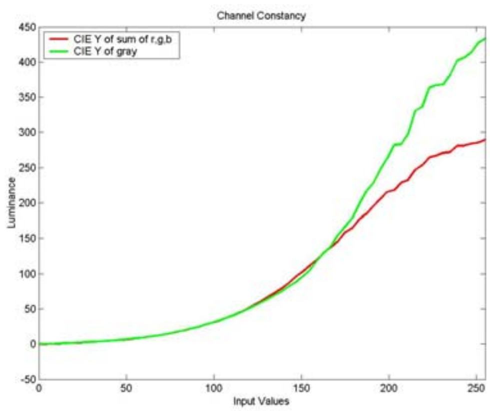

Figure 2. Channel constancy for DLP projectors with white filter

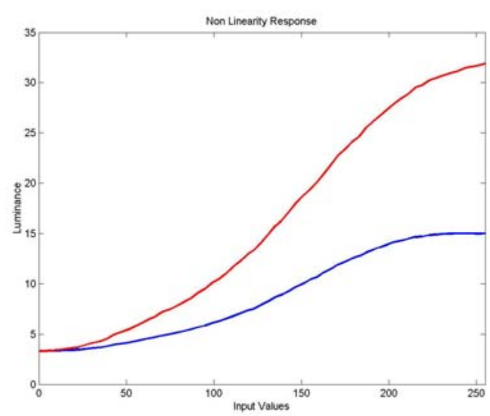

Figure 3. Non-Linearity Response of Projectors cannot be approximated by a simple power function

green and blue channels are not constant. This shows that projectors do not have channel constancy. A response of an ideal device is shown by the thin red, green and blue lines. However, this black offset can be mathematically modeled by a linear constant term as

$$C(r,g,b)-C(0,0,0) = C(r,0,0) - C(0,0,0) + C(0,g,0) - C(0,0,0) + C(0,0,b) - C(0,0,0),\ \ 0.0 \le r,g,b \le 1.0$$

However, it is important to point out here, that the input response characteristics of some DLP cannot be modeled even by the above equation. They deviate substantially from channel constancy. On investigation, we found that the reason for this is not the black offset but the use of a completely different extra filter for projecting the grays which does not have any relationship with the red, green and blue filters to actually satisfy such an assumption. Figure 2 shows this effect. The red line shows sum of the luminance of input of red, green and blue channels measured separately. The green line shows luminance of gray of the same input value. The red and green curves in the graph should be coincident in case of a device that follows channel constancy. In case of deviation due to black offset, there should be a small constant distance between the two curves. The substantial difference as is seen in this plot indicates that this deviation is not due to the black offset, as was corroborated by our findings.

Nature of non-linearity: It has been shown before that the CRT monitors have a non-linear luminance response which resembles a power function [1,3,4]. This subsumes a monotonic nature of the response. Unlike this, we found that the projectors have S-shaped non-monotonic response as shown in Figure 3 (for two channels of a projector). However, in most cases, the shape of the curve in the monotonic region can be modeled in the normalized scale by a power function and an offset. Mathematically, if the monotonic region lies between $k1 \ge 0.0$ and $k2 \le 1.0$, then

$$C(k,0,0) = \{ (k-k1)/(k2-k1)\}^{\gamma} + C(k1,0,0)$$

where $C(k,0,0)$ is the normalized response of input $(k,0,0)$.

2.2 Temporal Variation

In this section, the temporal color variation at the same spatial location for the same input is investigated. It has been shown that display devices like CRT monitors or LCD panels [1,2] are temporally stable. But this is not true for the projectors because of the aging of the bulb. As the bulb of the projector ages, there is marked decrease in the luminance response of the projector.

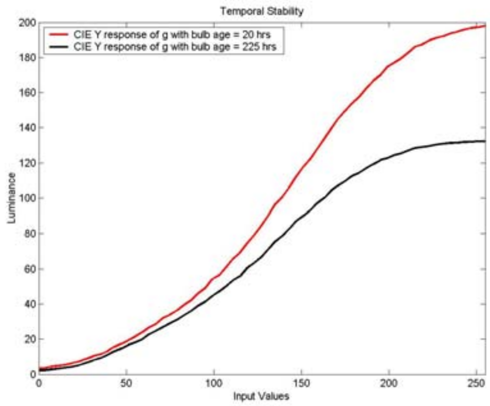

Figure 4. Change in luminance response of a single channel with bulb age.

For example, Figure 4 shows that after 200 hrs of use, the luminance of a channel can reduce by close to 35%. This indicates that most of the multi-projector display needs periodic recalibration.

2.3 Spatial Variation

The two major components of spatial color variation are the color non-uniformity within a single projector's field-of-view termed as intra-projector spatial color variation (Figure 5a) and the variation across different projectors termed as inter-projector spatial color variations (Figure 5b) [10].

2.3.1 Intra-Projector Spatial Variations

Nonlinearity Response Characteristics: We found that though non-linear response is not identical at every pixel location but its shape is similar in a normalized scale. Hence, for all practical purposes, one non-linearity correction look up table can be used to correct for the projector's non-linearity at all locations.

Luminance and Chrominance Characteristics: It is true that most traditional display devices are spatially inhomogeneous. But, the projectors are rather an extreme in this aspect. Our studies show that intra-projector luminance variation is large when compared to other display devices. We took measurements at five equally spaced location on the projector diagonal. We name the locations from 1 to 5 starting at the top left corner position. The results are shown in Figure 6. The luminance falls from the center of the projector towards the corner in a radial fashion. We have seen a decrease of about 80% from the center to the edges as shown in Figure 6. It has been shown before for the CRT monitors that the spatial inhomogeneity can be accounted for by a single scale factor [1]. Again, this is not true in case of projectors because of the black offset. Further, we

Figure 5(a) (left) shows a four projector display when the same color is input to all the pixels. This illustrates how the output color for the same input can differ even within a projector's field of view. Fig 5(b) (right) shows a simple two projector display

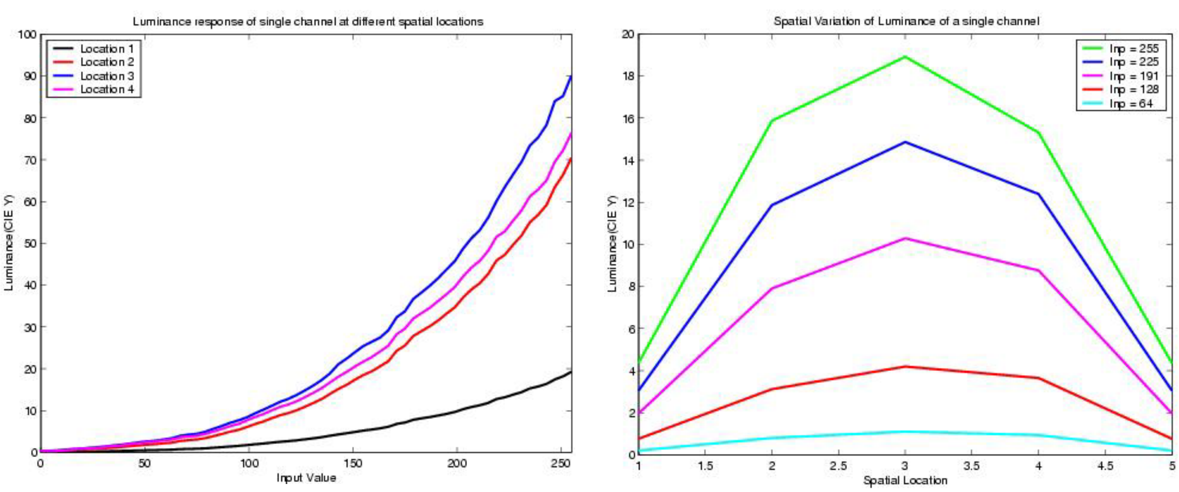

Figure 6. Left: Luminance response of the red channel plotted against input at four different spatial locations; Right: Luminance contour of different inputs of red channel plotted against spatial location. The responses are similar for other channels.

have also seen irregular blotched which makes it difficult to find a closed form function dependent on the pixel location for the scale factor. Hence, it is difficult to model the variation within a single projector's field-of-view analytically. However, the chromaticity coordinates of the primaries within a single projectors field-of-view remains constant.

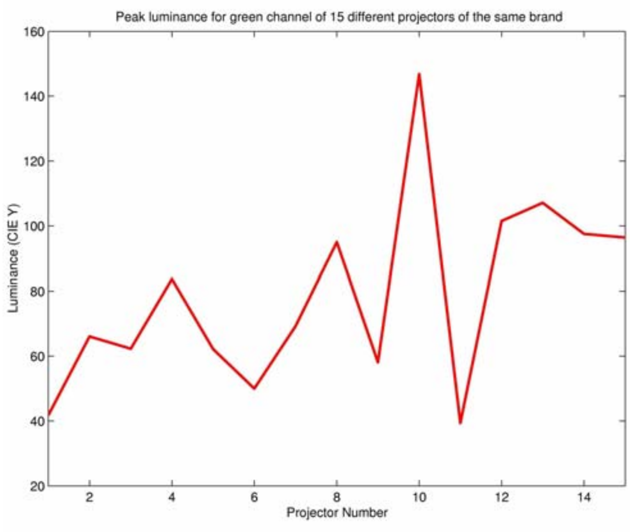

Figure 7. Luminance measured at the center of 15 different projectors.

2.3.2 Inter-Projector Spatial Variations

Inter projector variations in color arise not only from manufacturing differences like temporal variations in the age of the bulb and different filters, but also on positional parameters like pan, tilt, zoom and distance of the projector from the projection screen. Our studies show that the manufacturing differences lead to variation in both luminance and chrominance while the positional parameters affect luminance only. However, the chrominance variation across different brands of projectors is about 2-3% that can be ignored for all practical purposes. The following table summarizes our observation on measuring the average of the chromaticity coordinates of the three primaries for four Sharp XG-EG3000U, two NEC MT-1035, one nView D700Z, fifteen Epson 715c and two Proxima DX1 setup with identical positional parameters. Figure 7 shows the luminance variation across fifteen different projectors. From these, it is evident that the luminance variation is the primary cause of color variation across multi-projector displays.

Projector Brand	*Red*		*Green*		*Blue*	
	x	*Y*	*X*	*y*	*x*	*Y*
Sharp XG-3000U	0.62	0.32	0.33	0.62	0.14	0.07
NEC MT 1035	0.55	0.31	0.35	0.57	0.15	0.09
nView D700Z	0.54	0.34	0.28	0.58	0.16	0.07
Epson 715c	0.64	0.35	0.30	0.67	0.15	0.05
Proxima DX1	0.62	0.37	0.33	0.55	0.15	0.07

Table 1. Chromaticity Coordinates of different brands of projectors

4. Conclusions

The color variation across different display devices like LCD panels and CRT monitors have been studied before [2,3,4,9], but multi-projector displays have not been studied in the similar fashion till now. This paper discusses the nature of color variation across projector based displays. Thus, this work helps us to

- classify and identify the origin of different kinds of color variations arising in multi-projector displays,
- be aware of different kinds of simplifying assumptions that cannot be made for such displays,
- identify some important issues to concentrate on while designing better projectors, and
- better understand the issues to be dealt with while designing methods to achieve color uniformity across multi-projector displays.

5. References

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