Photometric Seamlessness in Multi-Projector Displays

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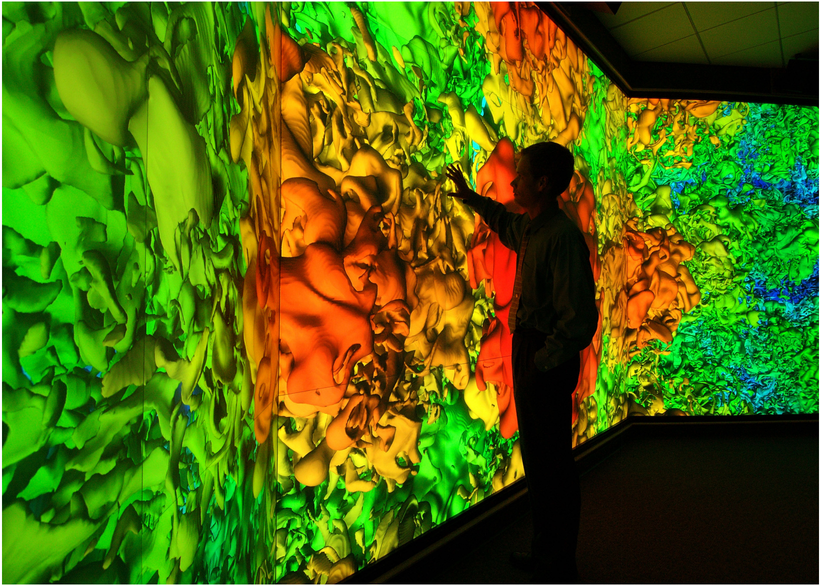
Outline

Introduction

VIEWS Display Wall



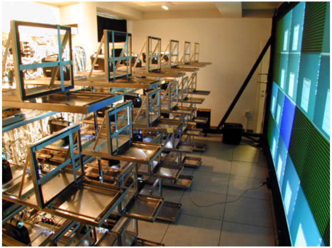
Why Projector based Displays?

- Scientific visualization,
- Immersive environments
- Entertainment applications . . .

'VIEWS' Display Wall at Sandia National Laboratory

- Driven by 64 PC's
- Resolution of 62 megapixels (48 x 1280 x 1024)

Issues



- Precise alignment of projectors is time-consuming.
- Ad-hoc arrangement introduces seams.
- Projector properties vary widely.
  - Luminance
  - Chrominance

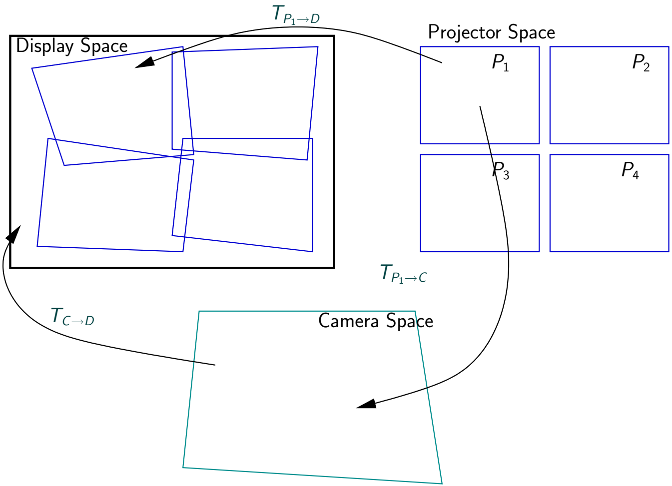
Steps to achieve a seamless display:

1. Geometric Alignment
2. Luminance and Chrominance Matching

Geometric Alignment

Geometric Alignment

Finding Projector→Camera→Display Warps



Calculation of Warps

- Geometric calibration is done to define the relationship between
  Projector pixels (x_{P_i}, y_{P_i}), Camera pixels (x_c, y_c) and Display pixels (x_d, y_d).
- Known static patterns are projected on the display and captured using the camera.

We retrieve the warps

$T_{P_i \rightarrow C}(x_{P_i}, y_{P_i})$ which maps (x_{P_i}, y_{P_i}) to (x_c, y_c)
$T_{C \rightarrow D}(x_c, y_c)$ which maps (x_c, y_c) to (x_d, y_d) and hence

$T_{P_i \rightarrow D}(x_{P_i}, y_{P_i})$ that maps from (x_{P_i}, y_{P_i}) to (x_d, y_d)

Luminance Matching[?]

Calibration Step

The following three stages make up the calibration step:

1. Measuring the Luminance Response
   - Luminance response of any pixel is defined as the variation of luminance with input at that pixel.
   - We measure this luminance response at every display pixel using a camera.
2. Finding the Common Achievable Response
3. Generating the Luminance Attenuation Map

Calibration Step

The following three stages make up the calibration step:

1. Measuring the Luminance Response
2. Finding the Common Achievable Response
   - Once the luminance response of every pixel has been measured, we find the common response that every pixel is capable of achieving.
   - This is called the *Common Achievable Response*.
3. Generating the Luminance Attenuation Map

Calibration Step

The following three stages make up the calibration step:

1. Measuring the Luminance Response
2. Finding the Common Achievable Response
3. Generating the Luminance Attenuation Map
    - We now generate a *Luminance Attenuation Map* per projector.
    - This transforms the luminance response of every pixel to the common achievable response.

Luminance Surface

Data Capture for Measuring the Luminance Functions(Maximum Input)

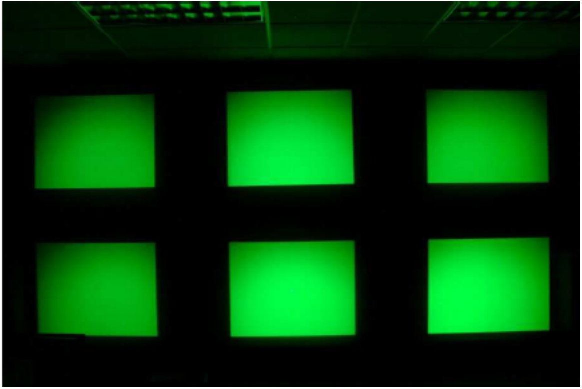


Figure: Green Channel Luminance Surface

Luminance Surface

Data Capture for Measuring the Luminance Functions(Maximum Input)

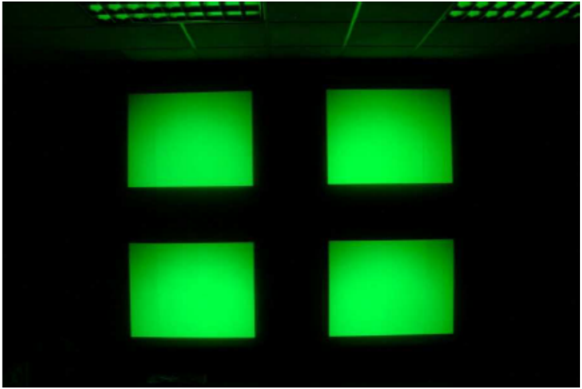


Figure: Green Channel Luminance Surface

Luminance Surface

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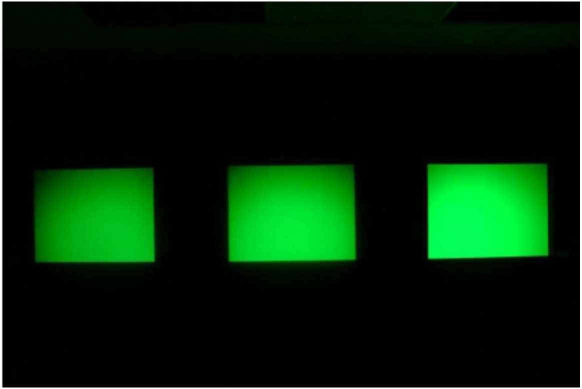

Figure: Green Channel Luminance Surface

Luminance Surface

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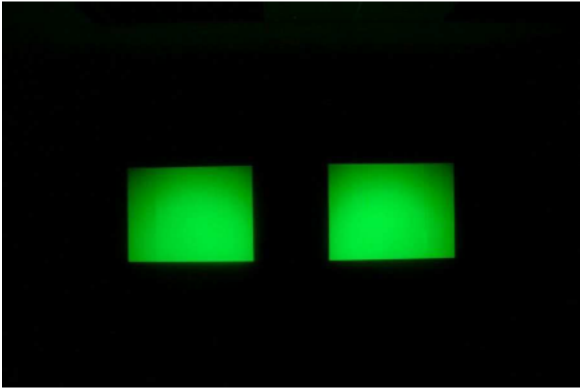
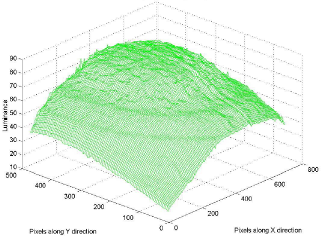


Figure: Green Channel Luminance Surface

Luminance Surface
for a Single Projector

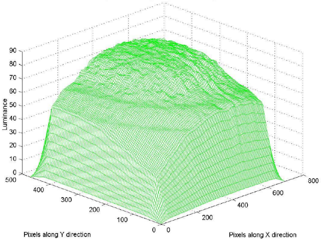


Luminance surface L_{P_i}

1. Each image I_i is linearized using the camera LUT. The images at max input are captured for every channel.
2. Luminance surface(camera coordinates) is generated by using the $RGB \rightarrow YUV$ transform $Y = 0.299R + 0.587G + 0.114B$
3. For each P_i, in projector coordinates

$$L_{P_i}(x_{P_i}, y_{P_i}) = I_i(T_{P_i \rightarrow C}(x_{P_i}, y_{P_i}))$$

Luminance Surface
for a Single Projector



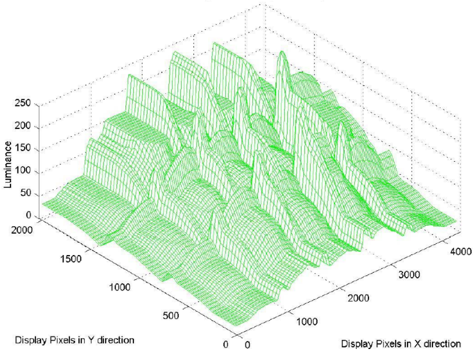
L_{P_i} After Edge Attenuation

1. Each image I_i is linearized using the camera LUT. The images at max input are captured for every channel.
2. Luminance surface(camera coordinates) is generated by using the $RGB \rightarrow YUV$ transform $Y = 0.299R + 0.587G + 0.114B$
3. For each P_i, in projector coordinates

$$L_{P_i}(x_{P_i}, y_{P_i}) = I_i(T_{P_i \rightarrow C}(x_{P_i}, y_{P_i}))$$

Luminance Surface for Display

In Display coordinates

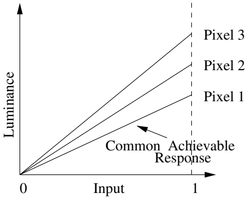


Summing up the contribution of every projector at (x_d, y_d),

$$L_d(x_d, y_d) = \sum_{i=1}^{n} L_{P_i}(T_{D\rightarrow P_i}(x_d, y_d))$$

Generating the LAM

Luminance Attenuation Map



Because of our assumption that projector responses are linear.

$$A_d(x_d, y_d) = \frac{L_{min}}{L_d(x_d, y_d)}$$

Per-projector LAM:

$$A_{P_i}(x_{P_i}, y_{P_i}) = A_d(T_{P_i}(x_{P_i}, y_{P_i}))$$

Image Correction

Using the LAM to attenuate projected images

- Image $M(x_d, y_d)$ is to be projected on the display.
- Part of the image to be projected by each projector P_i

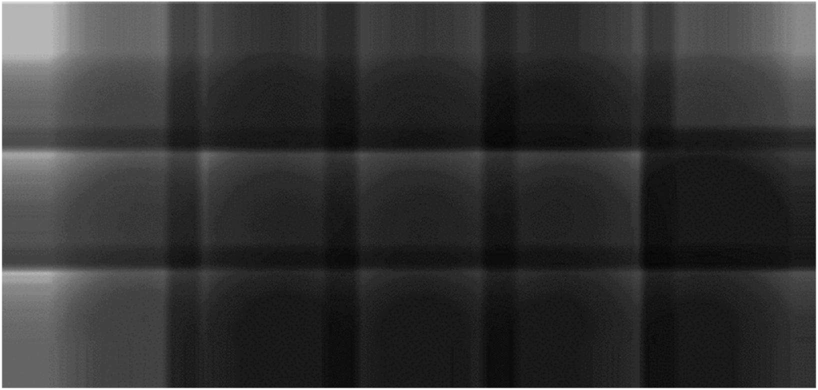
$$M_{P_i}(x_{P_i}, y_{P_i}) = M(T_{P_i \to D}(x_{P_i}, y_{P_i}))$$

Attenuated final image per projector

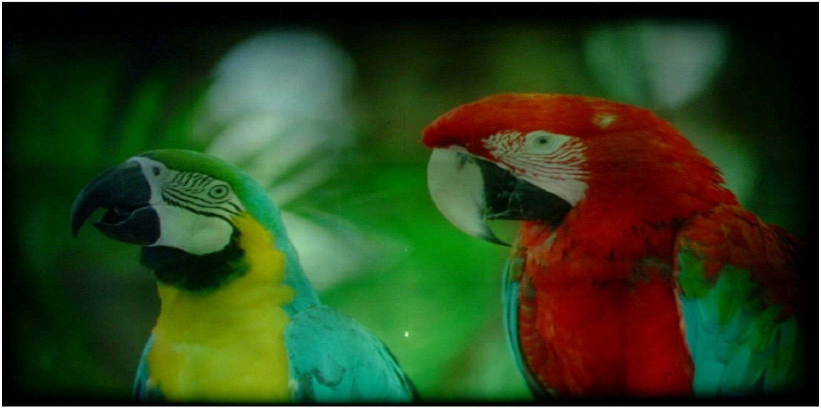
$$F_{P_i}(x_{P_i}, y_{P_i}) = M_{P_i}(x_{P_i}, y_{P_i}) \times A_{P_i}(x_{P_i}, y_{P_i})$$

Using the LAM to attenuate the image

Using the LAM to attenuate the image



Using the LAM to attenuate the image



Color Gamut Matching[?]

Full Color Gamut Matching (FGCM)

- Geometric alignment and luminance matching suffice for displays made of identical projectors
- Walls made of mixed DLP and LCD projectors need to be color matched.
- Color matching is harder
  1. Chromaticity values of RGB primaries of projectors of different brands are different.
  2. DLP projectors typically use a clear channel to boost the light output for bright colors.
  3. This results in non-additive gamut for the projector.

Color Gamut of a Projector

- Color transfer function

$$F : R^3 \longrightarrow R^3, (X, Y, Z) = F(r, g, b)$$

  - RGB triple (r, g, b) is sent to the projector.
  - Projector combines primaries to output color
  - From the spectrum of the output light, we get the *tristimulus values (X,Y,Z)*.

- **Color Gamut:** The subset of colors which can be accurately represented certain output device or in a given color space.
- Color gamut of a device with 8-bit depth.

$$G(F) = F(r, g, b) | r, g, b \in [0, 255]$$

Color Gamut of a Projector

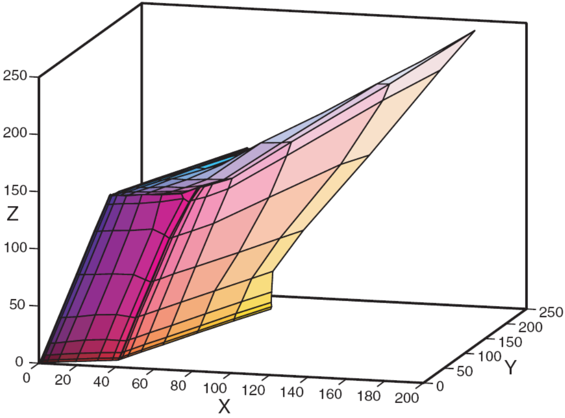


Figure: Color Gamut for a typical DLP projector

Color Map

- When gamut is not additive or device gamma is not set to 1.0 the transfer function becomes non-linear.
- Projectors must have a common color transfer function to look seamless.
- A linear model or even a piecewise linear model is not sufficient to model the gamut of a DLP projector.
- We need to use a 'Color Map' to achieve a common transfer function.

$$M : [0, 1, \ldots, 255]^3 \rightarrow [0, 1, \ldots, 255]^3, (r', g', b') = M(r, g, b)$$

Common Color Transfer function

Color Matching using the Color Map

- The color map is applied before the pixels are sent to the display.
- The final color transfer function can now be expressed as $F \circ M$.

The color matching problem can thus be stated as

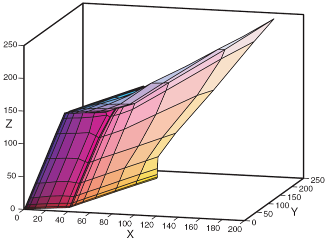
For each projector in $i = 1, \ldots, m$, find M_i such that

$$F_i \circ M_i = F_j \circ M_j, \forall i, j \in \{1, \ldots, n\}$$

Gamut of Projector

Gamut G(F) is the volume in XYZ space bounded by the following surface

$$S_1 = \{F(0, g, b) | g, b \in [0, 255]\}$$
$$S_2 = \{F(255, g, b) | g, b \in [0, 255]\}$$
$$S_3 = \{F(r, 0, b) | r, b \in [0, 255]\}$$
$$S_4 = \{F(r, 255, b) | r, b \in [0, 255]\}$$
$$S_5 = \{F(r, g, 0) | r, g \in [0, 255]\}$$
$$S_6 = \{F(r, g, 255) | r, g \in [0, 255]\}$$



- F is not measured at all the 2^{24} values, but only sampled at a lower spatial frequency.
- Because of the Gamma curve, F changes slowly at the lower end of RGB and faster as RGB values grow.

Common Color Gamut

Finding a Standard Color Transfer function

- If G_i is the gamut of the i'th projector, common gamut G_c is obtained from the intersection of all G_i

$$G_c = G_1 \cap G_2 \cap \cdots \cap G_n$$

- From G_c, we need to find F_s, the standard color transfer function

- The goal is to maximize volume of $G(F_s)$ such that $G(F_s) \subseteq G_c$

Projective Transform

$H : R^3 \rightarrow R^3$

$$F1, F2 : R^3 \rightarrow R^3$$

$$\begin{pmatrix} x' \\ y' \\ z' \\ w \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

Two color transfer functions are ‘projectively related’ if there exists a projective transform H such that

$$F_1 = H \circ F_2$$

Algorithm
to find the Standard Color Transfer Function

1. Pick one of the color transfer functions, say F_1
2. For each F_i, find and H_i such that the L2 distance of F_1 and $H_i \circ F_i$ is minimized.
3. Let

$$\bar{F} = \frac{1}{n}\sum_{i=1}^{n}(H_i \circ F_i)$$

Starting from the average shape of all gamuts allows us to preserve all the properties of the original color transfer function, such as its gamma.

4. Maximize the volume of $G(H_s \circ \bar{F})$ with respect to H_s such that $G(H_s \circ \bar{F}) \subseteq G_c$
5. The standard color transfer function is $F_s = H_{s,max} \circ \bar{F}$

Generating Color Maps

- M_i is the color map to be applied to projector P_i to give F_s

$$F_i \circ M_i = F_s$$

- thus

$$M_i = F_i^{-1} \circ F_s$$

- To emulate $\bar{F}$ in each projector, M_i is applied to the input before display.

$$F_s(r, g, b) \in G(F_s) \subseteq G_c \subseteq G_i$$

Results

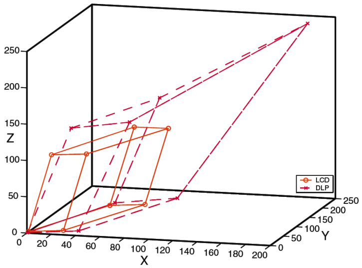


Figure: The FGCM algorithm applied to match the gamuts of an LCD projector and a DLP projector.

Summary

Summary

- Full Luminance matching across a display is sufficient when the projectors are of the same make.
- Color matching the gamuts of projectors of different brands is necessary because of chromaticity variation of the independent channels and also due to white enhancement.
- Issues that still need to be addressed include
  - Luminance matching and color balancing need to be integrated.
  - Color balancing displays to the level of perceptual seamlessness alone.

References I

Appendix

Measurement

Accurate measurement of color properties of display

The goal of them measurement process is to find the luminance and chrominance properties of different points of the tiled display accurately.

Two devices are used here

- **Spectroradiometer:** An expensive precision instrument to measure color projected by the projector.
  - Has a laboratory-calibrated device-independent color space.
  - Can measure only one point at a time at a very slow rate of 1-20 seconds per measurement.
  - Geometric accuracy is not guaranteed.

Measurement

Using a Camera as a Reliable Measuring Device

A **Camera** is used when the need is to find spatial color/luminance variation across a projector.

- The geometric correspondence between camera coordinates and projector coordinates is recovered.
- The non-linearity of the response of a camera is recovered and a color look-up-table is generated to linearize the response.
- The camera is used in a low-aperture setting to to prevent introducing additional spatial variation.
- The color gamut of the camera must contain the color gamuts of the projectors used in the display.

Measurement

Screen Material, View and Ambient Light

- Non-Lambertian screens amplify color variations depending on the viewing angle. This would affect images captured by a camera.
- But we are using a camera to correct the color variation for one viewer position.
- Ambient light is kept to a minimum if possible.
- When taking measurements on a projector, all adjacent projectors are turned off.

Intra-projector and Inter-projectorVariation

- Projectors have a non-constant black offset. The leakage light at zero input varies.
- DLP projectors have a separate clear filter used to boost output. This again might differ because of aging lamps etc.
- Luminance fall-off is due to distance attenuation of light.
- Projectors are not spatially homogeneous. Luminance at the fringes can fall by upto 80% for rear-projection systems.
- Color gamut however remains almost constant for projectors of same manufacturer.
- They are also not temporally stable with identical projectors of different ages having different luminance responses.

Definitions

Chromaticity Chromaticity is the quality of color determined by its ‘purity’ and dominant wavelength.

Purity Purity is roughly equivalent to ‘saturation’

Color Gamut The subset of colors which can be accurately represented certain output device or in a given color space.

Gamma The exponent in the equation that relates input values to a display and the output brightness. The human visual system is adapted to a gamma of 1.8 to 2.2

colorimeter Device that measures the tristimulus values (X,Y,Z)