

59.1: Invited Paper: A Display Simulation Toolbox

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Abstract

The Display Simulation Toolbox (DST) is an integrated suite of software tools that help the user characterize the key properties of display devices and predict the radiance of displayed images. Assuming that pixel emissions are independent, the DST uses the sub-pixel point spread functions, spectral power distributions, and gamma curves to calculate display image radiance. For LCD displays, the assumption of pixel independence assumption is reasonably accurate. For CRT displays it is not.

1. Introduction

The vast majority of image and video compression and coding tools are designed on the assumption that consumers view the images on one type of display – a conventional CRT. For example, digital cameras are typically designed to produce output for display on a standard sRGB display, which is a model of a CRT. Yet, most laptop and workstation computers are equipped with LCD displays whose color properties differ significantly from CRTs. Further, standard models of displays do not account for the spatial structure of the display pixels or their sub-pixel color components. The effect of such display features can be quite significant for the proper display of fonts and fine detail in images. This diversity of devices requires an expansion in the scope of image processing algorithms and metrics: such algorithms and metrics should include more information about display spatial and chromatic properties.

To understand how to best incorporate display information, we need a computational and empirical framework to characterize displays. Here we describe an integrated suite of software tools that provide such a framework. These tools help the user (a) characterize the key properties of display devices, (b) build images that contain controlled amounts of specific digital coding artifacts, and (c) predict the visibility of these artifacts given the display properties

2. Display Simulation Toolbox

The display simulation toolbox (DST) provides a framework that guides the estimation and simulation of the spatial-spectral radiance emitted from a display by any image. Calculating the spatial-spectral radiance is the useful input because, unlike the digital image values usually used for compression and coding, this is the stimulus that actually reaches the eye.

The DST uses three functions to predict the spatial-spectral radiance emitted by a display. First, the DST converts digital values into a measure of the linear intensity (display gamma). Second, the DST models the spatial spread of light using a point spread function for each color component (sub-pixel point spread function). Third, the DST uses the spectral power distributions of the display color primaries to calculate the spectral composition of

the displayed image. These three functions – the display gamma, the sub-pixel point spread functions and the spectral power distributions – are sufficient to characterize the performance of linear displays with independent pixels. Simplifying the process of modeling the radiance distribution makes it possible to use the radiance field as the input to objective image quality metrics.

The display simulation toolbox relies upon the assumption that displays can be modeled as linear elements controlled by digital values coupled to the display by a static nonlinearity (display gamma). We assume, for example, that the light emitted by each sub-pixel component (red, green and blue) can be described by a spectral power distribution and a spatial point spread function. The spectral power distribution describes how much light is emitted as a function of wavelength. The spatial point spread function describes how the light is distributed over space.

The display simulation toolbox models the pixel components as (a) space-wavelength separable functions and (b) sub-pixel independent. Separable means that the spectral power distribution emitted by a component is the same across the entire pixel. Formally, the spatial-spectral distribution of light emitted from the i^{th} sub-pixel can be defined by the product of two functions:

$$p_i(x, y, \lambda) = s_i(x, y)w_i(\lambda)$$

The function $w_i(\lambda)$ describes the spectral power distribution of the i^{th} sub-pixel. The function $s_i(x, y)$ is the spatial spread of the light from that sub-pixel. Sub-pixel independence means that the light emitted from a pixel is the sum of the light emitted by the pixel color components

$$p(x, y, \lambda) = \sum_i p_i(x, y, \lambda)$$

This additivity assumption means that the light emitted from the i^{th} sub-pixel does not depend on the intensity of the other sub-pixels.

We introduce notation to describe the usual static nonlinearity between the digital value, $\mathbf{v} = (R, G, B)$, and the emitted light, referred to as the display gamma. We describe the static nonlinearity for the i^{th} sub-component as $g_i(v)$. The i^{th} gamma function converts the digital controller values, $\mathbf{v} = (R, G, B)$, into the intensity of each sub-pixel. Taking all of these assumptions together, we expect the spatial-chromatic image from a pixel, given a digital input, (R, G, B) , to be

$$\begin{aligned}
 p(x, y, \lambda) &= \sum_i g_i(v) p_i(x, y, \lambda) \\
 &= \sum_i g_i(v) s_i(x, y) w_i(\lambda)
 \end{aligned}$$

These equations apply to the light emitted from a single pixel. We create the full display image by repeating this process across the array of display pixels. In so doing, we assume that the light emitted from a pixel is independent of the values at adjacent pixels. We refer to the spatial-spectral independence between pixels as display-independence (Brainard, 1989).

Farrell et al (2008) describe four conditions that are necessary for display-independence. First, the relative spectral power distribution of the display color primaries should be invariant as digital values increase (spectral homogeneity). Second, the spectral power distribution of any combination of pixel components can be predicted by the sum of the spectral power distribution of the individual pixel components measured separately (spectral additivity). Third, the relative spatial spread of each pixel component should be unchanged as digital values increase (spatial homogeneity). And fourth, the spatial distribution of light emitted by any combination of pixels is predicted by the sum of the spatial light distribution of the individual pixels (spatial additivity).

LCD displays meet all four conditions. For CRT displays, however, spatial additivity holds only for vertically adjacent pixels and fails for horizontally adjacent pixels [2, 3]. The failure of spatial additivity for CRT displays can be explained by sample and hold circuitry. CRT manufacturers use sample and hold circuitry to compensate for the slew rate limitations of the electron beam as it moves horizontally across the screen.

It is possible to create a more complex model for CRTs. For example, the failures of additivity can be used as an empirical basis for modeling the distortion introduced by the sample and hold circuitry. The measurements and subsequent simulations (see below) show that this added complexity is necessary to adequately characterize these CRT displays, and probably many others.

LCD displays are rapidly replacing CRT displays, both in the home and in the office. It is fortunate that most of the LCD devices we have tested satisfy the simple model properties. This makes it easier to calibrate, control and model these displays and thus predict their effect in the imaging pipeline.

3. Display Simulation

We can use the DST to predict the radiance emitted by images rendered on calibrated displays. The DST uses three functions to predict the spatial-spectral radiance emitted by a display. These functions are 1) the spectral power distribution, 2) the spatial point spread function, and 3) the static nonlinearity (gamma function).

We use a PhotoResearch PR650 spectrophotometer to measure the gamma functions and the spectral power distributions (SPD) of the color primaries for different displays.

We use a calibrated Nikon D100 digital camera with a customized lens and light baffle (Figure 1) to measure the spatial distribution of light intensity produced by red, green, blue and white pixels. The lens is a 20 mm focal length objective placed in the reversed direction. In this position, the lens magnifies the pixels by a factor of 10 on the camera sensor. In raw mode, the Nikon D100 produces

digital values that are linear with the display radiance. The spatial image, comprising 200 x 200 camera samples per display pixel, measures the spread functions at a spatial resolution of 1.5 microns per sample. This sampling rate is adequate to measure the spread of sub-pixels in all conventional displays. Figure 2 shows camera images of a white pixel illuminated on four different displays.



Figure 1. Nikon D100 digital camera with a customized lens and light baffle to measure the spatial distribution of light intensity produced by red, green, blue and white pixels. The lens is a 20 mm focal length objective placed in the reversed direction. In this position, the lens magnifies the pixels by a factor of 10 on the camera sensor.

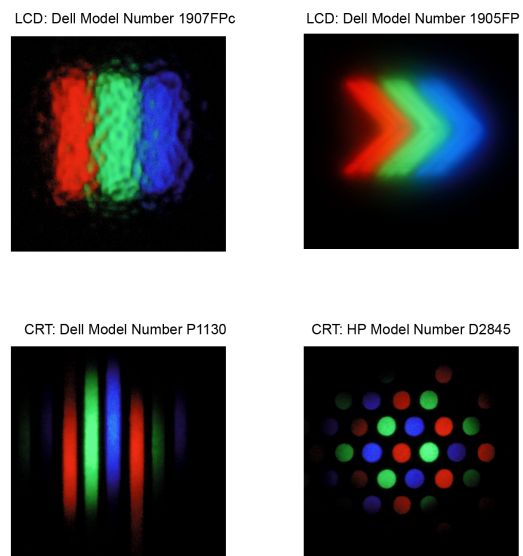


Figure 2. Camera images of a white pixel illuminated on a Dell LCD Display Model 1907FPc (top left), a Dell LCD Display Model 1905FP (top right), a Dell CRT Display Model P1130 (bottom left) and an Hewlett Packard CRT Display Model Number D2845 (bottom right).

To evaluate the accuracy of the display simulations we compare simulations of displayed images to measured display images. We used a calibrated Nikon D70 camera to capture images of a lower case 'g' (10 pt, Georgia) as rendered using the Microsoft ClearType technology on an LCD display (Dell LCD Display Model 1905FP) and a CRT display (Dell CRT Display model P1130).

We used the DST to compute the expected image radiance for this character on the two different displays. The prediction represents the screen at a spatial sampling resolution of 20 microns. We then used the simulated image radiance and an ISET-2.0 model of a Nikon D70 camera [4], to predict the camera RGB responses. In this way, we have a comparison of the predicted and observed Nikon images.

Figure 3 compares the measured and simulated characters for the LCD display. The point-by-point RMSE between the measured and simulated image is very small, 0.95%. This error is on the order of the camera measurement error. Hence, the display simulator produces a representation of the display radiance as accurate as the camera image.

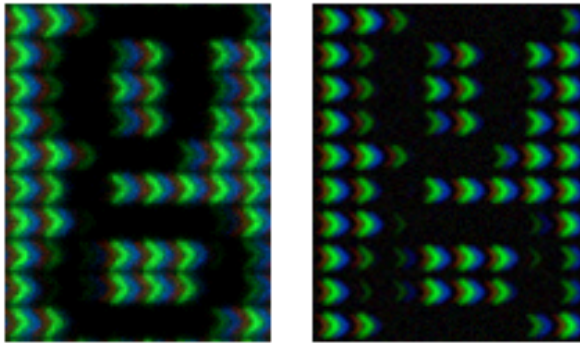


Figure 3. Comparison of measured and simulated characters. The image on the left shows the raw Nikon D70 sensor image of a character that was displayed on the Dell LCD monitor (Dell LCD Display Model 1905P). The image on the right shows the raw sensor image predicted by the DST simulation of the same character and the ISET simulation of the Nikon D70 camera. The two images appear to be green because they have not been color corrected.

Figure 4 compares the measured and simulated characters for the CRT display. There are noticeable differences between the measured (left) and simulated (right) images, revealing the failures of the DST model for this display. The point-by-point RMSE between the measured and simulated image is 3.1%. The prediction failures are anisotropic: errors in the horizontal direction are significantly larger than those in the vertical direction. We quantified this anisotropy by comparing the RMSE for the column sums and row sums separately. When we sum the column values, predicting the row sums, the RMSE is relatively low (2.7%). When we sum the rows, predicting the column sums, the RMSE is much higher (15.3%). The large horizontal errors can be traced to the failure of spatial additivity in this direction [2]. Additivity fails because the pixel intensity within a row does not switch off as rapidly as the additivity model predicts. Hence,

the measured column means differ substantially from the predicted column means.

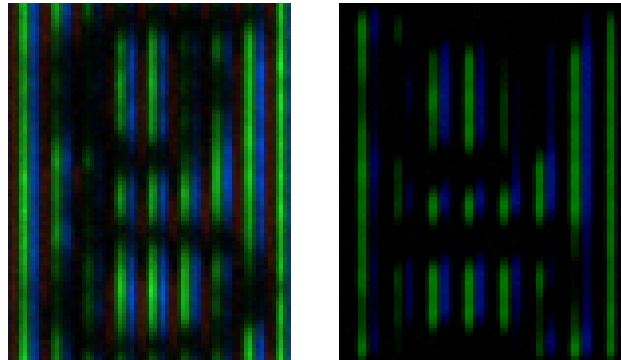


Figure 4. Comparison of measured and simulated characters. The image on the left shows the raw Nikon D70 sensor image of a character that was displayed on the Dell CRT monitor (Dell CRT Display Model P1130). The image on the right shows the raw sensor image predicted by the DST simulation of the same character and the ISET simulation of the Nikon D70 camera. The two images appear to be green because they have not been color corrected.

4. Conclusion

We describe a simulation technology that models the display image radiance from a small number of measurements. The model incorporates the sub-pixel point spread functions, spectral power distributions, and gamma curves. Using these inputs and the assumption that pixel emissions are independent, we can calculate the anticipated display image radiance.

We tested the model assumptions using data from two LCD displays and two CRT displays. For the LCD displays, the independence assumption is reasonably accurate. For the CRT displays it is not. We developed software to use the parameter measurements needed to implement the model and create a simulated display image. The simulations and measurements agree well for displays that meet the model assumptions and depart for displays that do not.

Display simulation is an important tool for the design and evaluation of imaging systems. For example, display simulation technology has been used to 1) evaluate the design of color matrix display pixel mosaics, [5]) characterize the angle-dependent color properties of LCDs [6], and 3) evaluate grayscale-resolution tradeoffs in digital typography [7]. We extend this prior work by modeling the spatial and chromatic properties of display pixels and predicting the radiance of a displayed image.

The display simulator saves considerable time and effort in predicting the radiance to a wide range of important calibration targets. Measuring the spatial-chromatic radiance from a display screen to each of these targets is a challenging and time-consuming experimental procedure. To obtain estimates of the radiance field involves the use of expensive radiometric equipment and high quality digital imagers and lenses. Making a relatively small number of measurements, and using these measurements to create a calibrated display model, permits the

user to investigate how the display will represent a wide variety of test images saving the time and expense of making additional measurements. The purpose of the Display Simulation Toolbox is to assist the user in capturing the information necessary for creating a simulation of the display, managing these data, and performing the final estimates of the radiance field.

The Display Simulation Toolbox models one component of an imaging system that may include other components, such as image acquisition and processing. By modeling these other components [4], it is possible to evaluate the effect that changes in these separate components have upon the perceived quality of the final output. A controlled simulation environment, then, can provide engineers with useful guidance that improves the understanding of design considerations for the individual parts and algorithms in a complex imaging system.

5. Acknowledgements

We gratefully acknowledge support from Microsoft Corporation, Nikon Corporation and Sharp Labs of America. We thank Greg Hitchcock, Tanya Matskewich, Scott Daly and Louis Silverstein for many helpful discussions. And we thank Dr. Ibrahim Sezan, Mr. Norihiro Aoki and Professor Bernd Girod for their continued support and encouragement.

6. References

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