Abstract

We describe an apparatus capable of displaying images with 1200 dpi resolution and 24 bit color. We used this display to simulate images printed at 200 dpi with varying levels of gray. We compared observers ratings of image quality for printed images with their ratings of displayed simulations. For both printed photographic images and displayed simulations we found that 1) optimal image quality was obtained when graylevels were equally spaced in L*, and 2) subjective image quality increased with increasing graylevels up to 32 levels beyond which observers could detect no perceptible change. Our results demonstrate that it is possible to simulate printed output on a 1200 dpi, 24 bit color display.

Introduction

In order to investigate the subjective image quality of color matrix displays (CMD), Silverstein et al (1990) built a CMD simulator based on a CRT monitor and an optical system that minified a virtual image of the monitor screen. The optical system was quite elaborate, (incorporating a laser optometer, rotating mirrors, prisms, lenses and shutters) enabling the investigators to vary both the virtual image distance and binocular disparity. We built a much simpler version of their simulator by limiting our optical system to monocular viewing. In this paper, we describe how we used this display system to simulate printed output.

Display Apparatus

Figure 1 is a simple illustration of the display apparatus which consisted of a 24 bit color monitor capable of displaying 2Kx2K images (Barco Chromatix, Model No. MX2500) enclosed at one end of a light-tight tunnel 13.5 feet long. At the other end of the tunnel was a small hole through which an observer could view images monocularly. Two 50 mm camera lenses were placed between the display and the viewer. The distance between the lenses, display and observer were such that a virtual image of the display was focused approximately 12 inches from the observer. At this viewing distance, a displayed image subtended approximately 8.2 degrees of visual angle. The virtual image was equivalent to a real image, 1.725 inches in height and width, displayed at 1200 dpi.

Figure 2 compares the transfer function of the 1200 dpi, 24 bit display with a transfer function estimated for photographic print (Higgins, 1971) assuming a 12 inch viewing distance, along with the human contrast sensitivity function (Campbell, 1968). The transfer functions for the display indicate that it is capable of producing images with spatial frequencies comparable to photographic print and beyond the limits of human resolution.

Figure 1: Simple illustration of display apparatus.

Figure 2: Comparison of transfer functions for 1200 dpi display, photographic print and human sensitivity, assuming a viewing distance of 12 inches.
Figure 3: Image processing pipeline for creating simulations of printed images

Printer and Display Calibration

Figure 3 illustrates the image processing pipeline used to generate the simulated and printed greyscale images. Device non-linearities were corrected in a two step process. First, a set of test patches ranging in grey values from zero to 255 were printed and displayed without any halftoning imposed. Reflective and emissive intensities were measured for the printed and displayed output, respectively. From these intensities, inverse look-up-tables (LUT) were generated to linearize the output devices. This stage corresponds to tone correction for printers and gamma correction for displays. Next, the test patches were printed and displayed using the full image processing pipeline including halftoning followed by tone correction (for printers) or gamma correction (for displays). Figure 4 shows a plot of the printed intensity of the test patches with halftoning versus intended intensity without halftoning. Clearly at two halftoning levels this is far from an ideal linear system. This non-linear behavior results from display slew rate limitations (Lyons and Farrell, 1989) and printer dot gain. To correct for this non-linearity, another inverse LUT is generated from these measurements (Trontelj et al, 1992). We refer to this LUT, which is placed before the halftoning stage, as our non-additivity correction. Figure 5 shows a plot of the printed intensity versus intended intensity for the test patches rendered with the non-additivity LUT in place.
Simulations of Printed Output

We used the display and the pipeline in Figure 3 to simulate images printed at 200 dpi on a monochrome grayscale printer. Beginning with a 2Kx2K 24 bit grayscale image, we decimated the image (low-pass filtering followed by sampling) to create the 200 dpi image. Next, we corrected for system non-additivity and halftoned the image to 2, 4, 8, 12, 16, 24, 32 and 256 levels of gray. Pilot experiments indicated that subjects could not discriminate between images displayed with 32 and 256 levels of gray. All images were halftoned in the L* domain using error diffusion (Floyd and Steinberg, 1975). To create the simulated image, we interpolated the processed image to its original size using a modified gaussian model of a printed dot. The standard gaussian shapes create sharp peaks when they overlap instead of smooth constant regions. We then gamma corrected before displaying the image.

The printed images were generated using the same pipeline except that the interpolation stage was unnecessary. These images were printed using a calibrated Kodak XL, 200 dpi thermal dye diffusion printer.

Subjective Image Quality

Subjects were shown the printed and displayed images at different times. In the printer condition, subjects were asked to rank order the images from worst to best in terms of image quality. They did this task for ten different sets of printed images, each set containing images printed with 2, 4, ..., 256 levels of gray. In the display condition, subjects were shown two images in each trial and asked which of the two images they preferred. All pairwise comparisons of the images were displayed ten times in a random order of presentation.

Image quality ratings for the printed images were obtained by the rank orderings averaged over 10 trials. Image quality ratings for the displayed images were

Figure 6: Image quality ratings plotted as a function of number of gray levels for displayed and printed images.
obtained by summing the number of times subjects preferred one image over the other. Figure 6 shows the image quality ratings for printed and displayed images. Not surprisingly, image quality increases with gray levels up to a point.

The data illustrated in Figure 6 points out both the strengths and limitations of the 1200 dpi 24 bit display. On the one hand, image quality ratings of the printed and displayed simulations are comparable; for fewer than 16 levels of grey they demonstrate similar increasing trends, and both asymptote somewhere between 16 and 32 levels of gray. This suggests that the display can be used to simulate printed output. On the other hand, for three of the subjects, image quality asymptoted at 24 levels of gray for the printed images and at 8 or 16 levels for the displayed images. In general, while both ratings follow similar trends, it appears that the display ratings lag the printer ratings. This suggests that the display is not a perfect simulator of printed output. Of course, there are many differences between the printed and displayed images. Most obviously, printed images are reflective media and displayed images are emissive. Also, we used a very simple and quite naive model of the printed dot. Despite these differences, however, the ratings for the printed and displayed images are remarkably similar.

Conclusions

We conclude that the display simulator, first introduced by Silverstein et al (1990) is a powerful tool for image quality evaluation and can be used to draw conclusions about printed as well as displayed image quality.

References


