Applications of a spatial extension to CIELAB

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ABSTRACT

We describe computational experiments to predict the perceived quality of multi-level halftone images. Our computations were based on a spatial color difference metric, *S-CIELAB*, that is an extension of CIELAB, a widely used industry standard. CIELAB predicts the discriminability of large uniform color patches. S-CIELAB includes a pre-processing stage that accounts for certain aspects of the spatial sensitivity to different colors. From simulations applied to multi-level halftone images, we found that (a) for grayscale images, L^*-spacing of the halftone levels results in better halftone quality than linear-spacing of the levels; (b) for color images, increasing the number of halftone levels for magenta ink results in the most significant improvement in halftone quality. Increasing the number of halftone levels of the yellow ink resulted in the least improvement.

1. Introduction

For many image systems engineering applications it is useful to predict the visual effect of changes in the imaging algorithms and hardware. In this paper we describe a set of computational experiments with a color difference metric, S-CIELAB, that was designed to evaluate image quality. We report on the metric's evaluation of the image quality of grayscale and color images reproduced using multi-level halftoning algorithms.

Metrics for predicting the visibility of color changes to large uniform portions of the visual field, such as CIELAB and CIELUV, have played an important role in setting engineering tolerances for color reproduction of large samples in the paint and dye industry. However, these metrics do not describe the visibility of color differences in patterned targets, such as images. Hence, we have implemented a spatial extension to CIELAB to account for how spatial pattern influences color appearance and color discrimination (Zhang and Wandell[1]) .

The spatial extension in S-CIELAB consists of three pre-processing stages. First the input image, which is normally represented in a device-dependent space, is converted into a device-independent representation consisting of one luminance and two chrominance color components. Second, each component image is passed through a spatial filter that is selected according to the spatial sensitivity of the human eye for that color component. Third, the filtered images are transformed into the CIE-XYZ format such that standard CIELAB color difference formula can be applied.

Because of the design of the spatial filters, for large uniform targets the S-CIELAB predictions are the same as the CIELAB predictions. For textured regions, however, the two formulae often make very different predictions.

2. Applications: Predicting quality of multi-level halftone images

2.1. Multi-level grayscale halftone

We evaluated image quality using two multi-level halftoning methods. We applied both methods to a simple grayscale target.

Test target In general, the halftone error size depends on the gray level of the original. Therefore, it is important to use a grayscale test image that spans a number of different gray scale levels. The grayscale test target we used was an exponential grayscale ramp that spanned 3 degrees of visual angle. The ramp profile was defined by the function:

$$Y = (X/3)^3 \times 73.$$

where X is the spatial position specified in degrees of visual angle, and Y is the intensity of the corresponding pixel. The Y values of this ramp ranged from 0 to 73, and the xy-chromaticity coordinates of the grayscales were constant at (0.29, 0.30). The simulation was run under the assumption that the observer viewed the target at a distance of 12 inches.

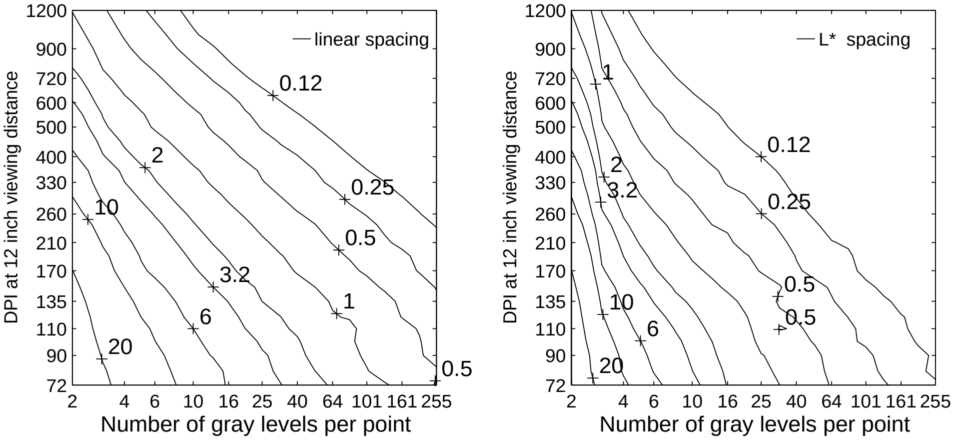

Figure 1. Iso-quality contour plots for grayscale ramp test image.

Halftoning algorithm The grayscale ramp target was halftoned at 27 different spatial resolutions (from 72 dpi to 1200 dpi) using a multi-level error diffusion algorithm. The number of halftone levels ranged from 2 levels (binary halftoning) to 256 levels. We performed multi-level halftoning using both linear-spacing and equal L^*-spacing of the halftone levels.

Iso-quality contours S-CIELAB differences between the original grayscale ramp and halftoned ramps were computed. For each combination of halftone resolution and number of levels, we calculated an S-CIELAB ΔE error map. The deviations between the original and the halftone consist of a large set of errors, one for each position in the image. We summarize the overall quality using the the 90th percentile of the ΔE values. We also measured the median, maximum and sum of squared ΔE values, and the results were all qualitatively similar to the 90th percentile results. Because the median does not capture the size of the largest halftone errors, the absolute maximum values are unstable, and sum of squared ΔE values is not meaningful, we chose to use the 90th percentile ΔE value to measure overall halftone quality.

The computational results are plotted in Figure 1 in the form of iso-quality contours. Quality measures are 90th percentile ΔE values so that smaller numbers imply better image quality. The top plot shows measurements using linear halftone level spacing; the bottom plot shows measurements using L^*-spacing of halftone levels. We make three observations about these plots.

1. These computations predict a grayscale-dpi tradeoff function for grayscale halftoning. For example, the plots show that a 1200 dpi binary halftone of the test pattern is approximately equivalent in quality as a 400 dpi four-level halftone image when the halftone levels are selected in L^*-spacing (bottom plot). The plots also show that an image with lower resolution and many levels of gray (e.g. 72 dpi with 256 levels) can look better than an image with higher resolution and fewer levels of gray (e.g. 1200 dpi with 2 levels). Dpi alone is an inadequate measure of printer quality (Farrell [2]).
2. When equated for the number of halftone levels, L^*-spacing of the levels is predicted to have better image quality than linear-spacing. For example, when using linear-spacing, a 1200 dpi 2 level halftone is equivalent in quality to a 300 dpi 15 level halftone, or a 150 dpi 50 level halftone; when using L^*-spacing, only 5 levels for the 300 dpi halftone and 16 levels for the 150 dpi halftone are needed to reach the same quality as 1200 dpi 2 level halftone. This result agrees qualitatively with the empirical observations by Anthony and Farrell [3] that L^*-spacing in multi-level halftoning gave better visual quality than linear-spacing.
3. Halftone errors do not decrease linearly with the increase of DPI or number of gray levels. As the number of halftone levels increase beyond 16, or dpi increases beyond 800, the halftone quality improves very little. Again, this agrees with empirical observations by Farrell and Anthony .[2,3]

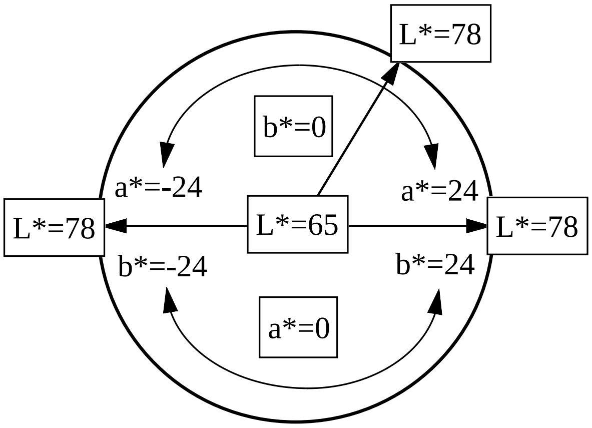

Figure 2. Illustration of the color test target

While S-CIELAB was principally designed as a color metric, these calculations show that the metric can be applied to grayscale images and generate meaningful predictions. Now, we apply S-CIELAB to predict color halftone image quality.

2.2. Multi-level halftoning of color targets

Test target To generate a color test target suitable for testing color halftoning, we created a disc pattern with colors sampled from the $L^*a^*b^*$ color space. The upper half of the disc has a* values from -24 to 24, with constant b* value 0. The lower half of the disc has b* values from -24 to 24, with constant a* value 0. From the center to the outer rim of the disc, L^* values change from 65 to 78. Figure 2 illustrates how the color test image was constructed. The test image size was 224x224 pixels.

Halftoning algorithm The color test pattern was halftoned using multi-level error-diffusion on the C,M,Y color planes independently. The XYZ values of the hypothetical C,M and Y inks were (39, 53, 86), (32, 17, 79), and (41, 55, 9), respectively. The XYZ value of "white" was (56, 63, 87). We assumed linear mixing of different inks. We did not use black ink for halftoning in this simulation.

The color test pattern were halftoned at 2, 3, 4, and 5 levels on (a) the C, M, or Y inks separately (use 2 levels on the other two inks), and (b) all three of the inks. The multiple halftone levels were selected according to L^*-spacing.

Results S-CIELAB errors between the halftoned images and the original test image were computed, assuming 300 dpi halftone resolution at a viewing distance of 12 inches. We plot the halftone error measure (90th percentile S-CIELAB ΔE values) as a function of number of halftone levels (Figure 3).

As the number of halftone levels increased, the S-CIELAB difference between the original and the halftone generally decreased. The improvement in halftone quality is greatest when we use multiple levels for all 3 inks together. Because using multiple levels on all inks is much more costly than using multiple levels of only one ink, we evaluated how much improvement could be obtained by allowing only one ink to have multiple halftone levels. The S-CIELAB predictions showed that increasing halftone levels on the magenta ink will produce the highest improvement in visual quality. Increasing halftone levels for the yellow ink on the other hand did not have much effect on the halftone quality.

This simulation result reflects the empirical observation that the human visual system is less sensitive to high spatial frequency chrominance contrast than to luminance contrast. The yellow ink has a Y value closest to "white", therefore putting down a yellow ink dot on the hypothetical white paper does not change the luminance of that point very much. Consequently, the halftone texture in the yellow color plane is not easily visible. Magenta ink is much

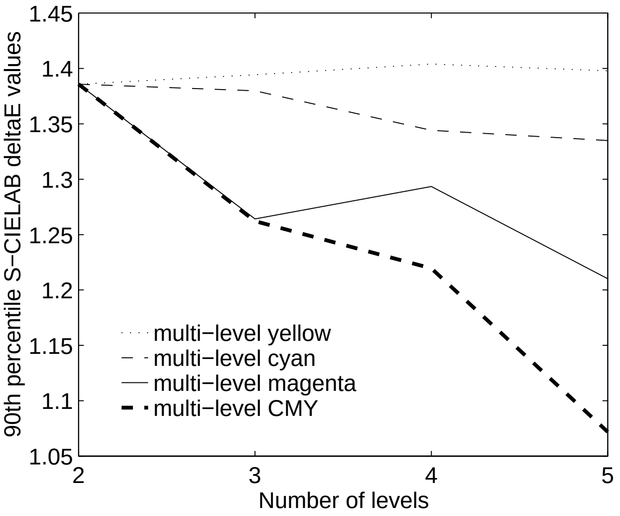

Figure 3. Comparison of using multiple ink levels on different inks. The thick line represents simulation results using multiple ink levels on all 3 inks. The thin lines represents simulations using multiple ink levels on one of the inks (with 2 levels on the other two inks).

darker than the white point so that the halftone errors in the magenta plane are in the luminance directions and much more visible: Adding magenta levels reduces these visible halftone errors. The spatial pre-processing of the S-CIELAB color metric captures some of this visual sensitivity effects.

3. Conclusions

The S-CIELAB calculation extends CIELAB by incorporating factors related to the pattern-color sensitivities of the human eye. The S-CIELAB color difference metric can be used to make predictions about such features of multi-level halftone image quality as grayscale/resolution tradeoffs. These predictions can be used to help make decisions about algorithms and hardware in the digital imaging pipeline.

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